Midden Volume, Harvested Fish Biomass, and Pre-contact Minimum Population Estimates for Nuu-chah-nulth Territories in Barkley Sound

by

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B.A., Humboldt State University, United States of America, 2012
M.A., University of Alberta, 2015

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Supervisory Committee

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Abstract

Coastal shell midden deposits are a quintessential element of the archaeological record on the Pacific Northwest Coast recording thousands of years of daily life. This dissertation develops a methodology which contributes to understandings of pre-contact Indigenous demographics and marine resource use in Nuu-chah-nulth Territories in Barkley Sound, British Columbia, Canada. This dissertation combines spatial analysis, zooarchaeology, and human metabolic requirements to provide estimates of the volume of midden sites, the harvested fish that they contain, and the minimum local human population that could have been supported from these fish. These archaeologically derived estimates of population and biomass are grounded in a computationally conservative theoretical framework which draws on archaeological data and minimizes the use of analogy and historical comparison. I use these models to estimate that known Barkley Sound shell midden sites contain 241,253 m^3 (± 21,712 m^3) of sediment and are features on par in size with better known monumental sites in the Americas. This estimate of annual marine resource harvests represents approximately 10% of modern fisheries catches and indicates that nearly 1.2 billion fish were harvested by Indigenous fishers over the last three millennia. The protein rich calories contained in midden fish biomass would be sufficient to support a population of nearly 1,000 individuals per day for this time period. This research offers a framework for creating volume, biomass, and ultimately population estimates in other coastal sites and has important implications for governance and natural resource policy in Indigenous communities especially for the Tseshaht, Toquaht, Uchuklesaht, Ucluelet, and Huu-ay-aht peoples who inhabited this area for millennia.

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List of Acronyms and Abbreviations

3D	Three dimensional
aDNA	Ancient DNA
BMI	Body Mass Index
cal BP	calibrated years before present
cm	centimetre
CNF	Canadian Nutrient File
EEZ	Economic Exclusion Zone
g	gram
GIS	Geographic Information System
h	hour
IDW	Inverse Distance Weighting
kcal	kilocalorie
kg	kilogram
km	kilometre
L	litre
m	metre
mg	milligram
mm	millimetre
MNI	Minimum Number of Individuals
MRUS	Maximum Rate of Urea Synthesis
N	Nitrogen
NISP	Number of Identified Specimens Present
NOAA	National Ocean and Atmospheric Administration
PAL	Physical Activity Level
PATDEE	Protein Adjusted Total Daily Energy Expenditure
PDF	Person Days of Food
PYF	Person Years of Food
REE	Resting Energy Expenditure
SPD	Summed Probability Distribution

SI	Supplemental Information
TDEE	Total Daily Energy Expenditure
ZooMS	Zooarchaeology by Mass Spectrometry

List of Equations

Contributing Author Statement

Chapter 2 has been previously published in *Advances in Archaeological Practice* (https://doi.org/10.1017/aap.2022.9). I am the principal author and analyst on this article. Iain McKechnie assisted with data collection, spatial analysis, and manuscript preparation. Additional authors include Quentin Mackie and Chris Darimont who contributed to research design and writing the manuscript. An initial version of this paper was presented at the 2022 Canadian Archaeology Conference.

Chapter 3 is currently under review by the *Journal of Archaeological Science*. I am the principal author and analyst. Dylan Hillis assisted with data collection and the analysis of fish body mass. Jasmine Schuster performed sensitivity analysis. Iain McKechnie conducted zooarchaeological analysis including MNI calculations and assisted with research design and manuscript preparation. Other coauthors include Quentin Mackie and Chirs Darimont who assisted with research design.

Chapter 4 is being prepared for submission to a scholarly archaeological journal. Co-authors include Iain McKechnie, Quentin Mackie, and Chris Darimont who assisted with research design and provided feedback on the manuscript.

Acknowledgments

I thank the Tseshaht, and Huu-ay-aht First Nations for the privilege of conducting archaeological research in their traditional territories and for their support of this research initiative, and the Toquaht, Ucluelet, and Uchuklesaht First Nations for earlier archaeological efforts to document their heritage sites in Barkley Sound. Denis St. Claire provided invaluable guidance on this project. Thanks also to staff at Pacific Rim National Park Reserve, Tseshaht First Nation, Bamfield Marine Sciences Centre, and the Department of Anthropology at the University of Victoria for funding and supporting my research. I would also like to thank Keith Holmes, Derick Heathfield, and the rest of the Geospatial Analysis team at the Hakai Institute for their work to help produce the lidar and orthomosaic imagery used in this project; and Audrey Dallimore and Randy Enkin at the Geological Survey of Canada for support in logging sediment core data. I also thank Alan McMillan, Tommy Happynook, Kathryn McKenzie, Jacob Salmen-Hartley, Camilla Speller, Hank Gus, Cody Gus, Freya Harrison, Wanda Robinson, and Jenn Yakimishin for their help with this project. Much thanks to Andrew Fitzsimons, Jack Bakker, Chris Hebda, Meghan Efford, and everyone else at UVic who helped keep me sane over the last 7 years. Many thanks to Torben Rick for serving as external examiner. Lastly a huge thanks to my co-authors through this project Quentin Mackie, Iain McKechnie, Chris Darimont, Dylan Hillis, and Jasmine Schuster for collaborating with me and helping to guide this research.

Dedication

To my family for their limitless love and support.

Chapter 1. Introduction

This dissertation contributes to archaeologists' understanding of how geospatial analysis, zooarchaeology, historical ecology, and demography can be pulled together to better understand how marine resources have supported robust human populations over thousands of years along the Northwest Coast of North America. Here I explore the long-term relationship between Indigenous peoples and marine environments by presenting a methodology for estimating precontact population size based on the harvest, consumption, and discard of marine foods at shell midden sites. These population estimates address enduring questions about the intensity of human activity and use of marine resources on western Vancouver Island prior to European contact. I show that archaeological sites in this area had the capacity to support large human populations dating back thousands of years. Additionally, this work highlights that the use of marine resources by the Tseshaht, Toquaht, Uchuklesaht, Ucluelet, and Huu-ay-aht peoples was significant and sustained for thousands of years. This work marshals a diverse set of data to contribute to our understandings of subsistence patterns, disease events, marine lifeways, cultural complexity, site formation processes, engineered landscapes, historical ecology, and the analysis of large complex shell midden sites, among other topics.

These findings have importance for modern Indigenous communities as reserves and Indigenous rights and territories were created through a political and governance structure that is predicated on demographic reconstructions, which failed to account for introduced disease and other negative impacts of European contact (Harris 2002). Understanding the degree of population collapse has the potential to help us better understand how Indigenous peoples lived through catastrophic times and responded to the reconfiguration of their population in their own social, political and economic terms. Better estimates of the size of pre-contact populations also has legal and ethical ramifications related to social justice and have significant real-world implications especially in light of recent dialogues in Canada with Indigenous peoples about the legacy and impact of colonial policies (Truth and Reconciliation Commission of Canada 2015).

The number of people living in coastal British Columbia, and North America more generally, prior to the arrival of Europeans is poorly resolved with significant variability in the size and scope of estimates (Borah 1962; Denevan and Lovell 1976; Dobyns 1966; Koch et al. 2019; Kroeber 1963a, 1963b; Mooney 1928). Accurate population counts are integral to understanding social structures, migration events, the role of humans in ecosystems, disease events, demographic processes, and trade systems among many other processes (Cameron 1991; Coupland 2006; Gallivan 2002; Kohler 1978; Marshall 2006; Williams 2013). Many different methodologies have been employed over the last one hundred years to try and answer this question employing diverse approaches employing among other data radiocarbon dates, depopulation ratios, summed population counts, living space studies, and environmental information (Boyd 1999; Campbell 1990; Koch et al. 2019; Naroll 1962; Rick 1987; Schiffer 1975). A significant portion of these efforts [but not all, see Campbell (1990) and Croes and Hackenberger (1988)], have relied on ethnographic and historic analogy to generate their estimates; these methods may fail to adequately account for the rippling social, technological, and epidemiological impacts of early European contact, or assume that recorded lifeways were the same as those practiced in much more distant time periods. Here I present a new inductive bottom-up method of minimum population estimation employing archaeological accumulations of long-term fish remains to create estimates that avoid or minimize the issues of previous approaches (e.g., Ascher 1959; Fossile et al. 2019). I build on prior scholarship and legacy archaeological data combined with modern analytic methods to offer original contributions to our understanding of shell midden site spatiality, Indigenous fish harvests, and the energy requirements of Indigenous peoples, to generate precontact population estimates.

Minimum population estimates are generated through a multistep process in which each step builds off the results from the previous step. The methodology presented in this dissertation first develops a geometric model to estimate the size of accumulated anthropogenic shell midden sediments in Barkley Sound, British Columbia, Canada. I then used these volumes and zooarchaeological analysis of sediment samples to estimate the density of fish remains in these sites. The density of fish is then used to model the preserved total biomass of Indigenous harvesting efforts as recorded in shell midden sites across the region, which in turn is converted into caloric energy. From this, estimates of daily energy requirements were used to project how many people could have been supported based on the available calories over the last three millennia. This research has globally applicable implications for understanding how many people could have been supported by harvested fish, the sustained use of marine resources, and present-day Indigenous resource use.

1.1 Methodological and Theoretical Framework

The theoretical framework for this research is based on a computationally conservative inductive approach grounded in archaeological data. Ethnographic and historical analogy provide vital tools for archaeologists (Arima 1983; Drucker 1951; Sapir and Swadesh 1939; Sproat 1868) but many of these processes for the Northwest Coast were recorded after European contact and cannot avoid bias stemming from the massive social reorganization caused by introduced diseases and technologies (Boyd 1999; Harris 1997). To create estimates which predate these changes and reflect time-averaged pre-contact populations, I based my research in archaeological, fisheries, and human biological data and avoided the usage of analogy or data generated from contemporary diets and populations when possible. This approach has the added benefit that it is not directly tied to the study area and can be applied to other temporal, cultural, and geographic contexts.

This research was guided by an ethos of computational conservatism in which deliberate effort was taken to create defensible estimates, which are designed to avoid overestimation of midden volumes, harvested fish, and associated population size. Throughout this analysis I demonstrate the range in which derived values have fallen using error assessment of midden volumes, sensitivity analysis of biomass estimates, and modelling of population size based on different scenarios of caloric availability and consumption. My approach in developing this research methodology was to err on the side of making cautious estimates of model inputs so as to produce minimum estimates of population. For example, I use Minimum Number of Individuals (MNI), which usually produces an undercount of the individuals represented [but see Grayson (1979) and Lyman (2009) for exceptions to this] by a faunal assemblage compared to other methods of faunal quantification, and thus the actual biomass of the study area's faunal assemblage was almost certainly higher than what is presented here. Similar decisions were made throughout the dissertation especially when characterizing fish populations and human energy requirements. This approach is required because of the significance of pre-contact marine resource use and population estimates to modern discussions of Indigenous rights and title and the creation of policy that accurately and defensibly reflects the intensity and antiquity of human habitation in Barkley Sound. In several instances archaeological evidence has been used in Canadian courts to refute Indigenous claims to land use and resource rights (Hogg and Welch 2020; Martindale 2014). I created conservative, incremental, and future oriented estimates through a methodology that produces results which could be useful in legal proceedings.

Applying estimates that are too high could undermine present-day Indigenous aspirations and potentially harm these communities. On the other hand, underestimating populations is not without the risk of diminishing the intensity of Indigenous people's connection to their traditional lands but could arguably comprise the lesser risk in comparison to creating estimates which could be critiqued as over representing populations.

Geographic Information Systems (GIS) and remote sensing have become essential elements of the practice of archaeology and this project helps to develop the theoretical basis for geospatial archaeology by demonstrating how geomatic techniques can be integrated with other disparate sets of data to answer archaeological questions (Lock and Pouncett 2017; McCoy 2021; Verhagen 2018). Some practitioners have argued that the application of geomatics in archaeology has reached methodological maturity while development of supporting theory has remained stagnant (Menéndez-Marsh et al. 2023; Ullah et al. 2024). I concur with this assessment and my approach to research is rooted in the application of GIS in ways that advance the field of geospatial archaeology. Complex approaches to estimate shell midden volume for example enabled an analysis of preserved fishery biomass to inform a demographic estimate, and geospatial analysis underpins the foundations of this work. I apply geomatics to allow for questions to be asked in new ways that would not be possible without spatially aware data and analysis.

Middens represent a major component of the archaeological record in many coastal areas and due to their favourable organic preservation have particular relevance for understanding long-term ecological histories (e.g. Claassen 1991; Erlandson 2001; Rick 2023; Waselkov 1987). My dissertation contributes to our knowledge of long-term ecological baselines by demonstrating the intensity of pre-contact fisheries activity recorded in shell middens. "Shifting Baselines" resulting from over fishing has altered contemporary stock size and species composition so that they do not represent pre-industrial fisheries (Jackson 2001; Pauly 1995; Pitcher 2001). Biomass estimates of the fish represented by shell middens, like those in Chapter 3, can be used to examine fisheries over longer temporal windows providing insight into thousands of years of sustained marine resource use. These estimates were contingent on volumetric estimates of these large complex sites (Chapter 2**)**. As such shell midden research can guide contemporary policies for marine resource management and stewardship (Erlandson et al. 2008; Fossile et al. 2020; McKechnie and Wigen 2011; Palmer et al. 2018; Slade et al. 2022).

Middens can be monumental structures that can dominate the terrain on which they have accumulated (Grier et al. 2017; Letham et al. 2017; Marquardt 2010; Pluckhahn et al. 2015; Randall 2015). The estimates that I create demonstrate that the volume of accumulated midden sediments in Barkley Sound is a substantial and defining feature of this landscape. They represent the totality of thousands of years of daily life and are the result of the collective labour of communities over thousands of years (Letham et al. 2017; McNiven 2013; Reeder-Myers et al. 2022). They modify the landscape in profound ways demonstrating that their creators were a driving force in the dynamic coastal environments they inhabited (Armstrong et al. 2022; Lepofsky et al. 2017; Trant et al. 2016). These landscape modifications have implications for discussion around the role of humans as driving forces in global ecosystems (Braje 2018; Chaput 2018; Crutzen and Steffen 2003). My work on midden volumes provides new holistic understandings of middens from a social landscape perspective.

A recent trend in Northwest Coast scholarship has been to broaden understandings of systems of food production. Scholarship over the last ~15 years has sought to disrupt traditional understandings of Hunter-Gatherer-Fisher subsistence practices. This growing body of work has brought attention to the cultivation of Wapato, Camas and plants; and mariculture activities facilitated by clam gardens, fish traps, and other features (Deur 2002; Deur et al. 2015; Greene et al. 2015; Groesbeck et al. 2014; Hoffmann et al. 2022; Lepofsky et al. 2015; Lepofsky and Caldwell 2013; Lokman and Tomkins 2020; Lyons et al. 2021; Lyons and Ritchie 2017; Moss and Wellman 2017; Toniello et al. 2019; White (Xanius) 2006). This resurgence of interest in food production greatly benefits studies of population and resource use. These efforts produce more accurate and culturally nuanced assessments of Indigenous diets which are the product of resource enhancement and sophisticated methods of hunting and harvesting wild resources. In this framework, my focus on the diversity and magnitude of fish contributions to the diet can eventually inform newly emerging understandings of Northwest Coast food systems. With accurate dietary biomass estimates the impact of these mixed economies on important variables such as population size and density, and ultimately, population change through time can be produced.

1.2 Study Area

The Pacific Northwest Coast cultural area broadly extends from coastal Northern California to Southeast Alaska. This area is home to a complex diversity of Indigenous peoples whose ancestors have been characterized as Complex Hunter-Gatherer-Fisher cultures (Ames and Maschner 1999). These groups have been of perennial interest to archaeologists for the combination of their cultural complexity and marine focused subsistence patterns (Moss 2011). This area is known for its high population densities and degree of sedentism relative to terrestrial hunter-gatherers (Ames 2002). The large number of shell midden sites as previously discussed is a defining archaeological feature of this area and the size and complexity of these sites can lead to challenges in the characterization and regional analysis of these features.

Barkley Sound is an approximately 900 km^2 marine embayment located on the southwest coast of Vancouver Island in British Columbia, Canada. Two major groups of islands, the Broken Group and Deer Group, are contained within the Sound which together with the surrounding shoreline, constitute the study area for this research (Figure 1). This area has a temperate climate averaging over 3,300 mm of rainfall each year and the embayment is composed of littoral marine environments and densely forested terrestrial areas (Environment and Climate Change Canada 2024). Extensive archaeological research has been conducted in this area over the last 40 years in the form of large-scale archaeological survey and excavations (e.g., Buxton 1969; Haggarty and Inglis 1985; Huu-ay-aht First Nations 2000; Mackie and Williamson 2003; McKechnie 2005a, 2013; McMillan 1999; McMillan and St. Claire 1977, 1982, 1992, 1996, 2005, 2012; Monks 2006; St. Claire 1975). A robust ethnographic and oral historical record exists (Arima et al. 1991; Blenkinsop 1874; Drucker 1951; Sapir et al. 2000; Sapir and Swadesh 1939) with specific oral histories stretching back thousands of years (McKechnie 2015; McMillan and St. Claire 2005). Whereas the entire shoreline has not yet been completely surveyed, over 186 shell midden sites have been recorded within the study area. Many of these sites have accurate scale drawings and maps of site boundaries accurately recording the footprint and estimated depth of shell middens. Additionally, a multi-decadal program of subsurface testing and investigation has provided an extensive record of zooarchaeological data providing detailed insight into coastal subsistence patterns and taxonomic composition. Considerable biological and ecological research has also been conducted in this region providing for a nuanced understanding of marine food sources which provide essential context for understanding how past humans interacted with their environment. This rich history of research makes this an ideal location for volumetric approaches to midden sites, historical ecology at multiple scales, and modelling populations.

Historical records and censuses provide valuable context for the population estimates I created. The earliest documented contact between the Indigenous Nuu-chah-nulth peoples of Barkley Sound and Europeans occurred in 1787 when Captain William Barkley sailed the British ship Imperial Eagle into the Sound (McMillan 1999; McMillan and St. Claire 2005). This was followed by additional short visits by Europeans over the next several years including the Meares expedition in 1789. In 1791 José María Narváez was sent by the Spanish to explore and map Barkley Sound. His expedition produced the first population estimates for this area (McMillan 1999; McMillan and St. Claire 2005). He stated that Barkley Sound contained more people than Clayoquot Sound, where he had estimated the population to be 8,500 people (Wagner 1933:149). Thus, the earliest estimates place the late 1700s population of Barkley Sound at greater than 8,500 people. This estimate is not a formal survey or census and very likely does not reflect the actual number of people inhabiting this area. Additional population counts for Barkley Sound place the mid-19th century population at 399 men (Sproat 1868) and as many as 700 individuals in total (Grant 1857). Boyd (1999), using extrapolations of historic 1800's populations to earlier time periods, posited a total Nuu-chah-nulth (Figure 1) precontact population of at least 6,000 which stands in stark contrast to the estimate suggested by Meares of 31,000 people (Meares 1790). A Hudson Bay Company census in 1840 places the Nuu-chah-nulth population at 7,093 (Boyd 1999) and the first government census conducted in 1885 found that the combined Nuu-chah-nulth and Ditidaht population to be 3,500 individuals (Duff 1964). The population nadir occurred in 1924 with 1,459 Nuu-chah-nulth individuals reported in the census (Boyd 1999). The Barkley Sound study area considered here represents less than 3% of traditional terrestrial Nuu-chah-nulth territories (Figure 1) and it is not surprising that Meares's estimates for the entire Nuu-chah-nulth population are significantly larger than Narváez's estimates for the Barkley Sound population. These trends mirror patters observed across the Americas (e.g. Boyd 1999; Dobyns 1966) and had global impacts (Koch et al. 2019; Nevle and Bird 2008).

The historically recorded population counts reveal two important facts. First is that Indigenous populations in Barkley Sound drastically declined between contact and the early 1900s. This decrease in population was extreme and resulted in substantial social, economic, and cultural reorganization for Indigenous peoples (McMillan 1999; McMillan et al. 2008; McMillan and St. Claire 2012). The second crucial observation from these numbers is that the historically recorded values, which were used to allocate reserves and set policy in the 1800s (Duff 1964; Harris 2002) were, not reflective of the previous long-term populations, a reality I illustrate with empirically derived estimates. My minimum population estimates, relevant to several millennia, help to place previous estimates into important context which has implications for contemporary discussions between First Nations and government about the length and intensity of human activity in Barkley Sound. These findings are also significant for a broad cross-section of modern stakeholders including government, commercial fishers, and local communities as they provide insight into the long-term use of marine resources, which in turn have implications for informing modern fisheries policy.

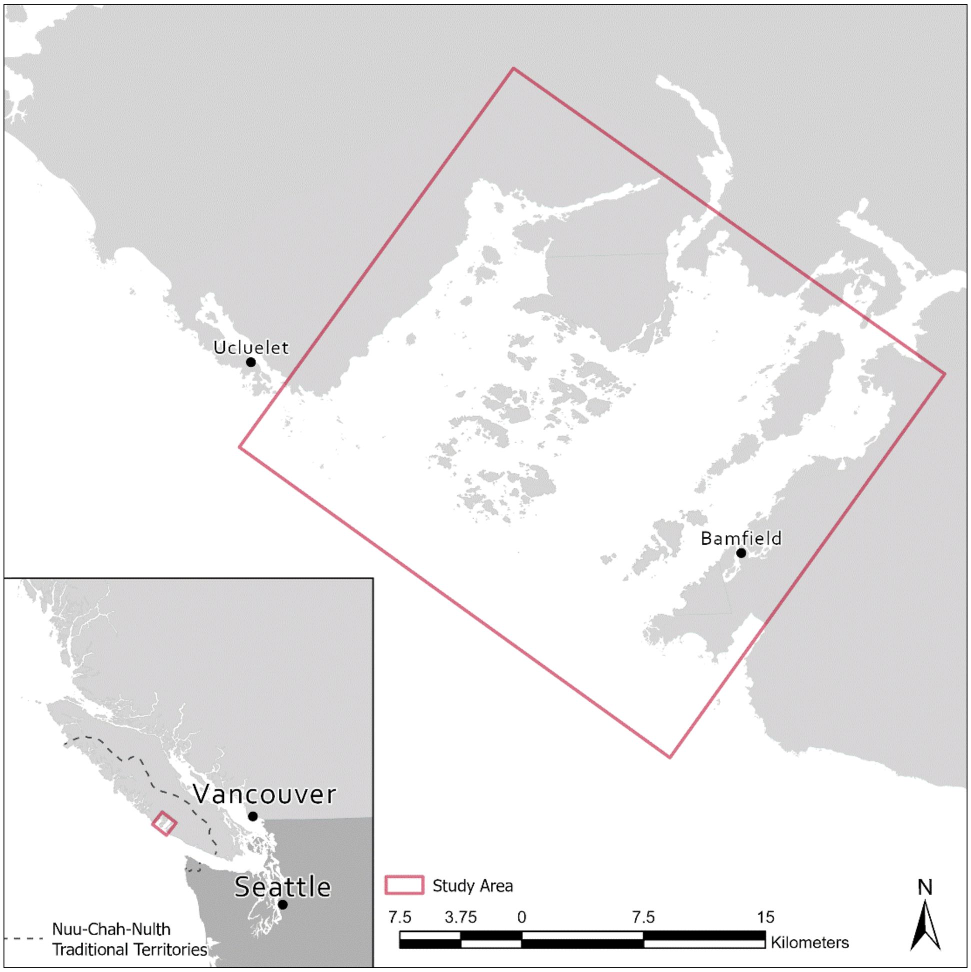

Figure 1. Project study area in Barkley Sound, British Columbia, Canada.

1.3 Research Questions

The primary objective of this research was to derive an archaeological estimate for the number of Nuu-Chah-Nulth people who lived on the islands and coastline of Barkley Sound prior to European contact. Three questions guide this research, each of which is a self-standing research project, which has been or will be published separately. In aggregate these three projects build off each other to describe a cohesive methodology for estimating past populations.:

1. Can a generalized three-dimensional model of midden shape be developed for the purpose of estimating midden volume?

a. Can a geometric solid be used to model midden shape?
b. What is the volume of study area midden sites?
c. How can midden volume estimates be validated?

2. What is the total biomass of harvested fish represented by midden site volumes in Barkley Sound?
    a. What is the representative weight of different harvested fish taxonomic groupings?
    b. What is the density of fish biomass by taxonomic grouping within middens?
    c. How does the biomass of Indigenous catches compare to modern fisheries?
3. Based on total Barkley Sound fish biomass, how many people lived in this area prior to European contact?
    a. Can estimates of fish biomass be converted to caloric energy?
    b. Can the daily caloric requirements of study area inhabitants be modeled?
    c. How many people could the estimated total calories from harvested fish support based on estimated human daily energy requirements?

The estimates presented in this analysis are constrained by the temporal window considered and the scope of foods included. In the process of this research, it became apparent that it was unrealistic to attempt to account for all consumed foods in calculating population estimates and the analysis was limited to include only fish. As these resources were only a portion of the foods consumed by the inhabitants of these sites the population estimates presented here should be viewed as minimum values. Additionally, despite the presence of sites in Barkley Sound dating back to 5,000 cal BP (McMillan et al. 2008), and probable human occupation much longer than that (Mackie et al. 2011), this work focuses mainly on the last

3,000 years as most of the known shell midden record is concentrated in this chronological window. Each of the main chapters in this dissertation addresses a different research question moving in sequence building off the previous chapter(s) to create a minimum population estimate (Figure 2).

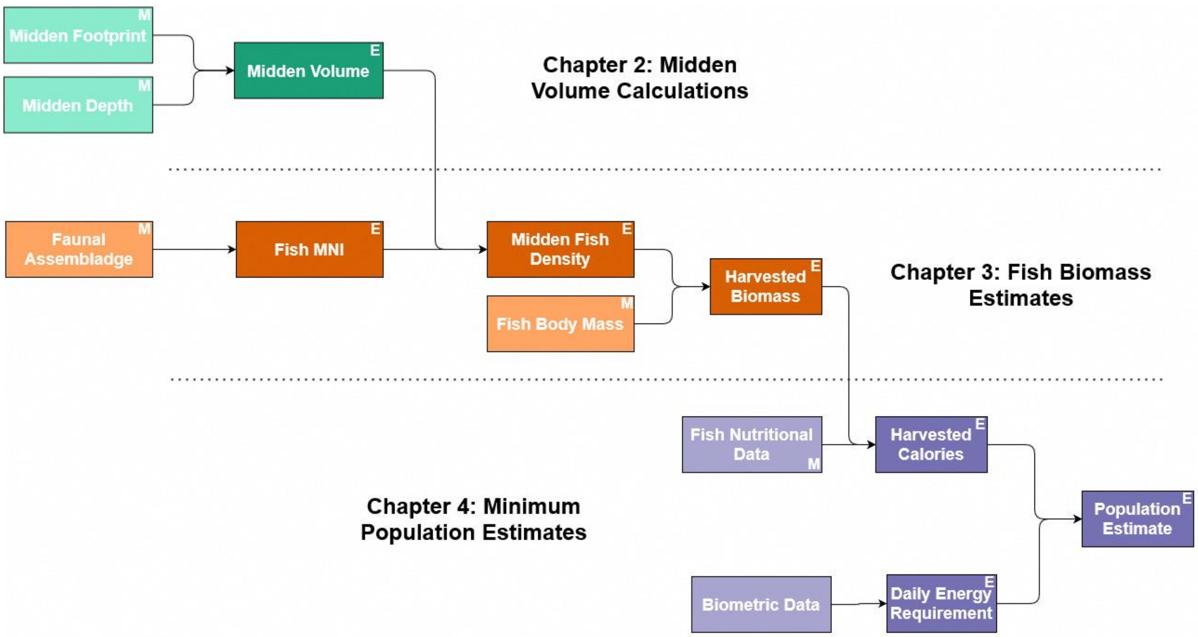

Figure 2. Analysis process flow chart. Results from each chapter are carried forward to the next chapter. Midden volume estimates from Chapter 2 are used to calculate deposited biomass in Chapter 3. Total biomass is in turn used to calculate population estimates in Chapter 4. “M” indicates a measured value and “E” indicates an estimated value.

1.4 Chapter Overview

The following three chapters comprise the main body of the dissertation and address the research questions stated previously.

1.4.1 Chapter 2: Midden Volume Calculations

This chapter was published in 2022 in Advances in Archaeological Practice https://doi.org/10.1017/aap.2022.9. Two figures, one table, and two values reported in the original publication of chapter have been updated here to reflect corrections made in a forthcoming corrigendum submitted to Advances in Archaeological Practice.

Gustas, Robert H., Iain McKechnie, Quentin Mackie, and Chris Darimont
2022 Estimating Volumes of Coastal Shell Midden Sites Using Geometric Solids: An Example from Tseshaht Territory, Western Vancouver Island, British Columbia, Canada. *Advances in Archaeological Practice* 10(2):200–214. 10.1017/aap.2022.9.

In Chapter 2 I examine how the volume of midden sites can be calculated and how those results can be validated. A key portion of this is determining if the maps and measurements that are collected as part of the process of recording a coastal archaeological site can be employed to create representations of these sites useful for estimating their surfaces and volumes. I accomplished this modelling using a semitriaxial ellipsoid fitted to a midden's length, width, and depth as recorded in site maps and site reports. I then compared these volumes to a set of more precise volumes across the Northwest Coast which have more thorough and precise mapping and depth measurements from subsurface testing to validate my results from the semitriaxial ellipsoid model.

Shell middens are robust features which can record material aspects of the daily lived experience of humans over thousands of years. Estimates of shell midden volume are important because this topic has not been given proper consideration in archaeological literature. Recent studies have looked at midden accumulation rates (Duffield et al. 2022; Letham et al. 2020; Stein et al. 2003; Taylor et al. 2011; Zangrando et al. 2020) but less thought has gone into quantifying the amount of sediment that comprise shell midden sites (Fossile et al. 2019; Letham et al. 2017; Sorant and Shenkel 1984; Treganza and Cook 1948). Volumetric estimates provide a common way of quantifying middens that moves beyond width and length. Within the study area their longest dimensions can be hundreds of metres, and they can have depths in excess of 5 metres (McKechnie 2015). While not as well-known as the monumental features of other parts of the world these sites deserve the same attention that other massive anthropogenic structures receive (Grier et al. 2017). To be truly contextualized these sites need to be viewed as three dimensional entities of accumulated anthropogenic sediments. Modern geospatial techniques as demonstrated here allow for new ways of accomplishing this and can be used to successfully model site volumes with high accuracy across large areas. Site volumes are a fundamental element of my research and are a required element of both the fish biomass and population estimates.

1.4.2 Chapter 3: Fish Biomass Estimates

This chapter was submitted to the Journal of Archaeological Science on September 27, 2024. A revised version of this chapter will appear as a published article in the future and should be considered the version of record.

Gustas, Robert H., Dylan Hillis, Mackie, Quentin, Jasmine M. Schuster, Chris T. Darimont, and Iain McKechnie
2024 Estimating Ancient Nuu-chah-nulth Fisheries Biomass at Shell Midden Sites on the Northwest Coast. *Journal of Archaeological Science*. Manuscript Number: JASC24-527

In Chapter 3 of this dissertation, I estimated the quantity of fish that were harvested and subsequently deposited to form middens in the study area. This was accomplished by combining the estimated midden volumes from Chapter 2 with zooarchaeological analysis of sediment samples from sites to estimate total deposited fish biomass. Additionally, I demonstrate how the density of fish in middens can be extrapolated from samples to model the total amount of fish biomass contained in individual sites as well as in sites across a larger region. This created a regional perspective allowing for a larger scale of analysis which considers the totality of harvesting efforts across a multitude of sites. Challenges in this process included determining the representative size of different fish species and calculating the count of individuals represented by a faunal assemblage. Once measures of fish weight were determined I developed a process for scaling estimates beyond a single site. The density of fish counts and biomass was determined from sediment samples and then applied across the study area to model total biomass. This estimated biomass established an ecological baseline of harvesting activity spanning thousands of years and were compared to modern fisheries catches showing that, while smaller, the precontact harvested biomass was a significant fraction (~10%) of modern catches. In this chapter I demonstrated how previously gathered data can be employed to answer these questions and that biomass estimates can be successfully scaled up to the regional level from thorough sampling collected at a subset of sites.

1.4.3 Chapter 4: Minimum Population Estimates

This chapter is in preparation for submission to the Journal of Archaeological Method and Theory. A revised version of this chapter will appear as a published article in the future and should be considered the version of record.

Gustas, Robert H., Mackie, Quentin, Chris T. Darimont, and Iain McKechnie
Archaeologically Derived Minimum Estimates of Indigenous Population Sizes in Nuu-chah-nulth Territories, British Columbia, Canada.

The last chapter I present combines the results of the previous two to create minimum population estimates. Once biomass is calculated for the fish contained in a midden, then by extension the total caloric energy represented by these resources is knowable. Nutritional information is used to convert fish biomass to caloric energy which allows for a more nuanced look at how these resources might be used to support a human population. Using a combination of archaeological and ethnographic biometric data primarily from adults, I estimate total daily energy requirements for a population by calculating the minimal energy requirements for sustaining human life and then adjust these to account for daily physical energy expenditure to derive the total caloric energy required. Additionally, I had to consider the composition of the diet and additional modifications made to account for natural limitations on how much protein humans can metabolize. This is a necessary adjustment as these population estimates are derived solely from protein dominant foods (fish). The result of this is a thoroughly grounded minimum population estimate which addresses the questions of how many people could have been fed from the fish represented in Barkley Sound shell middens assuming a stable population through time; and the result serves as a conservative minimum population for the region considering all possible food sources.

In summary, this research constitutes a major contribution to several themes in Northwest coast archaeology. Through the methods and results presented here I contribute to archaeology's understandings of marine resource use, cultural complexity, pre-contact demographics, site formation, and midden characterization. Additionally, this research is significant for Indigenous peoples in British Columbia as it demonstrates that post contact population counts, which were highly influential in the creation of reserves and government policies were not reflective of the pre-contact population. Prior to the arrival of Europeans Barkley Sound was home to a large populace which could have been sustained for thousands of years. The chapters presented here were prepared as independent articles for publication in scholarly journals. The second chapter has been published in *Advances in Archaeological Practice* (Gustas et al. 2022), the third has been submitted to the *Journal of Archaeological Science*, and the fourth is being prepared for submission to a peer reviewed academic journal in archaeology. Since this dissertation is composed of these three thematically related, but independent papers, there will intrinsically be some redundancy among these chapters when compiled into this single volume. Additionally, there are minor formatting differences between the published papers and the chapters as presented here because of the compilation process. All Supplemental Information (SI) is hosted on Borealis[1], the University of Victoria's academic data repository, and links to these files can be found in Appendix A. Supplemental Data.

[1] The borealis repository can be accessed at: **https://borealisdata.ca/dataverse/uvic**

Chapter 2. Estimating Volumes of Coastal Shell Midden Sites Using Geometric Solids: An Example from Tseshaht Territory, Western Vancouver Island, British Columbia, Canada

2.1 Introduction

Shell middens are a globally distributed archaeological site type with considerable value to understanding the long-term history of Indigenous use of coastal ecosystems. Analysis of the constituents of shell midden deposits is a common research activity, but extrapolating data sampled from a small number of sites to the overall study area remains a methodological and interpretive challenge. Global research on shell middens is refining methods for linking evidence of settlement and resource use across a variety of settings (Astrup et al. 2019; Bailey and Hardy 2021; Litster et al. 2020; Parkington et al. 2020; Sanger 2021). On the Northwest Coast of North America, shell middens are ubiquitous and have formative roles in cultural historical frameworks and zooarchaeological analyses (Ames and Maschner 1999; Cannon 2013). Although these cultural deposits are primarily composed of shell, bone, and other organic matter (Álvarez et al. 2011; Stein 1992; Waselkov 1987), they are also recognized as complex millennial-scale records of everyday life, including both the mundane and monumental with a variety of economic, social, political, and environmental significance (Álvarez et al. 2011; Blukis Onat 1985; Cannon 2000; Claassen 1991; Erlandson 2013; Grier 2014; Letham et al. 2020; Pluckhahn et al. 2015; Villagran 2014).

Coastal shell midden deposits can be large and topographically complex, which presents unique methodological challenges to survey and investigation (Claassen 1991; Lyman 1991; Stein 1992; Waselkov 1987). To date, little research has been undertaken that has explicitly looked at the spatial metrics and three-dimensional shape of shell midden deposits. Most of the research that has been conducted has focused on recording the two-dimensional footprint of these features and sampling locations within them. Questions about the volume and shape of middens date back over 100 years (Nelson 1909; Spier 1916), and a few notable projects have attempted to estimate their physical extent and volume (Ceci 1984; Cook 1946; Letham et al. 2017; Randall 2015; Sorant and Shenkel 1984; Widmer 2014). Comparatively greater effort has been expended to explore the volume of terrestrial earthen mounds and other monumental features that are not shell bearing (Bernardini 2004; Blitz and Livingood 2004; Jeter 1984; Johnson 2015; Lacquement 2010; Magnani and Schroder 2015). Although the cultural contexts and formation process of earthen mounds differ substantially from shell middens, calculating the volume of these features involve similar principles and require engagement in the problem of modelling sediment shape and volume.

In this article, we present a new geometrically scaled model to estimate the volume and shape of coastal shell middens in sites on the Pacific Northwest Coast. This approach utilizes Geographic Information Systems (GIS) and 3D modelling in combination with archaeological survey data to characterize and visualize site deposits. For validation, we use digital elevation models and subsurface testing data to create 3D models of shell middens, which can be used to calculate midden volumes for comparison to volumes estimated from a general shape. The implementation of these techniques allows for exploration of shell midden deposits at the landscape scale, and we present the first estimate of shell midden volumes along western Vancouver Island in British Columbia, Canada. This article concludes that a general model of midden shape can be created to estimate volume and spatial attributes for shell middens on the Northwest Coast and elsewhere. Additionally, we propose that this model is more accurate than previous efforts to employ geometric solids for modelling sediment volume.

2.1.1 Study Area

The study area encompasses the Broken Group Islands located in Barkley Sound, a marine embayment on western Vancouver Island. Covering approximately 100 km^2 and over 900 km of shoreline, the Broken Group Islands are a highly productive marine environment with more than 100 islands and islets fringed by rocky reefs, kelp forest habitat, and dense temperate rainforest (Figure 3). These islands are part of the traditional territory of the Tseshaht First Nation, a Nuu-chah-nulth group that occupied the region for millennia and now cooperatively manages this portion of Pacific Rim National Park Reserve with the federal Parks Canada agency (McKechnie 2005a; McMillan 1999; McMillan and St. Claire 2005).

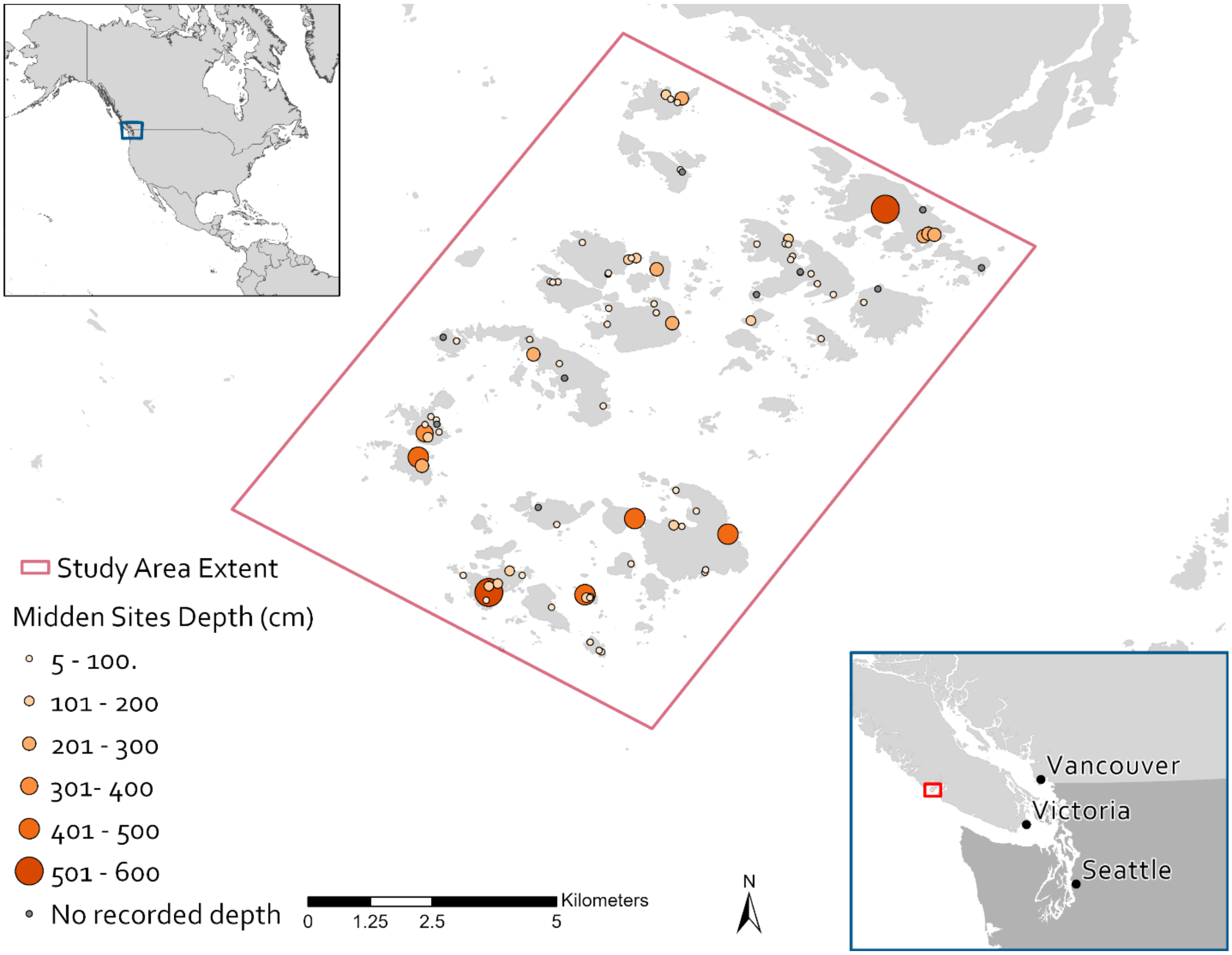

Figure 3. The study area showing locations of shell midden sites. Lower inset map shows maximum depth of shell midden sites within the study area. The upper inset map shows the study area in relation to North America.

A considerable amount of archaeological survey and excavation has been conducted in the study area over the last 50 years (Haggarty and Inglis 1985; Hillis et al. 2020; McKechnie 2013; McMillan and St. Claire 1982, 2005; St. Claire 1975). In the early 1980s, the entirety of the Broken Group Islands was systematically surveyed as part of the process of establishing a cultural heritage baseline for Pacific Rim National Park Reserve (PRNPR) (Haggarty and Inglis 1985). These pedestrian shoreline surveys in combination with additional cultural heritage monitoring and research over the subsequent 35 years have resulted in detailed site maps that record the locations and physical extent of shell-bearing midden deposits for 81 sites in the study area (Sumpter and St. Claire 2007, 2009; Sumpter and Suski-Armstrong 2005). In addition to this extensive history of archaeological work, this area also has a robust ethnographic and oral history record (Arima et al. 1991; Blenkinsop 1874; Drucker 1951; McKechnie 2015; Sapir et al. 2000; Sapir and Swadesh 1939; St. Claire 1991). These data provide a strong foundation on which to consider research into the distribution of shell middens in the Broken Group Islands; and they are an extension of a multiyear collaborative research project between the Tseshaht First Nation, the University of Victoria, PRNPR, and the Bamfield Marine Sciences Centre (Tseshaht First Nation et al. 2017).

2.2 Methods

We present a new process for modelling the volume of shell midden deposits using a geometric solid that is designed to be scaled across multiple sites where only midden location, extent, and maximum measured depth of cultural sediments are known. This process does not require extensive topographic surveying and can be applied at the regional level. Results are evaluated against primary data obtained from percussion coring at eight sites in the Broken Group Islands as well as three other sites on the northern British Columbia coast where similar surveys and subsurface testing have been conducted (Figure 4; Table 1). This validation process involves comparing volumes obtained from detailed archaeological investigation of these sites with the generalized geometric midden shape volumes.

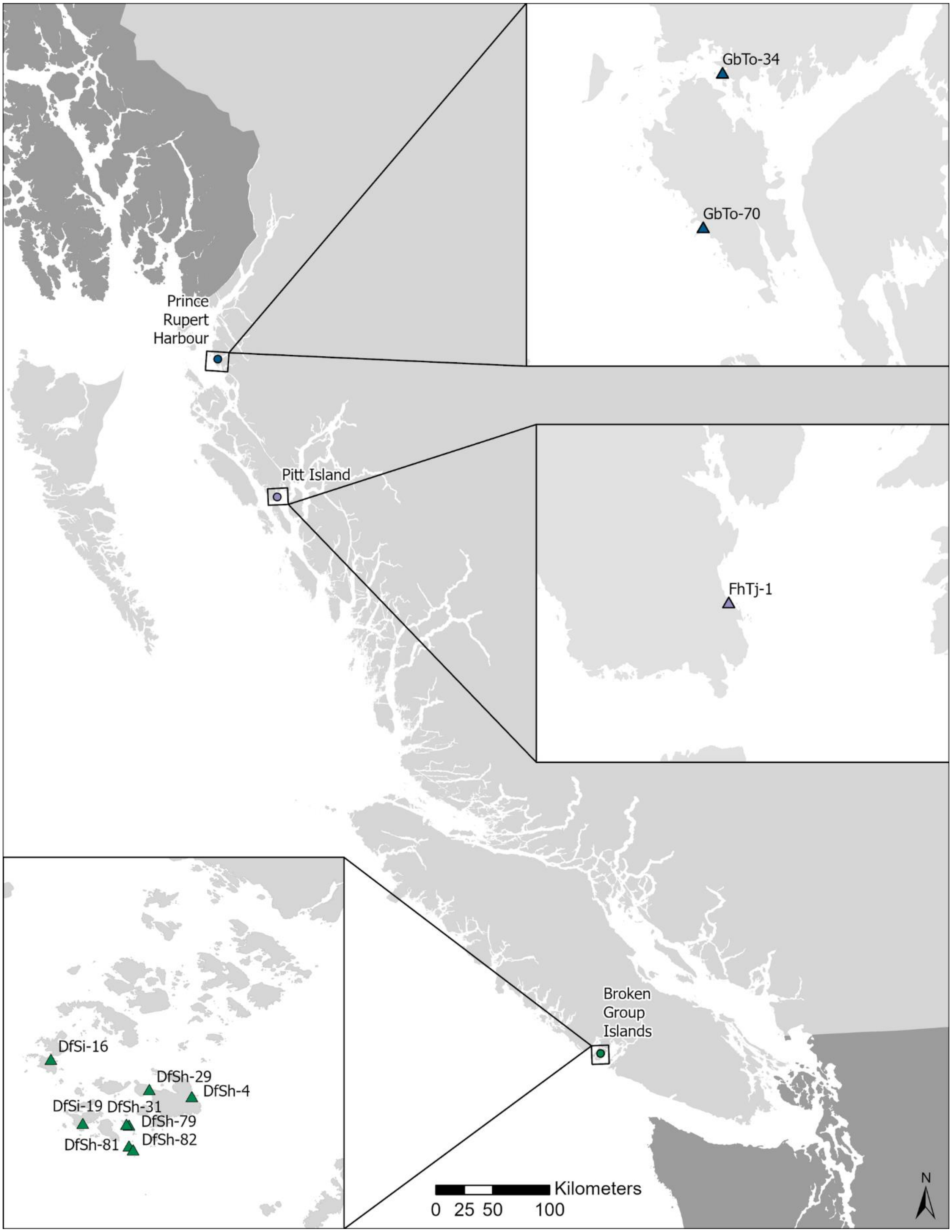

Figure 4. The location of reference middens used to assess ellipsoidal volume estimates.

Table 1. Comparison of volume estimates.

Site	Location	Area	Number of Cores	Max midden Depth (cm)	Midden Area (m^2)	Reference Volume (m^3)	Ellipsoid Volume (m^3)	Diff(m^3)*	%Diff†
DfSh-4	Omoah	BGI	22	443	9,785	12,775	14,826	2,051	16
DfSi-19	Wouwer Island	BGI	9	550	3,573	5,828	6,488	660	11
DfSh-79	Upper Dicebox	BGI	24	150	1,729	815	846	31	4
DfSh-31	Lower Dicebox	BGI	23	433	2,727	4,851	4,062	-789	-16
DfSh-81	North Cree	BGI	3	42	1,183	163	160	3	-2
DfSh-82	South Cree	BGI	3	32	130	12.7	13.1	-0.93	8
DfSi-16	Ts'ishaa	BGI	13	500	11,207	15,167	18,463	-3,209	22
DfSh-29	Gilbert Island	BGI	8	200	1,931	2,747	2,904	157	6
GbTo-70	Digby Island	PRH	20	400	2,800	4,170	3,872	-298	-7
GbTo-34	Kitandach	PRH	40	400	8,200	12,900	12,098	-802	-6
FhTj-1	Citeyats	Pitt Isl.	23	441	7,347	11,852	11,197	655	6
Average			**17**	**348**	**4,601**	**6,480**	**6,812**	**-267**	**3 (9)[c]**

* Difference equals ellipsoid volume subtracted from reference volume

† %Difference equals difference divided by reference volume (×100)

‡ The absolute average error is 9% and is determined by summing the absolute value of each number in the %Diff column and dividing by the number of sites.

2.2.1 Midden Volume Estimation

To estimate shell midden volumes, we draw on the significant body of work employing the concept of a "geometric solid" (Shenkel 1986:201) as a representation of archaeological deposits based on idealized categories of geometric shapes (Ceci 1984; Cook 1946; Jeter 1984; Johnson 2015; Lacquement 2010). The geometric solid concept calculates volumes for geometric shapes and can be readily scaled across a range of sites without requiring highly specific topographic or photogrammetric data (Magnani and Schroder 2015). Provided that legacy mapping data for shell midden deposits are accurate, this approach can be used to estimate volumes for large numbers of sites with known boundaries. A geometric model will always be less accurate than a highly specific three-dimensional model at an individual site (Álvarez et al. 2011), but as we describe below, our results improve on previous research by applying a new shape and developing a GIS-based method for linking the geometric solid to nonorthogonal footprints of shell-bearing archaeological deposits. The benefit of our approach is that it can also be applied without requiring lidar or other types of remote sensing data. SI2.1 includes the Python code that was used to calculate shell midden volumes.

After a review of previous approaches, we observe that the generalized shape that seems to best represent shell-bearing midden deposits is a semitriaxial ellipsoid (Figure 5). This oblong and rounded shape is more specific and less symmetrical than other shapes previously used to estimate midden and mound volume such as cones (Sorant and Shenkel 1984), cylinders (Cook 1946), spheres (Treganza and Cook 1948), parabolas of revolution (Jeter 1984), pyramids (Shenkel 1986), and truncated "frustrum forms," all of which do not correspond to the elongated crescent form of shell midden extents in our study area. The semiellipsoid shape can be scaled to the width, length, and depth of a midden with the assumption that its centroid corresponds to the deepest portion of the site and recedes in thickness to its horizontal margins at a curvilinear rate. We have observed that the deepest point in shell midden deposits tends to fall near the centre, further indicating the suitability of this shape (Table 2). Given that coastal shell midden deposits tend to "smooth out" underlying landforms and shoreline topography, we truncate the ellipsoid into a half shape or "semitriaxial ellipsoid" to better represent a less topographically complex surface. A triaxial ellipsoid shape is defined by Equation 1:

Equation 1. Formula for a triaxial ellipsoid.

$$1 = \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}$$

In Equation 1, *x*, *y*, and *z* represent the coordinates of the ellipsoid surface; *a*, *b*, and *c* are respectively the width, length, and depth of the ellipsoid as measured from the origin, which is placed at the site centroid (Figure 5). At each midden, the footprint is used to create a 1 x 1 m raster grid. Each cell in the raster is then converted to a point feature, thereby creating a regular grid of points within the midden, each of which represents 1 m^2 of space.

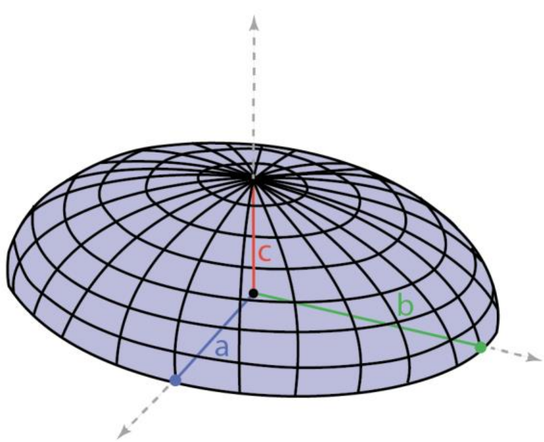

Figure 5. The semitriaxial ellipsoid: (a) the width of the ellipsoid as measured from the origin; (b) the length of the ellipsoid as measured from the origin; (c) the depth of ellipsoid as measured from the origin of the ellipsoid.

Table 2. Distance from site centroid to deepest core.

Site	Distance (m)
DfSi-19	12.83
DfSh-79	15.26
DfSh-31	5.41
DfSh-29	6.13
DfSh-4	91.33
DfSh-81	5.36
DfSh-82	1.57
DfSh-17	32.59
DfSh-5	23.90
Average	**22.86**

For each point feature in the grid, the x and y grid coordinates (UTM Zone 10 N) are recorded in the attribute table. As the UTM system records coordinates in metres north and east from an arbitrary origin, the raw coordinates enable volume calculations. The x and y distance from the midden centroid is used in Equation 2 (below) to calculate the height of the upper surface, or "skin," of the ellipsoid at each point within the grid. Here, the variables represent the same attributes of the ellipsoid as Equation 1, with the addition of z, which is the vertical height (i.e., shell midden depth) of a point on the skin of the ellipsoid above a transverse plane drawn through the origin.

Equation 2. Formula for height of ellipsoid skin.

$$z = \sqrt{\left(1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}\right) \times c^2}$$

The a and b values in both equations are based on the width and length of a minimum bounding rectangle drawn around the site. The value of c is the maximum depth, as previously described. The height of the ellipsoid above the transverse plane can be calculated for any location on the ellipsoid’s skin by solving for z. The UTM grid is oriented north, but the long axis of the shell midden deposit can have any orientation. For this reason, a rotational adjustment must be made to the x and y values of each point to account for the difference between the orientation of the midden and the coordinate system (Figure 6). These x′ and y′ correction values are derived using Equation 3 and Equation 4:

Equation 3. Formula for x’ correction value.

$$x' = -x \times \cos(\theta) + y \times \sin(\theta)$$

Equation 4. Formula for y’ correction value.

$$y' = -x \times \sin(\theta) - y \times \cos(\theta)$$

Each point created within the midden represents 1 m^2 of space, and it is assigned a height value representing the vertical distance from the transverse plane to the “skin” of the ellipsoid. The volume can be calculated by summing the z values of all the points on the grid within the ellipsoid. Recall that the volume contributed by each cell is $z(m) \times 1\ m^2$, or $z(m^3)$. To calculate the volume of a full ellipsoid, this value would be doubled.

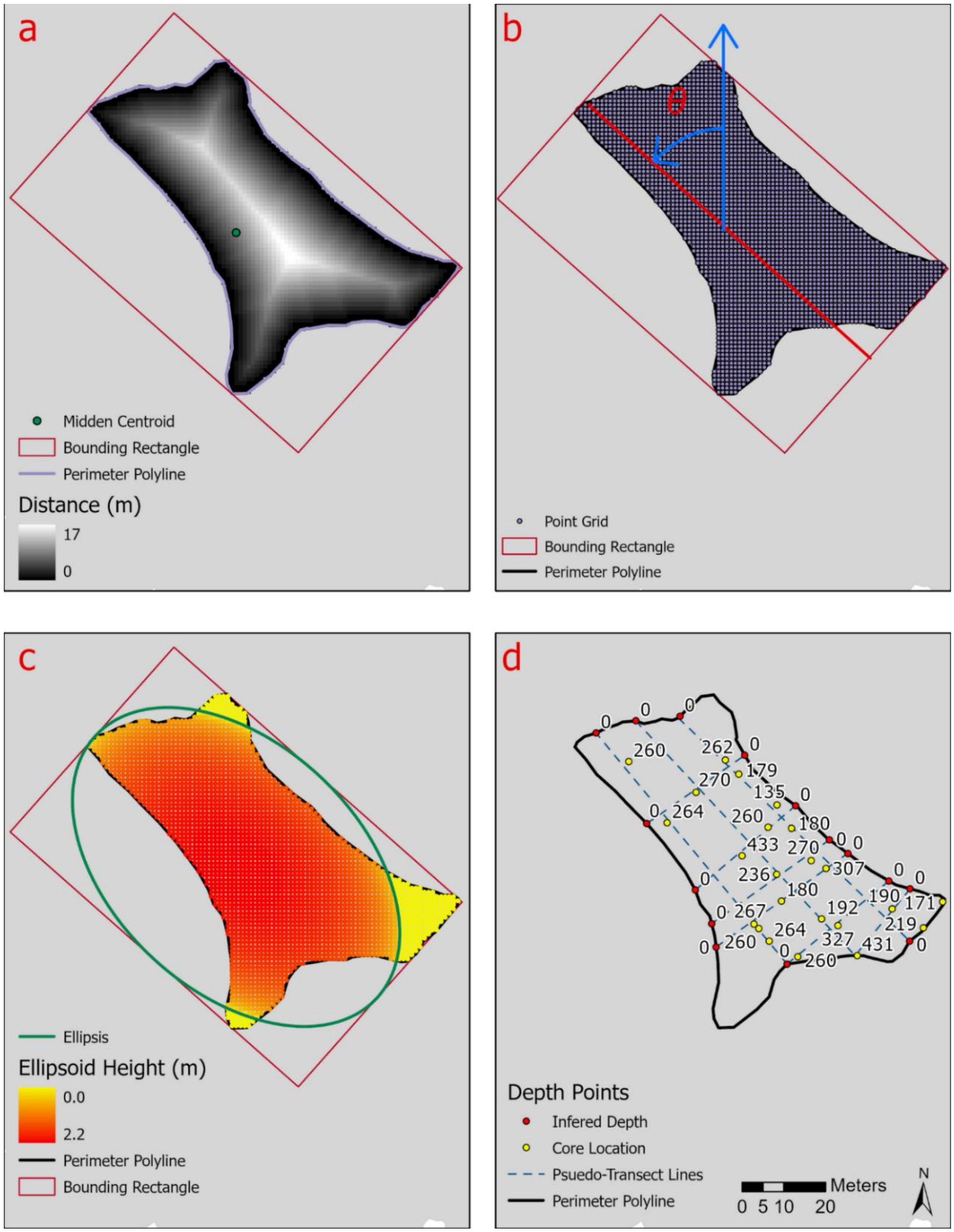

Figure 6. The steps of the volume estimation process: (a) shell midden site DfSh-31 with centroid, perimeter polyline, bounding rectangle, and raster grid; (b) the same site with points on a 1m grid, showing angular adjustments to align the x′ and y’ calculations to the cardinal direction of the midden’s long axis; θ represents the angular correction to the orientation of the midden; (c) midden points symbolized by depth with the ellipse layered over the midden; (d) core and inferred depth points placed on pseudo-transect lines at DfSh-31.

A benefit to an ellipsoidal shape is that it progressively thins toward the margins. However, in some cases, portions of a shell midden have irregular shapes that extend beyond the oval-like boundary of the ellipsoid. This is accounted for in our model through a spatial selection procedure that assigns the shallowest depth value found inside the ellipsoid footprint to those areas that extend beyond the ellipsoid perimeter. This manipulation is necessary to maintain the assumption that middens thin as they approach their edges. If left uncorrected, shell midden depth values begin to increase (rather than thin) as they extend beyond the ellipsoid boundary. This step effectively “clips” the footprint of the midden (Figure 6), like an oval cookie cutter passing through the shape of the midden where the area of the ellipsoid left inside the “cookie cutter” is what is used to calculate the midden volume. We believe this increases the realism and generality of the volume calculations when working with irregularly shaped middens while retaining the scalability and shape required for archaeological applications.

Our approach constrains the outline of the ellipsoid to the shell midden footprint and incorporates the desirable geometric qualities of both shapes. By preserving the unique shape of the midden footprint rather than using a standard geometric shape, we create a method that incorporates the individuality of discrete middens while also being applicable to a large number of sites—provided that the shell midden outlines are known. Previous methods that included this level of individuality (lidar or photogrammetry) cannot be as readily scaled, and they require unique calculations for each midden.

The shell midden settlements in this study include a wide variety of shapes, from relatively shallow sites with irregular boundaries to massive crescent-shaped mounded ridges hundreds of metres long and more than 5 m deep (McKechnie 2015). We did not encounter any sites in our study area that had footprints so irregular that they prevented the calculation of volume estimates using this method. That said, shell middens that do not fulfil the basic assumptions of being thickest near the highest point and gradually taper toward the edges would be less suitable for this method. Shell rings such as those found in the American Southeast would be an example for which this technique would not be appropriate (Thompson and Andrus 2011). However, for "stepped pyramid" mounds that do meet the stated assumptions, this technique would be appropriate (Pluckhahn et al. 2016). If a shell midden has been disturbed to the point where the footprint and depth cannot be measured (e.g., plowed-out middens), then this technique would not be applicable.

As can be discerned from the discussion above, we employed two foundational assumptions to develop our model. The first is that shell midden deposits are thickest nearest their centres and become thinner as they approach their margins, as variously observed through subsurface survey, mapping, and excavation on western Vancouver Island (Haggarty and Inglis 1985; McKechnie 2013). The second assumption is that shell midden deposits tend to occur on sloped shoreline landforms with a concave profile oriented toward the ocean. This is supported in the study area by exploratory data analysis of digitized midden footprints and lidar data, which shows that shell middens are predominately situated on sloped shoreline landforms. We employ the ellipsoid in our modelling because this shape captures both qualities of shell middens while retaining conservatism, in that a smoothed ellipsoid shape strikes a balance between overestimating volume on margins and underestimating volume taken up by irregular topography underlying shell midden deposits.

2.2.2 Location and Depth

We assembled digitized copies of original hand-drawn archaeological site maps from the Royal BC Museum survey records on file with the British Columbia Archaeology Branch

(Haggarty and Inglis 1983a, 1985). These data, including site reports and site locations, were used to roughly position site maps on the landscape. Site maps were loaded into a GIS and georectified using the scale bar on the original maps to resize the images to their correct size. Maps were then aligned to their real-world locations using digital elevation models and aerial imagery (Figure 7). Site maps for three shell midden sites out of the 81 in the Broken Group Island study area could not be located and were excluded from this analysis.

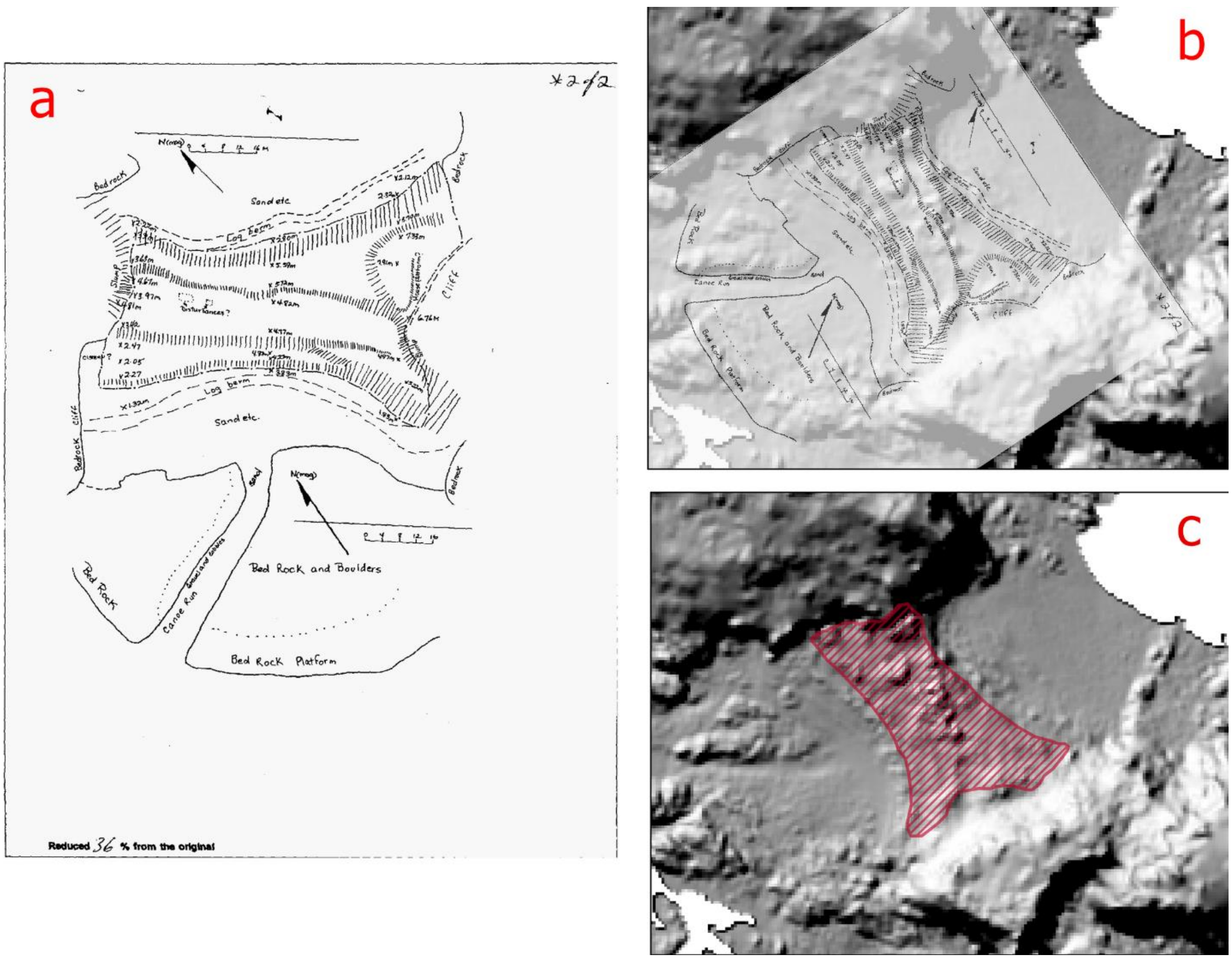

Figure 7. Site map georectification process: (a) the original site map for DfSh-31(Haggarty and Inglis 1985); (b) the site map after being georectified; (c) the digitized midden footprint from the site map.

Once correctly positioned, midden extents were digitized by hand in ArcGIS Pro 2.7.1, creating a midden extent polygon layer. The majority of site maps for the study area were created using systematic surveying and mapping, and the internal accuracy of these records is very good, as described in Haggarty and Inglis (1985:55). Rubber-sheet georectification techniques were not employed because we found that these transformations introduced greater error than is present in the original maps. This is because most sites lack sufficient identifiable tie points to use in this process due to the heavy forest cover and the ephemeral nature of beach and coastline landscapes.

Midden depth data were compiled from a variety of sources including original survey reports, Parks Canada cultural resource management records, archaeological permit reports, and academic literature (SI2.3). For each shell midden, the survey estimated or directly measured depth below surface of the basal cultural layer, which was recorded (Figure 3). Many sites in this area have had their depth measured. However, a smaller number have not been examined through subsurface depth testing, and for these locations, the reported depths are estimates based on observations of exposed stratigraphy at the site (Haggarty and Inglis 1985:55). For each site, the most specific depth measurement was used with preference given to depths generated from subsurface testing, and observational estimates were only used when a direct depth measurement was not available.

Eleven sites lack depth measurements and were estimated at a depth of 121 cm, which is the mean depth of sites within the study area. The use of mean depth is appropriate here because these sites include a wide variety of shapes and depths consistent with the larger sample population. We believe that the mean is the appropriate measure of central tendency to use here. For thoroughness, we also calculated volume estimates using median site depths and found that this change did not produce a significant change in volume (reducing the volume by about 1.5% on average).

2.2.3 Volume Estimate Assessment

To assess the accuracy of the volume estimates created from the semitriaxial ellipsoids, we compare these values to volume measurements created from excavation, percussion coring, augering, and total station mapping of midden sites. Although our sites have variable levels of sampling intensity, these comparisons allow us to assess how the model estimates perform as a measure of predicted shell midden volume. Sites used in this comparison were selected because they have many depth measurements that are well distributed across their extent.

2.2.4 Reference Volume Calculation

To assess the accuracy of the semitriaxial ellipsoid midden volume estimates, we developed a method of calculating shell midden volume from systematic subsurface surveys. A number of sites within the Broken Group Islands (n = 12) were cored (McKechnie 2013, 2015), and of these, eight sites were tested on a grid pattern. The data from this research provide detailed information about the basal depth of the shell middens and can be used to estimate volume. In order to create a more robust dataset to validate the model estimates, two middens that have been cored on a 10–20 m grid pattern in Prince Rupert Harbour (GbTo-34 and GbTo-70; Letham et al. 2017:7) and on the British Columbia Northern Coast (FhTj-1) (McKechnie 2009) were added to our sample (Figure 4). From this point forward, we use the term “reference midden” to refer to these sites. A premise of this approach is that archaeological sites subjected to subsurface testing more accurately characterize sediment depths and volumes, which in turn can be compared with sites where only estimated depths and extents are known. We recognize that the total volume of a shell midden cannot be definitively known without complete excavation, and we consider this approach as coming closest to determining the total volume with existing data. The shell midden volumes from the Prince Rupert Harbour sites were used as reported, whereas volume calculations as described in the following paragraphs were performed on the raw data from the other nine sites. We have observed that a more thorough coring effort produces data that are better suited to measuring volume. As described by Martindale and colleagues (2009), percussion coring should obtain a large number of cores and be evenly distributed throughout the site to address variability in site depth, proportional to the size of the site and where smaller sites would not require as many depth measurements.

The first step in the calculation of reference midden volumes is to record the location of percussion cores and the maximum depth of cultural sediments from those cores in a GIS. Cores collected in the Broken Group Islands were analyzed at the Canadian Geologic Survey's Pacific Geoscience Centre, which produced high-resolution orthorectified photos. This imagery was used to determine the thickness of sands and gravels at the bottom of the cores, and this noncultural material was subtracted from total core length to derive the terminal depth of cultural sediments. The core depths and locations were then passed to the Inverse Distance Weighted (IDW) interpolation tool in ArcGIS Pro, creating a surface representing the bottom of the shell midden (Figure 8). IDW was determined to be the most appropriate method after comparing results using a variety of techniques (e.g., spline, kriging). This method has also been employed in other similar analyses (Johnson 2015; Monteleone 2013). For some sites, depth data from excavation units were also used to produce a more robust sample of midden depth measurements. High-resolution DEMs created from Total Station surveys (McKechnie 2013) and lidar data collected in 2018 allowed for detailed topographic surfaces to be created for each midden. Using these data, the volume of space between the top and bottom surfaces of the midden was determined using the ArcGIS Pro "Cut and Fill" tool (Figure 8; ESRI 2020). Although not as precise as conventional excavation, this volume calculation is derived from broadly spaced subsurface testing, and it offers an empirical basis for comparing with the ellipsoid estimation.

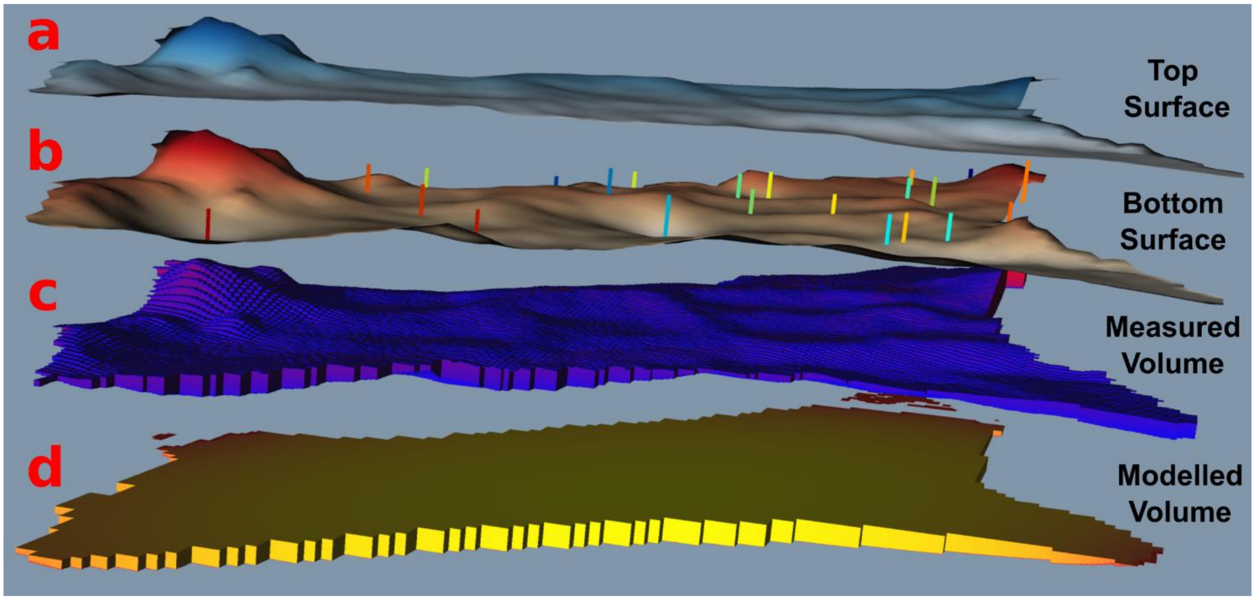

Figure 8. Visualizations of the reference and ellipsoid volumes for DfSh-31: (a) visualization of the top surface of DfSh-31; (b) visualization of the bottom surface; (c) the reference volume for this shell midden; (d) the semitriaxial ellipsoid volume of DfSh-31. The colored lines in B represent the location and depth of core tests used to derive the bottom surface.

A challenge in estimating volume from percussion core and topographic surface data is the need to use the inverse distance weighting (IDW) method to extrapolate the midden basal surface from known depths. As percussion cores surveys in the Broken Group Islands study area did not sample along the "edge" or outside site boundaries, we introduce additional "zero" data points following a "pseudo-transect approach" (Figure 6). Once these "pseudo-transect" lines were drawn, "assumed depth" points were placed at the site boundary and were given a depth of

0 cm. This is a variation of the technique that was used by Johnson (2015), who placed assumed zero-depth points at the vertices of midden boundaries. We modified Johnson's approach because the irregular midden shape can produce a high number of points and disproportionately influence IDW calculations, resulting in unrealistic thinning in large parts of the site. The pseudo-transect approach strikes a balance between edge points and core depths to be more reflective of the three-dimensional shape and ultimately volume.

2.3 Results

The integration of legacy survey data and geoarchaeological methods combined with geospatial analyses allows us to estimate site volumes in the Broken Group Islands. In addition, the digitization of sites in a GIS allowed us to determine that there is a high density of shell middens in the study area, with 3.93 sites per km^2 or roughly one site for every 430 m^2 of terrestrial terrain above low tide (Table 3). Following Mackie (2001), we additionally calculate the density per "coastal kilometre"—the Broken Group Islands encompass 299 km of linear coastline, which equates to 0.28 sites per km, or approximately one site for every 4 km of shoreline. Furthermore, a nearest-neighbour analysis shows that the average straight-line distance between sites is a mere 270 m.

Table 3. Site density statistics.

	Area (km^2)	**Sites / km^2**	**Perimeter (km)**	**Sites / km**	**Number of Sites**
Study Area	20.63	3.93	299.58	0.28	81

Using the georectified site maps, the cumulative footprint of shell middens in the Broken Group Islands is estimated to be 106,988 m^2, which represents 0.5% of the total landmass (areas above low tide). The largest shell midden in the study has an area of 11,200 m^2, whereas the smallest encompasses 2.6 m^2, with the largest proportion tending to be smaller than 1,000 m^2.

The distribution of depth, size, footprint area, and surface area are reported in Figure 9. The estimated cumulative volume of sites in the Broken Group Islands derived by the semitriaxial ellipsoid method is estimated to be 90,640 ± 2,719 m^3.

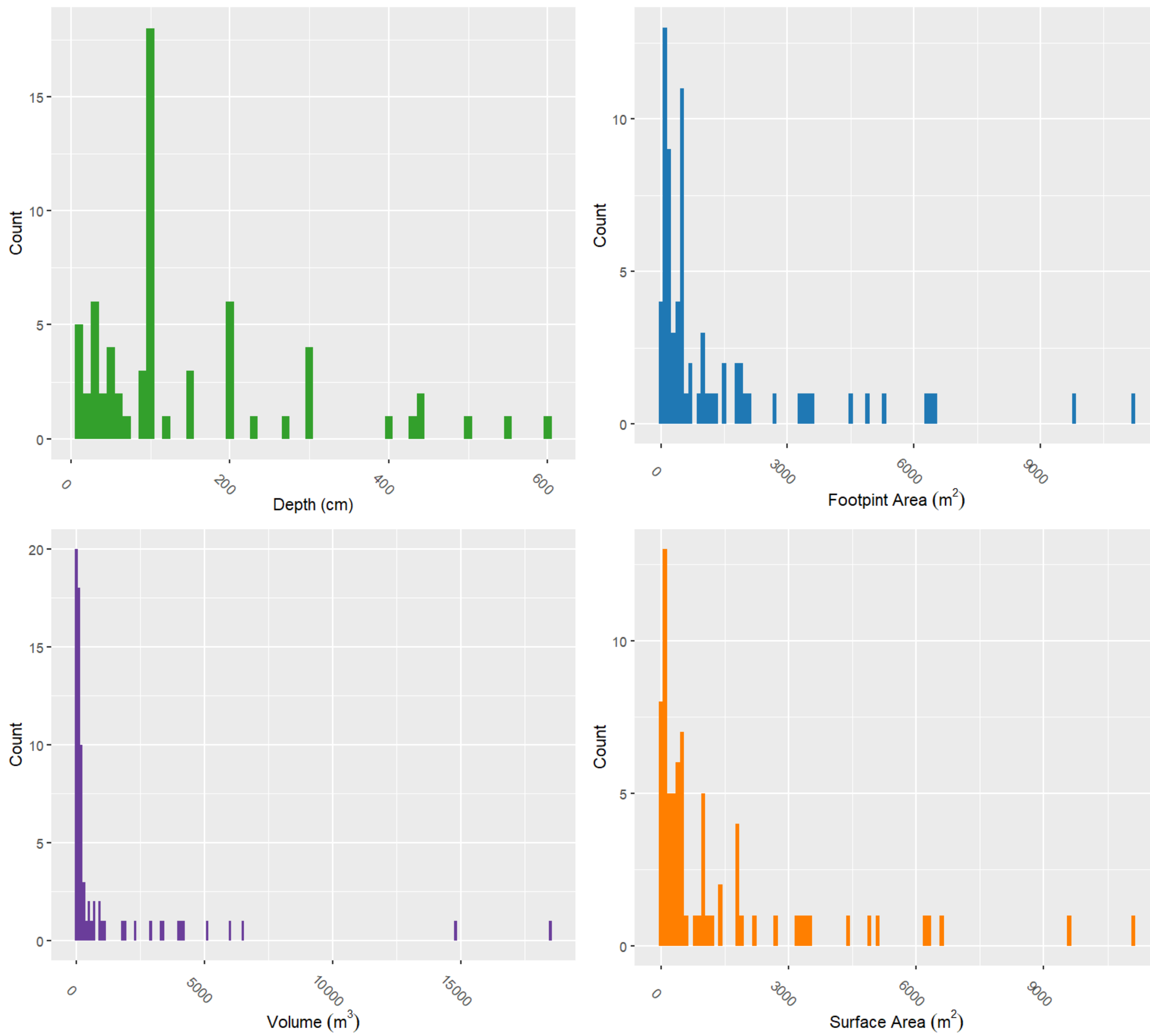

Figure 9. Summary statistics for middens in the study area: (a) histograms of midden depth, (b) footprint area, (c) volume, and (d) surface area.

The uncertainty around midden volume calculations was determined by comparing the volumes generated from the ellipsoid models to the reference midden volumes across the nine sites (Table 1). This comparison suggests that, on average, the ellipsoid volumes have an absolute error of 9%. The net effect of under- and overestimation was 3% higher on average than the recorded volume. which we consider to be the margin of error for the volume calculations. Accordingly, the mean volume of a midden within the study area is 1,066 ± 32 m^3, where the error margin is 3% of the volume. This increases to ± 96 m^3 when the absolute error is considered. A large range in the size of shell middens with a skew toward large numbers of small shell middens results in a median value of 98 m^3, which is considerably smaller than the mean volume. Such long-tailed distributions are not uncommon and were also reported in large-scale studies of shell middens north of the study area on western Vancouver Island and southern Haida Gwaii (Marshall 1993).

To assess the accuracy of reference midden volumes and how they vary with sampling intensity, we used percussion core data for the eight reference sites in the Broken Group Islands and a site on the North Coast (Table 4). We created a Python script in which 25% of cores were randomly removed, and then we recalculated volumes with the remaining depth measurements. To calculate coefficient of variation, the average standard deviation of the volumes from each site created by this process were divided by the average volume. This time-consuming process required over 24 hours to run and limited attempts at larger numbers of repetitions. However, the average variation is 13.6% of site volume and site-specific variation can be seen in Table 4. Increasing the density of cores within a site increases the precision of the reference volume. We compared varying densities of cores per 100 m^2 of midden from our reference sites and found that the average coefficient of variation for a given density of cores increases as cores are removed in a linear fashion without any indication of what a suitable sample density might be

(SI2.2). This gives us a measure of confidence that we have sufficient core density in our samples for accurate calculation of volumes.

Table 4. Coefficient of variation for reference middens as calculated by adding and removing cores to volume calculations.

Site	Average Volume (m^3)	Standard Deviation	Coefficient of Variation (%)*
DfSh-29	2,725	379	13
DfSh-31	4,724	306	6
DfSh-4	12,511	1,361	11
DfSh-79	78,134	7,159	9
DfSh-81	3,820	12,575	30
DfSh-82	11	3	28
DfSi-16	14,704	1,838	13
DfSi-19	5,799	697	12
FhTj-1	29,350	430	1
Average	**16,864**	**2,749**	**13.6**

* Coefficient of Variation is calculated as standard deviation of midden volume divided by the average of simulated site volumes.

The accuracy of the volume estimates was evaluated by comparing the volume as calculated for the semitriaxial ellipsoid against reference volumes calculated from systematic percussion coring at 11 sites (Table 1). This comparison shows that the semitriaxial ellipsoid–based estimates of midden volume overestimate reference midden volumes by 9% on average (absolute error), with divergence increasing between volumes predicted by the ellipsoid model and reference volumes at larger middens. For the three more intensively sampled reference middens outside the study area, the ellipsoid method tends to underestimate volume slightly (93–94% of reference volume). For the Broken Group Islands, results are less consistent, likely reflecting the lower sampling resolution of percussion core depth measurement and the higher topographic complexity of the rocky intertidal shoreline in these wave-exposed island settings. At large sites (DfSh-4, DfSi-19, and DfSi-16), the ellipsoid estimate is between 11% and 22% larger than the reference volume, whereas for the other sites, the ellipsoid volume is less than 10% of the size of the reference volume. We observed that reference midden volume calculations perform better when more core data are available for a site because this increases the precision of interpolating midden basal surfaces. At the sites of DfSi-19 and DfSh-29, a relatively small number of cores were collected, whereas the other sites were more thoroughly surveyed, thereby producing a larger number of core tests. For instance, DfSh-79 is a “thin” but extensive defensive site located high on a steep-sided hill, and it has a highly irregular footprint that does not conform to the usual crescent or oblong pattern observed in the study area. Its unique shape and elevated setting likely explain the discrepancy between the model and reference volumes. We believe that further testing on small sites and of midden footprint shapes that are more representative of those typically observed in the study area will refine our approach. Further attention to the topographic complexity of underlying landforms and bedrock exposures will also help refine estimates.

Overall, this method is considerably more accurate than previous applications of geometric solids for calculating archaeological midden and mound volume. To evaluate how our method compares to previous estimates, we applied previously proposed geometric solids to our reference middens and found that these methods vastly overestimated the sediment contained in middens in comparison to the reference volumes (Table 5). This overestimation can be anywhere from 177% to 926% on average, depending on the shape that is used. The shapes that were included in this analysis include cones (Sorant and Shenkel 1984), cylinders (Cook 1946), spheres (Treganza and Cook 1948), and pyramids (Shenkel 1986). This comparison to other geometric solids that have been used illustrates that semitriaxial ellipsoids provide substantially improved estimates of midden volumes over prior approaches.

Table 5. Comparison of geometric solid models for sites used in reference calculations.

Site	Cone	% Ref	Cylinder	% Ref	Pyramid	% Ref	Spherical Cap	% Ref	Semitriaxial Ellipsoid	% Ref	Reference
DfSh-4	105,730	828	317,190	2,483	32,844	257	158,641	1,242	14,826	116	12,775
DfSi-19	21,308	366	63,925	1,097	12,242	210	32,050	550	6,489	111	5,828
DfSh-79	3,480	426	10,440	1,279	2,672	327	5,223	639	846	104	816
DfSh-31	9621	198	28,862	595	7,862	162	14,474	298	4,062	84	4,851
DfSh-81	249	153	748	459	250	154	374	230	161	98	163
DfSh-82	17	143	52	428	18	148	26	214	13	108	12
DfSi-16	60,896	402	182,689	1,205	32,786	216	91,410	603	18,463	122	15,167
DfSh-29	9063	330	27,190	990	4,403	160	13,630	496	2,904	106	2,747
GbTo-70	1,0094	261	30,282	782	5,427	140	15,174	392	3,769	97	3,872
GbTo-34	29,749	246	89,248	738	18,579	154	44,658	369	11,966	99	12,098
FhTj-1	23,555	198	70,665	593	18,089	152	35,377	297	11,852	99	11,917
Average		**309**		**926**		**177**		**464**		**103**	

% Ref is calculated by dividing the volume (m^3) of the geometric solid in the column to the left by the corresponding value in the Reference column and converting to a percentage.

2.4 Discussion

The semitriaxial ellipsoid method used for estimating midden volume from geometric shapes improves the basis for evaluating the archaeology of shell middens on the Pacific Northwest Coast. The generic shape, scalable to site size, performs well in the absence of detailed topographic data or geophysical survey and is more appropriate for estimating sediment volumes than those used in previous efforts.

By employing a solid geometric shape, we recognize that we are sacrificing accuracy, as compared to systematic depth measurement across the extent of a midden, in favor of creating a process that can be applied to large numbers of sites—those with just two types of data: extent and depth estimates. Such information is routinely collected during archaeological survey efforts, which means that volume estimates can be generated from existing datasets. A benefit of applying a general solid is that it does not require high-resolution topographic data such as the kind produced by lidar or Total Mapping Station DEMs, which would be prohibitively time consuming and costly to acquire for all known sites in the densely forested Northwest Coast. For this same reason, geophysical surveys and photogrammetry are very difficult to conduct in this environment. In contrast, basic site maps have been created for thousands of recorded shell midden sites in British Columbia, and this method enables this extensive record to be analysed with minimal additional fieldwork. The accuracy of the midden footprint and depth measurements will clearly influence the volume calculation. We do not recommend low-resolution data. Higher-resolution mapping produces more precise results, and we recommend using the best data available, but we suggest that the benefit rapidly diminishes beyond the submetre level. The resolutions of the input measurements are carried forward through the analysis to the final volume calculations. This method can be easily applied to very large collections of middens if they have been accurately mapped and they meet the model assumptions stated previously.

Through the application of GIS and Python scripting, volume calculations can be scaled across many sites simultaneously, with automated calculations allowing for examination of data on a landscape level. As discussed, empirical observations remain vital to refining this three-dimensional shape characterization through systematic coring (Letham et al. 2017) and, perhaps, application of geophysical methods (Cariou et al. 2018; Kenady et al. 2018), although heavily forested sites on the Northwest Coast can be challenging (but see Urban and Carter 2021 for a recent successful application). Coring and auguring provide a good balance of time and effort (Cannon 2000; Duffield et al. 2020; Martindale et al. 2009; McKechnie 2013), and greater attention to this methodology will allow for refinement of accurate volume calculations in different cultural regions and coastal settings.

The ability to estimate midden volume accurately has significant potential for understanding shell middens and connecting results from excavated material to regional-scale processes. For instance, there is significant potential for shell midden volume estimates to be combined with radiocarbon dates and zooarchaeological data to better understand site formation processes, accumulation rates, and the density of animal remains at sites. This could shed light on the biomass represented in sites as well as the intensity of site use over time with implications for the modern use of marine resources (Duffield et al. 2020, 2022).

This is the first study that we are aware of to employ the semitriaxial ellipsoid as a model of shape to predict shell midden volume. The most similar shape that we have encountered is the “parabola of revolution” (Jeter 1984:92), which is superficially similar in shape but mathematically more similar to a cone. We argue that the ellipsoid better represents Northwest Coast shell midden deposits versus other shapes because the volume of an ellipsoid is derived from the measurement of three commonly described dimensions: length, width, and depth. Additionally, this shape is superior to a Cartesian model because the semirounded shape lacks linear planes, edges, and sharp corners. In contrast to the ellipsoid, the volume of spheres, cones, and similar shapes are determined using fewer axes of measurement. Additionally, our method constrains the ellipsoid to the footprint of the midden, which helps refine volumetric modelling of archaeological sediments. Together, these attributes of our model address several limitations of other approaches and enable more accurate volume estimates at scale.

Our analysis affirms that the Broken Group Islands were a densely inhabited coastal landscape and were substantially modified by the human activity represented in shell midden deposits. Over more than 5,000 years, Indigenous peoples living in this archipelago generated tens of thousands of cubic metres of sediment, including tens of millions of shellfish, fish, marine mammals, birds, and other organisms and cultural materials. The legacy of this long-term human activity is intimately connected to the historical ecology of this coastal region, but the extent and scale of this activity is not well recognized. We estimate the volume of sediments deposited in the Broken Group Islands (90,640 ± 2,719 m^3) to be collectively equivalent to the volume estimates of famous monumental structures elsewhere in the Americas, such as the temples of Tikal (Webster and Kirker 1995) or the many mounds in the North American Southeast and Midwest (Shenkel 1986:214–215). These features in their totality represent the outcome of multiple generations of substantial labour and energy, especially considering the effort required to harvest materials in these deposits. Precontact modification to the landscape of the Broken Group Islands through the accumulation of sediments was not inconsequential, and we hope this study encourages archaeologists to consider ways that volume can enhance the interpretive and comparative potential of coastal archaeological landscapes.

2.5 Conclusion

Our geospatial analysis provides a novel method of estimating midden volume generated from readily available shape and depth information. Shell middens are often conspicuous deposits mapped with a considerable degree of accuracy and precision, but rarely are systematic subsurface testing, survey, and remotely sensed data combined to estimate site volume on the Pacific Northwest Coast. We suggest the use and application of a semitriaxial ellipsoid model to estimate coastal shell midden volumes, and we compared these estimates with well-surveyed sites to establish the accuracy of this method. This method is scalable and can be applied to legacy data using an automated workflow. Estimating shell midden volumes provides interesting opportunities to better understand these complex anthropogenic features, which comprise major components of archaeological landscapes across the world. We hope that this approach helps spark discussions about characterizing the shape and extent of shell midden deposits and the historical ecology of human engagement in these different coastal regions.

Chapter 3. Estimating Ancient Nuu-chah-nulth Fisheries Biomass at Shell Midden Sites on the Northwest Coast of North America

3.1 Introduction

Archaeological shell midden sites are characteristic and enduring features prevalent across much of the Northwest Coast. Typically, these deposits contain large quantities of shellfish, fish, and other faunal remains. Coastal shell middens on western Vancouver Island offer a unique opportunity to quantify the amount of fish biomass harvested over millennia by Nuu-chah-nulth peoples. Here, we examine fish assemblages from fifteen sites in Barkley Sound on western Vancouver Island, British Columbia, Canada, and extrapolate our findings to estimate the total harvested fishery biomass at 186 documented sites in the region. This work contributes to a body of zooarchaeological research in coastal archaeology, which moves the analytical boundaries of zooarchaeological quantification to enable comparisons with contemporary harvests and management targets (Efford et al. 2024; Fossile et al. 2019; Gavenus et al. 2023; Reeder-Myers et al. 2022). We take a long-term perspective by examining 5,000 years of fishing effort based on the harvested biomass preserved in archaeological sites by Nuu-chah-nulth peoples living in Barkley Sound and compare these findings to contemporary fisheries catch data. Such a comparison sheds light on the scale of Nuu-chah-nulth fisheries over time and provides a baseline for understanding shifts in fisheries activities over millennia. Furthermore, this work is relevant for current discussions relating to Indigenous fisheries sovereignty, as informed by historical use, given that we provide minimum estimates of the total harvested fish biomass caught by Nuu-chah-nulth fishers in the past.

Barkley Sound is an approximately 900 km^2 marine embayment located on the west coast of Vancouver Island (Figure 10). It is a hyper productive Eastern North Pacific ecosystem which is characterized by rugged coasts and temperate rain forests (McMillan et al. 2008). It has been inhabited for over 5,000 years by the ancestors of Nuu-chah-nulth speaking peoples including the Tseshaht, Huu-ay-aht, Uchuklesaht, Toquaht, and Ucluelet First Nations who have all traditionally lived in and made use of the lands and waters within the study area (McMillan et al. 2008). These Nations have relied on the rich marine resources found in this environment and better understandings of resource harvesting through time have direct impacts for these communities as they engage in marine resource stewardship and management. The archaeological materials contained within this area represents the efforts of ancestral Nuu-chah-nulth in this area to harvest marine resources.

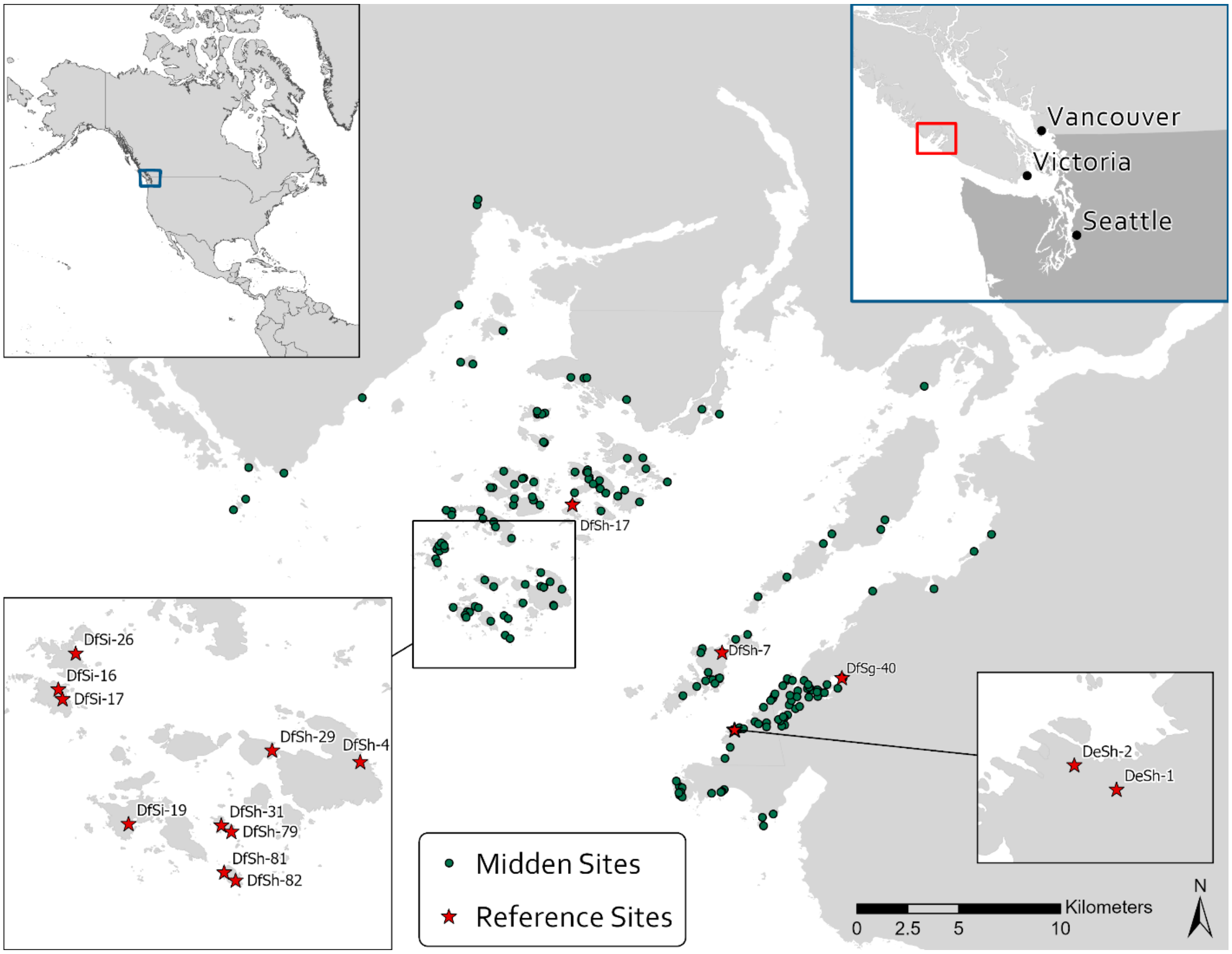

Figure 10. Map of documented shell midden sites in Barkley Sound used in this analysis. The red stars represent the locations of the 15 sites with quantified fish assemblages.

Estimates of 'edible meat weight' quantified from archaeofaunal assemblages have been extensively examined in zooarchaeological research on the Northwest Coast (Croes and Hackenberger 1988; Grier and Lukowski 2012; Hopt and Grier 2018; Huelsbeck 1988; Lyman 2008; Marshall 1989; Mitchell 1990; Moss 1993; Wigen and Stucki 1988). Such work, however, has tended to focus on proportional abundance and the nutritional contribution of harvested animals. In contrast, we shift the focus from estimating edible meat weight and relative dietary contributions to quantifying the total biomass of animals preserved in archaeological deposits, offering a broader estimate of cumulative Indigenous harvesting over long time scales. Biomass is a commonly used biological metric that represents the collective mass of a group of living organisms and differs from the archaeological concept of 'edible meat weight,' which seeks to estimate the weight of 'edible portions' of individual animals consumed by people (White 1953). The total edible mass and nutritional value of an individual animal will vary due to age, sex, physical condition, and season of capture (Speth 1990; Stewart and Stahl 1977). In addition, what is defined as 'edible' will depend on cultural practices, preferences, and circumstances; as well as other uses including skins, medicines, tools, raw materials, and myriad other applications (Reitz and Wing 2008). Furthermore, biomass is a common and widely applied metric in contemporary fisheries management and ecology, facilitating comparison among periods. In this sense, biomass is used to quantify the weight of fish harvested and to assess the abundance of a given species in an environment. In this paper, we focus on biomass as a proxy for fisheries landings, rather than as a measure of how many fish occupy a given environment at a point in time.

A foundational concern in zooarchaeology relates to estimating the proportional abundance of skeletal remains at sites as a measure of dietary and cultural importance (Gifford-Gonzalez 2018). As is widely documented, taphonomic processes can exacerbate differential preservation, anatomical representation, transport of body parts, purposeful fragmentation, microbes, scavengers, and other factors that directly influence what is recovered and identified by zooarchaeologists (e.g., Gifford-Gonzalez 1991; Kendall et al. 2018). Additionally, quantifying how many individual animals are present in a given deposit is a challenge in terms of analytical independence: how to ensure that the same individual animal is not counted multiple times, given its remains might occur in several locations (Grayson 1979).

Here, we approach biomass estimation from the perspective of archaeological fisheries data in a coastal environment. In this setting, fish bones constitute 99% of identified bone when using fine mesh screens and are so densely concentrated that 100 to 150 identifiable fish bones are often present in a single litre of fine-screened sediment in which there is rarely a single identifiable mammal or bird element (McKechnie 2005b:214). Given the relatively smaller body sizes of most fishes, compared to most medium to large mammals, a larger number of fish must be harvested to yield a similar biomass. As such, a single fish is more likely to be processed and consumed by an individual or family, thereby limiting the physical dispersal of remains in time and space. In the case of mass harvesting, where communal processing, storage, and prolonged consumption of many individual fish involve greater physical dispersal, the number of fish bones would similarly greatly exceed an equivalent number of mammals. Accordingly, fish are likely to be deposited in discrete locations over shorter time frames and exhibit less purposeful skeletal fragmentation than mammals, which would be distributed over a geographically larger area, subject to greater fragmentation (extracting fats and oils), scavenger modification and dispersal, and use as tools, architectural features, and displays of hunting prowess (McMillan 2015; Monks et al. 2001). The zooarchaeological implication is that fish are much less vulnerable to issues of overcounting and analytical independence.

This estimation method is based on the Number of Identified Specimens (NISP) which enables a calculation of the Minimum Number of Individuals (MNI) for fish. We then apply taxa-specific body mass estimates to extrapolate biomass based on MNI within examined sediment volumes for a group of 15 sites. The advantage of using biomass is that it allows for a more explicit understanding of the scale of Nuu-chah-nulth fishing efforts, as scaling biomass to a site focuses on an approximation of the overall fishing effort and builds on other common zooarchaeological methods for estimating counts of animals from their remains. We use site volumes, quantitative zooarchaeological data, and body mass estimates of different fish taxa to estimate how much each taxonomic group contributed to the total amount of harvested fish biomass preserved at recorded archaeological sites in Barkley Sound. We use these biomass estimates to better understand the scale of Indigenous fisheries activities and to provide context to contemporary fisheries.

3.2 Methods

We generated biomass estimates using three sources of data: the estimated total volume of shell midden sediment in archaeological deposits, the estimated MNI of fish taxa contained within volumetrically measured samples within these same sites, and body mass estimates of fish taxa. In short, the total harvested biomass is quantified using density of fish per litre (L) of sediment, which is then extrapolated to the volume of the site (kg per m^3). For this analysis, we calculated MNI and MNI per L for fifteen fine-screened zooarchaeological assemblages and combined these estimates with detailed site mapping efforts to calculate site volumes and MNI per site.

3.2.1 Site Selection and Sample Recovery

The fifteen sites with quantified fish bone data originated from a range of shell midden deposits located in a variety of coastal settings in Barkley Sound (i.e., exposed, semi-protected, and sheltered) (Figure 10). These included large permanent village settlements as well as smaller lookout and defensive sites. At each site, multiple column and/or auger samples recovered a series of vertically distinct sediment samples, from which bones were separated using fine mesh 2 mm geological screens (McKechnie 2005b; McMillan et al. 2008; Sumpter 2005). Multiple column or auger samples were obtained from various locations within each site and consisted of a series of volumetrically controlled vertical depth ranges. Radiocarbon dates from each site confirmed mid-to-late Holocene age ranges spanning the past 5,000 years (details in McKechnie 2013; McMillan 1999). Samples were recovered and processed using fine mesh screens except for portions of Ts'ishaa (DfSi-16) and Kiix7in (DeSh-1 and DeSh-2) where 3.2 mm screens were used. This substantial dataset from a variety of sites and temporal periods thus offers a representative basis for considering the composition and abundance of Nuu-chah-nulth fisheries across thousands of years of human activity as represented in archaeological sites in Barkley Sound (McKechnie 2013).

3.2.2 Zooarchaeological Identification and Quantification

Zooarchaeological data were morphologically identified to skeletal element using the Zooarchaeology Comparative Collection at the University of Victoria (McKenzie 2024). The Number of Identified Specimens (NISP) reflects confident identifications of skeletal elements assigned to the family, genus, or species level (McKechnie 2005b, 2012, 2013). To derive MNI estimates, we used primary bone identification data to estimate the number of identified skeletal elements, side, size, and state of preservation for each taxon, from each discrete column or auger level. MNI estimates were based on the greatest number of non-repeatable elements (e.g., left maxillae). This was adjusted in instances when there were numerous complete vertebrae such that a given species exceeded the average number for an individual fish (e.g., Pacific herring, (*Clupea pallasii)*, have an average of 55 vertebrae) or where there were clear size differences among fish bones from the same species or genus (e.g., both a large and small Kelp greenling, *Hexagrammos decagrammus,* vertebrae were present). This process was repeated for each of the 341 vertically discrete level samples collected from over 70 locations within the 15 sites.

Once an MNI for each sample was derived, we totalled minimum counts of fish according to the most specific taxonomic division possible and calculated proportional counts for each taxonomic grouping. To address the issue of analytical independence and minimize the possibility that bones from a single fish were counted more than once, we based our MNI counts on alternating, vertically distinct levels within individual columns or augers. This meant that there was 5-20 cm ‘gap’ of vertical midden accumulation between levels within a column or auger. In some cases, this meant sub-sampling a fully identified assemblage by subtracting MNI counts and examined volumes to ensure that only vertically spaced levels were used to generate MNI counts (Table 6). An exception to this was the site of Huu7ii (DfSh-7), where original MNI counts included contiguous levels from a small portion of the individual column samples representing less than 20% of the 155 examined levels (McKechnie 2012). Given these level samples are from stratified deposits with positive accumulation rates and large numbers of fish bones, we consider it unlikely that a bone from the same fish would be counted as two or more fish, given that small portions of a single fish would need to be widely dispersed in space and time for it to occur in more than one examined sample.

Estimates of MNI per L are based on excavated sediment volumes from specific samples from which fish bones were recovered and quantified. Volume was measured by water displacement (using bagged sediment samples) and/or individual in situ level dimensions (e.g., 10×10×10 cm = 1 L). The average examined volume for a discrete sample was 1.3 L, with a range of 0.75 to 6.25 L (McKechnie 2005b, 2013). Each examined archaeological sediment sample typically contained 10–200 identifiable bone specimens with an average MNI estimate of 3.8 individual fish per L of sediment or approximately 380 fish per m^3 (Table 6). As previously mentioned, samples from four of the 15 sites used slightly larger screen sizes (3.2 mm), resulting in notably lower MNI counts per L. In these instances, we adjusted the number of MNI per L counts upwards by 26% to make them consistent with the other assemblages, which does not change the relative abundance value. This latter step is based on a comparison of the observed recovery differences at the other sites used in this analysis between 2 mm and 3.2 mm screens (McKechnie 2005b).

3.2.3 Body Mass Estimates

To estimate fish body mass, we aggregated archaeologically identified taxonomic categories with more than one species unless there were clear size differences in the specimens [e.g., Pacific halibut, (*Hippoglossus stenolepsis)*, vs. miscellaneous flatfish (*Pleuronectidae sp.*) or Lingcod (*Ophiodon elongatus)* vs. miscellaneous greenling (*Hexgrammos sp.*)]. The relative proportion of MNI (% MNI) for each taxonomic grouping reflected the percentage of identified fish for each taxonomic category in the archaeological record. For the following subset of closely related species that are not morphologically distinguishable (e.g., rockfish [genus *Sebastes*] and salmon [genus *Oncorhynchus*]), we refined body mass estimates using aDNA identifications (rockfish *n* = 72; Rodrigues et al. 2018) and Zooarchaeology by Mass Spectrometry (ZooMS) (salmon *n* = 100; Zhu et al. 2023) to estimate the relative composition of species present in the archaeological assemblages (see SI3.1)[2]. All supplementary materials can be found in the UVic Research Data Collection in the Borealis repository: https://doi.org/10.5683/SP3/C11QWV.

3.2.4 Site Volume Estimates

Individual site volumes were calculated using the methods and results detailed in Gustas et al. (2022). Briefly, a semitriaxial ellipsoid was fitted to site boundaries, and the volume of these geometric shapes was used to estimate midden volume (Table 6). The length and width of the midden as derived from archaeological survey measurements, and depth as determined from natural exposures and subsurface testing (coring, auguring, or excavation), were used to define the size of the semi-triaxial ellipsoid. This method has been validated in multiple areas of coastal British Columbia with an estimated average error of less than 9% (Gustas et al. 2022). The relative simplicity of this approach means that the extensive record of archaeological survey in Barkley Sound (e.g., Sumpter and St. Claire 2007; Haggarty and Inglis 1983b, 1985; Mackie and Williamson 1985; McKechnie 2013) can be used to estimate volumes for 186 different shell middens in the study area. Using the method described above, we estimate that the 186 documented sites in the study area contain 241,253 m^3 (241,253,000 L) of shell midden sediment. Supplementary data file SI3.2 provides an overview of biomass calculations for each site and taxonomic group.

[2] Spreadsheets containing the calculations used in the methods section of the paper are provided as supplementary materials (SI3.1 to SI3.4).

3.2.5 Fish Body Mass

To estimate fish body mass, we built off the work of Hillis et al. (2022), who used a combination of archaeological, historical, and contemporary records to determine the median body masses of different taxonomic groupings of fish species across sites in the study. Given that not all skeletal elements have species-specific morphologies and that they have intrinsically different identifiability, some osteological identifications were based on broader taxonomic categories. For example, readily identifiable skeletal elements from species like halibut and lingcod were separated into individual species, whereas less morphologically distinct species were placed in larger taxonomic groups such as 'flatfish' (Suborder Pleuronectoidei) or 'greenling' (Family Hexagrammidae). We used linear regressions to predict body length from bone size as well as length-to-weight conversion factors, historical catch records, modern ecological surveys, and recreational catch data from the study area to generate distributions of fish body mass. Weighted body mass estimates for each taxon were then calculated using the relative proportion of identified specimens (i.e., % MNI).

Determining the body mass for each fish taxon involved combining data from a variety of sources [see details in Hillis et al. (2022)]. Briefly, a ranked process was established for selecting the most representative estimate of the size and body mass of fish targeted by Indigenous fishers, where datasets of greater time depth and spatial proximity to Barkley Sound were prioritized over data from more recent and/or geographically distant sources. Using the 25^{th}, median, and 75^{th} percentile body mass estimates allowed for a more detailed estimate of the size profile of fish, which can be highly variable depending on age, seasonality of harvest, and other elements of their life history. We considered the median as most appropriate for characterizing the representative body mass but include the 25^{th} and 75^{th} percentile body masses as these estimates enable examination of variation and uncertainty.

Table 6. Volume and biomass of each site used in this analysis.

Site Number	Estimated Site Volume (m^3)	Sample MNI	Examined Sample Volume (L)	MNI Per L	Estimated Fish MNI	Estimated Biomass (kg)*	Estimated Fish Per m^3	Estimated Biomass Per m^3 (kg)
DfSh-7	21,833	1,439	220.00	7	142,810,867	96,695,362	6,541	4,429
DfSi-16	18,463	485	148.00	3	60,504,225	50,417,859	3,277	2,731
DfSh-4	14,826	88	15.70	6	83,101,305	41,590,315	5,605	2,805
DfSi-19	6,489	204	37.90	5	34,925,441	21,311,367	5,383	3,284
DfSi-17	4,248	83	24.00	3	14,691,274	10,897,031	3,458	2,565
DfSh-31	4,062	215	41.65	5	20,673,497	15,089,702	5,090	3,715
DfSh-29	5,245	206	42.26	4	26,299,409	17,315,426	5,014	3,301
DfSh-17	1,837	91	18.90	5	8,843,289	3,397,767	4,815	1,850
DeSh-1	1,752	103	47.20	2	3,822,932	4,367,903	2,182	2,493
DfSh-79	846	195	42.05	5	3,882,949	3,107,446	4,590	3,673
DeSh-2	741	23	7.40	3	2,302,168	1,925,313	3,108	2,599
DfSg-40	271	59	9.50	6	1,682,528	610,643	6,211	2,254
DfSi-26	222	19	3.00	6	1,404,526	762,658	6,333	3,439
DfSh-81	161	8	2.95	3	435,392	121,746	2,712	758
DfSh-82	19	4	2.10	2	36,345	13,057	1,905	684
Sum	**78,674**	**3,089**	**633.95**	**7**	**394,491,142**	**259,731,397**		
Average†	**5,245**	**206**	**42.26**	**4**	**26,299,409**	**17,315,426**	**5,014**	**3,301**

* Median fish masses are reported but see Supplementary SI3.2 for estimated biomass using 1st and 3rd quartile body mass estimates.

† Average estimated biomass fish per cubic metre was calculated by dividing the summed estimated biomass by the summed estimated site volume. Average estimated fish per cubic metre was calculated by dividing the summed estimated fish MNI by the summed estimated site volume. Other average values are the summed values in each column divided by the 15 sampled sites.

3.2.6 Biomass Calculations

To estimate the harvested biomass of a fish taxon within a given site, we multiplied its median body mass by the density of fish (MNI per L of midden sediment) and then multiplied this product by the total estimated volume of the site. This process was then repeated for each taxonomic category of fish and summed to derive the total biomass of fish in a site (Equation 5).

Equation 5. General formula for calculating biomass for a taxon.

$$Biomass\ (kg) = Volume\ of\ Site\ (m^3) \times \frac{MNI}{m^3} \times Mass\ per\ fish\ (kg)$$

To illustrate how the biomass of a single taxonomic group at one archaeological site was calculated, consider the example of dogfish (*Squalus suckleyi*) for the site of Ts'ishaa (DfSi-16) located on Benson Island. Recovered sediments for the sampled portion of this site contained an MNI of 18 dogfish from an examined volume of 148 L, resulting in a density estimate of 0.122 dogfish per L (i.e., 122 dogfish per m^3). Given that the whole site was estimated to contain 18,463,145 L of sediment, this allowed us, by multiplying the density by total site volume, to estimate that the entire site contains 2,245,518 dogfish based on preserved skeletal remains. The body mass of an individual dogfish was determined from bottom trawl fishery surveys off western Vancouver Island (Anderson et al. 2019); the median mass is 1.250 kg with a 1st and 3rd quartile body mass of 0.912 and 1.778 kg, respectively. Thus, by multiplying the median body mass of a dogfish by the estimated total number of individual dogfish at Ts'ishaa we can derive a total harvested dogfish biomass of 2,806,897 kg (interquartile range of 2,047,912 - 3,992,530 kg). By linking midden volume estimates to the density of dogfish, and the median dogfish body mass, we can generate a total harvested biomass for this species at Ts'ishaa. Application of these values can be seen in Equation 6.

Equation 6. Biomass calculation for dogfish (MNI = 18) in DfSi-16.

$$2{,}806{,}897\ kg = 18{,}463{,}145\ L \times \frac{18\ individuals}{148\ L} \times 1.250\ kg\ per\ fish$$

Across all 15 sites with analysed sediment samples, we observed an average MNI of 0.191 dogfish per L of sediment (i.e., 191 dogfish per m^3). This value was derived by dividing the summed MNI of dogfish (n = 121) across the 15 sampled sites by 634 L of sampled sediment from these same sites. Accordingly, we estimated the recorded sites in Barkley Sound (n =186) to contain at least 241,253,000 L of sediment, which when multiplied by this density yields 56,174,476 kg of dogfish. This process was repeated for each of the 23 taxonomic groups present based on the 15 sampled sites for each taxon (Table 7). To calculate the total biomass and count of fish from all taxonomic groups at all sites in Barkley Sound we used a modified variation of the above process (Equation 7, Equation 8, and Equation 9), which assumes that the density of biomass in any given shell midden is generally represented by the averages from the 15 sampled sites. As explained below, observed fish densities from the 15 sampled sites are extrapolated across the volumes of all 186 middens in the study area. This assumes that on average across the entire study area that all fish species in this sample would occur in all sites and would also exclude fish that are known to occur in larger-scale excavations such as Bluefin Tuna (Frederick 2012) which tend to be under detected in small volume fine screened samples.

To estimate the number of fish for each taxonomic group contained in a litre of shell midden sediment (i.e., fish density), we summed the MNI of fish taxa from all 15 sites and divided this value by the volume of examined sediments. Next, this measure of fish density was multiplied by the summed volume of the 15 sampled sites to estimate the total number of fish in each taxonomic category (Equation 7). This total count of fish was then multiplied by taxon-specific body masses (Table 7) to derive the total biomass for the 15 examined sites. This process was then repeated for each of the 23 fish taxa, and these values were summed to derive the total biomass contained in the 15 sites (Equation 8). Finally, this biomass across all taxa was divided by the total site volume of the 15 sampled sites to calculate a single average biomass per L across all fish groups. This average density (kg per L) of biomass from the sample was then multiplied by the volume of each of the 186 shell middens in the study area (Equation 9). These estimates were summed together yielding an estimate of the total harvested fish biomass preserved in the sites within the study area. Supplementary SI3.2 and Supplementary SI3.3 provide the specific calculations used to derive the values reported here.

Equation 7. Formula for estimating the total number of fish in each taxonomic group in the 15 sampled shell middens in Barkley Sound.

Where
c_g = Count of fish in a taxonomic group across all sampled sites
u = Sample midden site volume
s = Index across the 15 sample sites
m = MNI count of fish in taxonomic group at a sampled site
v = Volume of sediments sampled at a site

then

$$c_g = \sum_{s=1}^{15} u_s \times \left(\sum_{s=1}^{15} m_s \div \sum_{s=1}^{15} v_s \right)$$

Equation 8. Formula for estimating the biomass of fish in a taxonomic group in the 15 sampled sites in Barkley Sound.

Where
b_g = Biomass of fish in a taxonomic group across all sampled sites
w_g = Weight of individual fish in a taxonomic group

then

$$b_g = c_g \times w_g$$

Equation 9. Equation for calculating the total biomass from fish in all 186 surveyed Barkley Sound middens.

Where
B = Total biomass of all Barkley Sound middens
U = Midden site volume
i = Index across the 186 individual middens in Barkley Sound
g = Index across the 23 fish groups
s = Index across the 15 sample sites

then

$$B = \sum_{i=1}^{186} U_i \times \left(\sum_{g=1}^{23} b_g \div \sum_{s=1}^{15} u_s \right)$$

Calculations for these and following formulae are detailed in Supplementary SI3.5. The capital sigma summation notation indicates that the following values are summed across the index from the low value to the high value.

3.2.7 Sensitivity analyses

To evaluate potential variability in biomass estimates, we conducted three sensitivity analyses to assess the effect of variability in taxonomic identifications (i.e., species, genus, and/or family-level). These relate to the issue of taxonomic resolution in zooarchaeology (Driver 2011; Gifford-Gonzalez 2018; Lyman 2008) and have the potential to influence proportional as well as total estimates of harvested biomass. The first analysis focused on salmon, which is a genus (*Onchorynchus* sp.) that is archaeologically abundant but not readily identifiable to species based on skeletal morphology alone (Moss et al. 2014). Secondly, we evaluated the sensitivity of biomass estimates relating to Pacific halibut, as this species has skeletal elements that are distinct from other substantially smaller flatfish taxa that also occur in our dataset. Lastly, we considered the influence of lumping Lingcod within the smaller and much more frequently occurring category of greenlings. Collectively these analyses aim to better understand the limitations of this approach and capture uncertainty in our biomass estimates. They show that these different ways of categorizing fish produce modest changes to overall biomass. See Supplementary SI3.6 for an overview of our sensitivity analysis methods.

3.2.8 Determining Modern Catch

Pre-industrial catch estimates provide a unique opportunity to examine how Nuu-chah-nulth fisheries compare in scale to modern industrial fisheries in Barkley Sound. The sites examined in this study highlight key differences when compared to fisheries catch data from the last century, which enable insight into the spatial and temporal context of Indigenous fisheries in the study area over millennia. The area of the Economic Exclusion Zone (EEZ) for Pacific Canada – from which these counts were generated – is 470,238 km^2. For our analysis, we filtered catch data using the Sea Around Us project database (Pauly et al. 2023), which includes more fish species than archaeologically detected in samples in Barkley Sound to match as closely as possible the same taxonomic categories used here (i.e., Table 7). However, the creation of identical categories was not possible due to differences in how the data are reported and tabulated. Even with this limitation, the categories drawn from the Sea Around Us catch data broadly capture the same set of species represented in the shell middens examined here.

Traditional fishing areas are considerably smaller than the Pacific Canadian EEZ. For the purpose of this comparison, we considered the size of the ancient Nuu-chah-nulth fishery in Barkley Sound to be 3,157 km^2 (Figure 11). This fishing territory represents an area that encompasses the offshore areas of Barkley Sound to a distance of 80 km to the west and the entrance to Alberni Inlet to the east. To the north and the south this area is bounded by lines drawn parallel to the shores of Barkley Sound. We used an offshore fishing distance of 80 km because this distance captures the edge of the continental shelf where ethnographic and historical records indicate fishing likely took place, and encompasses the maximum distance that could be paddled in a single day (Ames 2002; Sproat 1868:225).

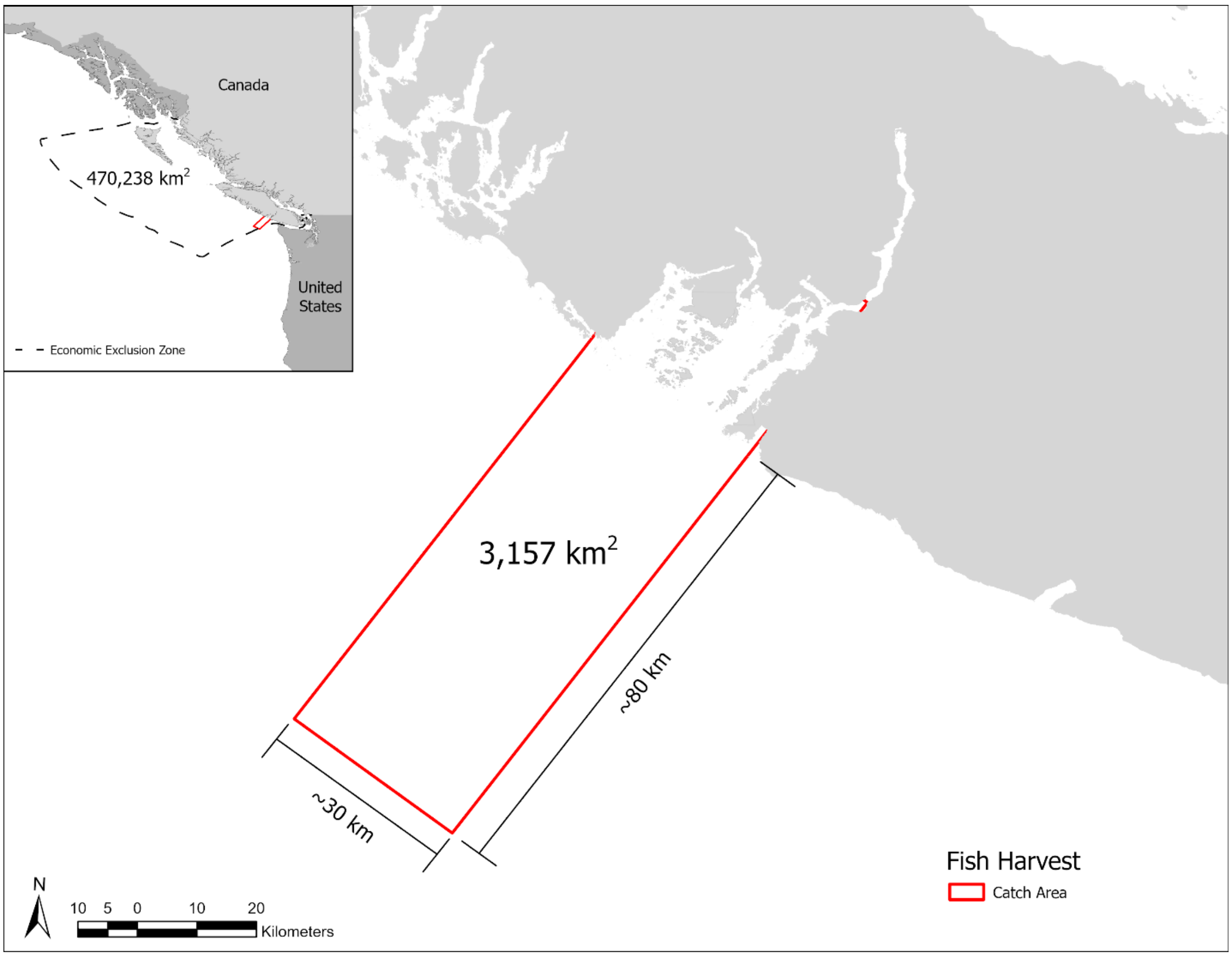

Figure 11. Spatial extent of fish harvesting areas considered in comparisons of historical and contemporary records of fishing activity.

3.3 Results

Each of the 15 sampled midden sites had an average of 5,244 m^3 of sediment with ~26 million (25,547,834) individual fish, representing over 18 million (18,133,973) kg of landed fishery biomass. Biomass estimates are based on a total midden volume of 78,672 m^3 from these 15 sampled sites. In turn these sediments contained 383,217,510 individual fish (Equation 7) with a total biomass estimate (based on median values for each taxon) of more than a quarter of a billion (272,009,601) kg (Equation 8, Figure 12, & Figure 13). By multiplying the volume of each site in Barkley Sound by the measured density of 4.87 fish per L and the calculated biomass of 3.46 kg of all fish in each litre we estimate Nuu-chah-nulth peoples harvested a minimum of almost 1.2 billion (1,174,900,848) individual fish over five millennia. This very large number represents an estimated harvested biomass that approaches almost 1,000,000 metric tonnes (834,734,491 kg) (Equation 9, Table 7). This approach allows us to capture the full variety of species represented in sites, as we suspect that deposition of fish taxa was proportionally equivalent across the study area.

				25 Percentile		50 Percentile		75 Percentile	
Taxonomic Group	**Species, Genus, or Family Name**	**% MNI**	**Estimated MNI**	**Body Mass (kg)**	**Total Biomass (kg)**	**Body Mass (kg)**	**Total Biomass (kg)**	**Body Mass (kg)**	**Total Biomass (kg)**
Anchovy	*Engraulis mordax*	13.24	194,589,516	0.019	3,697,201	0.021	4,086,380	0.023	4,475,559
Clingfish	*Rimicola muscarum*	0.10	427,723	0.0001	43	0.002	855	0.004	1,711
Dogfish	*Squalus suckleyi*	3.92	44,939,581	0.912	40,984,898	1.250	56,174,476	1.778	79,902,574
Flatfish	*Pleuronectidae*	1.68	19,375,036	0.363	7,033,138	0.580	11,237,521	0.883	17,108,157
Gadid (excluding Hake)	*Gadidae*	0.29	2,652,797	0.225	596,879	0.433	1,148,661	0.807	2,140,807
Greenling	*Hexagrammos sp.*	14.12	169,332,405	0.169	28,617,176	0.303	51,307,719	0.529	89,576,842
Gunnel	*Apodichthy sp., Pholis sp.*	0.03	304,332	0.028	8,521	0.029	8,826	0.03	9,130
Hake	*Merluccius productus*	2.33	23,317,287	0.094	2,191,825	0.630	14,689,891	0.869	20,262,722
Halibut	*Hippoglossus stenolepis*	0.55	6,018,196	4.399	26,474,043	7.567	45,539,687	13.352	80,354,949
Herring	*Clupea pallasii*	31.09	376,125,769	0.088	33,099,068	0.112	42,126,086	0.143	53,785,985
Lingcod	*Ophiodon elongatus*	1.88	19,925,452	1.085	21,619,115	2.408	47,980,487	3.689	73,504,991
Mackerel	*Pleurogrammus monopterygius*	0.03	304,332	0.455	138,471	0.760	231,293	0.915	278,464
Midshipman	*Porichthys notatus*	0.55	8,620,283	0.020	172,406	0.021	181,026	0.021	181,026
Perch	*Cymatogaster aggregata, Embiotocidae lateralis, Phanerodon vacca*	5.67	63,263,755	0.402	25,432,030	0.482	30,493,130	0.710	44,917,266
Prickleback	*Lumpenus*	0.49	4,888,988	0.012	58,668	0.013	63,557	0.014	68,446
Ratfish	*Hydrolagus colliei*	0.74	7,975,888	0.270	2,153,490	0.455	3,629,029	0.558	4,450,545
Rockfish	*Sebastes sp.*	9.81	125,331,038	0.243	30,455,442	0.556	69,684,057	0.911	114,176,576
Sablefish	*Anoplopoma fimbria*	1.33	12,760,051	0.358	4,568,098	0.403	5,142,301	0.546	6,966,988
Salmon	*Oncorhynchussp.*	8.42	93,800,250	3.828	359,067,358	4.146	38,889,5838	4.410	413,659,104
Sand lance	*Ammodytes hexapterus*	0.03	304,332	0.027	8,217	0.027	8,217	0.028	8,521
Sculpin	*Cottidae*	2.46	28,219,850	0.721	20,346,512	0.910	25,680,063	1.161	32,763,246
Skate	*Rajiformes*	0.23	2,148,107	0.909	1,952,629	2.244	4,820,351	4.971	10,678,238

Smelt	*Osmeridae*	1.00	6,116,249	0.020	122,325	0.022	134,557	0.025	152,906
Summary Information	**N Taxa=23**	**100%**	**1,210,741,217**		**608,797,553**		**803,264,008**		**1,049,424,753**

Table 7. The body mass of taxonomic groups used in biomass calculations and the total estimated biomass across all middens in the study area using the 25% quartile, median, and 75% quartile body masses of each taxonomic group.

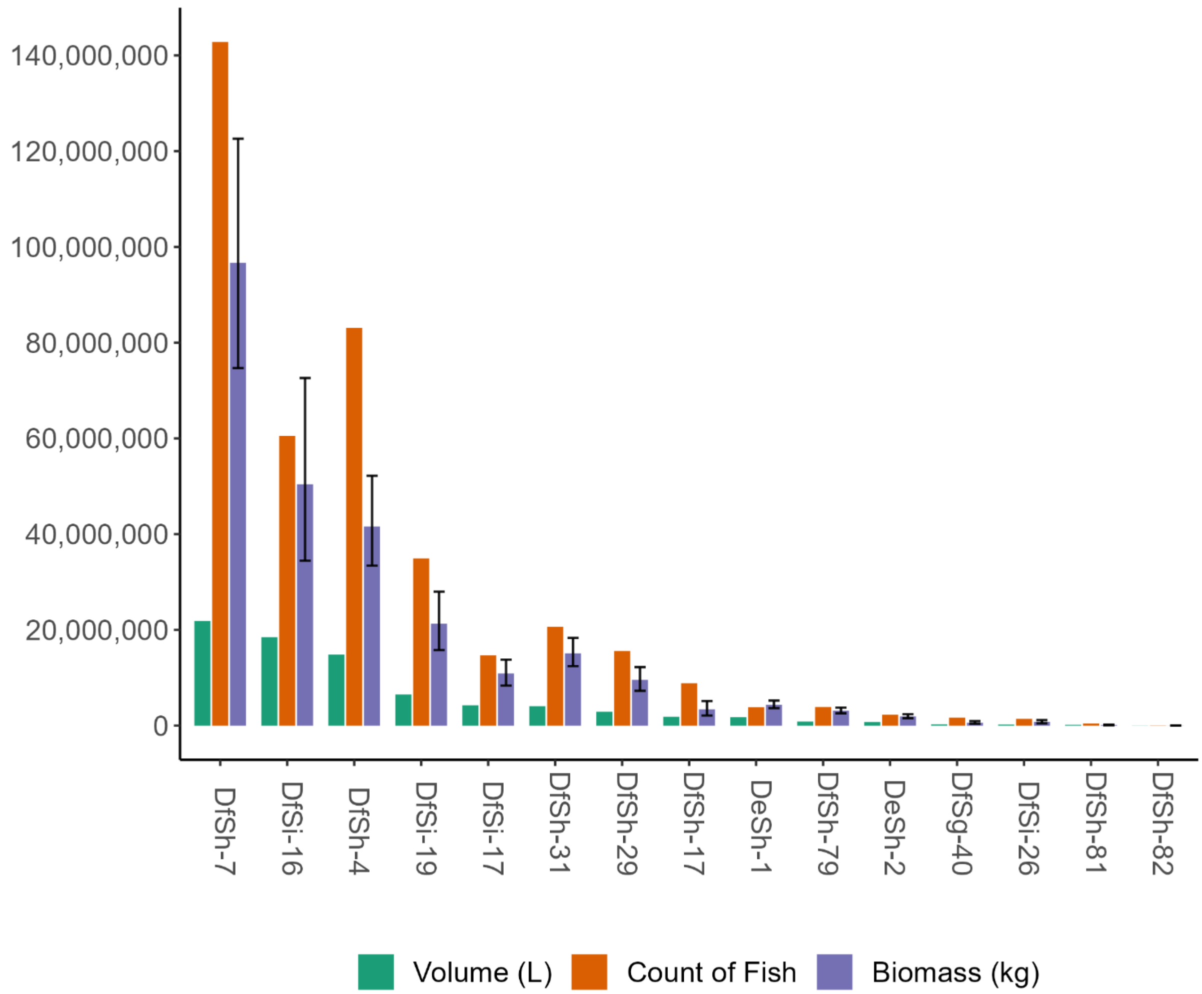

Figure 12. Volume (m^3), extrapolated count of fish, and biomass (kg) for each site. Whisker bars represent the interquartile range for biomass. Sites are ordered from largest to smallest volume.

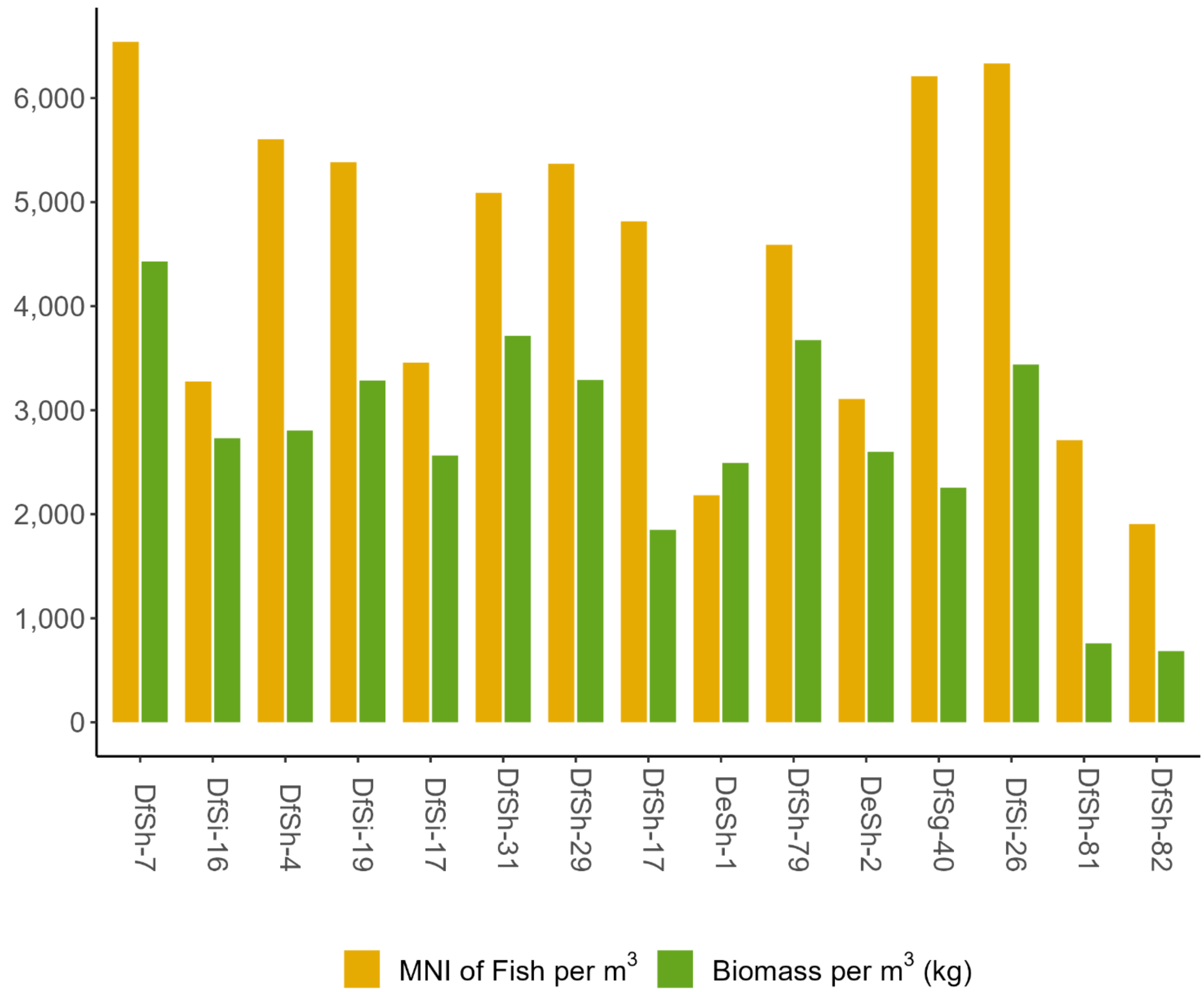

Figure 13. Density of MNI and kg per m^3 of biomass for sampled sites in Barkley Sound. Sites are ordered from largest to smallest volume.

3.3.1 Sensitivity Analyses

In the first of three sensitivity analyses, we compared the effect of salmon on biomass estimates by comparing a weighted body mass informed by a sample of species-level identifications from the study region against a body mass where each of the five species of salmon was given equal chance of occurring. When salmon species were weighted equally, the overall biomass estimate for all fish was reduced by 7%, reflecting the fact that larger salmon species (Chum *Oncorhynchus tshawytscha* and Chinook *O. keta*) were more common in the study area as suggested by both the ZooMS data and size estimates based on vertebral size estimates following Cannon and Yang (2006, 2011). Next, we assessed a scenario where halibut was lumped into the flatfish category vs. being considered distinct. Given the much higher median weight of an individual halibut, this caused the average weight of the flatfish category to increase, this substitution resulted in a 4% increase in total fishery biomass vs. the original estimate where lingcod remains distinct due to its lower abundance. Lastly combining greenling and lingcod estimated a 5% decrease in total biomass relative to the original estimate. See Supplementary SI3.6 for detailed sensitivity analysis results.

3.3.2 Comparison to Historical Catch

Drawing upon a 2016 synthesis of commercial fisheries data for the Pacific Coast of Canada from the Sea Around Us project, the estimated total annual landed fish biomass was 185,867,650 kg (Ainsworth 2015, 2016; Schinjs 2020). In the period from 1950 to 2016, the year with the greatest catch was 1987 in which 315,513,634 kg of fish were harvested. The year with the lowest catch was 1980 when 145,855,246 kg were collected. On average from 1950 to 2016, the EEZ produced 245,823,204 kg per year of harvested fish.

The overall fishing area can be used to estimate the yearly harvested biomass per square kilometre within this portion of the Nuu-chah-nulth world. The average yearly catch in Barkley Sound, as estimated from archaeological fish remains over 5,000 years, equates to 53 kg/km^2, while the catch for the EEZ is between 310 kg/km^2 (1980) and 670 kg/km^2 (1987), with an average of 522 kg/km^2 per year over the 67 years from which data are available. Despite considerable differences in technology, geography and time, these comparisons indicate that Nuu-chah-nulth fishery catches preserved in recorded archaeological sites dating to mid-to-late Holocene, represent a significant proportion (~10%) of modern industrial fisheries.

Individual species and genera can also be used to indicate comparisons between historical and modern fisheries. In 2016 the Sea Around Us dataset documents the summed catch of the five common Pacific salmon species (*Oncorhynchus tshawytscha*, *O. kisutch*, *O. keta*, *O. gorbuscha*, and *O. nerka*) within the EEZ was 30,123,101 kg or 64 kg/km^2. Across all years with modern catch data (1950-2016) the average annual salmon catch was 70,101,573 kg or 149 kg/km^2. In comparison, across 5,000 years the average harvested biomass of salmon in the Nuu-chah-nulth fishery was at least 25 kg/km^2 per year (~17% of average annual modern catch). In comparison to the previous example where we compared minimum and maximum recorded catch, in 1985, the year with the largest catch, 299 $salmon/km^2$ were harvested, and in 2008 the year with the smallest catch 19 $salmon/km^2$ were harvested. Halibut provides another example, in which we estimated that, in 1981, the year with the smallest catch, 8 kg/km^2 was commercially harvested, 44 kg/km^2 in 1969 the year with the largest catch, and 16 kg/km^2 were harvested in 2016 the year with the most recent data. Over the same 67 years an average of 10,210,402 kg per year were harvested (21.71 kg/km^2). In Barkley Sound, these archaeological data suggest that 2.88 kg/km^2 per year of (~13% of average annual modern catch) halibut were harvested with an interquartile range of 1.7-5.1 kg/km^2. These calculations are presented in greater detail in Supplementary SI3.4.

3.4 Discussion

The estimation of fish biomass preserved in archaeological deposits in Barkley Sound allows for several important observations about the scale of Indigenous fisheries documented in shell midden sites. The first is the continuity and long-term practice of harvesting large numbers of fish over 5,000 years of continuous use and occupation. Until recently, ecologists and resource managers have largely neglected the role of Indigenous peoples for creating, sustaining, and influencing biodiversity and productive social-ecological systems (Ellis et al. 2021). In marine settings, such Indigenous fishery landings data are not usually considered in quantitative terms by modern day fishery managers and ecologists working in coastal systems, even though there is increasing awareness of the significant role Indigenous peoples had (and continue to pursue) in managing fisheries (Atlas et al. 2021; Reid et al. 2021). Second, given the many taphonomic and cultural factors that would result in diminished preservation of fish remains in archaeological deposits, our calculations certainly underestimate and thus establish a lower-bound on the total biomass of fish harvested in the past. Moreover, when considering the potential for numerous undocumented sites and as well as large reductions in the size and diversity of spawning fish populations since the advent of industrial fishing our biomass estimates are likely highly conservative (Jeffrey et al. 2016; Oke et al. 2020; Ricker 1981). This work further highlights the fact that hundreds of millions of fish are preserved in shell midden deposits and are estimated to represent nearly 1.2 billion kilograms of Indigenous landings in this relatively small section of the Vancouver Island coastline. This is the first archaeological study to generate specific harvested biomass estimates of Indigenous fisheries efforts and activities on the Northwest

Coast. Furthermore, this project provides a new perspective on the scale of Indigenous fisheries harvests spanning millennia, which can inform contemporary conservation and resource management efforts by contextualizing historical baselines to inform policy decisions today. Such insights can also contribute to discussions around Indigenous rights and title and, ultimately, can support the revitalization of Indigenous food systems and food sovereignty by quantitatively demonstrating a component of the harvested biomass of culturally and economically valuable fish.

The biomass estimates presented here are grounded in archaeological data gathered over 50 years of research, illustrating that this technique did not require conducting new field work but rather the integration of existing data. Recent zooarchaeological scholarship on the Northwest Coast has taken a broadly comparative approach, based on compilations of *relative* fish abundance data from a large number of sites to draw conclusions about the regional prevalence of different taxa (Coupland et al. 2010; Jones et al. 2016; McKechnie and Moss 2016; Tushingham and Christiansen 2015). In contrast, our research uses a bottom-up approach that draws from a small number of sites to derive estimates of *absolute* abundance of harvested fishery biomass preserved in shell midden deposits within a small region. This approach allowed us to leverage the efforts of previous archaeological survey projects and zooarchaeological analyses to draw broader conclusions about the scale of Indigenous fishing effort from a small number of geographically clustered sites. As ecology and conservation science engages further with the legacies (and futures) of Indigenous relationships with their territories and resources (e.g., Bliege Bird and Nimmo 2018) one of the strengths that archaeologists can offer is to coalesce the substantial amounts of existing data, and in doing so demonstrate how such cultural heritage can be employed to inform contemporary analysis.

One of the broader strengths of this approach is that it is not intrinsically tied to a specific study area or even to coastal archaeological sites generally. This method is applicable to other areas with similar data. The primary requirements are the spatial and volumetric dimensions of a site, the calculation of MNI per unit of volume (e.g., MNI/m^3), and body mass estimates for the animals represented in a site. We have developed a relatively straightforward workflow, including spreadsheets with formulae (SI) for assessing total preserved biomass at a site, which allows extrapolation to an entire region to better understand the amount and relative proportions of harvested animals used by peoples in the deep past. Another advantage of this approach is that biomass is broadly reflective of a larger slate of cultural efforts and practices which encompasses more than 'edible meat weight'. Using biomass provides a key perspective on the scale and characterization of the relationship between humans and animals and as such, this approach offers additional insight that builds on other established zooarchaeological methods of quantification.

The approach taken here has broad applicability to sites that contain large amounts of fauna-rich sediments, such as has been recently accomplished using complementary approaches in coastal Brazil (e.g., Fossile et al. 2019). The generalizability of this approach enables archaeologists to estimate harvested biomass contained at many sites across a region without having to conduct analysis at each individual site. Our approach shows how a series of well-sampled and surveyed sites can be effectively used to extrapolate to other sites in a larger region, assuming that these other sites contain broadly similar faunal assemblages. The method can also be applied at individual sites or smaller groups of related sites (e.g., Table 6) after the density of fish and body mass of each taxonomic group have been determined, total harvested biomass estimates can be generated for any site by estimating the site's volume. Additionally, this method has value as a heuristic and can be used to model how different faunal compositions and site volumes would change biomass estimates.

The versatility of our technique is further demonstrated by its potential applicability outside of zooarchaeology. We envision that the method can potentially be applied to any relatively ubiquitous archaeological material that might accumulate in sediment. For example, the amount of pottery at a site could be determined by substituting the count of ceramic shards per cubic metre of sediment for the density of fish, and the weight of ceramic vessels could be substituted for fish body mass (Varien and Ortman 2005). This would produce first-order approximations, such as yearly production of pots, total clay consumption, yearly labour investment in a ceramic industry, and other relevant information about the manufacture and consumption of ceramics.

Regarding biomass calculations, this technique might not be appropriate for all types of fauna commonly found in shell middens. This method is best applied to small-bodied fish and shellfish; large birds and terrestrial mammals will require larger excavations where increased sample size and examined volume are needed to better characterize the wide range of mammal and bird taxa. For instance, this technique may be less suitable for calculating the biomass of marine mammals, given that these organisms were frequently butchered in intertidal zones while meat fats, and bones could be shared across multiple village sites (McMillan 2015; Monks et al. 2001). Compared to fish, however, marine mammals are less abundant within these sites and are less likely to be accurately represented as identifiable specimens in a given sediment sample, particularly at locations with a limited number of large-volume samples (Gray 2008).

The three scenarios assessed through sensitivity testing highlight the consequential role that very abundant (salmon) and or very large fish (halibut) have in these biomass estimates. In particular, salmon are the single greatest contributor to biomass thus modest differences in body mass between genera can have a pronounced influence. Similarly, when included in the flatfish category the large size of halibut can dramatically inflate flatfish biomass. Lastly, while greenling and lingcod are not difficult to morphologically differentiate, the commonality of greenling effectively lowers the total estimated biomass but otherwise exhibits relatively minimal impacts to the results.

Our comparison with ~70 years of commercial landings data indicates that Nuu-chah-nulth fisheries on a portion of southwest Vancouver Island may have been extracting a sizeable percentage of what is caught in modern industrial fisheries. Despite some differences in taxonomic resolution between archaeological and modern fisheries data, this effort has tangible value as these catch numbers show that over 5,000 years of fishing activity in Barkley Sound, large amounts of fish were harvested annually. Additionally, it illustrates that for the suite of salmon, the Nuu-chah-nulth fishery may have been smaller than the modern salmon fishery. Such historical baselines, associated with sustainability over millennia, can help orient the modern industrial fishery, which has a poor record of sustainability. Further research might allow for a refinement of these values and their application.

Our work does not inherently require the collection of new data in the field but instead makes extensive use of existing data. For many parts of the world, the required zooarchaeological and fishery management data to estimate fishery biomass are already available (Pauly et al. 2023). We show existing records alone, in this case over 50 years of site surveys and faunal analysis, alongside fisheries records, can generate new insights into Indigenous fisheries activities over millennia.

3.5 Conclusion

Our work here takes a step beyond quantification of relative abundance and meat weight to estimate the absolute biomass of fish harvested in Barkley Sound by Nuu-chah-nulth peoples. Our approach, focused on the harvested fish biomass represented in multiple archaeological sites, was estimated using this novel geospatially grounded method that combines the volume of archaeological sediments with MNI counts and fish body sizes. The method presented here is scalable and can be applied to individual sites, small groups of related sites, or regionally. The applications of this technique stretch beyond the calculation of fish biomass preserved in coastal shell middens and could be applied to other types of faunal remains. Moreover, this method can also be used to quantify the mass of other types of ubiquitous archaeological materials such as ceramics, lithics, and fire-altered rock within archaeological sediments.

The quantification of harvested fish biomass from archaeological sites has profound implications for how we think about fisheries both in the deep past and in modern contexts. Looking forward, we envision that the data presented here, as well as work from future studies, can help Indigenous rights holders, fisheries managers, and stakeholders better understand the dynamics of complex social-ecological systems to foster resilient and socially just fisheries for generations to come. Biomass estimates, while likely conservative underestimations, also provide an avenue for considering the demography of people who lived in Barkley Sound in the past. This study provides a framework for quantifying harvested fish biomass from coastal shell midden sites, although as we note, its applications extend well beyond the scope of zooarchaeological analysis. Further, we document the scale of Indigenous fishing effort over

5,000 years in one area of the Northwest Coast, which provides insight into ancient Indigenous fisheries use over millennia.

Chapter 4. Archaeologically Derived Minimum Estimates of Indigenous Population Sizes in Nuu-chah-nulth Territories, British Columbia, Canada

4.1 Introduction

One of the most important questions in North American archaeology is that of how many Indigenous people lived in the Americas prior to European arrival. Due to massive demographic and settlement changes during the colonial era, the existing estimates of pre-contact populations for many parts of North America are poorly resolved and highly variable. Reducing uncertainty and generating more refined population estimates is critical for creating more accurate understandings of past cultures (Denevan and Lovell 1976; Hassan 1979; Ortman 2016; Ubelaker 1992). This information is integral to strengthening understanding of past social structures, migration events, humanity's role in ecosystems, environmental change, disease events, demographic processes, and trade systems, among other topics (Boyd 1999; Cameron 1991; Coupland 2006; Gallivan 2002; Kohler 1978; Marshall 2006; Williams 2013). Estimates of past population sizes also have significance for contemporary Indigenous communities as treaties and Indigenous rights and territories have been imposed or negotiated from a political and governance structure that is potentially substantially reduced and changed by underrecognized demographic impacts. The population estimates which we provide have significance for modern communities as they indicate that the study area supported large populations of people heavily utilizing marine resources over long periods of time. This intense human presence has not been reflected in past government policy and of particular relevance is that the basis for allocation of land and reserve locations in the 1880s occurred at or near the demographic nadir, which is likely the lowest population density in the study area at any time in the past 3000 years (Boyd 1999; Grant 1857; Harris 2002; Sproat 1868). Correspondingly, allocations and rights associated with marine harvesting effort were much reduced and not reflective of past harvest levels. This work provides important context for new policy, governance, and allocation of resources informed by the thousands of years of human history in this place.

Researchers have developed many different methods of estimating the size of past populations, most of which relying on ethnohistoric accounts, ethnographic studies, and historical records with a comparatively smaller number using archaeological data. Such estimates have been markedly inconsistent, differing by orders of magnitude at their extremes for the same populations (Borah 1962; Denevan and Lovell 1976; Koch et al. 2019; Peros et al. 2010). Historical and ethnographic data have been used to generate estimates, and these approaches have generally fallen into two distinct categories. The first is an additive or 'dead reckoning' approach, which includes methods that combine early historical counts and subsequent formal census data of Indigenous populations (Boyd 1999; Kroeber 1963a; Mooney 1928; Ubelaker 1992). Secondly, historians have examined 'depopulation ratios', where historically-recorded population maxima are compared to a population nadir to derive a ratio of change (Campbell 1990; Dobyns 1966; Ramenofsky 1987; Spinden 1928). These ratios are then retroactively applied to estimate precontact populations. Estimates produced using both dead reckoning and ratio approaches are widely variable in source data and geographic scope. Moreover, early colonial accounts of Indigenous peoples often assume the observed people and their lifeways were unchanged by the rippling impacts of introduced European diseases and technologies, when it is likely that waves of disease spread much further and faster than the presence of early settlers and colonial expeditions that collected ethnographic data (Jones 2014).

Approaches drawing on data from living structures and archaeological radiocarbon sampling are also common but have limitations. Many archaeological approaches to population estimation have been grounded in per person living space requirements observed for ethnographical and historically recorded peoples living in traditional structures. These individual space requirements were applied to the available floor space and living areas in sites with preserved structural features to estimate population size. (Birch-Chapman et al. 2017; Brown 1987; Kolb et al. 1985; LeBlanc 1971; Naroll 1962; Shawcross 1970). This approach is typically applied to well-studied individual sites based on horizontal extents rather than to multiple sites across a region. Another estimation approach has focused on compilations of radiocarbon dates, known as the 'Dates as Data' approach and is operationalized through Summed Probability Distributions, Bayesian modelling, and other statistical techniques (Crema 2022; Edinborough et al. 2017; Goodale et al. 2008; Rick 1987). While informative, time-transgressive population proxies like these can be challenging to interpret due to calibration anomalies, variable sampling effort, and taphonomic factors. Additionally, this approach can be difficult to implement due to issues with the calibration of dates from the very recent past and the use of historical artifacts typologies instead of radiocarbon dating to chronologically situate very recent sites (Brown 2016; Williams 2012). Sea level change can also affect site visibility with recent sites having much higher radiocarbon dating frequencies than older sites.

Here, we build on previous work in accumulation-studies to estimate population size. This approach examines artifacts and food waste to produce estimates of adult population based on the number of people that would have been required to create or consume the discarded materials (Ascher 1959; Campbell 1990; Gallivan 2002; Palmisano et al. 2017; Porčić and Nikolić 2016; Schiffer 1975; Shawcross 1970; Varien and Ortman 2005). Our approach uses faunal remains deposited in coastal shell midden sites and human energetic requirements to create a population estimate for pre-contact Indigenous populations living on western Vancouver Island over the last 3,000 years.

Our study area is located in Barkley Sound, an approximately 900 km^2 marine embayment on the west coast of Vancouver Island in British Columbia, Canada (Figure 14). This area falls within the traditional territories of the Tseshaht, Toquaht, Ucluelet, Uchuklesaht, and Huu-ay-aht First Nations and various archaeological research indicates a continuous human occupation for at least 5,000 years (McMillan et al. 2008). While several population estimates have been generated from observations during the early contact era, the largest comes from the records of Spanish explorer Jose María Narváez who visited the area in 1791. Narváez visited the area 14 years after the initial European contact by William Barkley, and the intervening period was marked by regular contact with dozens of European ships. Narváez estimated the Indigenous population of Barkley Sound to be in excess of 8,500 individuals but did not conduct a formal census or count (Wagner 1933). This estimate, like many from this time, may have been influenced by the effects of prior European contacts, which may have had reduced Barkley Sound populations by the time Narváez arrived (Boyd 1999; Harris 1997). Additional population estimates for Barkley Sound in 1857 by Walter Colquhoun Grant place the population at 700 individuals (Grant 1857:287) and closely match estimates from 1868 where Gilbert Sproat estimated the male population at 399 individuals (Sproat 1868) (Table 8). This marks a significant decline in populations over time which is mirrored in the larger Nuu-chah-nulth population which rapidly declined to a nadir of 1,605 individuals in 1924 (Table 9). Populations have since grown considerably with 4,310 Nuu-Chah-Nulth people recorded in the 2016 Canadian Census of Population (Government of Canada 2018). The methodology we introduce here does not allow for direct comparison with these historic estimates given the mixture of geographic extents and enumeration criteria used by Narváez, Grant, Sproat and other in their tabulation of population. The estimate presented here is a minimum likely underestimating the true population and does not rule out that populations could have been as large or larger than what Narváez estimated.

Table 8. Barkley Sound population counts through time.

Barkley Sound Populations			
Year	**Population**	**Source**	**Context**
1791	8,500	Wagner 1933	Narváez's whole population estimate
1857	700	Grant 1857, 287	Count of whole population
1868	399	Sproat 1868, 308	Count of men only

Table 9. Nuu-Chah-Nulth population counts through time.

Nuu-Chah-Nulth Populations			
Year	**Population**	**Source**	**Context**
1788	31,000	Meares 1790, 229–31	Estimate from Meare's 1778 voyage
1840	4,850	Boyd 1999, 304	Hudson Bay Company census
1881	3,256	Guillod 1882	First government census of BC Indigenous peoples
1939	1,605	McMillan 1999, 193	Canadian Government census count
2016	4,310	Government of Canada 2018	Canadian Government census count

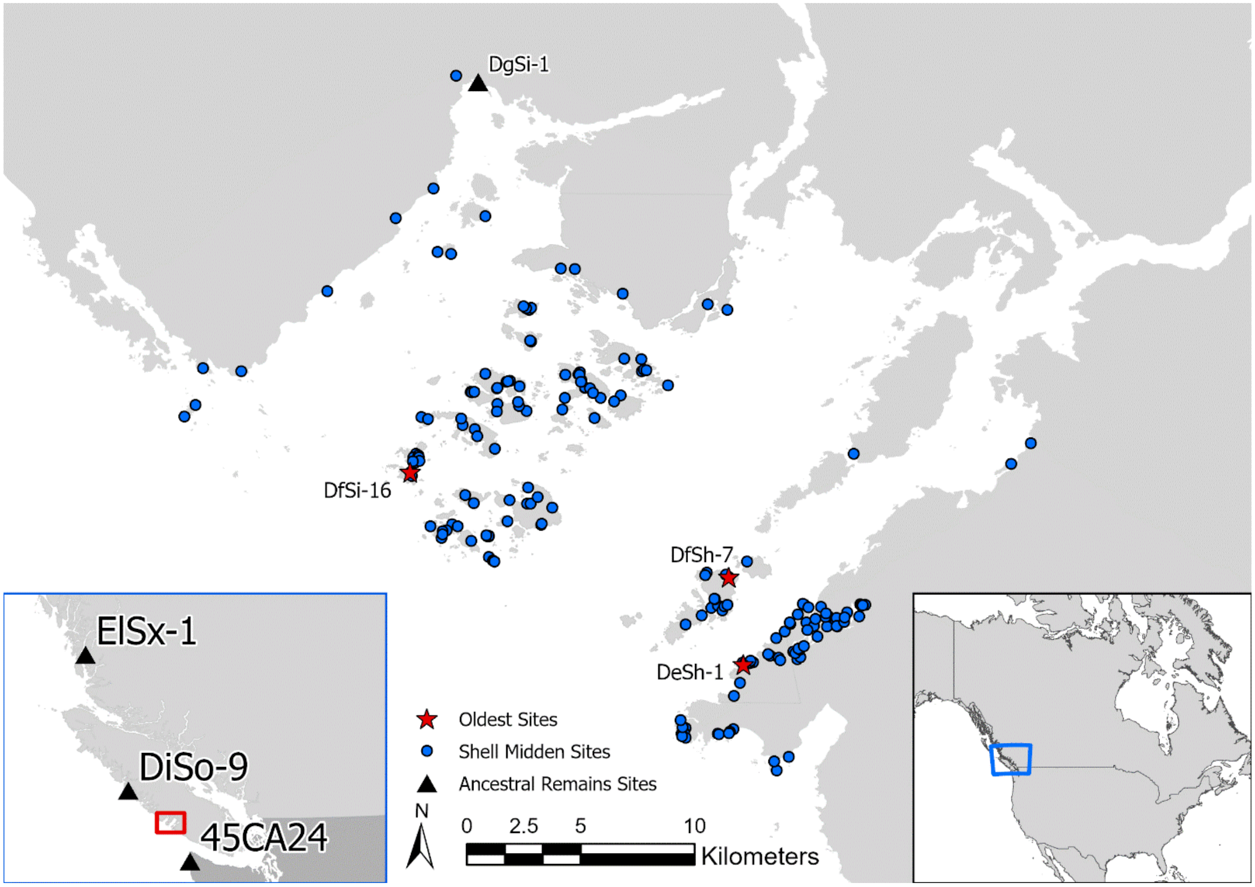

Figure 14. Map of Barkley Sound with the 186 shell midden sites used in this study. Red stars represent three sites with dated components older than 3,000 cal BP. Black diamonds represent locations of sites with ancestral remains.

Our population estimation method combines the volume of shell midden sites with the density of fish remains in those sites to estimate the total caloric energy embodied in the fish harvested over the human history of the study area. We combine this energy estimate with locally adjusted estimates of caloric demands per person to determine the number of people that could have been nutritionally supported from these foods preserved in these archaeological deposits. This serves as a basis for an archaeologically derived population estimate based on a regional inventory of site volume estimates and samples of zooarchaeological materials analysed at a subset of those sites. This estimate allows us to estimate the minimum population that could have been supported over thousands of years of human activity in this region as determined by the calories available from fisheries. Excluding calories from non-fish animals recorded in middens as well as foods which do not preserve as readily such as plants, we consider this to be a minimum estimate of the total harvested food energy collected and consumed by people over the last 3,000 years.

4.2 Methods

The method of population estimation presented here is based on caloric energy represented by fish biomass as applied to 186 recorded shell middens sites in the study area (Figure 14). Calculating the energy density (kcal/m^3) of fish in shell midden sediments required knowing the volume of the midden as well as the type and quantity of food resources (Gustas et al. 2024). The process for determining the volume of midden sites we use was based on fitting a semitriaxial ellipsoid to each midden using the recorded length, width, and depth of the site. The details of this process are detailed in Gustas et al. (2022). Based on this work we estimated previously that 186 recorded Barkley Sound shell midden sites have a total volume of 241,253 m^3 with an uncertainty of ±9% (Gustas et al. 2022:204).

Although Barkley Sound has been inhabited for at least 5,000 years, the majority of radiocarbon dates are concentrated in the last 3,000 years reflecting greater survey efforts on shorelines near the current relative sea level. Here we modelled the population of this period and as such midden volume and fish biomass estimates from Gustas et al. (2022; 2024) needed to be adjusted to reflect this window of Barkley Sound's history. Analysis of 209 dates from 29 sites (SI4.5) shows that only three dated sites [Huu7ii (DfSh-7), Kiix7in (Desh-1), and Ts'ishaa (DfSi-16)] have preserved fauna that predate 3,000 cal BP (Figure 14). These older dates are from elevated "back ridge" areas (effectively, raised paleoshorelines) of these sites. The extent of these oldest portions of these middens were identified using location of midden deposits at higher inland elevations, radiocarbon dates, relative sea level histories, and lidar contour mapping. We calculated the volume of these back ridge areas from mapped midden extents using the semitriaxial ellipsoid method (Gustas et al. 2022), resulting in sediment volumes of 2,649 m^3 and 792 m^3 for DfSh-7 and DfSi-16, respectively. The extent of sediments older than 3,000 cal BP could not be directly calculated from the available data for Kiix7in because this portion of the site is deeply buried by later midden deposits. The proportion of total sediment constituting the back ridge area of Huu7ii and Ts'ishaa was therefore applied to Kiix7in to estimate that 8.6% of the total volume predates 3,000 cal BP. The combined back ridge volume of all three sites (3,590 m^3) was then subtracted from the total aggregate midden volume for the study area. The volume of sediments from older portions of the three sites represent 1.5% of the total volume of sites used in this analysis, and as such the total estimated biomass and calories contained in all sediments were reduced proportionally.

To determine the total biomass of harvested fish we drew upon previously performed zooarchaeological analysis on sediment samples gathered from shell midden sites across the study area. This analysis identified the fish taxa based on the number of bone specimens for 15 sites with available data (Crockford 2019; McKechnie 2005b, 2012, 2013; Wigen 2003) and then calculated the Minimum Number of Individuals (MNI) for each group. An average density of fish by volume (MNI/m^3) was then determined and used to extrapolate the total count of fish. This number was derived by multiplying the density of fish in each site by the volume of the midden. Biomass was then determined by multiplying the count of fish in each taxonomic group by their median body mass, as detailed in (Gustas et al. 2024). This recent analysis determined that the study area contains nearly 1.2 billion (1,200,000,000) individual fish with an estimated total biomass of more than 790 million kg deposited over the last 3,000 years.

4.2.1 Caloric Energy

Using the nutritional information recorded in the Canadian Nutrient File (CNF) (Canada 2002) and Sidwell (1981) the total biomass of fish was converted into available caloric energy. The CNF is a database of detailed nutritional information for the Canadian context, which Health Canada derived from the United States Department of Agriculture National Nutrient Database for Standard Reference (U.S. Department of Agriculture 2019). Within this dataset there are often multiple entries for a single fish species describing different preparations (baked, broiled, poached, raw etc.) locations (Pacific, Atlantic, or Artic) and origins (raw or farmed). These labels are applied inconsistently across species in the database. We used the entry for each species that most closely corresponds to raw wild fish from the Pacific Ocean. Several species not commonly consumed by contemporary Canadians were not listed in the CNF; for these species we used the nutritional information in Sidwell (1981), which is a comprehensive National Ocean and Atmospheric Administration (NOAA) meta-analysis of 1,204 nutritional data points, creating a comprehensive database of the chemical and nutritional composition of marine fish. For five taxonomic groups constituting small nearshore fish, nutritional information was unavailable (Midshipman, Prickleback, Gunnel, Sand lance, and Clingfish). We used the average of other similar sized fish species for these species. These five small nearshore fish groups represent 0.03% of the total biomass in the study area and constitute a comparatively minor component of traditional diets.

The five species of salmon identified in the zooarchaeological assemblage were generalized into a single caloric energy category. We weighted each salmon species by their relative prevalence based on Zooarchaeology by Mass Spectrometry (ZooMS) testing conducted on samples from Barkley Sound midden sites (Zhu et al. 2023). The caloric and fat values for the aggregated salmon group are thus also weighted by this proportionality. Salmon warrants this extra attention because they represent more than half of the harvested calories and have broad cultural significance, as well as large variation in body mass (Jeffrey et al. 2016; Oke et al. 2020). To calculate calories the total biomass for each fish species in grams was multiplied by its energy density (calories per 100 g). These values were then summed across all the species, yielding the total caloric energy represented by harvested fish (Table 10).

Taxonomic Group	Species, Genus, or Family Name	Biomass (kg)	Volume Adjusted Biomass (kg)*	% of Total Adjusted Biomass	Calories (kcal / 100 g)	Fat / 100 g of flesh (g)	Source	Adjusted Total Energy (kcal)	Percent of Total Calories
Salmon	*Oncorhynchus sp.*	388,895,838	383,062,400	48.41	146	5.6	CNF	559,271,104,081	54.70
Rockfish	*Sebastes sp.*	69,684,057	68,638,796	8.67	90	1.3	CNF	61,774,916,850	6.04
Dogfish	*Squalus suckleyi*	56,174,476	55,331,859	6.99	130	4.5	CNF	71,931,416,275	7.04
Greenling	*Hexagrammos sp.*	51,307,719	50,538,103	6.39	138	7.3	Sidwell 1981	69,742,581,988	6.82
Lingcod	*Ophiodon elongatus*	47,980,487	47,260,780	5.97	85	1.1	CNF	40,171,663,118	3.93
Pacific halibut	*Hippoglossus stenolepis*	45,539,687	44,856,591	5.67	91	1.3	CNF	40,819,498,111	3.99
Herring	*Clupea pallasii*	42,126,086	41,494,195	5.24	195	13.9	CNF	80,913,679,877	7.91
Perch	*Cymatogaster aggregata, Embiotocidae lateralis, Phanerodon vacca*	30,493,130	30,035,733	3.79	91	0.9	CNF	27,332,517,165	2.67
Sculpin	*Cottidae*	25,680,063	25,294,862	3.20	92	1.5	CNF	23,271,273,390	2.28
Hake	*Merluccius productus*	14,689,891	14,469,543	1.83	90	1.3	CNF	13,022,588,256	1.27
Flatfish	*Pleuronectidae*	11,237,521	11,068,958	1.40	70	1.9	CNF	7,748,270,605	0.76
Sablefish	*Anoplopoma fimbria*	5,142,300	5,065,166	0.64	195	15.3	CNF	9,877,073,724	0.97
Skate	*Rajiformes*	4,820,351	4,748,046	0.60	93	1.3	Sidwell 1981	4,415,682,927	0.43
Anchovy	*Engraulis mordax*	4,086,379	4,025,084	0.51	131	4.8	CNF	5,272,860,227	0.52
Ratfish	*Hydrolagus colliei*	3,629,029	3,574,594	0.45	148	9.8	Sidwell 1981	5,290,398,476	0.52
Gadid (excluding Hake)	*Gadidae*	1,148,660	1,131,431	0.14	69	0.4	CNF	780,687,415	0.08
Mackerel	*Pleurogrammus monopterygius*	231,292	227,823	0.03	158	7.9	CNF	359,960,813	0.04
Midshipman	*Porichthys notatus*	181,026	178,311	0.02	85	1.2	Average	151,563,960	0.01
Smelt	*Osmeridae*	134,557	132,539	0.02	97	2.4	CNF	128,562,954	0.01
Prickleback	*Lumpenus*	63,556	62,603	0.01	85	1.2	Average	53,212,973	0.01
Gunnel	*Apodichthy sp., Pholis sp.*	8,826	8,693	<0.01	85	1.2	Average	7,389,267	<0.01
Sand lance	*Ammodytes hexapterus*	8,217	8,094	<0.01	85	1.2	Average	6,879,667	<0.01
Clingfish	*Rimicola muscarum*	855	843	<0.01	85	1.2	Average	716,226	<0.01
Total		**803,263,152**	**791,215,047**					**1,022,344,498,343**	

Table 10. Biomass, fat, and caloric energy for taxonomic groups. CNF stands for Canadian Nutrient File (Canada 2002).
* Adjusted biomass was reduced by 1.5% to account for removal of sediments older than 3,000 cal years BP.

4.2.2 Resting Energy Expenditure (REE)

Once total caloric energy was determined the next step in calculating population estimates was to model the Resting Energetic Expenditure (REE) of study area inhabitants. REE is the rate of energy required for homeostasis or the minimum amount of energy that is required to keep a person alive at a state of rest (Coulston et al. 2001:31; Henry 2005; Mason 2010; Plaza-Florido and Alcantara 2023). The Mifflin-St Jeor formula can be used to estimate daily REE (Mifflin et al. 1990) per person adjusted for sex, height, age, and body weight (Equation 10). REE was then converted to Total Daily Energy Expenditure (TDEE) which is a measure of the total energy that would be required both to sustain life and account for a person's Physical Activity Level (PAL). Lastly as our population estimates are based solely on the consumption of fish, we factored in human protein digestion limitations or Protein Adjusted Total Daily Energy Expenditure (PATDEE) to create more realistic final estimates of population. We describe the process of modelling the REE of Barkley Sound populations and converting it to TDEE and PATDEE in the following sections (See SI4.1 for energy requirement calculations).

Equation 10. Mifflin-St Jeor Resting Energetic Expenditure formula (Mifflin et al. 1990).

Where
m = mass of the individual
h = height of the individual
a = age

For males

$$\frac{kcal}{day} = \left(\frac{10.0\ m}{1\ kg} + \frac{6.25\ h}{1\ cm} - \frac{5.0\ a}{1\ year} + 5\right)$$

For females

$$\frac{kcal}{day} = \left(\frac{10.0\ m}{1\ kg} + \frac{6.25\ h}{1\ cm} - \frac{5.0\ a}{1\ year} - 161\right)$$

To estimate the caloric requirements of the pre-contact population of the study area we model distributions of age, height, and body weight data for this population from two datasets which included both archaeological and ethnographic samples (Figure 15) (See SI4.2 for biometric data). The first set of data included in this study was archaeological ancestral remains from pre-contact burials at four sites located within traditional Wakashan territory: Namu (ElSx-1), Hesquiaht Harbour (DiSo-9), Toquart Bay (DgSi-1), and Ozette (45CA24) (Figure 14) (Curtin 1984; McPhatter 1985; Hester and Nelson 1978; Cybulski 1978; Aronstam 1975) (Table 11). These sites contained 121 individuals with an estimate of at least one of the three measurements (age, height, and estimated body weight) required for calculating REE. Of these, 108 had an age estimate which was constrained to a 10-year range. If an exact age estimate was not supplied, then the mid-point of the estimated range was used.

Table 11. Summary of ancestral remains by site. For locations see Figure 14.

Region	Site Name	Site Designator	Number of Individuals	Source of Biometric Information
Central Coast BC	Namu	ElSx-1	70	Curtin 1984:37 & Hester and Nelson 1978:38
Vancouver Island	Hesquiaht Harbour	DiSo-9	43	Cybulski 1978:73
Barkley Sound	Toquaht Bay	DgSi-1	1	McPhater 1984
NW Washington	Ozette	45CA24	7	Aronstram 1975:57&70
Total			**121**	

Table 12. Combined biometric data of ethnographic and mortuary sample by sex.

	Male								Female							
	Mean	Median	Min	Max	Q1	Q3	SD	Count	Mean	Median	Min	Max	Q1	Q3	SD	Count
BMI	27	26	24	29	26	28	2	9	25	27	19	27	25	27	3	10
Body Weight (kg)	65	66	30	77	63	69	9	100	57	58	25	67	56	60	7	83
Age (years)	37	38	5	70	27	50	15	125	32	30	1	70	20	42	16	115
Height (cm)	160	162	109	175	158	166	12	100	150	152	99	163	149	155	10	83

This sample of biometric data was then expanded through the inclusion of age, sex, and height information as recorded by Franz Boas from living people in the 1890s (Boas 1891, 1895, 1899). We subset these data to include only those individuals speaking languages in the Wakashan family, which includes 157 individuals (70 females and 87 males) from the Nuu-chah-nulth in Barkley Sound as well as Kwakwaka'wakw, Heiltsuk, and Wuikinuxv Nations (First Peoples' Cultural Council of British Columbia 2024).

We drew on a sample of nineteen individuals from the sites of Hesquiaht Harbour (DiSo-9) and Ozette (45CA24) with recorded maximum femoral breadth measurement to estimate sex specific adult body weights using the formula developed by Grine et al. (1995) (Table 12 and Equation 11). This formula was developed using least squares regression of the means of 10 sex-specific measurements from a large sample of ethnically diverse modern humans. Individuals with femoral head sizes also had height estimates and sex determinations, which allowed us to estimate their Body Mass Index (BMI) (Eknoyan 2008; Quetelet 2013). When height and BMI are known body weight in kilograms can be calculated using the BMI formula (Equation 12). The average BMI for this mortuary sample was 26 which in combination with the height for each individual allowed for the body weight to be estimated and applied using the Mifflin St-Jeor equation (above) to all the individuals with stature height estimates regardless of whether they had associated femoral head breadth measurement. The estimated height from the 19 mortuary samples allowed for an average BMI value to be estimated which was used to estimate body weight for the larger collection of individuals with stature data. We assumed that the BMI of individuals from these two locations are representative of the BMI of the larger region, including Barkley Sound.

Equation 11. Grine body weight estimation from femoral head breadth.

Where
f = femoral head breadth

$$Body\ Weight = 2.268 \times F - 36.5$$

Equation 12. Body Mass Index adjusted to solve for body weight.

$$Body\ Weight_{kg} = Stature_{m}^{2} \times Body\ Mass\ Index$$

Combining these two samples of historic and pre-contact measurements for Wakashan speaking peoples produced a larger and more robust basis for characterizing stature, age, and body weight (Figure 15). The archaeologically encountered ancestral remains, particularly those from DgSi-1 and DiSo-9, are geographically and temporally associated with pre-contact populations in Barkley Sound. However, skeletal measurements lack the same precision as direct body measurements and are expressed as ranges. In contrast, Boas' late 19th century measurements are more spatially and temporally removed from the precontact population but have a level of specificity (i.e., exact age, height, and sex) that complements data from skeletal measurements. Together these nested population data create a much larger and more representative basis for determining caloric requirements for the adult population. In contrast using solely archaeologically documented mortuary data would have limited the sample size as few individuals had all three required biometric data points required to estimate caloric requirements.

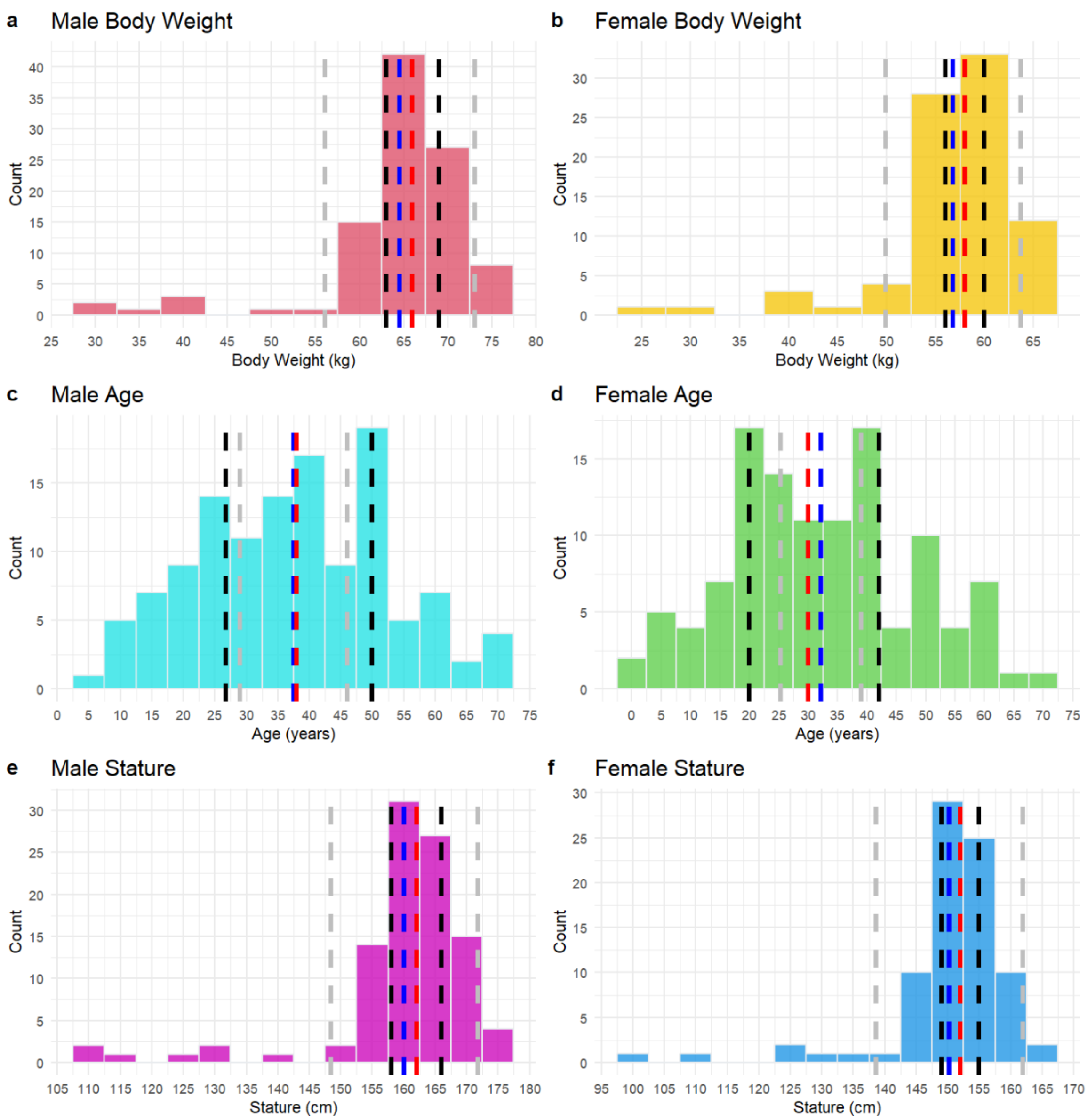

Figure 15. The distributions of body weight (a & b), age (c & d), and stature (e & f) with blue lines demarcating the median, red lines the mean, black lines the 1st and 3rd quartile, and grey lines one standard deviation. Data represent the combined Boas (1890; 1899; 1895; 1891) and ancestral remains (Aronstam 1975; Curtin 1984; Cybulski 1978; Hester and Nelson 1978; McPhatter 1985) measurements.

We used the median values from these distributions to determine the daily caloric requirements for a "typical" individual. This was supplemented by additionally calculating REE, TDEE, and PATDEE using the 1st and 3rd quartile values from *each* distribution of biometric data to create high and low energy consumption scenarios that characterize individual variation in energy consumption. Due to preservation and fragmentation, some of the ancestral remains lacked stature or age estimates so REE could not be calculated for those individuals. Thus, values were pulled from the combined distributions of measurements. Equation 10 reveals that the age component of the Mifflin-St. Jeor formula is subtracted from the combined body mass and height factors. In practice, this means that a tall, heavy, young individual represents the upper end of daily caloric requirements, while an older, shorter, lighter-weight person occupies the low end. Thus, a low daily energy expenditure is calculated using the 1st quartile body weight and height and the 3rd quartile age values for adults, while a high energy expenditure is calculated using the 3rd quartile weight and height and 1st quartile age values. Calculating REE is a required first step in determining Total Daily Energy Expenditure (TDEE) as this measure of total required energy is derived by adjusting REE by a multiplier. PATDEE in turn is derived from TDEE, and as such REE calculations form the foundation on which more complete energy requirements are determined. The substantive sample of Indigenous populations obtained from historic and archaeological contexts thereby comprise a solid basis for inferring the range of daily energy requirements as defined by the low and high energy scenarios, and that the requirements derived from median values best represents an adult living within the study area.

Our approach in estimating caloric requirements is another reason why the final population estimation provides a conservative, or low, value. The models presented here are constrained to estimating how many adult humans the study area could support through time.

This is an inherent undercount of people, given that typically children are going to require fewer calories, meaning that the same number of resources could support a larger mixed population of adults and children than for a population consisting solely of adults. Only 24 of the 281 individuals in the sample of biometric data are children and have an identified sex. Modelling the caloric needs of children is much more complex than adults because different energy requirement formulae are required for children of different age and sex (Schofield 1985). Thus, a sufficiently sized sample of data must be available for each age category, which was not possible with the 24 individuals. Instead, values from children were integrated with those from adults, which creates caloric energy requirement estimates slightly skewed towards pre-adults. The representative person that we model energy requirements for is younger, lighter, and shorter than what would be derived from adult only data. As such children are partially captured in the estimates and the model does reflect the presence of children to a limited extent. Pre-contact Indigenous populations would have been composed of around 30-40% children (Boyd 1999; Efford et al. 2024) who on average would have required less calories and hence population estimates that explicitly model the energy requirements of both children and adults would produce higher total populations. Children have historically been left out of Northwest Coast archaeology (Ruttle 2010) and we hope to incorporate them into future population estimates.

We also note that the collections of both ancestral remains and historical measurements are likely skewed. Boas's sample records few children, and it is possible that either he was not interested in recording these individuals or that Indigenous parents did not make their children available for measurement. Additionally, the long-lasting impacts of European disease events had already altered the demographic profile of these populations at the time of Boas' research (Boyd 1999). Burial practices may also create disproportionate ratios of children to adults in mortuary assemblages (Boldsen et al. 2021; Ruttle 2010). Moreover, mortuary samples are inherently subject to survivorship bias in the form of selective mortality where "...our data comes from samples of the dead that are biased representatives of the once-living populations..." (DeWitte and Stojanowski 2015:399). The individuals recorded in mortuary remains are not reflective of the larger living population cohort from which they are drawn (Wood et al. 1992).

4.2.3 Total Daily Energy Expenditure (TDEE)

Resting Energy Expenditure (REE) is the minimum amount of energy required for basic human biological functioning and by definition is an under estimation of the calories required to support an individual during a day of normal activity. A better estimation of energy expended by a person is their Total Daily Energy Expenditure (TDEE), which is a measure of the energy required both for basic human life and for the completion of physical activities (Westerterp 2013). TDEE is calculated by multiplying the REE by a conversion factor, which corresponds to the individual's activity level (U.S. Department of Agriculture and U.S. Department of Health and Human Services 2020) (Table 13). These conversion factors enable different scenarios to be modelled, capturing a range of exertion levels. The 'sedentary' level corresponds to a minimally active individual while the 'extremely active' level corresponds to the energy expenditure of a professional athlete with other levels falling along a spectrum defined by these two extremes (U.S. Department of Agriculture and U.S. Department of Health and Human Services 2020). For individuals of reproductive age we considered a conversion factor of ~1.7, corresponding to the Very Active level, as most appropriate (Westerterp 2013). A physical activity level conversion factor of ~1.7 has been observed cross-culturally in hunter-gatherer cultures in sub-Saharan Africa, Indigenous populations in eastern Siberia, and contemporary urban and suburban North

Americans (Katzmarzyk et al. 1994; Mifflin et al. 1990; Pontzer et al. 2012; Westerterp 2013) suggesting broad applicability to Indigenous populations on the Pacific Northwest Coast.

Table 13. REE to TDEE conversion factors.

Activity Level	Conversion Factor
Sedentary	REE x 1.2
Light Activity	REE x 1.375
Medium Activity	REE x 1.55
Very Active	REE x 1.725
Extremely Active	REE x 1.9

In our analysis we modelled proportions of median body weights, ages, and heights to determine the most likely caloric requirements for individuals living in Barkley Sound, where the low and high energy requirement caloric requirements provide a range for the majority of individuals. These energy requirements can then be combined with the estimated total caloric energy represented in fish to determine the person days of food (PDF) and person years of food (PYF) represented archaeologically. PDF is the number of days a single individual could have met their daily caloric requirements based on the total caloric energy from fish preserved in known and mapped shell midden locations while PYF is the same measure but expressed in years. We present both measures as determined using REE, TDEE, and PATDEE scenarios to show how dietary composition and physical activity levels can influence population estimates.

4.2.4 Protein Limits

Protein poisoning, also known as ‘rabbit starvation’ or ‘protein starvation’, is a form of malnutrition caused not by a lack of calories but by a lack of fat and carbohydrates in an individual’s diet (Cordain et al. 2000). The process is complex but relates to ammonia, a toxic byproduct of the catabolism (destructive metabolism) of protein, which is then processed by the liver into relatively non-toxic urea, which in turn is excreted by the kidneys into the urine. A typical human liver provides a Maximum Rate of Urea Synthesis (MRUS) of between 55 and 76 milligrams of nitrogen per hour per kg of metabolic body weight (Cordain et al. 2000; Rudman et al. 1973). Thus, given a specific body weight, there is a finite limit after which MRUS cannot effectively synthesize urea. As a result of this biological limitation humans cannot overconsume protein without risking the buildup of toxic compounds in the blood. This generally restricts protein consumption to 30-35% of total daily calories (Speth 1990, 2010). This threshold was derived from observations of numerous traditional diets globally, although it is biologically possible for some humans to consume greater amounts of protein for short periods.

A number of researchers have contributed to our understanding of the metabolic and nutritional requirements of hunting and gathering communities (Erlandson 1988; Mann 2000; Prentiss 2022; Speth and Spielmann 1983; Tushingham et al. 2021) and have established that diets consisting solely of protein and would lead to protein starvation. Considering that fish tend to be very lean and that the fish species accessible to Nuu-chah-nulth in Barkley Sound have a fat content that is equal to or lower than the weighted proportional fat content of all five Salmon species (~5 grams per 100g of flesh) (Table 10). This was determined using the proportionality of fish in Barkley Sound middens and their known nutritional information. As expected, individuals living in Barkley Sound would have not obtained all their daily required calories from fish alone, but they would also consume carbohydrates and fats from other sources such as plants, birds, mammals, and shellfish as is well documented in ethnographic accounts (Drucker 1951; Sproat 1868) and archaeological information (McKechnie 2005b; McMillan and St. Claire 2012).

Using the estimated median body weight of 62 kg[3] for an individual from the sample of ethnographic and ancestral remains data and following the well established limits on human protein metabolism (Cordain et al. 2000; Rudman et al. 1973; Speth 2022; Tushingham et al. 2021) we estimate that not more than 40% of calories could come from fish (See SI4.4 for calculations). This is slightly higher than the generally accepted 35% of calories from protein and suggests a conservative cap on the percentage of daily calories derived from protein. Our population estimates are based solely on the caloric energy available from fish, and as such we calculated Protein Adjusted Total Daily Energy Expenditure (PATDEE) caloric requirement estimates that incorporate the limits on maximum levels of protein consumption in the calculation of population estimates.

If biometric data is not available to estimate study area specific caloric energy requirements then values from contemporary populations can be used following the TDEE estimate of 2,120 calories presented in a recent study in the Salish Sea work Efford et al. (2024:7). Here a daily weighted caloric requirement was obtained from modern nutritional guidelines for different segments of the population including children, adults, pregnant/lactating adults and elders (U.S. Department of Agriculture and U.S. Department of Health and Human Services 2020). Nutritional recommendations for the population broadly related to the ancestral communities should be used when more specific biometric data is not available. An appropriate activity level should also be selected to match the lifeways of the population being modelled.

[3] Body weight was derived by averaging the median weight of males (66 kg) and females (58 kg) from the combined Boas and ancestral remains data set.

The use of modern nutritional guidelines may be appropriate as minimal differences have been observed in the caloric requirements of Hadza hunter gatherers and moderately active modern European adults (Pontzer 2017; Pontzer et al. 2012, 2016). Additional research has demonstrated that once adjusted for weight and age caloric requirements do not significantly differ geographically (Dugas et al. 2011). We refer curious readers to Pontzer's work as cited above for further details. Thus, caloric requirements can be broadly estimated and compared even when mortuary or ethnographic bodyweight, stature, age, and sex information may not be available or is inaccessible due to community concerns.

4.3 Results

The most representative (median) REE derived for adult females is 1,219 kcal with a range of 1,120-1,307 corresponding to the Low and High energy requirement scenarios. For adult males, the REE is 1,487 kcal with a range of 1,372-1,598 kcal. These relatively small ranges are due to relative homogeneity (in comparison to modern North American populations) of biometric data for this population. We defined the 'representative' individual using the median values from the distributions of weight, height, and age that were collected from the sample of ethnographic and ancestral remains (Figure 15). Using the sex ratio of 1.06:1 males to females (Table 14) we estimate that a representative inhabitant of Barkley Sound has an REE of 1,397 kcal/day and a TDEE of 2,376 kcal. Drawing on the median weight of all individuals (62 kg), we also derived the PATDEE to be 950 kcal, where 40% of caloric energy comes from protein. Of the 2,376 total calories that a person would need to consume daily on average, a maximum of 950 could be sourced from fish. The remaining 60% of calories would need to be derived from fats and carbohydrates. While we lack data on juveniles and children these values are expected to be proportionally reduced depending on body weight, sex, and activity.

Table 14. Count of individuals from Boas ethnographic and ancestral remains data by sex.

	Count Ethnographic	Count Ancestral Remains	Total Count	Total Percent
Male	89	35	124	44
Female	70	47	116	42
Undetermined		39	39	14
Total	**159**	**121**	**279**	**100**

Note that this produces a sex ratio of 1.06 males for every female. We assume that the undetermined individuals also have this same ratio of males to females.

Using the adjusted estimated biomass of 791 million kg of fish preserved in Barkley Sound shell middens, we estimate that these sites contain over 1 trillion calories of food energy (Table 10). The bulk of this energy was provided by salmon (*Oncorhynchus sp.; 51%)*, with rockfish (*Sebastes sp.; 6%*), dogfish (*Squalus suckleyi; 7%)*, greenling (*Hexagrammos sp.;* 7%*)*, Lingcod (*Ophiodon elongatus 4%*), halibut (*Hippoglossus stenolepis; 4%*), and Herring (*Clupea pallasii* 8%) also contributing significantly (Table 10). When equally distributed across 3,000-years of human activity this equates to over 340 million (340,781,499) calories per year of available energy.

In a scenario in which the study area had a static population over the last 3,000 years of human activity this combination of available calories and energy expenditure would support a continuous population of between 393 to 982 people, with the former based on the TDEE and the latter on PATDEE. See Table 15 for PDF, PYF, and static population estimates based on REE, TDEE, and PATDEE. We believe that the PATDEE estimate represents the most likely fish-based population estimate as TDEE and REE estimates represent unrealistic scenarios where individuals are either completely sedentary or ingesting unsustainable amounts of protein.

Table 15. Person years of food and person days of food based on resting energy expenditure, total daily energy expenditure, and protein adjusted total daily energy expenditure with estimates of the number of people that could be supported continuously over 3,000 years of occupation.

	Person Years of Food	Person Days of Food	Persons / 3,000 Years
REE (Resting)	2,003,716	731,356,164	667
TDEE (Total Daily)	1,178,656	430,209,508	393
PATDEE (Protein Adjusted)	2,946,640	1,075,523,771	982

Next, we consider additional ways in which our population estimate might range. We start by noting that our population estimates are calculated using a variety of variables, all of which have innate uncertainty and error. We have presented what we feel is a realistic yet conservative estimation of population (expressed in number of adults), but there is value in defining the upper and lower limits of this estimate. Our previous analysis of midden volumes (Gustas et al. 2022), which in part underlies these population estimates, showed that those estimates of volume had an error of ± 9%. Estimated caloric energy in middens is derived from applying the estimated density of fish to the total volume of midden sediments and consequently the total available caloric energy in Barkley Sound may also vary by this amount. In our work estimating total harvested fish biomass contained in Barkly Sound middens sites (Gustas et al. 2024) we calculated the interquartile range of total biomass using distributions of fish body mass by species. Using this information, we created low and high biomass harvest scenarios, which assumed that all harvested fish had a body mass as represented by either the 1st or 3rd quartile of recorded body weights for their species. In the current paper we determined the upper and lower bounds of possible PATDEE by using the 1st and 3rd quartile age, weight, and body weight for study area inhabitants as well as the lower and upper limits of protein metabolism, 34% and 48% of daily calories respectively.

Combining all of these upper and lower scenarios allowed for the modelling of what the highest and lowest count of persons that could be supported from fish calories (Table 16) (See

SI4.3 for these calculations). In a scenario where midden volumes are 9% smaller than estimated, all fish harvested are represented by the 1^{st} quartile weight for their species, and the PATDEE of study area inhabitants is represented by the 3^{rd} quartile weight and height and 1^{st} quartile age, a total of 627 adults could be supported every day for the last 3,000 years of human occupation in Barkley Sound. In the opposite scenario where midden volumes are 9% larger than modelled, all fish are represented by the 3^{rd} quartile weight of their species and TDEE is determined from the 1^{st} quartile weight, and height and 3^{rd} quartile age, this estimate rises to 1,902 adults.

If 30% of the population were children each requiring 1,776 calories on average (Efford et al. 2024) then the PATDEE decreases to 878 kcal which would support for a constant population of 1,063 individuals. For scenarios where specific caloric requirements cannot be created from biometric data then Efford's TDEE estimate of 2,120 calories can be applied. This equates to a PATDEE of 848 calories which is ~100 calories smaller than the biometrically derived Barkley Sound PATDEE. This nearly 10% difference illustrates the importance of determining local caloric requirements when data are available, using the most proximal sources of information. If this PATDEE is applied to Barkley Sound then a continuous population of 1,098 individuals could be supported. We feel confident that the minimum fish supported population estimate falls somewhere between the upper and lower limits and that the previously stated estimate of 1,000 persons is a defensible minimum value which represents a conservative population estimate. Many factors of uncertainty are present in these estimates (Table 17) it is very likely that actual populations were significantly higher than range presented here. Additionally, this model does not include energy from shellfish, marine mammals, or birds which would increase the size of the population that could be supported.

Table 16. Alternative midden volume and biometric data used to estimate ranges in population estimates for shell midden sites.

			Protein Adjusted Total Daily Energy Expenditure ‡						
Scenario	**Total Midden Volume (m^3)***	**Available Calories (kcal) †**	**Body Weight (kg)**		**Height (cm)**		**Age (years)**		**% Daily Calories from Protein §**
			Male	Female	Male	Female	Male	Female	
Lower Limit	219,541	807,604,547,449	63	56	158	149	27	20	34
Middle	241,253	1,022,344,498,343	66	58	162	152	38	30	40
Upper Limit	262,966	1,296,679,340,842	69	60	166	155	50	42	48

* The minimum and maximum midden volumes are calculated by increasing and decreasing by 9% total estimated midden volume as per Gustas et al. (2022).

† Minimum and maximum caloric energy values are derived from the 1st and 3rd quartile fish biomass estimates from Gustas et al. (2024).

‡ Minimum and maximum body weight, height, and age were derived from 1st and 3rd quartile values from the combined ethnographic and mortuary biometric data.

§ Minimum, middle, and maximum % Daily Calories from Protein is calculated based on Maximum Rate of Urea Synthesis (MRUS) of 55, 65, and 76 mg N / h·kg of metabolic body weight (Cordain et al. 2000).

Population densities are a valuable method for quantifying the intensity of population on a landscape however they are not an appropriate way of contextualizing the study area given that much of it is ocean. Suggesting a count of person per unit of land would potentially misrepresent the density of people on the seascape as they are exceedingly difficult to calculate for coastal peoples (cf. Ames 2002; Keeley 1988; Mackie 2001) where catchment areas are composed of both marine and terrestrial environments.

4.4 Discussion

The methodology developed to address this research question is strongly grounded in archaeological data and has significant advantages relative to population estimates and techniques applied to Indigenous settings over the last hundred years. Foremost of these is that this method is based on the biomass observed in archaeological sites adjusted for the caloric content of fish and the nutritional requirements of local Indigenous populations. This stands in contrast to other historical methods that have been based on explorer accounts and population estimates, projected rates of population decline, living space requirements, and other approaches that rely on ethnographic observations or historic analogies. Those methods are partially based on the assumption that historically observed lifeways are reflective of those of past populations, which introduces a potential source of error. Additionally, those observations are frequently from periods in which Indigenous peoples may have already experienced the deleterious impacts of European contact, which dramatically reduced their populations and altered lifeways. Thus, those estimates may not be reflective of earlier time periods.

The method that we present here is much less dependent on any prior knowledge about a group's behaviour and is rooted in caloric requirements and available food energy. Additive and ratio-based population estimates, for example, have well documented shortcomings, which centre on issues of over reporting of populations and the lack of validation for estimates (Boyd 1999; Campbell 1990; Dobyns 1966; Harris 1997; Ramenofsky 1987). Living space based estimates [e.g., Narroll's Constant (Naroll 1962) and other similar studies] are more directly connected to archaeological materials but are also contingent on having an understanding of the amount of space that a person would require (Cook and Heizer 1968; Kolb et al. 1985; Schreiber and Kintigh 1996), which are again informed by historical observation. Creating population estimates from compilations of data from a single well surveyed region avoids many issues associated with reliance on historical proxies and cultural analogies.

Resource variability is an endemic quality of the Northwest Coast resulting both from regional differences in habitat and seasonality (Suttles 1968, 1987). This variation would have created both periods of abundance (including potlach and other feasting events) and scarcity. The time average approach employed here to create minimum population estimates accounts for both of these conditions as the model parameters include the totality of harvested fish resources across thousands of years. Additionally, this model assumes that fish were readably available for consumption and that individuals had access to as much daily protein as they could metabolically handle. This framing helps to push back on idea of the "Savage-Slot" or the idea that hunter-gatherer societies existed on the margins (Cobb 2005). Maximal protein consumption is supported by the ethnographic accounts such as this recorded by John Jewitt who described Indigenous peoples in Nootka sound as "always eating to excess" and seldom wanting for food in the summer months (Jewitt 1807:85). Here we present scenarios in which individuals were consuming maximal quantities of fish and protein consumption may have been more in line with the cross culturally observed 30% of daily calories which would suggest even larger populations than those presented here (Speth and Spielmann 1983).

In addition to yielding population estimates, our approach illuminates the relative contribution of calories across different fish species, thereby highlighting particularly important resources. We found for example that salmon was an important component of Indigenous diets, with these fish alone representing over half of all harvested calories in Barkley Sound. However, herring, rockfish, lingcod, greenling, halibut, and dogfish were also significant contributors to the diet collectively contributing over 25% of the available caloric energy from fish.

Halibut is an excellent example of a species which may be underrepresented. Fragmentary halibut bones may be mistaken for other, typically much smaller, flatfish species causing them to be assigned fewer calories per individual, thus diluting their significance when converting fish counts to calories. Additionally, halibut bone may be more prone to high rates of taphonomic destruction, reducing visibility of this species (Orchard and Wigen 2016:50). Halibut may also be butchered on the beach, further reducing their prevalence among the remains recorded in midden sediments. Scholarship in Barkley Sound and other parts of the Northwest Coast has shown that a certain size of halibut may have been preferential targeted for harvest (Salmen-Hartley and McKechnie 2023), which might bias samples to certain range of halibut sizes that might not be reflected in body weight metrics generated from commercial catch data. This example illustrates how some non-salmonoid fish may be biased against in the formulation of MNI counts used to inform the calculation of available calories.

This study illustrates the analytical utility of zooarchaeological data generated from fine screened volumetrically controlled faunal samples from midden sites. Even infrequently occurring species like Gunnel, Sand lance, and Clingfish contributed hundreds of millions of calories of energy to Barkley Sound populations and in this sense were not minor in the context of fishery effort. When working across hundreds of archaeological sites and over thousands of years, even a small amount of faunal material recovered from a site can represent a significant amount of caloric energy in aggregate. Even small changes in how faunal materials are quantified into animal counts can produce significant differences in results, which illustrates the importance of the accurate identification of faunal remains. The use of a high-quality comparative collection for identification and the use of fine screens to capture most species of vertebrate fauna as well as volumetrically controlled column or matrix samples are essential so that bone counts can be accurately converted into densities of known fish taxa and used to calculate biomass.

Our research also illustrates the importance of being aware of the nutritional implications of different foods when using diet reconstructions to estimate population. The limitations of consuming lean protein significantly influence estimates of how many people that could be supported from eating fish. Factoring in natural human protein limits dramatically increases population estimates that are derived solely from the consideration of low fat, protein-dominant foods. Not incorporating this human nutritional limit would have resulted in underestimation of populations estimates. Creating the most inclusive reconstruction of past diets possible allows for better determination of how many calories were available for consumption. Including as many sources of nutrition as possible in the diet reconstruction will significantly improve the quality of population estimates.

Our population estimates could be expanded through the inclusion of additional non-fish food sources. In its current state our estimates present a minimum population size as we only incorporate a single (though important) source of food. The inclusion of marine mammals, birds, shellfish, and plant foods would improve the quality of population estimates and potentially allow for the accurate estimation of the total population; it would also by definition increase, probably significantly, the estimated number of humans that could be supported. Avenues through which other foods' caloric contribution to diets might be inferred or determined have been identified in recent scholarship (Gavenus et al. 2023). Isotopic analysis of domesticated dog species might offer an avenue into better understandings of the consumption of non-fish marine animal foods (Efford et al. 2024; Hillis et al. 2020; McKechnie et al. 2020). Additionally, isotopic studies of a small number of ancestral remains from Prince Rupert Harbour have provided insight into a potentially major proportion of diets coming from plant resources (Schwarcz et al. 2023). Still other paleoethnobotanical studies highlight aquatic plant cultivation and trade networks (Lyons et al. 2023). Future work using these techniques may allow for additional refinement of diet and available caloric energy creating more complete population estimates.

Additionally, the study area has not been completely surveyed with most survey efforts focused on modern coastlines. Relative sea level changes in Barkley Sound have been dropping by several metres over the course of documented human history (Dallimore et al. 2008) meaning many sites located on what are now relic shorelines in deeper time periods are likely stranded inland, significantly above modern shorelines and buried under thick natural sediment. Given that a significant number of these sites may remain un-detected and undocumented in Barkley Sound, population estimates will only increase as more shell middens are recorded and zooarchaeological analysis conducted to quantify the discarded food remains that they contain. Additionally, only about 60% of the modern Barkley Sound coastline has been surveyed. Assuming that the density of sites along the surveyed portions of the coastline is representative of the entire coastline the un-surveyed areas of the past and present coastline could contain a substantial number of additional sites.

The duration of human activity that calories are associated with also has significant impacts on the estimated population. If we had considered the entirety of Barkley Sound's 5,000 year human history and not removed the 1.5% of calories represented by the back ridge areas of the three oldest sites then 100% of the total calories would have been allocated across a period which is 66% longer, thereby reducing the calories available in each year. Conversely if the chronological window was shortened the calories would be concentrated, thereby increasing population estimates. This simple illustration reveals that the duration of the time period under examination is very important and must be carefully considered during the modelling process.

These estimates should be viewed as a starting point for building more complete estimates of population. Future directions for this work include creating estimates of the calories represented by shellfish and marine mammal remains contained in middens. Additionally, allocating harvested calories chronologically using an SPD based on the record of radiocarbon dates that have been collected from Barkley Sound sites might provide insight into potential variation in population sizes through time. This would also allow for estimates of maximum and minimum populations and targeted estimates for specific time periods. This effort would require further radiocarbon dating from midden sites and additional survey of relic shorelines to identify undiscovered sites.

These population estimates demonstrate that the pre-contact population of Barkley Sound was larger than the population estimates that were used by 19th century officials in British Columbia to allocate reserve lands and set colonial policy (Harris 2002). This highlights the importance of archaeologically derived population estimates as reserve size was partly based on populations which were not reflective of those that had inhabited Barkley Sound and other areas of British Columbia prior to European contact. We estimate that on average over the length of its human occupation a *minimum* population estimate for known archaeological sites in Barkley Sound is approximately 1,000 individuals. This is larger than Grant's estimate and on par with Sproat's (once adjusted to account for women and children) (Table 8 and Table 9). Our populations estimate is markedly smaller number than the largest historic population estimate of 8,500 people offered by Narváez and it is possible that he overestimated population size given that he did not conduct a formal count. However, we feel that it is also very likely that our estimate greatly under counts the population especially in light of recent work (Efford et al. 2024; Hillis et al. 2020; Schwarcz et al. 2023) and that the actual available energy (and hence population) might have been several times greater than what was supported from fish alone. Revised estimates of population offer a powerful contribution to shaping future policy and governance that can ensure that the long history of Indigenous land use in coastal Canada is accurately represented. Our work provides an important methodology for coastal First Nations to demonstrate the continuity and intensity of land use with implications for rights and title.

It is critical to emphasize that the estimates presented here are population minimums. Careful effort has been taken to employ a practice of computational conservative modelling in which highly defensible population estimates were created. A model of population that includes not just fish, but all the foods consumed by precontact Indigenous groups would be many times larger than the values presented here. Our hope is that future work on this topic will incrementally add in more sources of food, more accurate measures of midden volume, and biomass estimates based on body mass derived from archaeological fish remains to gradual create more accurate population estimates. We refrain from speculating on how much population estimates might increase as the history of precontact estimates shows that archaeological data of this nature are very powerful and can have significant real world impact for Indigenous communities (Duff 1964; Harris 2002; Martindale 2014). As such we wish to reduce volatility and inconstancy in population estimates through a careful and measured approach.

4.5 Conclusion

In this paper we present a novel zooarchaeologically and geospatially based method for estimating human populations from archaeological data, which calculates caloric energy represented by preserved fish remains in shell midden sites and estimates caloric requirements for Indigenous populations compiled from Wakashan language family including Barkley Sound. These represent the first archaeologically derived population estimates for this area. The methods presented here demonstrate a new implementation of accumulation research and avoids the disproportionate emphasis on the more limited early historical observations and later colonial census efforts, and which is empirically based primarily in the archaeological materials deposited at sites. This method provides minimum estimates of population solely on the calories calculated from fish and the expansion of this method to consider other food sources would allow for revisions to population estimates. We encourage additional scholarship to address the challenges related to quantifying the remains of other types of food consumed to derive even more robust population estimates.

Chapter 5. Conclusion

This research found that in known Barkley Sound archaeological sites 241,253 m^3 of midden sediment accumulated over 5,000 years of human occupation, with the majority deposited within the last 3,000 years. These features contain the remains of nearly 1.2 billion fish, with a collective biomass of ~800,000,000 kg. These fish provided over a trillion calories of energy to the people who harvested them, and the combined energy from these fish alone would have been able to feed ~1,000 people daily for the majority of Barkley Sound's known human history. The following paragraphs expand on these results and their implications.

This work comprises the first population estimate of its kind for the study area and has implications that extend far beyond the region. This method can be used to estimate populations for midden and mound features worldwide if the appropriate spatial, zooarchaeological, biometric data is available. Additionally, these findings have implications for Indigenous communities as they demonstrate their long term use of this landscape through the harvesting of large quantities of marine resources. In the course of establishing this population estimate several additional contributions were made to Northwest Coast archaeology:

- A new method for estimating the volume of midden sites was developed that uses a semitriaxial ellipsoid fitted to the bounding dimensions of the accumulated sediments. This method outperforms other previous approaches, that used solid shapes to model mounded anthropogenic sediments, by providing more accurate estimates of total volume. Additionally, a method was developed for validating these estimates using a sample of well surveyed sites that have been subject to subsurface testing. These results showed that *a minimum* of 241,000 m^3 of sediment have been deposited in Barkley Sound.

- This work established a realistic range for body weights of multiple taxonomic categorizations of fish. These values are generated from numerically robust samples and provide values that can be used by other archaeologists working in the Northwest Coast context to quantify the amount of harvested fish. These results have implications for biological, ecological, natural resources and other types of research that examine Pacific marine environments.
- This work produced estimates of the total biomass of the fish harvested by Indigenous peoples in Barkley Sound. Through this process I developed a method for estimating biomass from zooarchaeological analysis of faunal remains from a robust sample of sites. Additionally, I created a process for extrapolating these results across hundreds of sites within a region. These estimates show that in Barkley Sound 1.2 billion fish were collected resulting in ~800,000,000 kilograms of biomass. When placed in context of modern fisheries these results show that Indigenous harvests comprise nearly 10% of modern fisheries.
- This research examined several different ways of considering the daily caloric energy that required to support the population of Barkley Sound. Calculations drew on the assembly of a large dataset of biometric data from ethnographic and archaeological sources with thousands of data points. Determining the Resting Energy Expenditure and Total Daily Energy Expenditure of the Indigenous Barkley Sound population allowed for detailed locally calibrated estimates of how much energy a person living in this environment would require. This information was used to create a range of values into which the caloric requirements of the inhabitants of the study area were likely to fall. Additionally, a conversion factor was determined for these populations to account for natural human limits on the metabolism of protein, which can be used to create more realistic population estimates based on calories

solely from protein dominant foods. This work found that the typical Barkley Sound individual would have required slightly less than 2,400 calories per day with only 40% of that value (950 calories) being derived from fish.

- Lastly, this dissertation ultimately generated a new minimum population estimate for Barkley Sound that is empirically grounded in, and derived from, the archaeological record. The estimate is significantly smaller than many contact era estimates but should not be directly compared to those numbers as the estimates offered here are minimums and the actual population would certainly be much larger as it would also incorporate calories from mammals, invertebrates, birds, and plants. However, this estimate of ~1,000 people does suggest that a significant population could have inhabited Barkley Sound for several millennia. Importantly this minimum population is still larger than Grants 1857 estimate of 700 people and speaks to the antiquity of human occupation in this region and sustained, long-term practices of large-scale marine resource use.

Five categories of uncertainty in the calculation of midden volumes, estimated fish biomass, and minimum populations are summarized in Table 17. Taphonomic uncertainty arises from processes which affect material culture after its deposition, quantification uncertainty is the result of different ways of categorizing and enumerating data, survey and sampling methodologies can affect the recovery of data, and cultural uncertainty is the product of the behaviour of past humans. Taphonomic processes that may lead to the underestimation of fish within a midden include that not all fish deposited in a site will preserve to be recovered by archaeologists (Rick et al. 2002; Wigen and Stucki 1988; Willis and Boehm 2014) and that smaller middens as a whole are less likely to be preserved (Mackie 2001; Stein 1992). The differential preservation of faunal may lead to higher rates of identification of fish with larger skeletal elements overestimating the presence of larger fish (Cannon 2000; Lyons and Orchard 2007; Wigen and Stucki 1988).

5.1 Sources of Uncertainty

How shell midden site data is quantified can also have significant impacts on estimates. Sources of overestimation include that not all harvested biomass was consumed as food (Barrett 1993; Efford et al. 2024; Lyman 2008; Lyman et al. 1992; Stewart and Stahl 1977) and that the units of amalgamation used in MNI calculations can dramatically affect the size of MNI counts (Gifford-Gonzalez 2018). Sources of underestimation include that MNI counts are minimums (but see above comment about units of aggregation) which underestimate the total amount of fish deposited in a site (Grayson 1984; Lyman 2008). Additionally, salmon and some other species of fish are more identifiable from fragmentary remains and other species are likely to unidentified at greater rates (Butler and Chatters 1994; Hillis et al. 2022; McKechnie and Moss 2016; Orchard 2009.

How sites are sampled also has significance for estimated site volume and fish biomass. As demonstrated in Chapter 2 using the semitriaxial ellipsoid to model midden shape will slight overestimate site size and if high levels of precision are required for site volumes, then subsurface coring should be conducted so the pseudotransect method of volume estimation can be used. The size of mesh used in screening midden sediments has significant outcomes on faunal identification with large mesh sizes leading to the undercounting of fish with smaller skeletal elements. The density of fish in midden sediments may also vary due to sample location and site accumulation rate. As illustrated in the sensitivity analysis presented in Chapter 3 the composition of fish species within larger taxonomic groups can also affect calculated biomass estimates (Gustas et al. 2024).

The estimation of minimum populations is highly dependent on available calories and human nutritional requirements. The seasonality of fish is not accounted for in this analysis and fatty fish higher in calories may have been preferentially harvested (Freshwater and King 2024; Lyman 2008; Tester 1939). Some fish species have decreased in average body mass size since the start of commercial fisheries and biomass estimates derived from this fishing data may underestimate the size and biomass of fish in archaeological contexts (Jeffrey et al. 2016; Oke et al. 2020; Ricker 1981). Children are not explicitly accounted for in this analysis and usually consume less calories than adults and when included in models produce larger population counts as demonstrated in Chapter 4 (e.g. Nowell 2021; Ruttle 2010; Schofield 1985).

Human caloric energy requirements are also affected by uncertainty. The models presented here assume that human protein consumption was always near the maximum allowed by metabolic processes (Speth 1990, 2010). This model assumes that fish was always readably available and that populations enjoyed surplus conditions and lower amount of protein in the diet as have been observed in other hunter gatherer cultures would increase overall population size. Additionally, this work assumes very high Physical Activity Levels from the entire population and modelling in lower activity levels from very old and very young individuals would increase population estimates (Pontzer et al. 2016; Westerterp 2013).

A variety of cultural practices can lead to uncertainty in biomass calculations. Size specific harvesting as seen with halibut means that archaeological fish should be used whenever possible to establish species biomass (Croes and Hackenberger 1988; McKechnie 2007; Salmen-Hartley and McKechnie 2023). Scavengers and dogs may have consumed or dispersed biomass away from midden sites (Bernick and Wigen 1990). Fish may also have been processed outside of village sites resulting in underestimates of total available fish calories (Orchard and Wigen

2016). Additionally ritual practices of placing fish back in streams after harvest and repurposing fish to use as bait would have similar effects on results (Amoss 1987; Gunther 1926; Losey 2010). This work does not attempt to account for the spoilage of fish which would not be consumed by people but which would show up in the archaeological record (Hillis et al. 2020; Sproat 1868). It is also possible that animals were hunted so they could be used in tool production. (i.e. deer bones used for tools or dogfish skin used as a type of sandpaper) (Hodgetts and Rahemtulla 2001; Sapir 1922). Lastly animals may have been harvested and then traded or exchanged with other groups outside of Barkley Sound without being deposited in local middens (Crockford et al. 1997; Sproat 1868).

Table 17. Sources of uncertainty in volume, biomass, and minimum population estimates.

Factor	Source of Uncertainty	Directionality of Change (inferred)	Potential Methods to Address Uncertainty	References
Taphonomic				
	Not all fish bones preserve to be identified & counted due to post depositional decay	Underestimation	Examine taphonomic loss ratios from similar midden sites (% loss)	(Rick et al. 2002; Wigen and Stucki 1988; Willis and Boehm 2014)
	Differential preservation of certain durable bones may disproportionately represent specific fish species	Overestimation	Adjust to species	(Cannon 2000; Lyons and Orchard 2007; Wigen and Stucki 1988)
	Smaller more ephemeral shell middens are less likely to be preserved over time or encountered in surveys	Underestimation	Consider older sites buried under humic layers or subject to greater deterioration and resurvey areas to identify unrecorded sites	(Mackie 2001; Stein 1992)
Quantification				
	MNI bone count may exaggerate salmon due to high level of identifiability	Underestimation	Experimental fragmentation of identifiable bones in salmon vertebra	(Butler and Chatters 1994; Hillis et al. 2022; McKechnie and Moss 2016; Orchard 2009)
	Not all fishery biomass was directly consumed as food or used for nutrition	Overestimation	Apply meat weight conversions to determine edible biomass	(Barrett 1993; Efford et al. 2024; Lyman 2008; Lyman et al. 1992; Stewart and Stahl 1977)
	MNI aggregations provide minimum estimates of the total individuals deposited	Underestimation	Compare to NISP to define range in which counts fall	(Grayson 1984; Lyman 2008)
	Smaller units of amalgamation increase MNI count	Overestimation	Compare to larger units of aggregation to determine impact of amalgamation	(Gifford-Gonzalez 2018)
	Species composition of taxonomic categories affects biomass estimates	Underestimation or overestimation	Sensitivity modelling can reveal how variation in composition might affect total biomass	(Gustas et al. 2024)
Survey Effort				
	Not all sites included due to limited surveys of modern shorelines	Underestimation	Calculate number of sites per km of surveyed shoreline and apply to unsurveyed shoreline	(Mackie 2001; McLaren et al. 2011)
	Not all sites included due to lack of survey past shorelines from higher sea levels	Underestimation	Consider the potential for sites on paleoshorelines	(Mackie 2001)

Sampling				
	Using larger mesh sizes results in under identification of fauna with smaller skeletal elements	Underestimation	Consider the ratios between large and small mesh, screening techniques, and NISP counts - adjust where comparable data exists within sites where both coarse and fine screening was conducted	(McKechnie 2005b; Moss et al. 2017)
	Semitrixial ellipsoids volumetric estimates overestimate midden volumes	Overestimation	When possible, use subsurface testing to inform volume estimates	(Gustas et al. 2022)
	Density of fish may be variable due to sample locations and accumulation rates	Underestimation		
Nutritional				
	Nutritional values my vary for a species with season of harvest (seasonally fatty fish may have been targeted)	Underestimation	Use season specific nutritional information if available	(Lyman 2008; Tester 1939)
	Children are not explicitly included in the caloric energy requirements	Underestimation	Explicitly include children in modelled caloric requirements	(Nowell 2021; Ruttle 2010; Schofield 1985)
	Protein consumption may have been bellow the maximum metabolic limit	Underestimation	Perform sensitivity analysis to reveal how ranges of protein consumption and varying activity levels affect total population	(Speth 1990, 2010)
	Physical activity levels may have been higher or lower than modeled	Underestimation or overestimation		(Pontzer et al. 2016; Westerterp 2013)
	Fish body size has decreased in size over time	Underestimation	Use fish body mass data from archeological specimens when possible	(Jeffrey et al. 2016; Oke et al. 2020; Ricker 1981)
Cultural				
	Size specific selective harvest of fish	Underestimation or overestimation	Adjust fish body mass values to reflect targeted body size within species	(Croes and Hackenberger 1988; McKechnie 2007; Salmen-Hartley and McKechnie 2023)
	Scavengers (e.g., birds, rodents, wolves, dogs) may have consumed or dispersed bones into settings where they were less likely to preserve	Underestimation	Examine taphonomic loss using site with exceptional preservation and comparison of depositional contexts (e.g. wet vs. dry, rapid, burial, vs. slow)	(Bernick and Wigen 1990)
	Butchering practices that lead to deposition of skeletal elements away from middens	Underestimation		(Orchard and Wigen 2016)
	Deposition of salmon remains back into streams as part of ritual obligation	Underestimation		(Amoss 1987; Gunther 1926; Losey 2010)
	Repurposing fish for bait	Underestimation		(Drucker 1951)
	Stores of fish that were not consumed by people	Overestimation		(Hillis et al. 2020; Sproat 1868)

	Consider other ethnographic uses for animal products besides nutrition (i.e. tool use of faunal elements)	Overestimation		(Hodgetts and Rahemtulla 2001; Sapir 1922)
	Items harvested for trade & exchange rather than local consumption	Underestimation or overestimation		(Crockford et al. 1997; Sproat 1868)

5.2 Future Research

This work invites several additional lines of inquiry that could be investigated in the future. The population estimates presented in this dissertation should be interpreted as minima given that they are based on a single category of food adjusted for values associated with protein content. Expanding this analysis to include additional foods that were known to have been consumed in large amounts, such as shellfish (e.g. Ellis and Swan 1981; Moss 1993:193), marine mammals (e.g. Huelsbeck 1988), bords (Crockford et al. 1997), and seaweeds and plants (Turner 1982) would increase the size of the estimated population and provide a more accurate understanding of population levels. There are several associated challenges, which relate to how to quantify faunal counts from archaeological remains that would first need to be addressed. These include how exactly highly fragmented shell are quantified, accurate representation of marine mammals in column samples, and how the potential distribution and deposition of large marine mammals among multiple sites can be accounted for. Additionally, estimates would need to be created for the portion of the diet derived from plants and other food sources, which are neither preserved in the archaeological record nor recorded with the same fidelity as animal remains.

Another possible expansion of the population estimates is through the inclusion of additional proxies of diet. For example, the isotopic analysis of domesticated dog remains on the coast might be able to provide additional understanding of what portion of calories were derived from different sources of food. Recent studies have suggested that shellfish and marine mammals might have been important contributors to the canine diet, and while canine diets are not perfect proxies for human diets, they are able to inform and help refine estimates (Cannon et al. 1999; Hillis et al. 2020). Additionally, analysis of existing isotopic values from ancestral remains may also shed light on diets particularly with regard to high proportions of calories hypothesized to be derived from terrestrial plants (Schwarcz et al. 2023). There are significant ethical sensitivities to working with ancestral human remains and any use of these data, even data which have already been collected, should be conducted in an appropriate and respectful manner in collaboration with descendant communities.

Creating a better understanding of the chronology of Barkley Sound would allow for temporally specific estimates of population which could determine the number of people that could have been supported during specific chronological windows. This could be facilitated using a Dates as Data approach (Crema 2022; Edinborough et al. 2017; Rick 1987) in which dated radiocarbon material is treated collectively via summed probability analyses as a proxy for human activity, with the assumption that a greater number of dates indicate more intense human activity during a given period of time. For this analysis to be viable more radiocarbon dates would need to be collected from the study area and significant hypothesis testing and Bayesian modelling would need to be conducted to examine the strength of any patterns (Crema 2022). Alternatively, an accumulation rate-based approach, as employed by Letham et al. (2020), in which the rate of sediment accumulation between radiocarbon date pairs is used as a proxy for occupation intensity could also be employed. If successful this type of analysis would allow for refined estimates of population size at distinct temporal intervals, which in turn might complement knowledge offered by oral histories and human response to ecological change.

This research also has contemporary significance for Indigenous rights and title in Barkley Sound and more broadly elsewhere in Canada. Within the Canadian legal framework, Indigenous rights are based on demonstrated depth and breadth of connectivity to land (Hogg and Welch 2020). Notably, the number and size of reserves were established at a time (ca. 1870-

1890) when Indigenous populations were approaching their lowest point. Under federal government policy and practice modern treaty and land claims as well as what constitutes an aboriginal right is demonstrated based on evidence that they stem from activities practiced pre-contact and that were central to a group's identity and culture (Hogg and Welch 2020). There must also be continuity between the group's current practice and the pre-contact activity on which it is based. Claims to title are based on evidence of continuous occupation and sufficient degree of use by a group. This research demonstrates the significant connectivity to the land and the sea by pre-contact Nuu-chah-nulth populations through the harvesting of hundreds of thousands of kilograms of fish and their deposition into visible monumental features (Letham et al. 2020) which served as tangible outcomes of millennia of harvest effort. The fact that the volume of shell middens in a small archipelago are comparable to the volumes represented in the monumental architecture of Mesoamerica and other world regions is significant. This work also shows that these activities took place for at least three thousand years, which far outstrips the antiquity of any activity by settler communities in the Americas. Thus, the archaeological findings presented here have implications for ongoing treaty negotiations between the Nuu-chah-nulth Tribal Council and the national and provincial governments. In 2011 the Maa-nulth First Nations comprised of the Huu-ay-aht, Toquaht, Uchucklesaht, Ucluelet, and Ka:'yu:'k't'h'/Che:k'tles7et'h' signed a treaty with the governments of Canada and British Columbia, which codified ancestral fishing rights affirmed in the Ahousaht vs Canada court decision (Hogg and Welch 2020; Maa-nulth First Nations et al. 2009; Martindale and Armstrong 2019). I hope that the findings of this dissertation and the work that follows will be able to inform similar policy in the ongoing Nuu-chah-nulth Tribal Council's treaty process.

European contact created an intergenerational extirpation of Indigenous persons from their traditional lands disrupting the practice of traditional lifeways for generations (Harris 2002). This dissertation demonstrates that Barkley Sound was a “filled landscape” teaming with human communities and activity for millennia (Haggarty and Inglis 1985; McMillan 1999:193; McMillan and McKechnie 2015). Creating a better understanding of the geographic and demographic distribution of Indigenous populations helps to deconstruct the legacy of terra nullius (“nobody’s land”) and other historically biased perceptions of Indigenous peoples that continue to have problematic social and legal implications for descendent communities (Asch 2010; Duff 1964; Lutz 2007; Truth and Reconciliation Commission of Canada 2015). Clarifying the size and the extent of Indigenous populations can also help to better explain how these people lived through catastrophic times and responded to the reconfiguration of their population in their own social, political and economic terms (Harris 1997; Wolf 1982). Finally, this work affirms ethnographic and oral histories that suggest the Northwest Coast was a semi-urbanized and thoroughly “peopled” landscape (Martindale et al. 2017).

In conclusion, this research makes several significant contributions to the archaeology of the Northwest Coast providing a better understanding of the geospatial and geometric characteristics of shell midden sites, the scale of harvesting of marine resources, and regionally based estimates of minimum pre-contact Indigenous populations. More broadly this research is engaged with archaeological scholarship concerning subsistence patterns, disease events, marine lifeways, cultural complexity, sedentism, site formation processes, engineered landscapes, historical ecology, and the analysis of large complex shell midden deposits. These are significant findings which have implications for the archaeological practices that stretch beyond the Northwest Coast. I hope that the work presented here inspires other archaeologists to build off this foundation to create midden volume, fishery biomass, and other archaeologically generated population estimates for coastal areas in other parts of the world.

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Appendix A. Supplemental Data

Supplemental data for this dissertation can be found on Borealis the University of Victoria's Dataverse Repository. This is a long-term stable digital storage environment. Use the following URLs to access the project page for each of the three chapters which make up the main portion of this dissertation.

Chapter 2: https://doi.org/10.5683/SP3/NPG6SR

SI2.0: SI0_READ_ME.txt

SI2.1: SI1_PythonCode.py

SI2.1: SI2_Coefficanet_Variation.pdf

SI2.3: SI3_Site_Volumes.tab

Chapter 3: https://doi.org/10.5683/SP3/C11QWV

SI3.0: SI0_READ_ME.txt

SI3.1: SI1_WEIGHTED_BODYMASS.tab

SI3.2: SI2_BIOMASS_CALCULATIONS.tab

SI3.3: SI3_SITE_DATA.tab

SI3.4: SI4_CATCH_COMPARISON_DATA.tab

SI3.5: SI5_BIOMASS_CALCULATION_FORMULAS.pdf

SI3.6: SI6_SENSITIVITY_ANALAYSIS.pdf

Chapter 4: **https://doi.org/10.5683/SP3/DDZFHL**

SI4.0: SI0_READ_ME.txt

SI4.1: SI1_Vital_Statistics.R

SI4.2: SI2_Biometric_Data.tab

SI4.3: SI3_Error_Calculations_V2.R

SI4.4: SI4_Protein_Limits.R

SI4.5: SI5_Radiocarbon_Dates.tab

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