Ancient abundance, distribution, and size of Olympia Oysters (*Ostrea lurida*) in the Salish Sea: a perspective from the Lekwungen village of Kosapsom (DcRu-4), southern Vancouver Island, British Columbia

by

Taylor Mae Vollman
BA (Honours), University of Alaska Fairbanks, 2020

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We acknowledge and respect the Lək̓ʷəŋən (Songhees and Esquimalt) Peoples on whose territory the university stands, and the Lək̓ʷəŋən and W̱SÁNEĆ Peoples whose historical relationships with the land continue to this day.

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Abstract

Olympia oysters (*Ostrea lurida*) are the only oyster species native to the Northwest Coast of North America and are currently a focus of restoration and management following a collapse over the past 150 years. This thesis examines 42 archaeological assemblages containing Olympia oysters in the Salish Sea to better understand Indigenous uses, changes in abundance and distribution between ancient and modern and develops a method to estimate ancient size-at-harvest from partial valves. I observe that Olympia oysters are not a particularly abundant species in archaeological sites when measured by weight and MNI (<15% relative frequency) except in a few sites with high abundance in specific nearshore habitats and locations. Additionally, I examine the size and abundance of Olympia oysters from the Kosapsom Village site (DcRu-4), a site with exceptionally high Olympia oyster frequency (~68 % MNI) located on Southern Vancouver Island in British Columbia in the traditional territories of Esquimalt and Songhees Nations. I compare oyster size ranges from Kosapsom to modern restoration sites and observe that sizes are larger than modern oysters in the same waterway but are similar to a 20+ year restoration site in Fidalgo Bay, Washington. Both abundance and size at Kosapsom increased over 1800 years. I interpret these increased sizes (~14% increase) as reflective of harvesting restrictions and population enhancement strategies, which are consistent with maintaining long-term harvest stability. This research contributes to the growing recognition that archaeological records of traditional Indigenous shellfish use and management hold great potential to expand historical baselines and inform modern coastal restoration and conservation strategies.

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Dedication

For shellfish lovers past, present, and future.

And also, for my family members for whom life restricted a higher education.

Chapter 1 Introduction: Toward a Historical Ecology of Olympia Oysters in the Salish Sea

Shellfish have been harvested on the Northwest Coast since at least the beginning of the Holocene (Cannon et al. 2008; Erlandson 2001; Fedje et al. 2001; Moss 1993). Yet, for many years the importance of shellfish in Northwest Coast archaeology was understudied (Efford 2019; Moss 1993; Wessen 1988). This is in part because of the contradicting and understudied narratives of the importance of shellfish to Indigenous peoples, ranging from feast foods to dietary staples to foods only eaten during times of food stress (Butler and Campbell 2004; Efford 2019; Erlandson 1988; Erlandson 2001; Moss 1993). Shellfish studies on the Northwest Coast often focus on the importance of clams (e.g., Burchell et al. 2013; Cannon et al. 2008; Keen 1978; Moss 1993; Wessen 1988) with few exceptions (Croes 2015; Efford 2019; Moss and Erlandson 2010). While clams are undoubtedly important for Indigenous people on the Northwest Coast, the dominance of clams in archaeological shellfish research in the area likely reflects their commonality in the environment and accordingly in archaeological assemblages (Butler and Campbell 2004).

The Olympia oyster (*Ostrea lurida* Carpenter 1864) is an example of an understudied species encountered in archaeological sites on the Northwest Coast. Globally, zooarchaeological data has been used to illuminate oyster use in the past as well as changes in habitat and population, (Kirby 2004; Reeder-Myers et al. 2022; Rick et al. 2016; Tabarev 2007; Thompson et al. 2020; Winder 2017; zu Ermgassen et al. 2020), but studies utilizing oysters from archaeological sites to understand population and habitat changes before European colonization

remain rare on the Northwest Coast with a couple of recent exceptions (Hatch and Wyllie-Echeverria 2016; Reeder-Myers et al. 2022). However, while these papers are useful in understanding the scale of loss of oyster beds both globally (Reeder-Myers et al. 2022) and regionally (Hatch and Wyllie-Echeverria 2016) to guide restoration, other metrics for measuring changes to oyster populations (e.g. shell size), have not been utilized on the Northwest Coast, although this research is ongoing elsewhere (Rick et al. 2016; Thompson et al. 2020; Winder 2017). Determining shell size from archaeological sites is a crucial aspect of understanding Indigenous harvesting profiles and biological parameters of the population. This thesis explores the archaeological importance of Olympia oysters in the Salish Sea through the case study of a site with an exceptionally high abundance of Olympia oysters. By examining both traditional archaeological measures of abundance (dry shell weight & Minimum Number of Individuals) and morphometric size estimates, this thesis contributes to the growing literature on broadening perspectives on Indigenous foodways, environmental change, food security, and restoration potential.

Background

Ecology and Biology

Like all bivalve mollusks, oysters are marine calcifiers, creating their shells by taking carbonate ions and bicarbonate out of the water and creating calcium carbonate (Gibson 2015). As suspension feeders, oysters consume phytoplankton and suspended organic matter (Department of Fisheries and Oceans Canada 2009; Gillespie 2009), enhancing water quality and promoting primary productivity (Gibson 2015). Olympia oysters can filter water at optimum temperatures at a rate of 3.08 litres per hour per gram of dry tissue weight (zu Ermgassen et al.

2013) which can help to reduce eutrophication. Eutrophication is the process of excessive nutrients, sediments, and toxins accumulating within the water column, leading to increased phytoplankton growth and hypoxia from the decay of organic material (Gibson 2015).

Olympia oysters (*Ostrea lurida* Carpenter 1864) historically range from southeast Alaska to Baja California (Committee on the Status of Endangered Wildlife in Canada (COSEWIC) 2011; Dinnel et al. 2011), although there is some debate whether their range extends that far north (Department of Fisheries and Oceans Canada 2009; Gillespie 2009). The northern limit is based on Dall (1914), although Galtsoff (1929) places it off northeastern Vancouver Island and recent investigations have not yielded any occurrences in southeast Alaska (Department of Fisheries and Oceans Canada 2009; Gillespie 2009). Olympia oysters are nearing the northern range of their habitat in the Salish Sea where the season of reproduction only lasts three months compared to seven months in southern California (Department of Fisheries and Oceans Canada 2009). Olympia oysters require water temperatures of at least 12.5°C for successful reproduction with temperatures between 14-16°C being optimal (Department of Fisheries and Oceans Canada 2009; Gillespie 2009). These temperature thresholds limit Olympia oyster spawning in northern latitudes to once or twice yearly in mid-summer, often restricting Olympia oysters to warmer shallow bays (Department of Fisheries and Oceans Canada 2009; Lawlor and Arellano 2020).

The preferred habitat of Olympia oysters is the intertidal to less than 10 meters deep, but sometimes occur up to 50 meters deep (Gillespie 2009). Olympia oysters are most common in estuaries and saltwater lagoons but can also be found in tide pools, tidal channels, sounds, and bays, attached to pilings and floats, as well as on mud-gravel tidal flats (Committee on the Status of Endangered Wildlife in Canada (COSEWIC) 2011; Gillespie 2009; Norgard et al. 2010). In the Salish Sea, Olympia oysters are small compared to introduced Pacific oysters (*Crassostrea*

gigas) (aka. Japanese oysters), typically only growing to 60 mm or smaller; however, sizes up to 90 mm have been recorded (Dinnel et al. 2011; Gillespie 2009). Olympia oysters can live at least 10 years, although their maximum age is unknown (Gillespie 2009).

Globally, oyster species are often considered ecosystem engineers, wherein populations create their own physical habitat (through generations of deposition of shell), and this becomes habitat for a host of other aquatic species (Tolley and Volety 2005); however, to my knowledge, no study has specifically been conducted with Olympia oysters. There is divergent evidence as to whether Olympia oysters formed "oyster beds" (c.f. Blake and Bradbury 2012; Blake and zu Ermgassen 2015; Dinnel et al. 2011). As Olympia oyster larvae preferentially grow on other oyster shells (Department of Fisheries and Oceans Canada 2009; Dinnel et al. 2011), is it possible that reefs were formed, but this may also be a result of a lack of clear definitions of what constitutes an "oyster bed," lack of understanding of pre-European Olympia oyster distribution, or transposing expectations of what an "oyster bed" should be from other locations. In areas especially conducive for Olympia oyster growth, reefs may have been formed, especially in subtidal areas, but were later destroyed by dredging following European colonization and Olympia oyster overharvesting. Examination of archaeological oyster shells may be able to answer whether Olympia oysters formed dense "oyster beds."

Historic Information

Past oyster abundance and collapse of multiple oyster species (e.g. *Crassostrea virginica*, *Saccostrea glomerata*, and *Ostrea lurida*) following European colonization is understood by examining oyster fishery records. Kirby (2004) examined historic oyster populations in 28 estuaries in North America and Australia, including the Pacific Northwest, using four proxies to

determine the timing of degradation 1) the first laws regulating oyster fisheries in each estuary, 2) the beginning of juvenile and adult oyster importation to restock estuaries, 3) the total weight of oyster catches per year, and 4) the earliest evidence of bottom dredging. Using colonial urban centers as a starting point, Kirby (2004) identified how the degradation of oyster reefs in seemingly unrelated estuaries occurred over centuries of exploitation and is one of few studies to incorporate Olympia oysters in a comparative perspective. On the west coast of North America, Olympia oysters began to be overharvested after the start of the San Francisco gold rush in 1849. As Olympia oysters in the San Francisco Bay were quickly depleted in the 1850s, Olympia oysters from farther and farther up the coast were imported, including from Puget Sound in the Salish Sea, where annual production ranged between roughly 20,000 and 225,000 bushels between 1896 and 1926 (Galtsoff 1929:Table 4). After the completion of the US transcontinental railway in 1869, imported eastern *C. virginica* were farmed and became the preferred oyster in San Francisco (Kirby 2004). However, both species continued to be harvested at least until 1920, when intertidal Olympia oysters in Washington were depleted and Pacific oysters (*C. gigas*) became the more viable commercial oyster option (Blake and Bradbury 2012). The interrelatedness of Olympia oyster exploitation and reef degradation across multiple locations is critical in understanding how the widespread population crash of Olympia oysters occurred.

Pollution, including industrialization, antifouling, and forestry and timber operations, has also been observed to have negative effects on Olympia oyster populations (Department of Fisheries and Oceans Canada 2009). Additionally, the start-up of pulp and paper mills affected local oyster populations in the Salish Sea (Dinnel et al. 2011). In southern Puget Sound effluent from a mid-20th century pulp mill in Shelton, Washington was viewed by growers as the main cause for Olympia oyster decline (Steele 1957:97). The Shelton pulp mill released sulphite waste

directly into the water between 1927 and 1957, where Olympia oyster mortalities occurred, perhaps due to increased blooms of algae and siltation, which could smother oyster beds (Blake and Bradbury 2012).

Research Questions and Research Aspirations

Within the Salish Sea, Olympia oyster restoration projects are ongoing and gaining momentum; however, thus far, there has been less effort in incorporating archaeological and zooarchaeological data to aid restoration goals. Through interdisciplinary research, joining ecology and archaeology, zooarchaeological data offers the opportunity to examine past Olympia oyster locations, population stability, and size before European colonization and overharvesting. To date, efforts towards compiling such information from Indigenous archaeological sites have been limited (e.g., Butler and Campbell 2004; Hanson 1991; Hatch and Wyllie-Echeverria 2016).

In this thesis, I consider archaeological and historical data to confront the 'shifting baseline syndrome,' which refers to how management decisions are often based on limited baselines established from already degraded ecosystems (Kirby 2004; Pauly 1995). Archaeological information spans a much longer time scale and is helpful in reconsidering modern management goals and the response of species to climate change and human harvesting. Current management decisions are based on data from the past 200 years, a time when Olympia oyster fisheries were collapsing (Kirby 2004). Archaeological data provides an opportunity to understand preindustrial Olympia oyster distribution and size prior to the 1800s (Kirby 2004). Olympia oysters have not recovered and remain in small, intermittently assessed, isolated populations throughout the Pacific Northwest (Blake and Bradbury 2012; Department of Fisheries and Oceans Canada 2009). By examining Olympia oyster shells from archaeological

sites in the Salish Sea and focusing in particular on the site of Kosapsom this research contributes an archaeological baseline for past Olympia oyster abundance and size. These data can then be compared to modern Olympia oyster populations to better understand Olympia oyster ecology and the cultural history of Coast Salish peoples' use of this valued intertidal food.

Olympia oysters also offer the opportunity to examine how the diverse environments of the Northwest Coast can influence and enhance the social relationships of Indigenous communities. As discussed by Suttles (1987), Coast Salish practices of marriage and family connections established trust and care between households and villages, enabled access to rarer resources, and assisted in times of scarcity. Butler and Campbell (2004) found that at most archaeological sites, Olympia oysters in the Pacific Northwest are found in low frequencies compared to other shellfish. The rarity of Olympia oysters allows for the ability to examine ancient Indigenous oyster harvesting and management strategies.

In this thesis, the primary motivating research questions are:

1. *How does archaeological Olympia oyster abundance vary in the Salish Sea and compare with modern Olympia oysters in the Pacific Northwest?*
2. *How does the size distribution of Olympia oysters at Kosapsom compare to modern size distributions in the Salish Sea?*
3. *What do oyster abundance and size distributions at Kosapsom indicate about Indigenous harvesting practices and cultivation techniques?*

This introductory chapter introduces this thesis research and describes its contribution to Northwest Coast archaeology and Olympia oyster restoration. I demonstrate how Olympia oysters from archaeological sites and shellfish, in general, are worth closer examination to

increase our understanding of ancient Indigenous shellfish harvesting and management and environmental changes.

To address the first research question, I compare the geographic distribution and relative abundance of the occurrence of Olympia oysters from archaeological sites in Chapter 2, including ethnographic accounts and modern Olympia oyster locations in the Salish Sea. I discuss archaeological methods for measuring the relative abundance of shellfish species and compare the relative abundance of Olympia oysters across sites. The distributions of modern and archaeological Olympia oyster locations are compared to address Indigenous Olympia oyster harvesting and management practices.

In Chapter 3, I develop a regression-based method for estimating past Olympia oyster shell size using modern cultivated Olympia oysters of various sizes. As archaeological shellfish assemblages are often highly fragmented, I developed a method for quantifying oyster sizes and harvesting profiles. Applying this method to a sample of oysters recovered from the Kosapsom Village archaeological site (DcRu-4), I consider Lekwungen oyster management and cultivation practices by examining Olympia oyster size over time. Understanding past Olympia oyster size prior to European colonization is an additional step to informing contemporary restoration efforts that often do not engage with archaeological data and ethnographic information. The method I present in Chapter 3 estimates size from fragmentary Olympia oyster remains in the Salish Sea and enables a better understanding of how Olympia oyster size has changed throughout time. This allows for the opportunity to compare sizes within an individual archaeological site and to modern restoration sites in the region.

Theoretical Frameworks

In this thesis, I draw on two domains of theory in anthropology and ecology to develop and shape my research objectives and interpretations. I explore these further in the sections below, followed by a summary of how these research objectives are addressed in the concluding chapter.

Historical Ecology

Historical ecology can be a valuable framework for exploring human-environment interactions. Balée (1998:14) posits that "Historical ecology focuses on the interpenetrations on culture and the environment, rather than on the adaptation *of* human beings *to* the environment" (original emphasis). Trying to understand the type and timing of these interpenetrations is especially important in modern species management, where many researchers take for granted the 'natural environment' without necessarily recognizing the enduring history of Indigenous peoples shaping aspects of those environments (Armstrong et al. 2022; Bliege Bird and Nimmo 2018; Rick 2023). One example of this on the Northwest Coast is clam gardens which is where rock walls were built at the low-low tide mark, trapping sediment and increasing the zones of ideal clam growing habitat (Lepofsky et al. 2015). Indigenous peoples shaped and tended to these habitats as indicated by studies on northern Quadra Island which demonstrate increased growth rates (size-at-age) for butter clam (*Saxidomus gigantea*) (Toniello et al. 2019). These built rock wall structures represent one of the active roles Indigenous peoples on the Northwest have taken in shaping and adapting to the local environment and occur as far north as southeast Alaska (Moss and Wellman 2017).

Another aspect of historical ecology is in utilizing archaeological and historical data, which helps confront the 'shifting baseline syndrome' which has arisen in Pauly's (1995:430)

words, “because each generation of fisheries scientists accepts as a baseline the stock size and species composition that occurred at the beginning of their careers, and uses it to evaluate changes.” Longer-term baselines are helpful in expanding perspective and revaluating modern management goals to shed light on species responses to climate change and human harvesting (Alleway et al. 2023). Globally, historical, archaeological, and palaeoecological data suggest centuries of overfishing have “fundamentally altered coastal marine ecosystems” (Jackson et al. 2001:636). However, the time lag between fishing down the food web and ecosystem collapse can be long enough that restoration guidelines do not encompass larger species that play key ecological roles in ecosystems because their former abundance is so diminished (Jackson 2001; Jackson et al. 2001). Understanding how the ecosystems have been altered would not have been possible without archaeological and/or palaeoecological data. Archaeological data especially illustrates the connections between people and the environment because archaeological data directly results from past human actions and reflects how people are embedded within the ecosystem (Rick 2023).

In the case of Olympia oysters, the “forgotten” Indigenous oyster fisheries are represented mainly by archaeological data and provide the opportunity to understand abundance and size prior to overharvesting by European colonial settlers beginning in the mid-1800s (Kirby 2004). Olympia oysters have not recovered and remain in reduced populations throughout the Pacific Northwest. In this thesis, I examine the distribution and abundance of archaeological oysters in the Salish Sea, develop a method to estimate the size of fragmentary Olympia oysters and apply this method to generate size distributions from the Kosapsom Village site in the Gorge Waterway on southern Vancouver Island. This combination of approaches provides an opportunity to consider the distribution of Olympia oysters before historic removals and can be

compared with modern data from recent conservation efforts to help inform ongoing restoration efforts and community knowledge of this unique oyster species.

Variability in Northwest Coast Resource Abundance and Coast Salish Social Relationships

As influentially discussed by Suttles ([1962]1987:32), the Salish Sea is "characterized by a variety of types of natural resources, local diversity and seasonal variation in their occurrence, and year-to-year fluctuation in their abundance." While this suggests that environmental variation guides human choices, insights from historical ecology also reveal that humans can alter (as well as be altered by) their environments, acting to create 'built' environments (Balée 2006). In Chapter 2, I explore how the spatial concentration of archaeological sites with Olympia oysters and modern or historic oyster bed locations might also influence and be influenced by longer-term oyster harvesting along with environmental variability in the Salish Sea. Shellfish assemblages from archaeological sites can be a signal of preferential human use of local habitats (Moss 2012), and proximity to resource locations can be used as a proxy for communal ownership and proprietorship (Lepofsky et al. 2007; Letham et al. 2020), which suggests that variability in shellfish assemblages may relate to harvesting rights and restrictions. In Chapter 2 of this thesis, I explore variability in Olympia oyster harvesting and how community use rights likely were restricted to groups who held rights to harvest in those spaces.

Coast Salish people are known to be proprietors of coastal habitats traditionally, with many individual families maintaining control over specific harvesting areas (Hatch and Wyllie-Echeverria 2016; Lepofsky et al. 2015; Lepofsky et al. 2007; Suttles 1987:20; Trosper 2002), likely relating to increased investment and control over an area (Grier 2014) and for the ability to access a variety of resources to enable resiliency (Trosper 2002). In Chapter 3 of this thesis, I

explore how examining oyster size may reveal how community members occupying a long-term settlement (i.e., an archaeological site) near oyster beds may have maintained proprietorship of the beds. In Chapter 2, I consider the location of sites with oysters particularly whether sites with low and high abundances of Olympia oysters are further away or close to known oyster beds as this may indicate ties through kinship and/or the proprietors of the beds (Elmendorf 1960; Lepofsky et al. 2015; Suttles [1951]1974). I further explore how these data relate to other ethnographic evidence from Coast Salish and other Indigenous groups on the Northwest Coast, indicating how productive habitats and resource-gathering areas may indicate management by families who controlled harvesting access (Lepofsky et al. 2015; Moss 1993; Suttles 1987, [1951]1974).

In the concluding chapter, I review how the results from this research address the research questions above and identify further research possibilities. I also consider how this research contributes to Northwest Coast and Coast Salish archaeology and can help inform restoration and management in the Salish Sea, specifically regarding Indigenous harvesting and climate change.

Chapter 2 Comparing Contemporary, Historic, & Ancient Oysters in the Salish Sea

Introduction

This chapter uses archaeological, ethnographic, historic, and modern location data to explore the distribution and abundance of Olympia oysters in the Salish Sea. I explore Indigenous relationships with Olympia oysters by comparing these different types of sources. I begin by summarizing a survey of ethnographic sources relating to Coast Salish shellfish harvesting, resource management and cultivation. I also introduce previous studies that have examined Olympia oyster occurrence archaeologically, historically, and currently. In this chapter, I explore where within the Salish Sea Olympia oysters occur within archaeological sites and how this compares to more recent distributions. I also examine which archaeological sites have a high relative abundance of Olympia oysters and what this tells us about past Indigenous foodways. Additionally, I compile previously collected ecosystem data to explore the habitat surrounding archaeological sites with Olympia oysters. I also compare archaeological Olympia oysters' locations to restoration sites in the Salish Sea to discuss how archaeological site location and abundance data can and should inform restoration efforts. Archaeological data can explore this "forgotten" fishery to improve our understanding of past Indigenous Olympia oyster harvesting.

Ethnographic Information

Coast Salish peoples have shared a considerable amount of knowledge with anthropologists during ethnographic research. While bivalve shellfish are regularly mentioned; in

the sources I reviewed, Olympia oysters are rarely explicitly discussed (e.g., Elmendorf 1960; Elmendorf 1993; Haeberlin and Gunther 1930; Suttles [1951]1974; Suttles and Lane 1990) despite their presence in archaeological sites suggesting that they were harvested, and sometimes frequently (Smith 1907:355). However, this does not mean that Indigenous knowledge of Olympia oysters does not exist or that Olympia oysters are not a culturally important food. Rather, this indicates that Olympia oysters, and shellfish in general, have not been a focus of ethnographic research and documentation. This may relate to shellfish gathering being primarily done by women and ethnographies written by men (Daniels 2009; Lepofsky et al. 2015; Moss 1993; Moss 2013; Suttles [1951]1974). Ethnographic accounts of other bivalves, such as clams, may be able to provide information about the social context of shellfish use that can be inferred for Olympia oysters.

When Olympia oysters are mentioned in Coast Salish ethnography, little context or specificity is given except for general harvesting location maps from Suttles ([1951]1974). Suttles ([1951]1974:65) discusses how "mussels and oysters often had to be pried up." Oyster harvesting is also explained by Suttles and Lane (1990:489), who describe how "Cockles, mussels, and oysters are surface dwellers and were simply gathered." In discussing Salish peoples in Puget Sound, Haeberlin and Gunther (1930:21) remark "several kinds of shellfish were used such as: clams, oysters, barnacles and crabs." Suttles ([1951]1974:65-66) also mentions, "butter clams (and oysters?) were usually, if not always, steamed." Steaming as the preferred cooking method of oysters is corroborated by another source (Elmendorf 1960:124). While I only encountered one ethnographic account specifically about smoking oysters for storage (Haeberlin and Gunther 1930:24), clams were dried, smoked, or barbecued for storage through the winter (Elmendorf 1960:123-124; Haeberlin and Gunther 1930:24; Kennedy and

Bouchard 1990:445; Suttles 1990:459; [1951]1974:66; Suttles and Lane 1990:489) and can offer insight into how bivalves in general were prepared by Coast Salish peoples.

Indigenous peoples on the Northwest Coast are known to practice forms of cultivation and traditional resource management (Mathews and Turner 2017). For instance, clam gardens have been observed in many regions of the Northwest Coast and expand and enhance clam habitat and clam growth rates (Groesbeck et al. 2014; Lepofsky and Caldwell 2013; Lepofsky et al. 2015; Toniello et al. 2019). These intertidal rock features are created by placing cobbles parallel to the shoreline to form an intertidal wall. The lack of large cobbles in the digging area and the finer gravels and sediment trapped behind the wall improve clam growth and dramatically increase the area where clams grow. The regular digging for clams also loosens the sediment providing ideal conditions for clam growth (Groesbeck et al. 2014; Lepofsky and Caldwell 2013; Lepofsky et al. 2015; Toniello et al. 2019).

Similar forms of management are present in the ethnographic and archaeological record for fish and plants on the Northwest Coast (Lepofsky and Caldwell 2013; Lepofsky and Lertzman 2008; Thornton 2015; Thornton et al. 2015). The presence of these other forms of resource management in the region suggests that Olympia oysters could have been actively managed and cultivated but in different ways than clam gardens. By cultivation, I am adopting the definition of cultivation discussed by Deur and Turner (2005:15) defined as the "repeated and intentional manipulation of both plants *and* their environments as a means toward plant resource enhancement" (original emphasis). The sessile nature of these bivalves suggests that definitions of plant cultivation can be applied.

Ethnographic accounts describe how Central Coast Salish groups were proprietors of different resource-harvesting locations. For instance, productive clam harvesting locations were

controlled by different families (Grier and Angelbeck 2017; Lepofsky et al. 2015; Moss 1993; Suttles 1987, [1951]1974; Trosper 2002). Long-term proprietorship "was contingent on proper management of territory" (Trosper 2009:14). In this way, proprietors are managers, with the added idea that they preside over a defined location. Given that Olympia oyster beds are readily observable and spatially concentrated in the intertidal zone, particular beds were also likely maintained like other resource harvesting locations, especially in locations adjacent to large persistently occupied village sites with shell midden deposits containing high oyster abundance. As I review in this chapter, archaeological sites with unusually high relative frequencies of Olympia oysters are relatively rare and, in the sections, below I consider the potential for ancestral management strategies to make Olympia oysters a sustainable and valued food source.

Archaeological, Historic, and Modern Data on Oysters

Historic and modern distributions of oysters on the west coast of North America have been recently published by Kornbluth et al. (2022). This team compiled oyster records from published and unpublished ethnohistoric records from the years 1792-2020 to examine historical changes in distribution. Kornbluth et al. (2022) estimate that Olympia oyster abundance declined in 82% of estuaries by comparing their pre-2000 and post-2000 historic abundance data. Since they do not include archaeological data, this may still be an underestimate but is in line with other research (Blake and zu Ermgassen 2015; Kirby 2004). Here I build on this to consider the past distribution and abundance of Olympia oysters in the Salish Sea using additional archaeological and ethnographic records.

While Olympia oysters have been identified and sometimes quantified at archaeological sites in the Salish Sea, few studies have utilized the archaeological data to look at a more

regional view (Butler and Campbell 2004; Hanson 1991; Hatch and Wyllie-Echeverria 2016). One of the few studies of Olympia oysters that have made use of archaeological data is Hatch and Wyllie-Echeverria (2016) who examined eight archaeological and two ethnographic reports, and early maps and journals from European settlers to evaluate the spatial and temporal distributions of Olympia oysters in the San Juan Archipelago. Eighteen oyster beds were identified from deposits dating as early as 6,000 BP. These data can be used to guide restoration projects and the longevity of harvesting points to the stewardship of Coast Salish peoples.

Butler and Campbell (2004) explore zooarchaeological assemblages from archaeological sites in the Pacific Northwest to determine if the common argument that certain resources were used more intensively over time is supported. By mostly examining sites with fine screen bone and shell assemblages, the authors compared sites over time throughout the region. They examined quantified mammals, fish, birds, and invertebrates from 22 sites on the Northwest Coast and 51 sites in the Northern Plateau. Olympia oysters were present in 10 of the 22 coastal assemblages but were never ranked first in abundance within an assemblage. Olympia oyster was ranked 9th among the ten most abundant shellfish taxa throughout the region. This suggests they do not occur as often as other shellfish families (e.g., Veneridae, Mytilidae, Cirripedia). Overall, the study found that the archaeological faunal data shows no evidence of resource depression or intensification over time.

Zooarchaeological Measures of abundance by weight and Minimum Number of Individuals

Estimating the proportional abundance of different species within an archaeological site can help determine contributions to diet and comparisons between sites. However, in many cases, shellfish taxa observed during archaeological excavation were compiled into basic species

lists (Hanson 1991; Lyman 2015; Mitchell and Donald 1988). It was not until the 1970s that shell analysis and quantification became a more established feature of coastal excavation. Due to their overwhelming abundance, small volume, controlled excavations (column samples, augers, systematic unit sampling, etc.) are commonly utilized to produce relative abundance data for shellfish in sites on the Northwest Coast (Cannon et al. 2008), although systematic quantification is still rare. These infrequently generated data make it harder to conduct inter-site comparisons of relative abundance (Hanson 1991), yet much information has been generated in consulting reports and various research projects. Despite the difficulties of quantification and taxonomic specificity, regional comparisons are still worthy of analysis.

The benefit of using proportional weight to quantify the relative abundance of shellfish in archaeological sites is that it considers all taxonomically identifiable shell fragments (Glassow 2000). This is helpful for species like Olympia oysters whose shells are relatively fragile and may differentially fragment relative to other shellfish. However, proportional weights are also problematic as smaller or lighter weight shellfish species are less influential than heavier and larger taxa as a percentage of the total weight of shell, inflating their importance in diet (Mason et al. 1998). Olympia oysters' shells are smaller, thinner, more fragile, and weigh less compared to most clam species which tend to have thicker and heavier shells. These taphonomic factors may lessen the contribution of oysters to total shell weight and as a portion of diet.

The benefit of using MNI or Non-Repeating Elements (NRE) counts is that smaller, lighter shellfish species are counted on an equal basis with heavier larger species (Giovas 2009). The aggregation issues with MNI that are problematic for vertebrate faunal (Lyman 2008:45-46) assemblages do not apply to invertebrates because usually MNI calculations for invertebrates are based on NREs, such as hinges in the case of Olympia oysters (Giovas 2009; Mason et al. 1998).

However, utilizing MNI can lead to an overinflation in the importance of abundant but small shellfish species to diet and are similarly biased by taphonomic factors such as differential fragmentation and morphological identifiability (Glassow 2000).

Methods

Archaeological and Ethnographic Locations of Olympia Oysters

In 2021, Iain McKechnie, Marco Hatch, and I compiled existing archaeological oyster data[1] on 42 archaeological sites in the Salish Sea as part of a larger project to explore "forgotten" Indigenous oyster fisheries in colonial contexts (Reeder-Myers et al. 2022). While not an exhaustive and comprehensive search, we sought out sites with examined shellfish assemblages across a wide range of sites in Puget Sound in Washington and southern British Columbia, including the mainland, Gulf Islands, and eastern Vancouver Island. For sites containing Olympia oysters, we documented Minimum Number of Individuals or percent by weight when reported or simple occurrence data when they were not. We additionally used ethnographic information from Northern Puget Sound to identify 10 Olympia oyster bed locations in the Salish Sea. These ethnographic locations were originally compiled for Hatch and Wyllie-Echeverria (2016) and are not a comprehensive effort to compile ethnographic locations for the entire Salish Sea. Reeder-Myers et al. (2022) combined these data with archaeological information from Eastern North America, California, and Eastern Australia to demonstrate a large-scale loss of oysters globally as well as the long-term sustainability of oyster harvesting practiced by

[1] It should also be acknowledged that Jingle Shells (*Pododesmus macrochisma*) are also called "rock oysters" which could lead to some confusion if it is only referred to as oysters; however, for archaeological sites *Ostrea lurida* or native oyster are usually specified.

Indigenous peoples in these places prior to European colonization, overexploitation, and habitat destruction.

In following up on this work, I chose to further examine data in the Salish Sea region on the Northwest Coast, expanding on the data reported in Reeder-Myers et al. (2022). I broadly estimated site locations and created maps in QGIS illustrating sites with only occurrence data reported and sites with quantitative data enabling comparisons of relative frequency by taxon. Accordingly, this chapter presents expanded and revised data from what was previously presented in Reeder-Myers with a focus on a more detailed summary of both proportional weights and MNI counts for Olympia oysters. Occurrence data is used to represent Olympia oysters in the site that were only identified as present in an archaeological context. The locations of archaeological sites with Olympia oysters predominantly date to within the late Holocene (ca. < 2500 cal yr BP) and are examined by relative frequency to enable an exploration of ancient Indigenous foodways in the Salish Sea.

Additionally, to better understand the range of coastal ecosystems in which these sites occur, I examined two established variables: wave exposure and proximity to small 'pocket estuaries' around archaeological sites with Olympia oysters. I gathered wave exposure data and the distance of a pocket estuary or lagoon from the archaeological sites using ShoreZone compiled for both British Columbia (Government of British Columbia 2023; SeaChange Marine Conservation Society 2023) and Washington State (Washington State Department of Natural Resources 2001a). If the closest shoreline to a site was equidistant to two different exposure categories, the more exposed option was chosen. Distance from pocket estuaries was defined by comparing the location of known pocket estuaries or lagoons reported by Cereghino (2020) and Washington State Department of Natural Resources (2001b) for sites located in Washington

State and Government of British Columbia (2023) for sites located in British Columbia and measuring the linear distance in Google Earth Pro.

Historic and Modern Locations

To compare the modern abundance and location of oysters with archaeological sites in the Salish Sea, I utilized location and abundance data compiled by Kornbluth et al. (2022 supplementary material) which includes historic and modern observations of Olympia oyster abundance from 1792 to 2020[2], excluding archaeological and paleontological records. Kornbluth et al.'s observations came from peer-reviewed and grey literature sources, including local experts, and iNaturalist records verified by trained interns including a photo that could be positively identified as alive. These records are a useful comparison for archaeological Olympia oyster locations by providing more recent distribution information.

To compare oyster occurrences over time within the Salish Sea, I placed data in different time periods, with the caveat that some of the observations are based on the year that the source was published and may reflect an earlier distribution. The first period (1792-1900) contains 59 occurrence observations and makes the qualified assumption that sources[3] prior to 1900 most closely approximate their distribution before European colonization, although by the late 1800s Olympia oysters in the Salish Sea were already in decline (Kirby 2004). The second period (1900-1950), with 32 occurrence observations, likely reflects when Olympia oyster populations were collapsing (Blake and zu Ermgassen 2015; Kirby 2004). The third period (1950-1999) has 67 occurrence observations and likely represents when Olympia oyster populations in the Salish Sea were severely degraded and before restoration efforts were gaining traction (Blake and

[2] With the majority of the records from after 2000.
[3] Does not include archaeological or paleontological sources.

Bradbury 2012; Gillespie 2009). The most recent period (2000-2020) contains 234 occurrence observations and reflects a renewed interest in surveying, restoring, and protecting Olympia oysters in British Columbia and Washington. The increase in total observations after the year 2000 reflects greater search effort (Kornbluth et al. 2022:13).

These historic datasets were mapped using QGIS (Figure 1) along with ethnographic and archaeological locations (Figure 2). I compared archaeological frequency using either %MNI or %Weight with a categorical cut-off of 15% for sites to be deemed 'high frequency' versus 'low frequency.' This figure was chosen based on a gap between sites with 15% or lower and sites with 50% or higher. Sites with no relative frequency were represented as Olympia oysters present.

Additionally, I mapped the locations of Olympia oyster restoration locations (Figure 4). Many restoration site locations in Washington were obtained from McKenna (2022) and others in both Washington and British Columbia came from the Native Olympia Oyster Collaborative (NOOC) (2018). These data are rendered as points on a map and may not fully illustrate the total area that is being restored.

Results

There are a total of 392 historic and modern observations for Olympia oysters adapted from Kornbluth et al. (2022) encompassing 228 years (AD 1792-2020) broken up into four time periods (Figure 1). In Period 1 (AD 1792-1900), Olympia oysters were observed only as present in 9 locations and common in 49 (84% of 58 total) locations in the Salish Sea. In Period 2 (1900-1949), Olympia oyster abundance was less frequent, with fewer total observed locations (31) and fewer locations being judged as locations where Olympia oysters commonly occur (18 or 58%).

Period 3 (1950-1999) Olympia oysters were observed even less with 29 total locations observed and 21 locations (72%) where they are reported as commonly occurring. In Period 4 (2000-2020), Olympia oysters were observed in 164 total locations and were identified as common in 51% (83) of them. The increase in total observation is likely due to increased monitoring and surveying as restoration efforts have gained momentum. Relative to the number of observations of Olympia oyster occurrences during each timer period, locations where Olympia oysters are commonly occurring have decreased after 1900.

The historical and modern locations of Olympia oysters provided by Kornbluth et al. (2022) broadly correspond with locations that have ethnographic and archaeological evidence with a few notable exceptions (Figure 1; Figure 2). In the San Juan Islands and Burrard Inlet, archaeological sites with oysters are present but few or no historical or modern observations exist. Conversely, there are many locations where Olympia oysters have been observed without known archaeological sites (Figure 1; Figure 2).

Of the 42 archaeological sites with Olympia oysters, 17 sites or 40% of the 42 archaeological sites have relative frequency reported (Figure 2; Figure 3). Relative frequency data is reported throughout the Salish Sea, although is not as well represented in assemblages recovered from the US Gulf Islands (Figure 2). However, not all reports are clear if these frequencies are relative to bivalves or all shellfish (e.g., including barnacles and univalves) in the assemblage. This may result in underreporting of oysters within certain sites if they are reported as a percent of all shellfish or inflation of relative importance for sites with a percent bivalve reported. Despite this, it seems unlikely that sites would change between being classified as high or low relative frequency due to the large differences in relative frequency between sites with high relative frequency (>15% MNI or weight) and low relative frequency. With this in mind,

the average percent weight for Olympia oysters of the 13 sites with weight reported is 7.7% (with a standard deviation of ±18.2%). In contrast, of the 7 sites with percent MNI reported, the average percent MNI is 36.9% (with a standard deviation of ±34.8%). This is much larger than the percent weight and likely reflects that all four sites with high relative frequency report MNI. When the four sites with high %MNI are excluded, the average is only about 1%. The variability in relative frequencies is likely influenced by variability in the habitat types of sites in this sample with all sites with high relative frequencies located in very protected or protected areas (Figure 5).

At the 42 archaeological sites with Olympia oysters, most are located on protected shorelines (Figure 5). All sites with high relative frequencies of Olympia oysters (more than 15%) are in very protected or protected areas. Additionally, only six of the 42 sites are located more than 2 kilometres from a pocket estuary or lagoon. For all relative frequencies, the most frequently occurring distance from a pocket estuary or lagoon is less than 500 m (Figure 6). For sites with high relative frequencies of Olympia oysters, all are located within 1000 m of at least one pocket estuary or lagoon.

Olympia oyster abundance values are highest in four sites where this species represents over 15% by either MNI or weight-based abundance (Figure 3; Table 1). Notably, each of these sites are in areas where Olympia oysters were also formerly abundant prior to 1900 (Figure 1) and where oysters occur today (Figure 4). The archaeological site of Kosapsom (DcRu-4), located in Lekwungen (Esquimalt and Songhees) territories on Southern Vancouver Island, is unique because of its high abundance of Olympia oysters as indicated by both MNI and weight (Figure 3; Table 1). At the site of Seal Rock (45-JE-15**)**, located in Skokomish territories along Hood Canal in Washington, Olympia oysters are still present in high densities (Figure 1). The

site in Sinclair Inlet (45-KP-109) in Suquamish territory in Central Puget Sound contains high frequencies of Olympia oysters by MNI and somewhat lower frequencies by weight (Table 1). Olympia oyster densities are high in Central Puget Sound in historic and modern observations, especially in the time periods 1792-1900 and 2000-2020 (Figure 1). At Qwu?gwes (45-TN-240), located in Squaxin territory in Southern Puget Sound, Olympia oysters total 73.5% MNI and occur abundantly throughout the occupation of the site (Allyn 2013 in Croes et al. 2013). High densities of Olympia oysters are reported for this area throughout the historic era (Figure 1). Notably, high Olympia oyster frequency, especially in MNI, does not necessarily indicate that oysters were a larger portion of the diet. For instance, at Qwu?gwes, the %MNI for Olympia oysters is 73.5%, but the %Total Meat Weight is just under 10% of bivalves (Croes et al. 2013:184). In contrast, butter and horse clams at Qwu?gwes total 18% and <1% of the MNI, but 55% and 32% of the total meat weight, respectively. More detailed analyses of butter clams from the site suggest active management practices were in place to ensure continuity of harvesting (Allyn 2013 in Croes et al. 2013); a practice that may have also occurred with other shellfish species at the site, such as Olympia oysters.

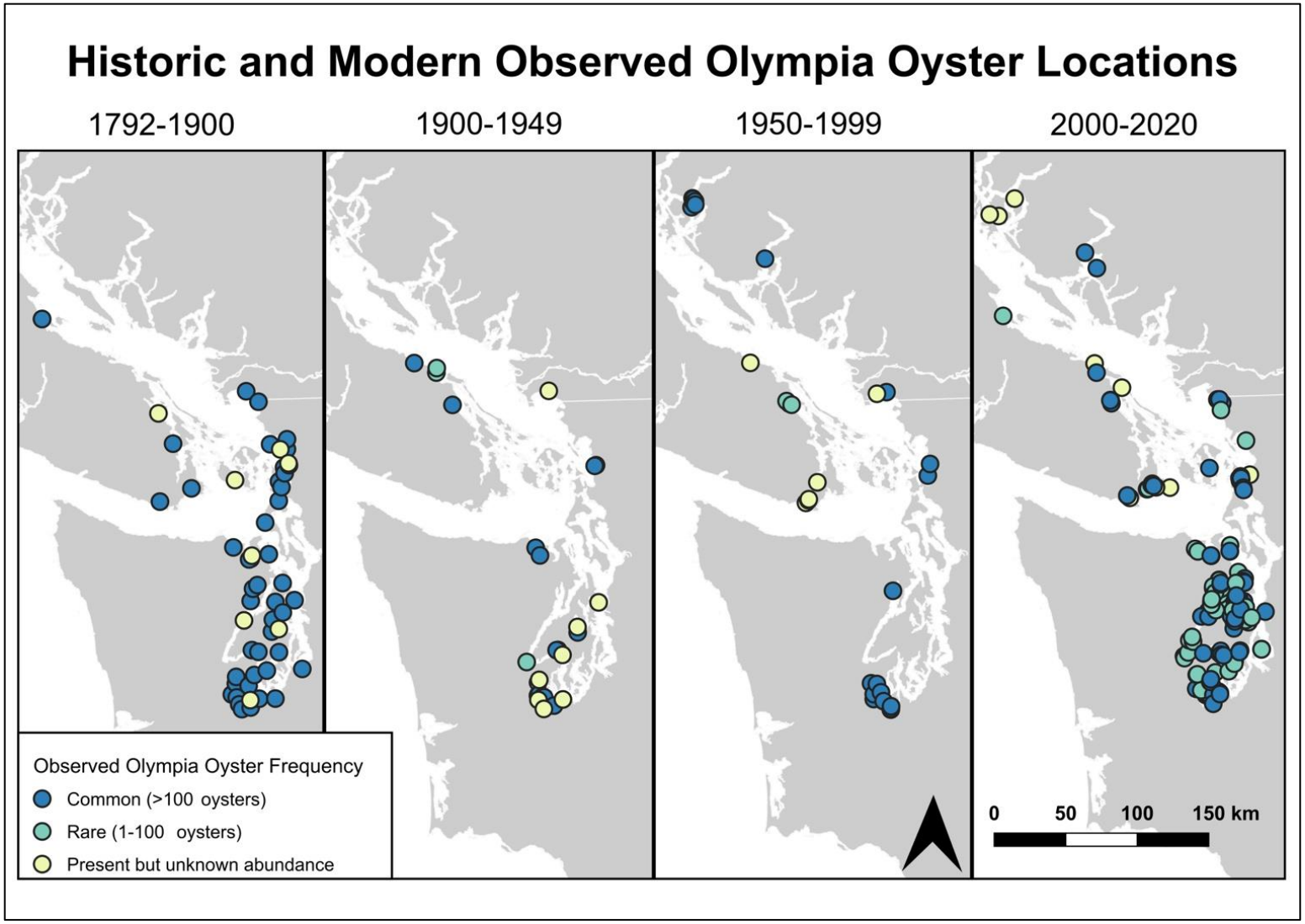

Figure 1: Historic and modern observed Olympia oyster locations in the Salish Sea divided into four time periods: 1792-1900, 1900-1949, 1950-1999, and 2000-2020. All data points are from Kornbluth et al. (2022). Olympia oysters are considered common if there are more than 100 in a 20 m^2 area, rare if there are between 1-100 oysters in a 20 m^2 area, or present if the abundance is unknown.

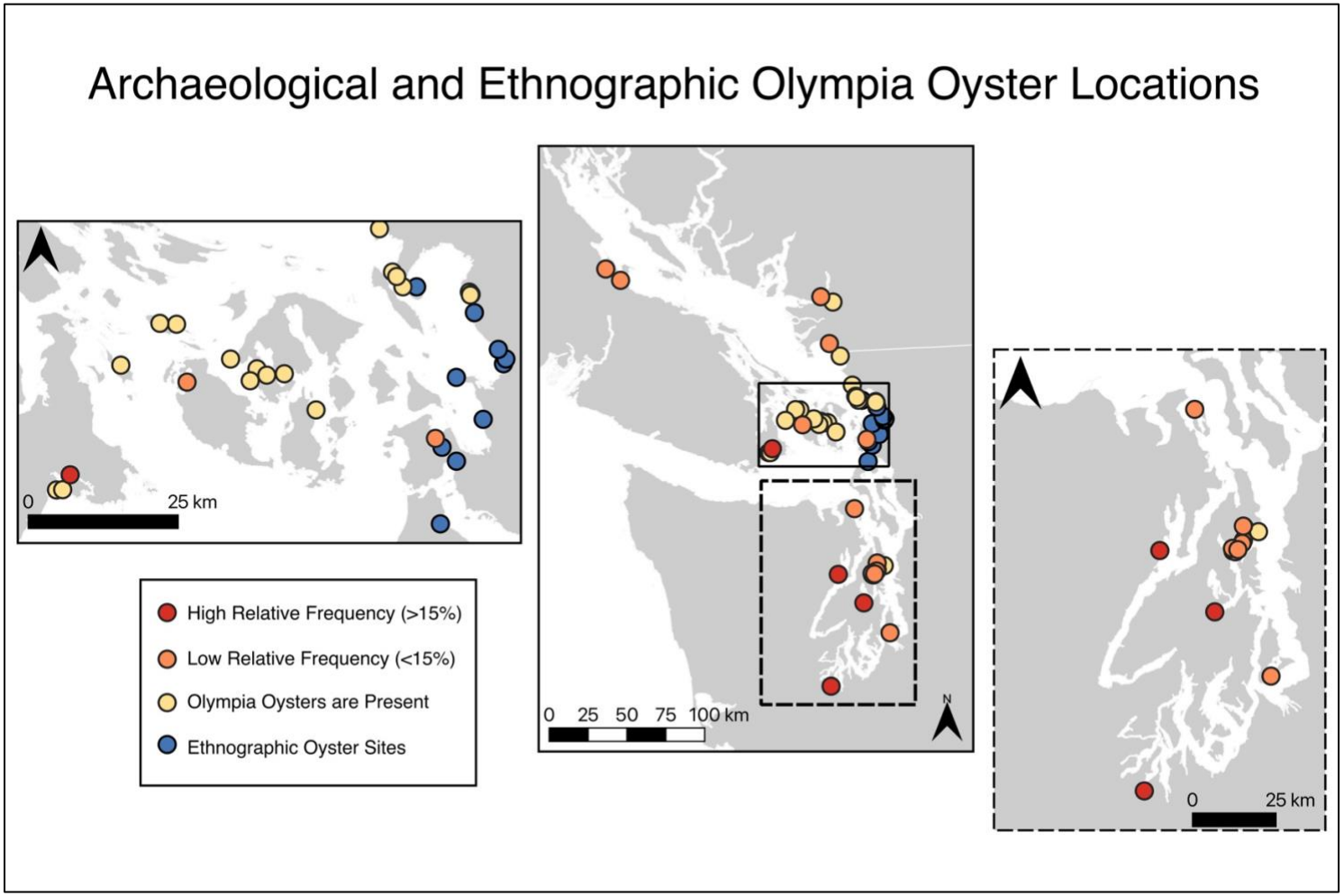

Figure 2: Archaeological and Ethnographic Olympia Oyster Locations. Sites with unusually high Olympia oyster frequencies are in red. Sites with low oyster frequencies are orange. Sites with only presence/absence data are yellow. Relative Frequency is based on either %MNI or %Weight, see Table 1 for details on which method was used at different sites. The left inset shows the high number of archaeological sites in the San Juan Islands. The right inset shows the low number of archaeological sites in Puget Sound compared to historic and modern observations in Figure 1. Archaeological and ethnographic data were compiled by Hatch, McKechnie, and Vollman as part of the Forgotten Fisheries Project (Reeder-Myers et al. 2022) and augmented by additional archaeological site reports.

Table 1: Archaeological Sites in the Salish Sea with Olympia Oyster Relative Frequency Reported in either %MNI or %Weight relative to other identified and weighed shellfish.

Region	***Archaeological Site***	***%MNI***	***%Weight***	***Source***
Puget Sound	*45JE06*	0.04	—	(Davy and Nachmanoff 1999:9.3-9.4)
Puget Sound	*45JE15*	58.6	—	(Wessen 1987:27)
Puget Sound	*45KI843*	0.31	0.02	(Deppen et al. 2014:77-78)
Puget Sound	*45KP109*	57.6	18.2	(Morgan 1993:16)
Puget Sound	*45KP32*	—	5	(Schalk and Rhode 1985:Table 1)
Puget Sound	*45KP40*	—	0.01	(Schalk and Rhode 1985:Table 1)
Puget Sound	*45KP43*	—	0.06	(Schalk and Rhode 1985:Table 1)
Puget Sound	*45KP44*	—	4.3	(Schalk and Rhode 1985:Table 1)
Puget Sound	*45KP47*	—	1	(Schalk and Rhode 1985:Table 1)
Puget Sound	*45SJ24*	—	0.16	(Daniels 2009:201-202)
Puget Sound	*45SK43*	0.02	—	(Nelson et al. 2010:Appendix F)
Puget Sound	*45TN240*	73.5	—	(Croes et al. 2013:184)
Mainland B.C.	*DgRr-1*	—	5.3	(Ham 1982:251)
Mainland B.C.	*DhRr-18*	—	0.001	(Lepofsky et al. 2007:205)
Vancouver Island	*DcRu-4*	68	66	(Wigen 1996:Table 3; Figure 5)
Vancouver Island	*DiSe-7*	—	0.9	(Monks 1977:184, 188)
Vancouver Island	*DjSf-13s*	—	0.009	(Mason and Hoffmann 1998:Table AIV-2, Table AIV-6)

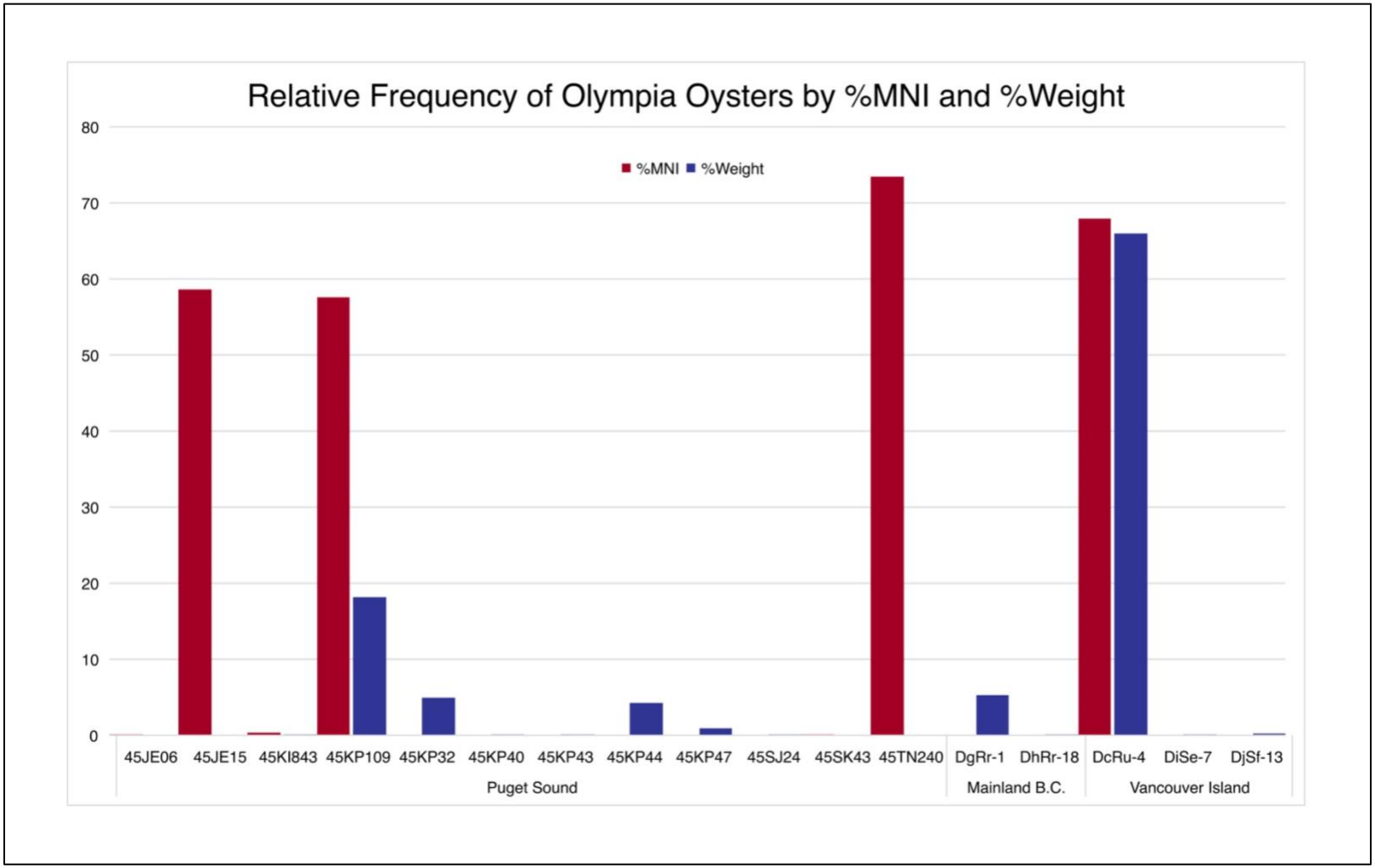

Figure 3: Relative Frequency of Olympia Oysters at Archaeological Sites in the Salish Sea by %MNI and %Weight. For specific relative frequencies, see Table 1. Sites with the designation 45 are in Washington State, whereas sites in British Columbia have a four-letter code followed by a number.

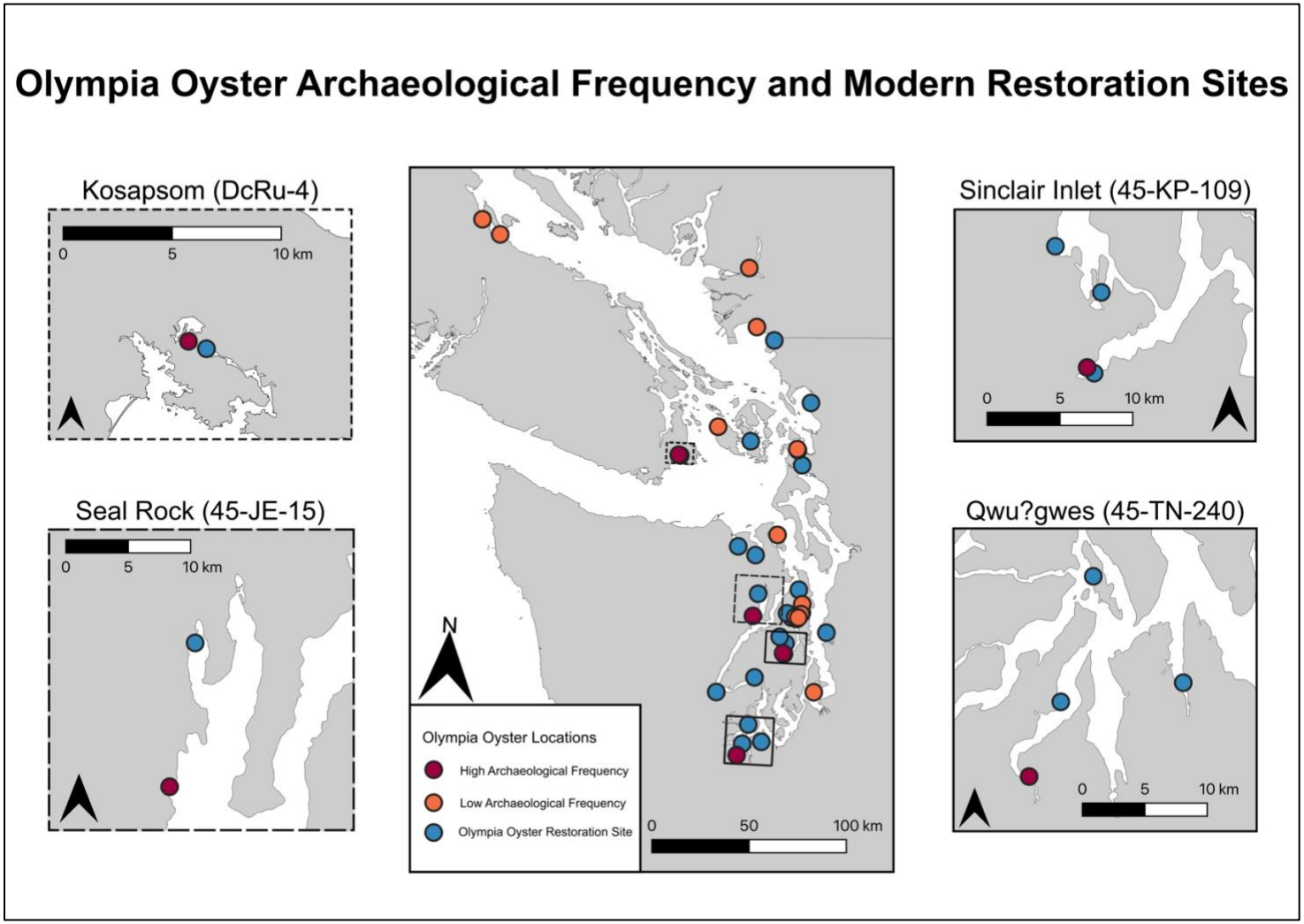

Figure 4: Map of Olympia oyster Archaeological Frequency and Modern Restoration Sites. Sites with high archaeological frequency are defined as greater than 15% by either %Weight or %MNI. Low archaeological frequency is defined as under 15%. All archaeological data was compiled by Hatch, McKechnie, and Vollman for the Forgotten Fisheries Project (Reeder-Myers et al. 2022). Modern Restoration Site Locations were originally reported by McKenna (2022) and NOOC (2018).

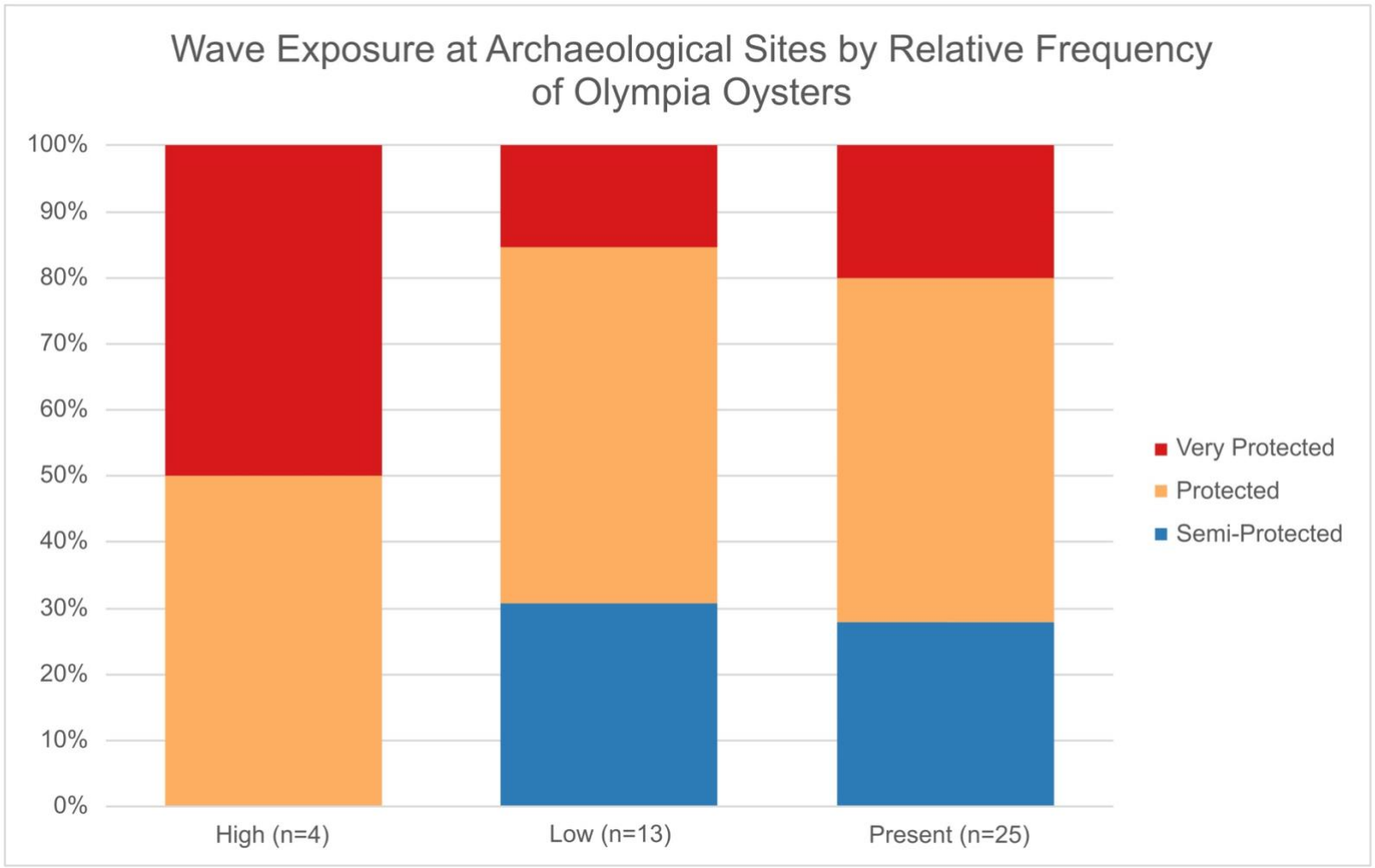

Figure 5: Wave exposure at archaeological sites with Olympia oysters by relative frequency reported. Wave exposure for sites located in the State of Washington was reported by Washington State Department of Natural Resources (2001a). Wave exposure for sites located in British Columbia was reported by Government of British Columbia (2023) and SeaChange Marine Conservation Society (2023).

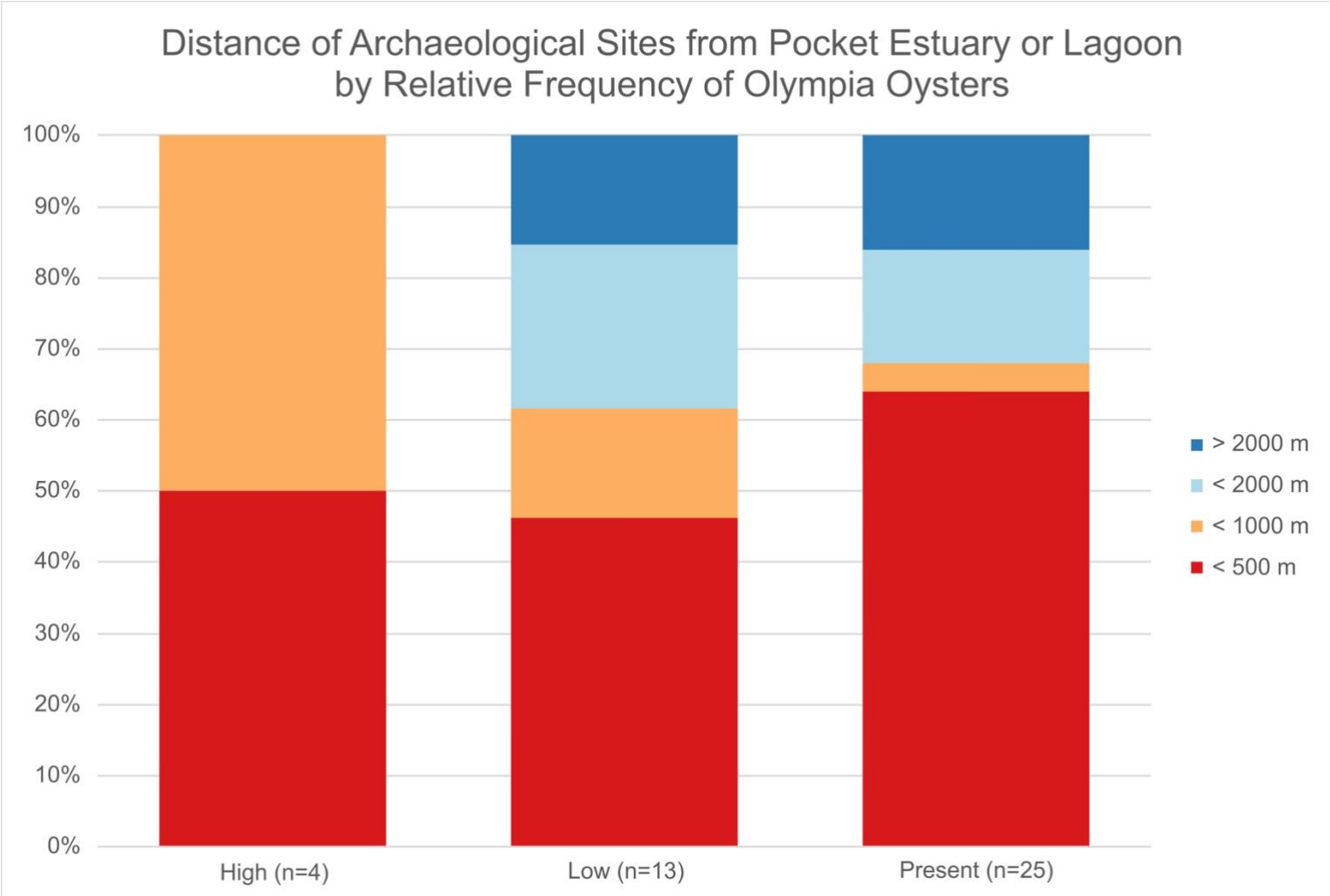

Figure 6: Distance of archaeological sites with Olympia oysters from a pocket estuary or lagoon by relative frequency of oysters. Locations of pocket estuaries and lagoons were compiled for Washington State (Cereghino 2020; Washington State Department of Natural Resources 2001b) and British Columbia (Government of British Columbia 2023).

Discussion and Implications

The data on oyster distribution compiled in this thesis indicate oysters were found in a few sites with high abundance and at many more sites with persistent but proportionately small abundance values. A closer examination of the geographic settings of these sites suggests the site locations with oysters are in small microhabitats that are unique relative to most coastal areas with only 9% of the 42 sites occurring further than 3 kilometres from a pocket estuary or lagoon and over 75% of sites occurring in very protected or protected waterways. Pocket estuaries or shallow lagoons and protected shorelines seem likely to provide conditions suitable for larval growth and development relating to decreased salinity (Beamer et al. 2009) and higher temperatures (Barber et al. 2016). Decreased salinity and higher temperatures are known to positively affect Olympia oyster larval growth (Lawlor and Arellano 2020). These factors likely contribute to the limited distribution of archaeological sites with a high abundance of Olympia oysters, although further evaluation and sampling would be necessary to confirm this. Additional research could also explore if the size of the pocket estuary correlates with relative frequency.

All of the archaeological sites with high abundance in this study are located within 1 kilometre of at least one pocket estuary or lagoon and are located on very protected or protected shorelines This accords with the broader clustering of certain resources and the territorial proprietorship of Coast Salish communities where certain families and kin groups owned and cared for valued resources. Following Suttles (1987), the presence of aggregated but abundant resources on the Northwest Coast and the potential surplus that could be mobilized by controlling access to them accords with the broader clustering of certain resources and the territorial proprietorship of Coast Salish communities where certain families and kin groups owned and cared for valued resources. Like other spatially concentrated resources, access to

Olympia oysters may have become valued and people maintained affinal ties to gain and maintain access to them.

The potential of the community-based ownership of Olympia oyster beds can be illustrated in a few different ways. Olympia oysters do not burrow as they grow but remain visible when paddling a canoe in clear shallow water and by foot during low tides. Shellfish in general tend to be easily detected, sessile, and predictably accessible during low tides (Whitaker 2008). In addition, small coves and estuaries tend to have more restricted access, thus enabling monitoring of canoes coming and going. Ensuring the continued abundance of oysters might have facilitated more active forms of management in places known to have abundant shellfish as such places could ensure a sustainable backup source of food in the event of periodic shortages and or social conflicts that restricted other food gathering activities (e.g., periods of warfare). The Northwest Coast is characterized by seasonal fluctuations in the availability of natural resources with winter being a season in which people lived on stored food as reported by Suttles ([1968]1987:47-50). Thus, Olympia oysters and other known shellfish harvesting areas could have been a key reliable fresh food source targeted during the low tides which predominantly occur at night in the winter in the Salish Sea and/or during the day in the mid-summer. Additionally, the spatially concentrated occurrence of Olympia oyster beds on the Northwest Coast makes them valuable for accumulating for trade and accruing prestige. Preserved clams and other mollusks could then be traded to groups without access to the same resources. Elmendorf (1960:310) explains how trading foods was sometimes used as a way "to obtain some specially prized delicacy." When the compiled archaeological data are considered as indicating a limited number of places with abundant Olympia oysters (Figure 5), it supports the possibility that oysters in those places were valued as a 'special' local food, and perhaps featured during

feasts as is documented on the Northwest Coast (Perodie 2001).Additionally, a local abundance of oysters would have represented a broader opportunity for a desired item of trading with people who lack direct access.

In the San Juan Islands and Burrard Inlet, archaeological occurrences of Olympia oysters contrast with few to no modern observations in these same areas today. This difference could be due to a combination of factors including, industrial development, surveying efforts, local extirpation, or transport of oysters. While it is possible that Olympia oysters exist in these locations, but have not been observed recently, this seems unlikely due to the diligence of modern iNaturalist observations, the highly populated urbanized nature of Burrard Inlet and the recreation popularity of the San Juan Islands. It could also potentially be a case of local extirpation where Olympia oysters occurred in the area at the time an archaeological site was occupied, but they were no longer there by the time of the earliest written records. Additionally, pollution and habitat destruction in heavily industrialized areas such as Burrard Inlet in Vancouver may have led to significant decreases in shellfish and fish populations (Morin et al. 2023; Trost 2005). Another way to consider the disjunct is through the former transport of harvested Olympia oysters to a site when it was occupied. In the San Juan Islands, Salish peoples may have regularly travelled between islands and shared access and or harvesting rights with Lekwungen peoples in the Gorge Waterway (Figure 2) since the two closest archaeological sites to the area are within 25 km (40 km by water).

In the case of archaeological sites with persistent Olympia oyster occurrence such as those observed on San Juan Island, it may also be these archaeological oysters were harvested and transported live from areas such as Kosapsom to establish Olympia oyster beds in new locations. In addition to plants and trees, this form of transplantation has been reported for other

marine bivalve species (Lepofsky et al. 2015) and Pacific herring and salmon eggs on the Northwest Coast (Thornton 2015; Thornton et al. 2015). This introduces the possibility that oysters from highly productive habitats such as those might have been transported to other locations found near other archaeological sites and if those habitats were less suitable the persistence of those populations may have diminished. In the case of archaeological sites with high Oyster abundance (such as in proximity to Kosapsom, Qwu?gwes, Seal Rock, and Sinclair Inlet), this may be visible with archaeological oyster shells occurring outside their ideal habitat but in low abundance. While these observations are tentative and not strongly supported, observing data from modern and ancient observations on San Juan Island could be explored further in the future, perhaps with geochemical and genetic approaches should there be community interest and research support.

A stronger basis for interpretation is the observation that Indigenous peoples living at numerous sites in the Salish Sea at sites with high oyster abundance likely had abundant and regular access to oysters. Moreover, given their proximity and ability to monitor harvests at these locations, it is likely that households (and families) maintained priority access to and cared for these productive beds nearby. These families could then exchange and share with relatives and or those who lacked access to this rare food and receive or accrue wealth in return, as has been discussed with important resources and foods more generally by Suttles ([1960]1987:22). Within the Coast Salish world, this could be one of many ways for nations, chiefs, and families to accrue prestige through generously distributing collected wealth (ibid.) Additionally, Olympia oysters were likely consumed and served during feasts and winter ceremonies. When guests arrived, they were provided food as part of the gathering (Elmendorf 1960; Kennedy and Bouchard 1990; Perodie 2001; Suttles 1987, 1990; Suttles and Lane 1990). While the ethnographic descriptions

of potlatches and feasts I reviewed do not specifically mention shellfish, many specialty foods were consumed at these events, especially if the hosts were known for their unique local cuisine (ibid.). Since Olympia oysters appear to be relatively rare in archaeological sites in the Salish Sea compared to other bivalves, communities who controlled access to nearby harvesting locations likely fed oysters to visitors as a desirable local food.

Conversely, I observed there are areas with Olympia oysters present today which are much more abundant than frequencies indicated in archaeological sites. This likely reflects the patchy and general lack of consistent archaeological sampling and analysis efforts but not necessarily a lack of their occurrence in the precolonial past. In the case of fauna identified from archaeological sites, absence of evidence does not necessarily mean evidence of absence of a species especially given a low and or geographically variable sampling effort (Lyman 1995). Moreover, considering the specific habitat requirements of Olympia oysters and their overall low abundance in archaeological sites in the Salish Sea, areas without well analyzed archaeological assemblages may not detect the presence of Olympia oysters or may instead reflect preservation or identification biases (ibid.). Future archaeological work in areas with large numbers of observations of historic and modern oysters is likely to encounter them (Figure 1), especially in southern Puget Sound and Hood Canal in Washington State. Previously excavated sites with unanalyzed sediment samples are also likely to contain Olympia oysters, but many excavation projects continue to not report basic shellfish identification and quantification. Future excavation projects at ‘shell’ middens in the region should consider requiring more rigorous shellfish identification and quantification and can identify additional sites with abundant Olympia oysters and expand our knowledge of their pre-colonial distribution and abundance.

As discussed in the next chapter, many Olympia oyster restoration efforts are still ongoing. Currently, there are at least 21 Olympia oyster restoration projects in the Salish Sea[4] (McKenna 2022; Native Olympia Oyster Collaborative (NOOC) 2018). The Puget Sound Restoration Fund reached its 10-year goal of restoring 100 hundred acres of Olympia oyster habitat by 2020 (McKenna 2022). However, considering that 10,000-20,000 acres (~ 4,050-8100 hectares) existed historically (McKenna 2022), and 100 acres is less than 0.01% of the historic habitat, there is still a long way to go. Archaeological information and data on invertebrate assemblages offer the opportunity to consider ancient Indigenous harvest records as a crucial perspective to bring to modern restoration projects. The high frequency of Olympia oysters observed at only four of eighteen archaeological sites with relative frequency reported in the Salish Sea indicates the comparative rarity of these habitats but also suggests that large numbers of harvest-sized oysters must have been present in proximity to these Indigenous settlements. Accordingly, it is likely those areas were particularly ideal habitats for Olympia oysters and offer a new way to consider the ecological conditions suitable for oyster restoration. Olympia oyster populations in these locations may be able to grow faster and maintain stable population sizes quicker than in other areas where oysters were not as frequent in the past. If restoration projects identify similar microenvironments or pursue restoration near these sites and consult with Indigenous communities, this may lead to more successful and faster outcomes, due to ideal Olympia oyster growing conditions over the long term. In other words, there is value in considering archaeological sites and the specific areas that productively supported Olympia oysters in the ancient past and likely will be able to again if managers recognize and engage with archaeological information and Indigenous knowledge.

[4] Some of the locations are not active or lack funding to continue taking an active role in increasing population size.

Currently, the State of Washington requires that all oysters be 2.5 inches (63.5 mm) or larger for recreational harvesting[5] (Washington State Department of Fish & Wildlife 2023). Since Olympia oysters usually only grow to 60 mm (Dinnel 2018; Gillespie 2009), this effectively limits Olympia oyster harvesting. Similarly, in British Columbia, harvesting Olympia oysters has been closed since 2007 (Department of Fisheries and Oceans Canada 2009). These two regulations limit the harvesting of Olympia oysters on non-cultivated beds by Indigenous peoples in the Salish Sea. Involving local Indigenous peoples in the decision-making process is necessary for future management because their land once supported more sustainable fisheries over 4000 years before they were forcibly displaced (Reeder-Myers et al. 2022). Involving Indigenous peoples in restoration and management decisions fosters the opportunity for cultural revitalization and retention (Gibbs et al. 2023) This may be a step towards Indigenous re-harvesting of Olympia oysters and reconciliation and is explored in more detail in the next chapter.

[5] The 63.5 mm size requirement was set in part to conserve Olympia oyster populations.

Chapter 3 Case Study: Morphometric Analysis of Archaeological Oysters at Kosapsom, historical ecology of an urbanized marine inlet on Southern Vancouver Island

Introduction

In this chapter, I develop a method for estimating past Olympia oyster (*Ostrea lurida)* size from fragmented shell valves. I then apply this method to an archaeological site in the Salish Sea with high Olympia oyster abundance. The estimated oyster shell sizes from the site are examined by chronological period to understand change and stability over 2000 years. Building on the approach outlined in the previous chapter, I compare ancient and modern Olympia oysters but in addition to just abundance, I focus on size-at-harvest which adds another dimension to increase the utility and potential of examining archaeological data in the context of recent monitoring and restoration efforts in the Salish Sea. Accordingly, the goal of this chapter is to develop and apply a method for documenting ancient Indigenous harvest profiles for Olympia oysters using size estimates from fragmentary archaeological assemblages and discuss potential factors contributing to the differences observed between modern and ancient as well as over millennia within archaeological deposits. The benefit of estimating archaeological Olympia oyster size adds to the ecological baseline for Olympia oysters which were severely overharvested in the late 19th and early 20th centuries.

Zooarchaeological measures of abundance are often relative. A specific species (or less specific taxonomic categories) is commonly measured in archaeological assemblage by numbers of bone specimens (% NISP), or numbers of individuals (% MNI), or as is often the case of

shellfish, proportional weights (% of one taxon vs. all others). None of these alone can explain the whole picture of resource harvesting practices and a crucial but often unaddressed component is body size. By additionally incorporating body size, different types of research questions relating to human impacts and domestication can be addressed (Dombrosky et al. 2022; Owen et al. 2014; Thangavelu et al. 2011). Such 'morphometric' methods are widely utilized in zooarchaeology globally and build upon traditional zooarchaeological measures of abundance (ibid).

On the Northwest Coast, morphometric measurements have helped address a variety of research questions. For example, morphometric measurements have been used to identify different dog breeds in archaeological sites wherein complete dog bones were measured to identify two distinct sizes of dog breeds (Crockford 1997) , a result that species identification alone would not have yielded. Additionally, morphometrics can determine size from fragmentary or partial skeletal elements by relating a given element to body size (Orchard 2001). Morphometric regressions for halibut body sizes were developed to estimate fork length based on a series of vertebrae measurements (Salmen-Hartley 2018). These size estimations were then applied to archaeological assemblages in Barkley Sound to estimate the proportional biomass of Indigenous halibut and other fish (Hillis 2022). Morphometric regression-based methods have also been utilized for shellfish species on the Northwest Coast. A regression based on hinge teeth length and total length of archaeological littleneck clams (*Protothaca staminea*) and basket cockles (*Clinocardium nuttallii*) enabled estimates of shell size from fragmented valves (Daniels 2009, 2014). The archaeological size estimations were utilized to see how size distributions at two archaeological sites in the San Juan Islands in Washington varied throughout their occupations and compared to modern average sizes (ibid). More recently, linear regressions have

been calculated for three clam species in British Columbia (Hillis 2022). These regressions were then applied to an archaeological site in Tseshaht First Nation territory on Western Vancouver Island to estimate size-at-harvest and revealed sustained intensive harvesting spanning 3,000 years (Hillis et al. n.d.). Assessing size in these contexts contributes not only to our past understanding of human behavior, but also provides a longer time depth to ecological and environmental baselines.

Historical ecology seeks to understand human relationships with location environments with people as active and influential participants in ecological relationships (Balée 2006). Another aspect of historical ecology is using archaeological data to help unravel past human-environment interactions, which is especially important in confronting 'shifting baseline syndrome', a problem that arises when ecological baselines do not consider the extent of historical change but mark already degraded ecosystems as a goal for restoration (Jackson 2001; Pauly 1995). In this chapter, I develop a method for estimating past Olympia oyster size from archaeological contexts and address the broader history of human-oyster interactions with the aim to improve perspective on contemporary restoration baselines.

Below, I describe a morphometric method to estimate past Olympia oyster size and apply this to archaeological data from the Kosapsom Village Site on southern Vancouver Island. These length data are then compared to data from contemporary Olympia oyster restoration projects in the Victoria Gorge Waterway and Fidalgo Bay located in northern Puget Sound in Washington State.

Summary of the Archaeology at Kosapsom

The archaeological site of Kosapsom (DcRu-4) is a large shell midden and Indigenous settlement site on a very protected inlet and south facing shoreline in greater Victoria. Portions of the site were excavated between 1994 and 1997 by University of Victoria field school students under the supervision of Don Mitchell, Quentin Mackie, and Becky Wigen and more recently as part of the Craigflower Bridge reconstruction project in 2011-2013 (Huculak 2012; Huculak and Pratt 2017; Mitchell 1996; Stewart and Wigen 2003). Kosapsom is located along the Gorge Waterway on southeastern Vancouver Island in urbanized Victoria within the traditional territories of the Esquimalt and Songhees First Nations whose reserve lands are only a short distance away (Figure 7).

Radiocarbon dates from both projects suggest a documented occupation spanning the past 3,000 years with a continued record into the historic and contemporary period with European artifacts and historic disturbance present in the upper 50 cm (Figure 9; Table 2). As the site was later part of a historic schoolhouse and then a heavily landscaped municipal park, historic disturbance in the upper portions of the site is expected.

To examine fine screen constituents at the site, 20x20 cm column samples were taken in 5cm level increments from within quadrants of 1x1m excavation units. For the 1995 field season, these column samples were increased to 30x30 cm to ensure a larger volume for dietary reconstruction (Mitchell 1996). Fourteen levels of a column sample from Unit N10-11/E9-10 were sorted by a small team of students and volunteers, under the supervision of UVic laboratory instructor and zooarchaeologist Rebecca Wigen. They used comparative collections and printed identification keys to identify shellfish taxa with varying levels of specificity to family, genus, and species. Each 5 cm column sample level was sieved through nested 6.35 mm (1/4”), 2.00

mm and all faunal materials from the 6.35 mm and 2.00 mm screens were “identified to the most precise taxonomic category possible” (Wigen 1996:2). MNI was calculated for bivalve species using hinges, while for univalve spires were counted. Along with MNI, percent by total shell weight was also calculated thereby representing two measures of proportional abundance. By weight, bivalves were the largest component of all shell, ranging between 91-98% (Wigen 1996). Within the bivalves, Olympia oyster was the most abundant by both weight and MNI, ranging from 42-97% MNI and 44-89% weight with bay mussel (*Mytilus trossulus*) ranked the second most abundant bivalve. While this fits with the local sheltered environment of the Gorge, this is among the highest percent abundance by weight and/or MNI for oysters in the Salish Sea (*see* Chapter 2).

Figure 7: Location of Kosapsom within the Greater Victoria Area. The Gorge Waterway is outlined in blue. Contemporary Songhees First Nation and Esquimalt First Nation reserve lands are in red and orange respectively.

Additional surveys and excavations at the Kosapsom site were undertaken in 2011 and 2012. Two bulk samples, collected from sections where midden deposits were intact, were identified by Becky Wigen after they were dried, screened, and sorted (Table 3). Similarly, these bulk samples were estimated to contain around 90% Olympia oyster by weight (Huculak 2012; Wigen 2011, 2012).

In 2013, monitoring and excavation were undertaken at Kosapsom in conjunction with the Craigflower Bridge Replacement Project (Huculak and Pratt 2017). Weight was calculated for all shellfish, while MNI and meat weights were calculated for bivalve species (Table 3). Bay mussel followed by Olympia oyster were found to dominate the analyzed column samples both for MNI and meat weights.

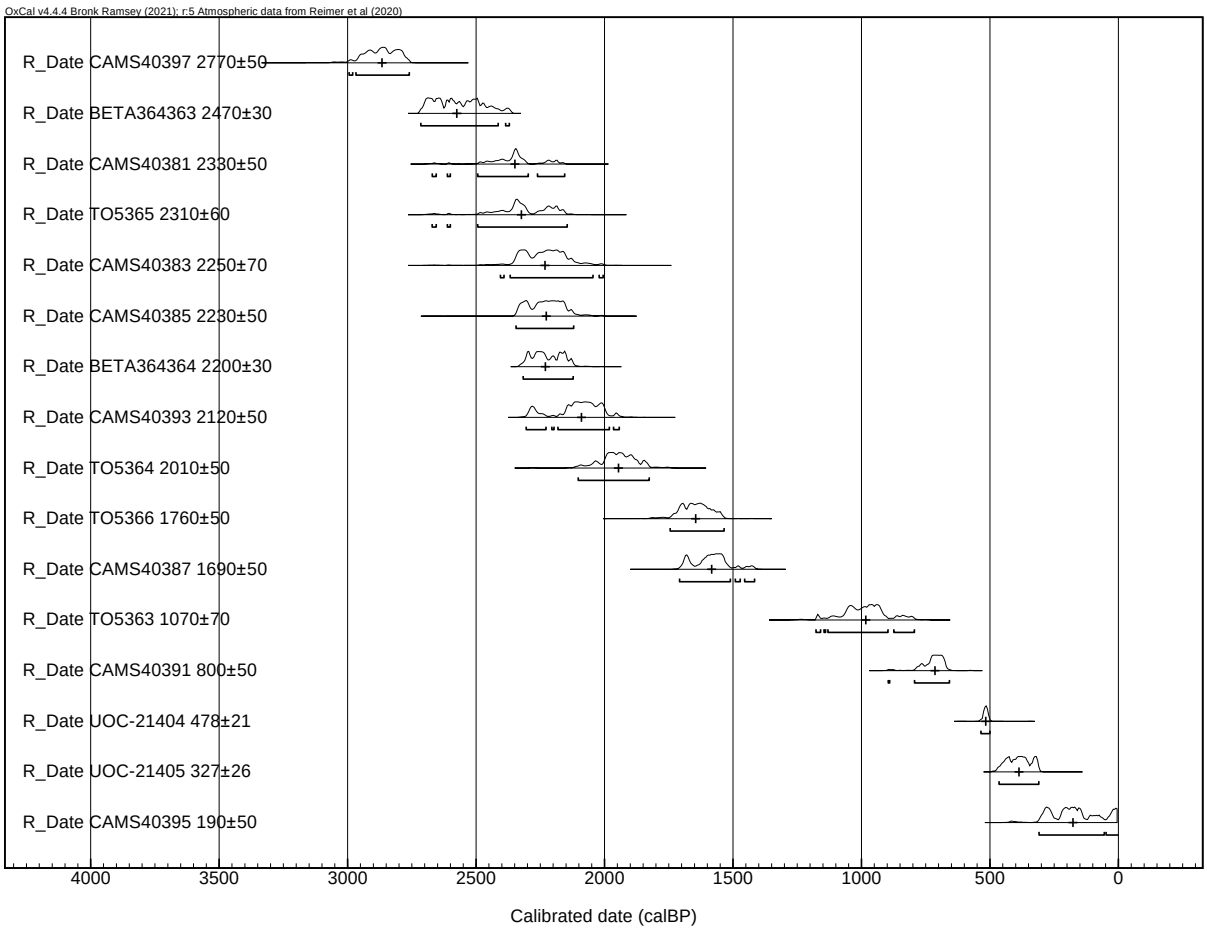

Figure 8: Calibrated radiocarbon dates from Kosapsom sorted from oldest to youngest, indicating nearly continuous occupation for the past 3000 years. Individual dates are listed by lab numbers and additional source information is shown in Table 2.

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Table 2: Calibrated and Uncalibrated Terrestrial Radiocarbon Dates from Kosapsom with Source. The radiocarbon samples were collected from various locations in the site from various depths. Dates associated with samples used in this study are in bold.

Lab Number	***Radiocarbon Age***	***Error***	***Calibrated Age-Range (2σ)***	***Unit***	***Material Dated***	***Depth Below Datum (dbd) or Centimeters Below Surface (cmbs)***	***Source***
TO-5363	1070	70	1180-790	N24-25/E24-25	charcoal or charred wood	5.88 dbd	(Mitchell 1996)
TO-5364	**2010**	**50**	**2110-1820**	**N45-46/E32-33**	charcoal or charred wood	**5.33 dbd**	**(Mitchell 1996)**
TO-5365	2310	60	2680-2140	N78-79/E51-52	charcoal or charred wood	6.93 dbd	(Mitchell 1996)
TO-5366	1760	50	1750-1530	N24-25/E24-25	charcoal or charred wood	6.68 dbd	(Mitchell 1996)
BETA-364363	2470	30	2720-2370	EU23	charcoal	130-140 cmbs	(Huculak and Pratt 2017)
BETA-364364	2200	30	2320-2120	EU25	charcoal	58 cmbs	(Huculak and Pratt 2017)
CAMS-40381	2330	50	2680-2150	N23-24/E23-24	charcoal	6.18 dbd	(Southon and Fedje 2003)
CAMS-40383	2250	70	2410-2000	N23-24/E22-23	charcoal	6.61 dbd	(Southon and Fedje 2003)
CAMS-40385	2230	50	2350-2120	N51-52/E36-37	charcoal	6.24 dbd	(Southon and Fedje 2003)

CAMS-40387	1690	50	1710-1410	N23-24/E23-24	charcoal	6.62 dbd	(Southon and Fedje 2003)
CAMS-40391	800	50	790-650	N28-29/E24-25	charcoal	5.71 dbd	(Southon and Fedje 2003)
CAMS-40393	2120	50	2310-1940	N51-52/E35-36	charcoal	5.54 dbd	(Southon and Fedje 2003)
CAMS-40395	190	50	310-0	N37-38/E35-36	charcoal	5.57 dbd	(Southon and Fedje 2003)
CAMS-40397	2770	50	3000-2760	N44-45/E31-32	charcoal	6.17 dbd	(Southon and Fedje 2003)
UOC-21404	**478**	**21**	**540-500**	**N10-11/E9-10**	**charcoal**	**5.45-5.50 dbd**	**This study**
UOC-21405	**327**	**26**	**470-310**	**N10-11/E9-10**	**charcoal**	**5.80-5.85 dbd**	**This study**

Table 3: Methods used for previous zooarchaeological identification and quantification of Olympia oysters at Kosapsom.

Year	***Number or size of column samples***	***Estimated examined volume of shellfish or number of levels***	***Quantitative methods/ screen size***	***% Oyster Weight***	***% Oyster MNI***	***Reference***
1995	One 20x20 cm column sample w/ 5 cm levels	14 Level Total (28 Liters)	6.35 mm & 2 mm Screens	Avg 64%	Avg 68%	(Wigen 1996)
		5.07-5.10		44%	42%	
		5.10-5.15		49%	63%	
		5.15-5.20		48%	41%	
		5.20-5.25		60%	53%	
		5.25-5.30		66%	61%	
		5.30-5.35		62%	61%	
		5.35-5.40		79%	83%	
		5.40-5.45		89%	89%	
		5.45-5.50		77%	97%	
		5.50-5.55		52%	68%	
		5.55-5.60		59%	68%	
		5.60-5.65		73%	83%	
		5.70-5.75		78%	84%	
		5.80-5.85		58%	62%	
2010	Two Bulk samples	115-130 cm depth below surface (specific dimensions not reported)	Sieved (specific screen size not reported)	Estimated to be over 90%		(Huculak 2012; Wigen 2011, 2012)

Year	*Number or size of column samples*	*Estimated examined volume of shellfish or number of levels*	*Quantitative methods/ screen size*	*% Oyster Weight*	*% Oyster MNI*	*Reference*
2013	15x15 cm column sample w/ 10 cm levels	Seven Levels Total (15.75 liters)	6.35 mm & 2 mm Screens	19%	38%	(Huculak and Pratt 2017)
				38%	43%	
				20%	52%	
				71%	78%	
				38%	44%	
				28%	30%	
				1%	19%	

Methods

Hinge and Shell Measurements

To create size estimates for archaeological oysters, I measured complete modern Olympia oysters and developed a regression model that can be used to calculate total shell length from hinge thickness. In December 2021, Taylor Shellfish Company in Shelton, Washington donated 125 modern cultivated Olympia oysters of ranging in maximum growth axis size from 21.68 mm to 56.87 mm. The sample included 22 larger 'harvest size' oysters (which were mostly likely the oldest), 24 summer 2019 'ground' oysters (which had been grown on the bay bottom), 25 fall 2019 'grow bag' oysters (grown in grow bags in the ocean), 24 summer 2020 grow bag oysters, and 30 less than 1 year old oysters. To prepare these shell valves for measurement, oysters were steamed to avoid damaging the valves, particularly the hinge which needed to be measured to determine the relationship between the hinge thickness and total shell length. Oysters that did not open this way were shucked but from the side to not damage the hinge or the maximum growth axis. For the smallest oysters, a sewing needle was used to pry the oyster open. The paired valves were bagged individually and labelled by age group.

At the UVic Department of Anthropology Environmental Archaeology Lab, the total length of the oysters (Figure 9a) and hinge thicknesses were measured using digital calipers and recorded to the nearest 0.1 mm in a spreadsheet (Appendix A: Table 11). The hinge thickness for each was measured from the umbo to the middle of the growing edge of the hinge (Figure 9b). Left and right valves were determined based on morphological characteristics. The left valve is cupped, the hinge is slightly concave, and is the side that may be attached to hard substrates (COSEWIC 2011). The right valve is typically flat, and the hinge is slightly convex. For the left valve, all oysters were able to be measured, but for the right valve six were unable to be

measured due to damage to the umbo. In the process of opening the oysters, I noticed that the right valve tended to be more fragile and susceptible to breakage.

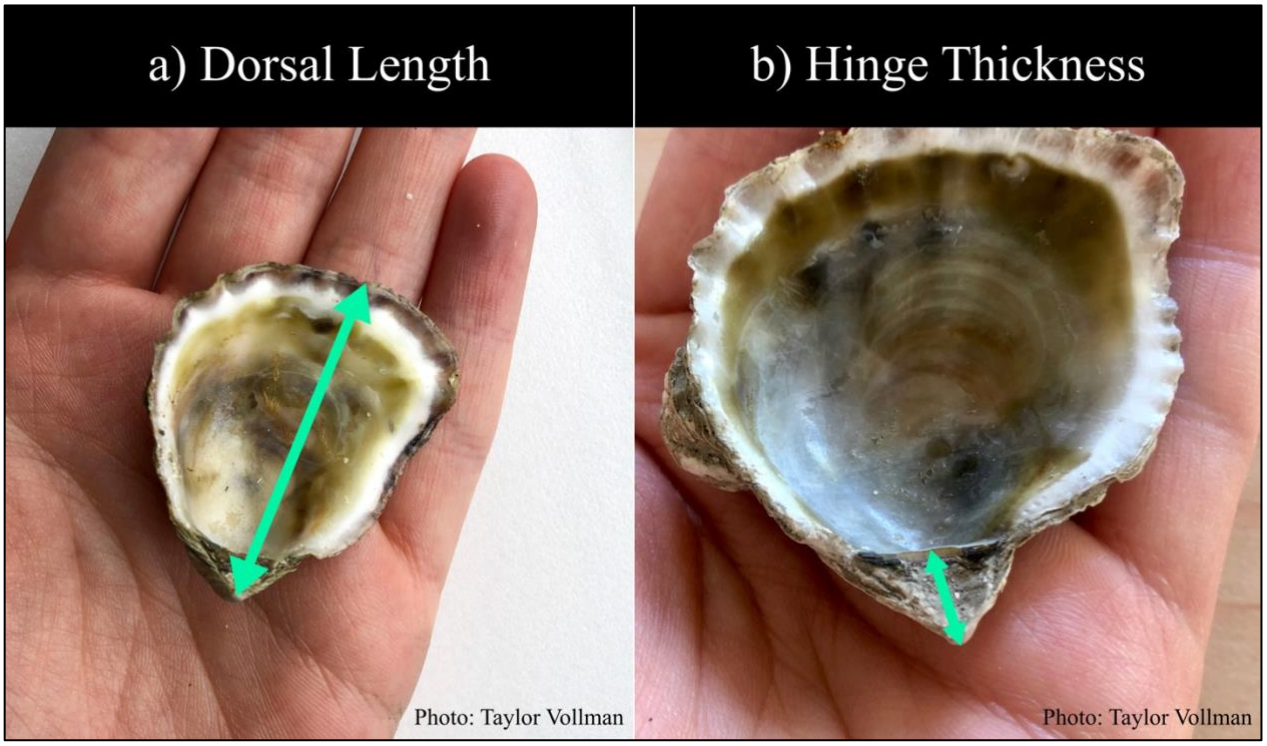

Figure 9: Measurements made on Olympia oysters (a) total shell length and (b) left valve hinge thickness for generating regressions to estimate dorsal shell length.

Development of a regression for Olympia oyster size prediction

The relationship between umbo thickness and total shell length has been developed using linear and saturating regressions for other bivalve species on the Northwest Coast (Daniels 2014; Earle 2020; Hillis 2022; Singh and McKechnie 2015; Slade et al. 2022). I plotted the hinge thickness measurements versus the total shell length using RStudio and observed a strong relationship. I then developed a regression to predict Olympia oyster size based on hinge thickness. Regression analysis creates a line of best fit to predict future values based on the 'predictor' variable. For this analysis, the hinge thickness is the predictor variable, and the

dependent variable is shell length. Regressions for both the left and right valves were tested, but the left valve led to a slightly larger R^2 value and lower Standard Error of the Residuals. The code used in RStudio is included in Appendix A of this document. However, as the increase in shell length is likely linear while hinge thickness likely increases with valve volume, I ran a logarithmic transformation on the hinge thickness to better represent this relationship. This resulted in an R^2 value of 0.86 (Figure 10; Table 4). This can be interpreted as 86% of the variation in length can be explained by the natural logarithm of hinge thickness. Although there remains the potential for morphological variability between ground and grow bag oysters, the regression produced an R^2 value of 0.86 with both ground and grow bag oysters represented in the sample.

Table 4: Regression equation for estimating maximum growth axis length of Olympia oysters from measurements of the hinge, including R^2 values, residual standard error (±), and sample size (n).

Measurement Description	**Regression Equation**	**R^2 Value**	**SE (±)**	***n***
Hinge (Figure 9b)	Length = 30.46($\log_e$ Hinge) -12.82	0.86	3.67	125

Archaeological Shell Measurements

This strong relationship between hinge length and shell length was used to generate shell length measurements from fragmentary oysters at Kosapsom. I measured left valve fragments (which are distinguishable in archaeological samples) with complete hinges using digital calipers from column sample levels from Units N10-11/E9-10, N45-46/E32-33, N45-46/E31-32, and N44-45/E31-32. Shellfish from Unit N10-11/E9-10 had been previously identified and quantified by weight and MNI by Rebecca Wigen as part of the 1994-1997 University of Victoria field

school. The other three units were previously unanalyzed column samples from units excavated stored at the University of Victoria. I measured a total of 583 left hinges from Wigen's previously analyzed unit, 443 of which were from mixed historic deposits, 140 of which were from deposits dating from approximately 300-500 calibrated years BP (Table 2), and 202 from previously unanalyzed units N45-46/E32-33, N45-46/E31-32, and N44-45/E31-32 dating to roughly 1500-2000 BP. Portions of two levels from each of the three units (N45-46/E32-33, N45-46/E31-32, and N44-45/E31-32) were wet screened through 2 mm mesh. All washed material was then dried, and Olympia oyster hinges were sorted from the other material. To test for potential differences between each time period, I ran a Kruskal-Wallis test to account for samples that may lack a normal distribution.

Shellfish Quantification and Abundance

To track the relative proportion of oysters alongside oyster size, I use MNI quantification data reported by Wigen (1996) in Unit N10-11/E9-10 and newly calculated data from previously unanalyzed units N45-46/E32-33, N45-46/E31-32, and N44-45/E31-32. Wigen (1996) found that mussel is the second-ranked shellfish after oysters across all levels in Unit N10-11/E9-10, which contrasts with MNI data from older areas of the site reported by Huculak and Pratt (2017). To generate comparable data from the previously unanalyzed units I counted bay mussel (*Mytilus trossulus*) valves from subsampled column sample levels (25 or 12.5% of the original sampled volume) using a sample splitter. This enabled mussel umbos MNI to be compared against Olympia oyster MNI for each level of the previously unanalyzed units (Table 5).

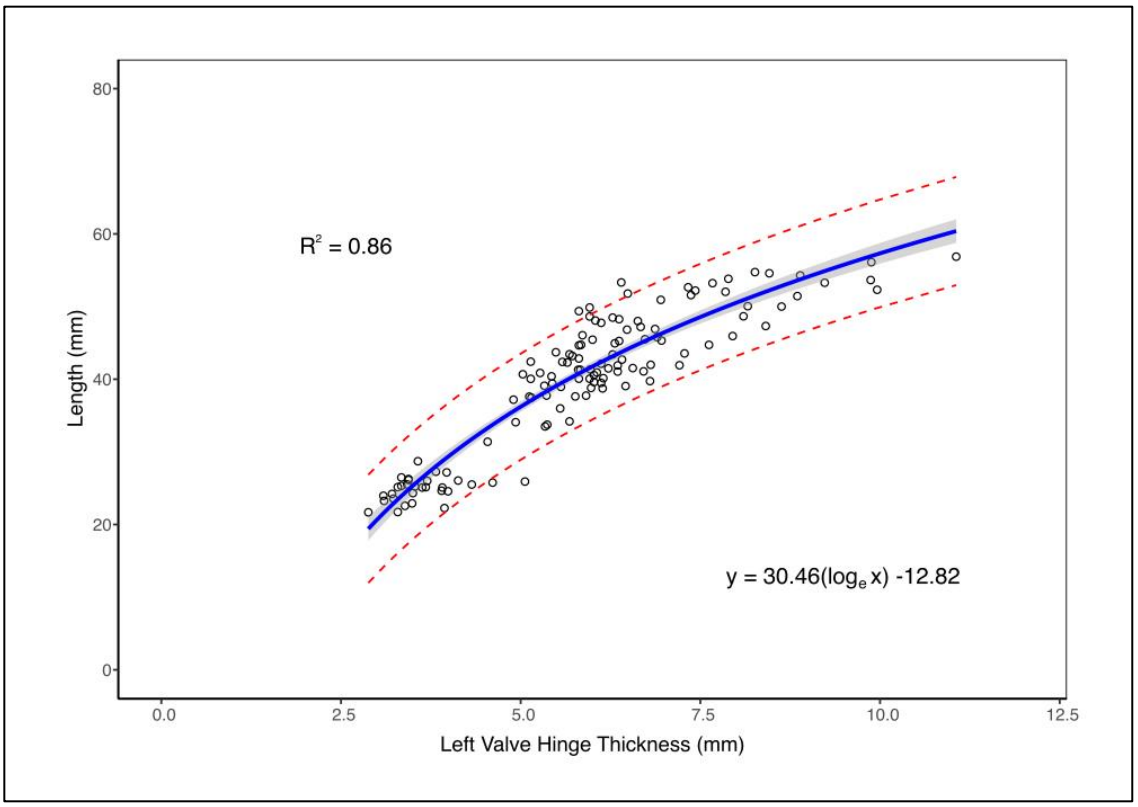

Figure 10: Logarithmic Regression of Modern Olympia Oysters (n=125). Residual Standard Error (SE) = 3.67. The blue line is the line of best fit. The shaded area around the line of best fit is the 95 % Confidence Interval of the line. The red dashed lines are the 95% prediction interval.

Comparisons to Modern Olympia Oysters

To compare the size estimates from the Kosapsom Village Site to modern observed size measurements, I compiled ecological data from two restoration sites in the Salish Sea: the Victoria Gorge waterway as well as a large-scale Olympia oyster restoration project in Fidalgo Bay on Anacortes Island in Washington near the archaeological site of Weaverling Spit (Nelson et al. 2010). For the oysters measured in the Victoria Gorge, I extracted oyster size data from quadrat data reported in Norgard et al. (2018) and Chalifour et al. (2012) by examining histograms using WebPlotDigitizer (Rohatgi 2022). This process entailed uploading histograms and using the program to count the frequency of each size category (estimated accuracy ±1 mm). Olympia oyster size measurements from Fidalgo Bay are reported in Dinnel (2018). Due to

concerns about meeting the expectations for normality, I used Mann-Whitney U tests to compare measured total lengths from each survey effort (Norgard et al. 2018; Chalifour et al. 2012; Dinnel 2018) to archaeological material from Kosapsom.

For instance, Chalifour et al. (2012) measured a total of 219 dive-collected Olympia oyster shells (alive and dead) from two locations within the Gorge Waterway (one of which was adjacent to Kosapsom and placed survey quadrats on a transect line across the Gorge during a dive survey). All shell from a given quadrat was taken back to the lab to measure and live oysters were returned to the same area. The dead oyster shell valves likely represent a longer time period than the live shells and may skew the distribution. Dead oysters likely included both younger and/or older oysters and younger oysters may not have reached average adult size. However, more recent survey efforts in the Gorge (Norgard et al. 2018) produced similar size ranges from live oysters.

Similarly, Fidalgo Bay was reseeded beginning in 2002 to restore Olympia oysters (Dinnel 2018) that had suffered from habitat alteration, pollution, and overharvest. Since that restoration project began, oysters in Fidalgo Bay have increased from an estimated 50,000 in 2002 to almost 3 million by 2018. Between 2008 and 2018, oyster sizes were measured to assess growth and natural recruitment rates. Although the 2018 data has a small sample size (n=32 oysters), I additionally compared Kosapsom to older data from Fidalgo Bay measured in 2015 (n=149 oysters), with similar results. The larger sample size from 2015 can be used to assess the stability and validity of the 2018 size measurements of Olympia oysters in Fidalgo Bay.

Results

Archaeological hinge thickness measurements

The mean and median hinge thickness measurements for all analyzed time periods from Kosapsom are 6.1 mm and 5.8 mm respectively. The mean and median estimated lengths are 40.6 mm and 40.8 mm. A Shapiro-Wilk normality test returned a p-value of $p = 0.001$, which indicates the data is not normally distributed, although the less than 1 mm difference between the mean and median suggests that the estimated lengths are not skewed (Table 6). As illustrated by the histogram of estimated lengths (Figure 11), the distribution is slightly bimodal, meaning that it has two peaks, located between 39-40 mm and 44-45 mm. However, when the estimated lengths are divided by time period, all but one of the chronologically distinct distributions appear normal, and these visual observations are supported by Shapiro-Wilk test values of over $p=0.05$, except in the case of the historic/mixed deposits that are also bimodally distributed (Table 6). Valves from the younger areas of the site tend to have larger sample sizes than older areas of the site (Table 6). Additional descriptive statistics including mean, median, interquartile range, and standard deviation for the entire site and for each time period are presented in Table 6.

Of the measured sample of archaeological hinges, 5.5% fall outside the range of the modern Olympia oysters used to develop the regression model. In other words, 27 of the archaeological hinges are thinner than the modern size range and 16 of them are thicker. However, because this totals only 5.5% of the measured sample these data are unlikely to impact the overall trends. Moreover, based on the best fit line, these outlier size estimates appear reasonably accurate and are expected given the much greater time depth and healthier ecosystem states that are represented. However, some caution is needed when interpreting the precise sizes of both the smallest and largest measured oysters.

While sorting through the previously analyzed column sample from Unit N10-11/E9-10, I observed a few cases where the oysters grew back-to-back (Figure 1) which may be evidence of past reef formation. Admittedly this was not something I was on the lookout for so there is no quantification of how often this occurred.

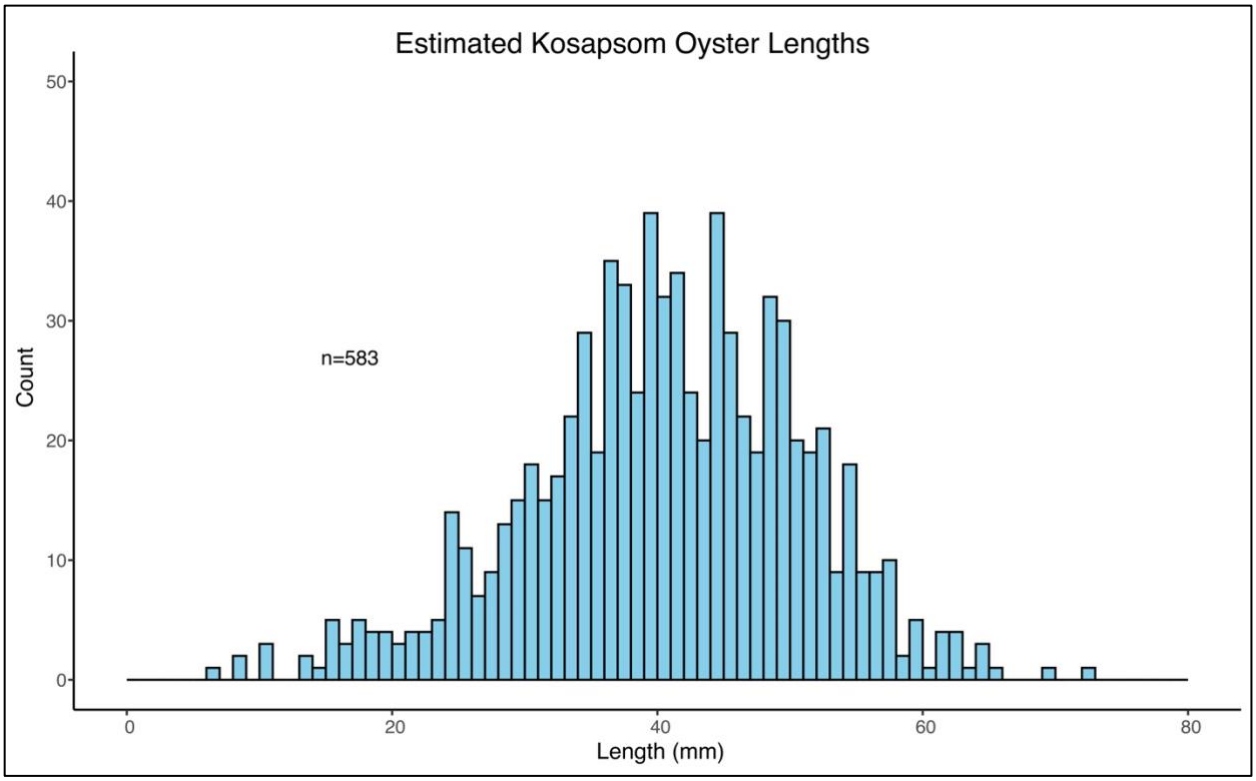

Figure 11: Histogram of estimated Olympia oyster lengths from Kosapsom for all analyzed column sample levels. Oyster shell lengths were calculated by taking each measured hinge thickness from the archaeological sample and plugging that into the regression equation (Table 3). The estimated shell length is on the x-axis in bins of 1 mm increments. The number of estimated shell lengths within each 1 mm increment represents the count on the y-axis. 75% of measured hinges have estimated sizes between 34.26 and 48.07mm.

Changes Over Time

For archaeological oyster sizes for all units measured from Kosapsom 75% of measured hinges have estimated sizes between 34.3 and 48.1 mm (Figure 11). Small differences between

older and younger time periods appear in violin plots, means, and medians (Figure 13; Table 6). To evaluate better differences in time periods, I applied a Kruskal-Wallis test to assess changes by time period at Kosapsom, which resulted in an *H* value of 25, and a p-value of 0.00004 on 4 degrees of freedom, The effect size is small at 0.02. suggesting only small differences between time periods. The results of the Dunn's Multiple Comparisons Test indicate that there are significant differences between ~1800 BP and both ~500 BP and Mixed/Historic Deposits (Table 7), meaning that Olympia oyster size ~1800 BP is smaller than ~500 BP and Mixed/Historic time periods. There are no other statistically significant differences between time periods, However, there does appear to be an incremental increase in mean size following ~1800 BP (Figure 13). The oysters from ~2000 BP are slightly larger on average than the oysters from the ~1800 BP deposits, indicating a slight decrease in size between these two time periods (Figure 13), although the difference is not statistically significant.

Additionally, there is an increase in Olympia oyster relative frequency. For the assemblage dating within the past 500 years (N10-11 E9-10), Olympia oyster is the most frequently occurring shellfish taxa, by both weight and MNI (Wigen 1996:Table 5). However, at older areas of the site (~2000 BP), bay mussel MNI represents a greater proportion of shellfish (Huculak and Pratt 2017:51). MNI of bay mussels from the previously unanalyzed column samples representing ~1500-2000 BP also follows this chronological trend. There is a flip between oyster and mussel relative frequency during this time with oysters becoming the most frequent bivalve at the site around 1500 BP (Table 5). The increase in relative frequency represents an increase in oyster harvesting intensity.

Figure 12: Example of two archaeological Olympia oysters that grew attached. The remnants of Oysters A and B are incomplete left (cupped) valves. Oyster A likely settled on Oyster B based on the larger size of Oyster B. This is preliminary evidence of Olympia oysters growing in clumps and potentially forming reefs.

Table 5: Bay Mussel vs Olympia Oyster MNI from the previously unanalyzed column sample levels. These MNIs are based on subsamples of the larger column sample.

Column Sample Level (meters below datum)	***Unit***	***Time Period[6]***	***Bay Mussel MNI***	***Olympia Oyster MNI***
4.80-4.85	N45-46/E31-32	~1500 BP	8	42
5.05-5.10	N45-46/E31-32	~1500 BP	20	38
5.20-5.25	N45-46/E31-32	~1800 BP	176	57
5.25-5.30	N45-46/E31-32	~1800 BP	264	77
5.30-5.35	N44-45/E31-32	~2000 BP	164	43
5.35-5.40	N44-45/E32-32	~2000 BP	114	35

6 Time period represents an estimate based on relative position between dated contexts.

Table 6: Descriptive Statistics of Estimated Length for Each Time Period Measured.

Unit	***Column Sample Levels (Depth Below Datum)***	***Mean***	***Median***	***IQR***	***SD***	***Min***	***Max***	***n***	***Time Period***	***Shapiro-Wilk Test p-value***
All Combined	All Combined	40.55	40.78	34.26-48.07	10.32	6.90	72.32	785	Historic to ~2000 BP	*p = 0.001*
N10-11/E9-10	7 Levels (5.07-5.40)	41.48	41.51	36.18-48.58	9.69	8.45	72.32	443	Historic/ Mixed	*p < 0.001*
N10-11/E9-10	7 Levels (5.40-5.85)	41.60	41.91	34.11-50.51	11.79	6.90	69.47	140	~500 BP	*p = 0.6*
N45-46/E32-33	4.80-4.85, 5.05-5.10	39.33	40.75	34.28-45.18	9.90	14.73	65.03	64	~1500 BP	*p = 0.2*
N45-46/E31-32	5.20-5.25, 5.25-5.30	36.63	36.99	30.75-43.01	9.58	10.36	62.16	89	~1800 BP	*p = 0.8*
N44-45/E31-32	5.30-5.35, 5.35-5.40	37.85	38.27	29.79-44.06	11.27	8.60	64.48	49	~2000 BP	*p = 1*

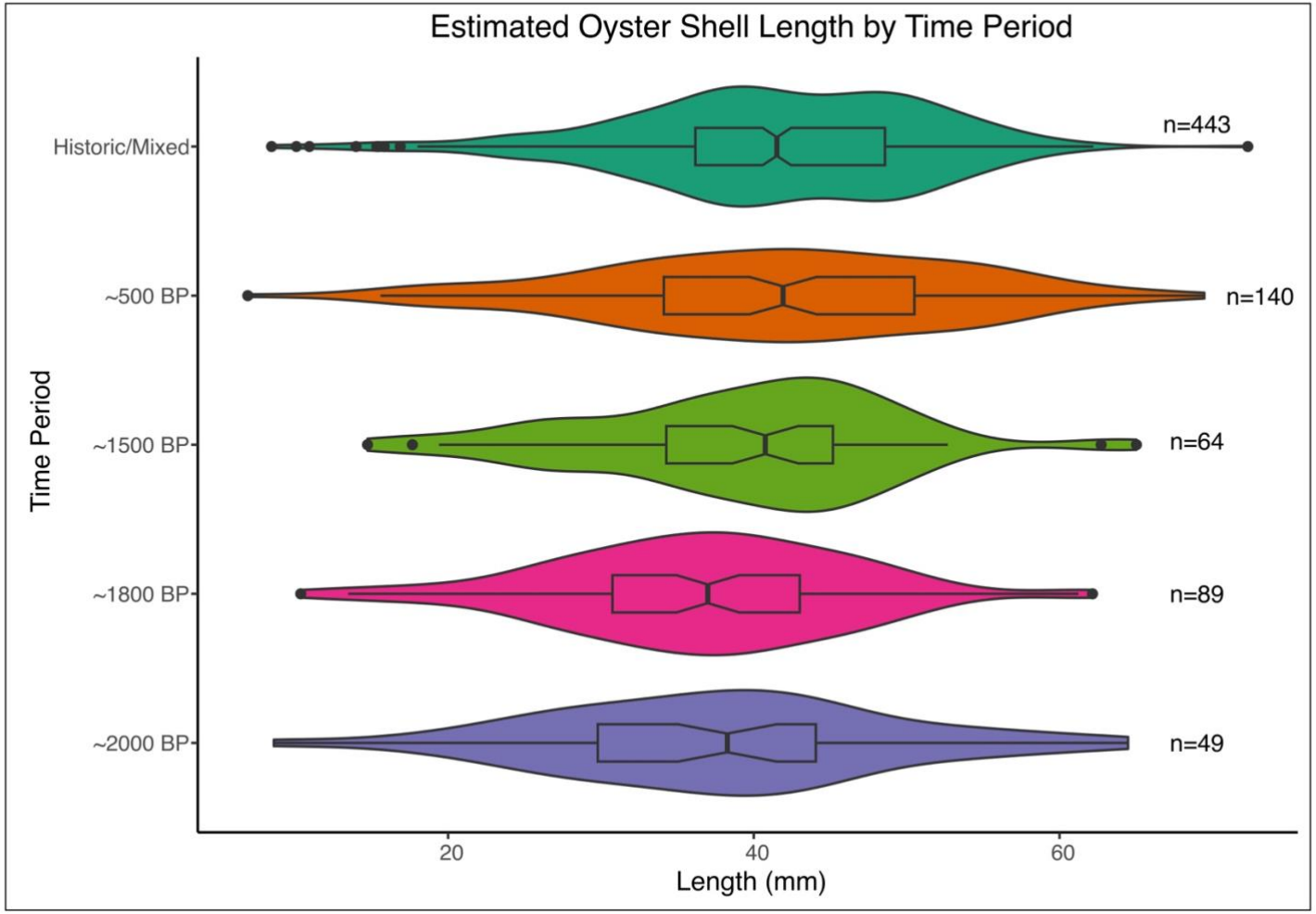

Figure 13: Violin plots of 785 estimated Olympia oyster sizes by time period. The boxplots within the violin plots illustrate the interquartile range (IQR) and the median. The notches on the boxplots represent the 95% confidence interval of the median. The dots represent outliers in each dataset, defined as smaller or larger than 1.5 (IQR).

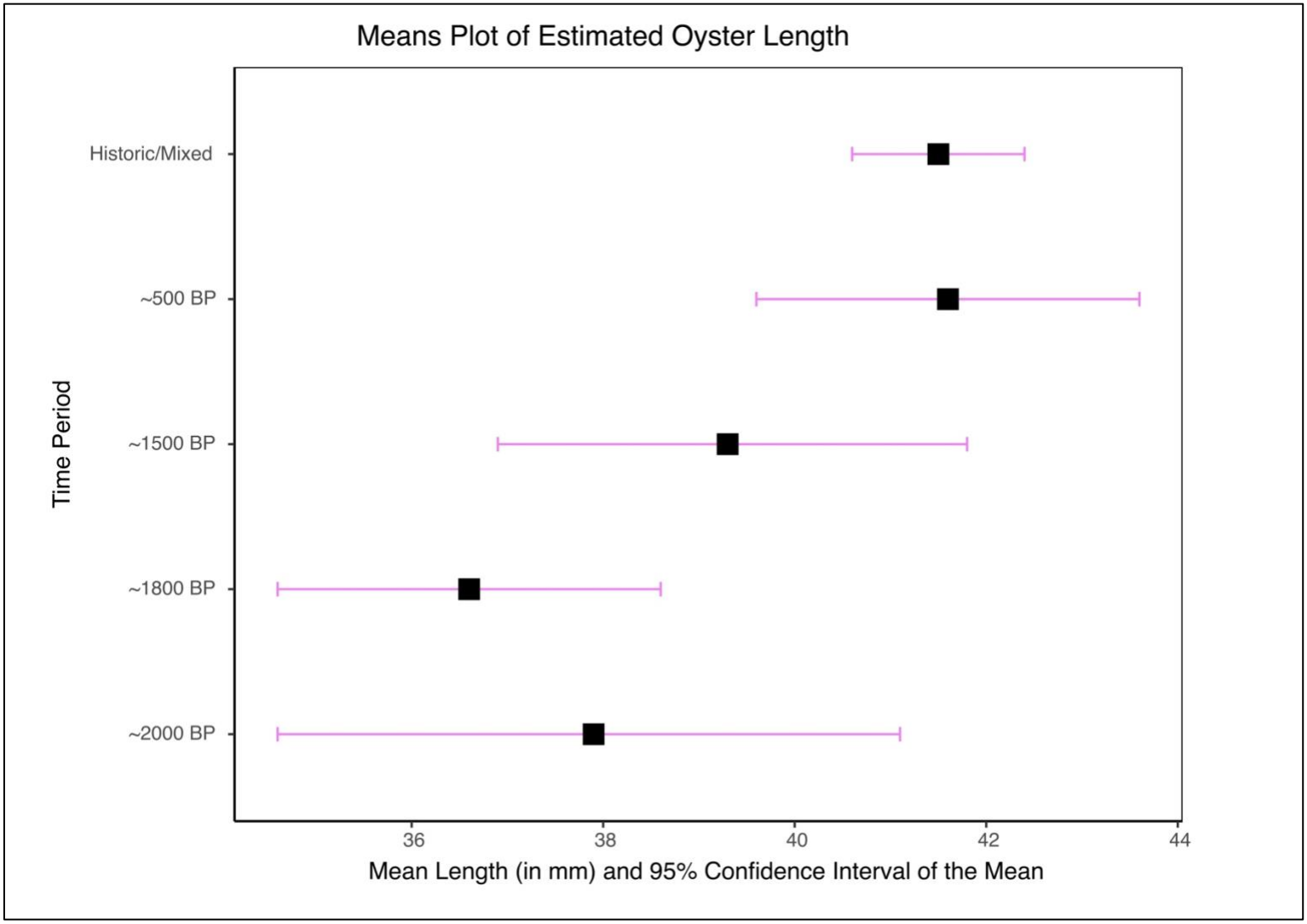

Figure 14: Means and 95% confidence interval of the means of the estimated lengths (mm) by time periods.

Table 7: Results of Dunn's Multiple Comparisons Test between Time Periods. Z-values are listed first followed by *p-values*. Asterisk and yellow cells indicate a significant difference.

	~500 BP	**~1500 BP**	**~1800 BP**	**~2000 BP**
Historic/Mixed	0.03 *p=1.00*	-1.63 *p=0.51*	-4.38 *p<0.001**	-2.51 *p=0.097*
~500 BP		-1.46 *p=0.57*	-3.77 *p=0.001**	-2.29 *p=0.15*
~1500 BP			1.77 *p=0.45*	0.84 *p=1.00*
~1800 BP				-0.73 *p=1.00*

Comparisons to Modern Olympia Oysters

The results of the Mann-Whitney U test indicate that the estimated oyster sizes from Kosapsom are significantly larger than modern Olympia oysters measured in the Gorge Waterway (Figure 15; Table 8). More recent size monitoring data from Norgard et al. (2018) confirms the same pattern (Figure 15; Table 8). The oysters from the Gorge Waterway measured in 2016 are on average, 7.7 mm smaller than the predicted lengths from Kosapsom. This accounts for an 18.9% decrease in mean size and a 16.6% decrease in median size between the time of the occupation of Kosapsom and the last decade. The results of the Mann-Whitney U test comparing Kosapsom to Fidalgo Bay oysters (2015 and 2018) are not statistically significant, indicating no difference in size (Figure 15; Table 8). At Kosapsom, there are sixteen estimated sizes over 60 mm and seven over the 63.5 mm harvest-size requirement in Washington (Washington State Department of Fish & Wildlife 2023). However, only one oyster in any of the modern surveys is over 60 mm long and was encountered during the 2011 Gorge survey (Chalifour et al. 2012).

A Kruskal-Wallis Nonparametric test between the 2016 Gorge Olympia oyster lengths and each of the time periods at Kosapsom resulted in a statistically significant result ($H=95$,

df=5, *p<0.001*). The modern survey data and all archaeological time periods at Kosapsom are significantly different, suggesting that even the smaller Olympia oyster lengths observed at Kosapsom dating to ~1800 BP are larger than modern Olympia oysters in the same area today. The pattern holds true for the 2011 survey size from the Gorge as well.

Table 8: Summary of Mann-Whitney U Test Results Comparing Kosapsom to Modern Olympia Oysters. Asterisk and yellow cell color indicates a significant difference between ancient and modern.

Kosapsom vs	**Test Statistic**	**P-Value**	**Effect Size**	**Magnitude**
Gorge 2016	**W=28511**	***p<0.001****	**0.277**	**Slight (Archaeological oysters are slightly larger)**
Gorge 2011	**W=41395**	***p<0.001****	**0.371**	**Moderate (Archaeological oysters are moderately larger)**
Fidalgo Bay 2018	**W= 11606**	***p = 0.5***	**N/A**	
Fidalgo Bay 2015	**W= 55447**	***p=0.3***	**N/A**	

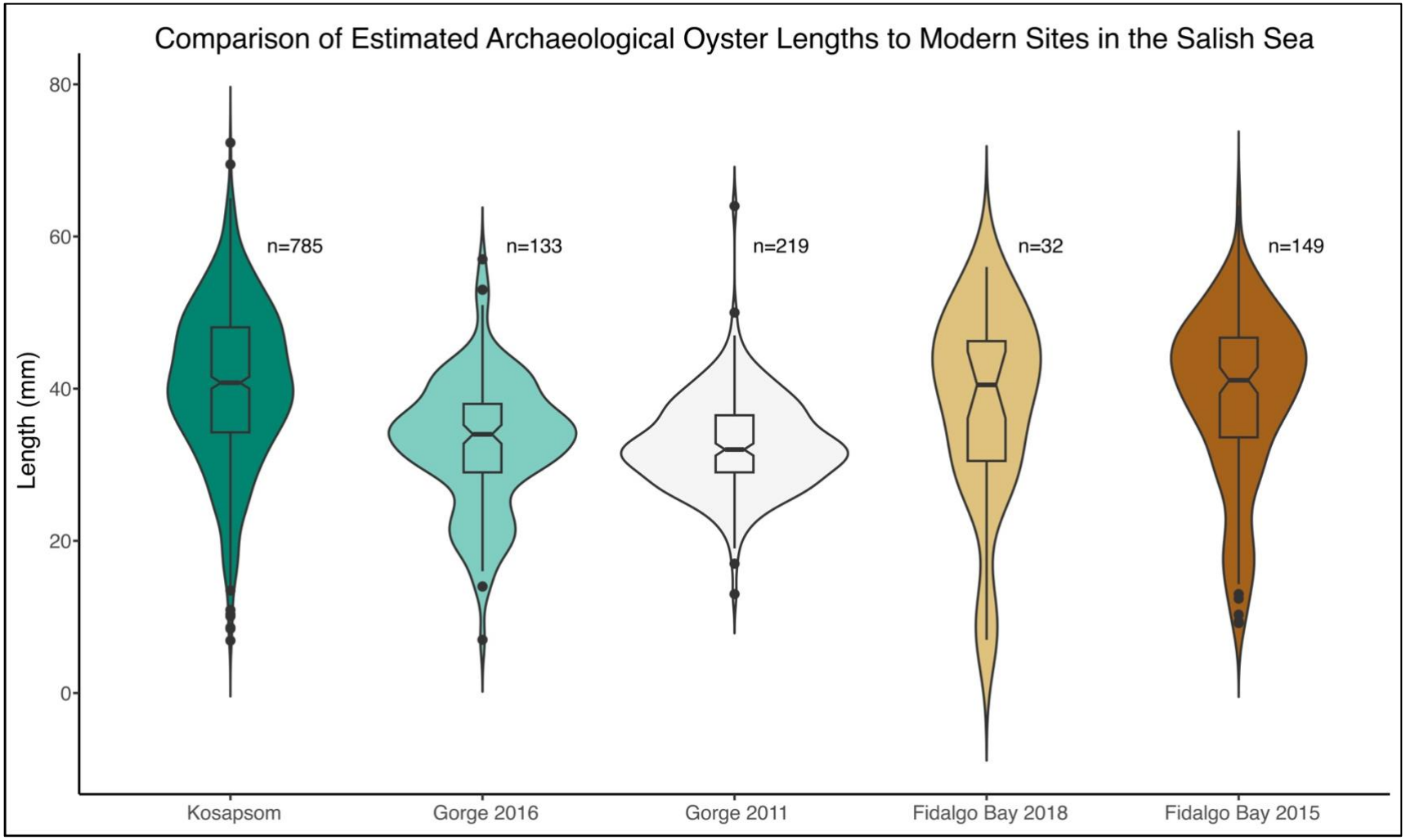

Figure 15: Violin and boxplots of size distributions from the Victoria Gorge (including the archaeological site of Kosapsom as well as 'modern' data from 2011 and 2016 restoration monitoring) and modern restoration efforts in Fidalgo Bay. The boxplots within the violin plots indicate the interquartile range (IQR), the median, and the 95% CI of the median. The dots represent outliers in each dataset, defined as smaller or larger than 1.5(IQR). Modern Gorge data is from Chalifour et al. (2012) and Norgard et al. (2018). Fidalgo Bay data is from Dinnel (2018).

Discussion

This study provides an estimate of shell size-at-harvest profiles from fragmentary left Olympia oyster valves from samples with 100% fine mesh recovery from the precolonial Indigenous archaeological site of Kosapsom. These estimated size-at-harvest profiles and relative abundance calculations indicate that Olympia oysters from Kosapsom increased slightly but significantly between ~1800 BP and ~500 BP. This has implications for understanding past Indigenous management of Olympia oysters, including the potential for population enhancement increased productivity, and or restrained harvests. Additionally, Olympia oyster sizes from Kosapsom are statistically larger than modern Olympia oysters from the modern restoration project that has been in place for over 10 years and aimed to increase oyster populations in the Gorge Waterway. These archaeological size distributions are most similar to Olympia oysters from the larger-scale longer restoration project in Fidalgo Bay that began in 2002. This has implications for understanding modern population health at these locations and could be applied to other areas of the Salish Sea as has been undertaken elsewhere with other oyster species (cf. Rick et al. 2016; Thompson et al. 2020).

Implications for cultivation, management, and sustainable harvesting

The high frequency of Olympia oysters at Kosapsom indicates that there was a very large and healthy oyster population in the Gorge waterway persisting over the past 2000 years which enabled ancestral Songhees and Esquimalt communities to regularly harvest oysters at this location. The relative rarity of archaeologically identified productive Olympia oyster beds within the Salish Sea suggests that highly productive Oyster beds, like those formerly found in abundance in the Gorge Waterway with its restricted access and high visibility from multiple

points on shore, were likely more tightly managed by the community through individual families and households as is documented with other productive shellfish habitats in the Salish Sea (Elmendorf 1960; Lepofsky et al. 2015; Suttles [1951]1974; see this thesis Chapter 2). The human harvest effort and management potentially observed at Kosapsom may have additionally shaped the environmental productivity of oysters.

The sessile nature of oysters and their lifespan of roughly a decade makes them susceptible to overexploitation through overharvesting, as observed in other Pacific Coast bivalves (Codding et al. 2014; Croes 1992; Croes and Hackenberger 1988; Erlandson et al. 2008). This suggests that even no change in Olympia oyster size over time would indicate that management practices were in place. Notably, however, the abundance and size of Olympia oysters at Kosapsom exhibit a small but steady increase in abundance after ~1800 BP with oysters from ~500 BP significantly larger than oysters from ~1800 BP (Figure 14; Table 5; Table 8). This slight increase in Olympia oyster size, despite increased harvesting effort (as indicated by abundance) suggests that management practices were not only successful in maintaining Olympia oyster populations but also expanding the population so that more oysters could be harvested indicating cultivation methods were potentially in place.

To sustain generations of Indigenous harvests reliably for centuries in a constrained estuary would benefit from structured harvest and/or cultivation methods. These methods might aim to control the timing of harvests, the amounts harvested, the method of procurements, and any effort to control predators or sources of pollution or sedimentation. Specific practices and strategies relating to management of plant resources by Indigenous peoples on the Northwest Coast are discussed by Lyons et al. (2021:Table 1) and in more detail by Turner et al. (2013:Table 1). Other clam-specific cultivation strategies are discussed by research relating to

clam gardens including Augustine et al. (2022) and Olsen (2019). A number of these could have been or were likely in place to manage Olympia oyster populations and are listed in Table 9. Such techniques are commonly represented in community-based resource management practices that aim to ensure long-term harvesting stability (Hunn et al. 2003; Lertzman 2009; Turner et al. 2013). For a community relying on nearby resources, “the sustainable management of the resources on which it depends” is a requirement for “its continued existence” (Hunn et al. 2003:S82). Sustainability depends not only on ensuring continued harvesting but also on "managing the ongoing trend in a much larger set of resources, environmental services, and values” (Lertzman 2009:345). When all of this is considered within the Northwest Coast system of proprietorship that incentivizes sustainability (Trosper 2002), it seems likely that Olympia oysters would have been managed to ensure harvesting for future generations. The Northwest Coast system of Indigenous proprietorship is intertwined with a larger value system that works to ensure productive use of land for future generations through reciprocity and public enforcement (ibid.) Failure to act within these systems could result in loss of proprietorships because proprietorship is partially contingent upon sustainable use of resources (Trosper 2009).

While the growth pattern and structure of Olympia oysters differ, future research could determine age-at-harvest for Olympia oysters at Kosapsom to see if traditional management practices led to increasing growth rates, as has been observed with butter clams in the northern Salish Sea (Toniello et al. 2019). Additionally, size-at-age cumulative percentage curves could be determined for Olympia oysters which could be compared to cumulative percentage curves based on estimated shell size from Kosapsom as a proxy of the regularity of the harvest as has been done with mussels in California (Whitaker 2008). Determining the growth-stage profiles of senile vs. juvenile bivalves (Cannon and Burchell 2009) might also be productively utilized to

refine shellfish harvesting strategies and provide additional evidence of resource sustainability, harvest intensity, and cultivation.

Table 9: Management strategies that may have been in place at Kosapsom to tend to Olympia oyster populations.

Practice, Strategy, or Approach from Turner et al. 2013: Table 1	**Relation to Olympia Oysters**	**Supported by Evidence in this Thesis?**
Clearing, weeding, 'cleaning' and predator exclusion	Clearing out of predators such as crabs and sea stars would enhance Olympia oyster growing conditions	Further research needed
Habitat creation, extension, or alteration	Habitat may have been altered through disposing of shells or other hard substrates for spat to grow on	Further research needed
Bounding of resource areas	Relatives closely to proprietorship because ownership of productive beds would be contingent upon knowing the boundaries of the beds	Yes
Selective, partial, rotation, or non-damaging harvesting	Crucial to ensure overharvesting did not occur	Yes
Ownership/proprietorship	Higher productive Olympia oyster locations clustered in the Salish Sea and were likely owned (discussed in more detail in Chapter 2)	Yes
Monitoring	Understanding of oyster population size necessary to know when non-damaging harvesting could occur	Yes
Trade and exchange	Maintain relationships with individuals in other communities	Tentative
Knowledge transmission	Required to maintain harvesting over generations	Yes
Combined management strategies	Management of Olympia oysters would likely also affect other organisms living in the same space	Further research needed

Other factors offer additional insights or explanations to the patterns I observed in changing Olympia oyster size and frequency at Kosapsom. Interpretations of nearby archaeological sites, Indigenous knowledge, cultural-environmental interactions, and climate change offer different facets to the narrative of Olympia oyster abundance and size during ~2000

years of occupation at Kosapsom (Table 10). Multiple factors likely influence the patterns of Olympia oyster frequency and size at Kosapsom; however, the range of data available makes it difficult to parse. Additionally, it is likely a combination of these factors that influences Olympia oyster growth and abundance, with some factors having more impact than others.

The regression-based method developed in this chapter is suitable for use at other archaeological sites with Olympia oysters and can enable size estimates in the Salish Sea through the creation of harvest profiles. This study is the first to estimate Olympia oyster size-at-harvest profiles prior to colonization. The method is suitable for generating measurements from fragmentary specimens that are common in existing small volume sediment and column samples. It is now possible to generate additional size profiles from other archaeological sites to understand if regional differences in size occurred archaeologically and expand evidence of Indigenous Olympia oyster use, potential cultivation, and management.

Olympia Oyster Restoration Efforts

Comparisons between archaeological and modern Olympia oyster sizes suggest that Olympia oyster restoration projects in the Salish Sea can increase Olympia oyster populations if sufficient resources are devoted to the appropriate locations as indicated by archaeological sites with numerous oysters. The oyster length data from Kosapsom provides a new precolonial baseline for a healthy population and can help inform new restoration and conservation goals for Olympia oysters. Although a regional baseline would benefit from additional preindustrial size baselines, this is the only one so far. The data presented here provide a baseline of Olympia oyster sizes prior to European colonization and Olympia oyster fishery collapse.

It is important to consider that the oysters from Kosapsom represent selective human harvesting, especially when comparing them to modern monitoring surveys. Selective human harvesting can influence the size structure of the oyster shells measured for this analysis, likely skewing the archaeological sizes to slightly larger than might be found naturally. However, the effect may be small because Oysters often grow in clumps, and whole clumps were likely harvested at once for easier harvesting. In the ethnographic record, this has been observed for mussels where "women pried sheets of mussels off snags and transported them in that form" (Suttles [1951]1974:65). This will lead to smaller oysters still appearing in the record, but maybe not as frequently due to smaller oysters having more fragile shells which might not survive. Additionally, the smallest estimated oyster size from Kosapsom is 6.9 mm which is smaller than any measurements from the modern surveys in the Gorge Waterway and Fidalgo Bay. Although there are inherent uncertainties when utilizing archaeological data to expand management baselines, the data is still useful because it allows for a better understanding of population changes prior to colonization and industrialization, which are known to have catastrophic effects on ecosystems worldwide (Alleway et al. 2023; Jackson et al. 2001; Morin et al. 2023).

Despite the absence of modern harvests, Olympia oysters in the Gorge Waterway are not growing as large as they did in the past even given restoration efforts. In British Columbia, recreational harvesting of Olympia oysters has been closed since 2007 (Department of Fisheries and Oceans Canada 2009) and all shellfish harvesting in the Gorge is closed due to contamination concerns (British Columbia Centre for Disease Control). This notable size difference has a range of potential implications for future management decisions for Olympia oyster restoration efforts within the Gorge. Chalifour et al. (2012) only encountered one oyster longer than 60 mm (0.46%) and Norgard et al. (2018) encountered none, while there are a total

of sixteen oysters (2.04%) with an estimated length over 60 mm from the Kosapsom sample. Additional research should focus on why Olympia oysters in the Gorge are not growing as large as they did in the past. It likely relates to the urbanized nature of the waterway, but specific factors are worth further exploration.

In this study, 16 archaeological oysters are estimated to be over 60 mm in contrast to the 2018 sample from Fidalgo Bay where none were larger than 60 mm despite the fact that oysters in Fidalgo Bay are not exposed to any recreational harvesting pressure. This is due to the location in waters closed to shellfish harvest near a large oil refinery and other sources of pollution (Washington State Department of Health 2023). The results from this 20-year restoration project in Fidalgo Bay are not statistically different than Kosapsom indicating that the restoration effort in Fidalgo Bay offers an example of how Olympia oyster restoration can increase oyster size and abundance in other areas of the Salish Sea and beyond, especially if similar resources were put forward (e.g., Toft and Peabody 2021). Applying the regression developed in this chapter to an archaeological assemblage with Olympia oysters near Fidalgo Bay such as at Weaverling Spit (e.g., Nelson et al. 2010) would provide a better understanding of changes in size over time in Fidalgo Bay.

Although there is no recent scientific literature on how oyster size affects the reproductive potential of Olympia oysters, Steele (1957:89) attests that "the number of larvae per brood depends generally upon the size of the maternal oyster" and fecundity and size are always positively related. Harvest size (~40 mm) Olympia oysters will produce between 250,000 and 300,000 larvae (Hopkins 1937)[7]. For other viviparous (larvae develop inside the oyster) oyster species, brood size does correlate with shell length (Cole 1941), although the condition of the

[7] The sample size of this study is small (n = 25) and size ranges are only between 23.5 mm and 45.7 mm in length.

maternal oyster also influences egg production, with an oyster in good condition producing 50% more than an oyster in poor condition of the same size (Walne 1964). When this is considered with how Olympia oysters alternate between male and female throughout their lives (Gillespie 2009), this indicates that having larger oysters in the population is crucial for maintaining and growing oyster populations. Similarly, the smaller sizes of Olympia oysters in the Gorge compared to Kosapsom may have consequences for population health. Restoration efforts need to focus not only on increasing oyster numbers but also on ensuring that the oysters are growing large enough to help maintain the population.

There is some evidence Olympia oysters had the potential to form reefs, that is where oysters settle and grow on top of other oysters. I observed tentative evidence of reef formation in the form of archaeological oyster shells growing together in the Kosapsom material (Figure 12). Olympia oyster larvae settle on hard substrate and have been found to prefer other oyster shells (Dinnel et al. 2011). This implies that Olympia oysters may have grown together and potentially formed reefs and clumps over time. Admittedly, this is not a research question I was focusing on as I examined the archaeological material, so there is no quantification of how often this occurred at Kosapsom although I did note it a few times (Figure 12). Currently, the evidence presented here remains speculative and will require additional research examining Olympia oysters for attachment scars and clumped oysters from archaeological sites with this specific research question in mind to find more conclusive evidence.

In addition, thirty oysters from Kosapsom are estimated to be less than or equal to 20 mm long. These very small oysters are unlikely to be harvested specifically for food due to their small size are minuscule amount of edible meat. Since an archaeological site is the product of human activity, the presence of small oysters unlikely to be eaten suggests that they came to the

site as bycatch or ‘riders’ (e.g., Ainis et al. 2014; Whitaker 2008), attached to larger Olympia oysters.

Table 10: Summary of archaeological, cultural, and environmental factors that interrelate with Olympia oysters in the Gorge Waterway.

Other Factors to Consider	Evidence	Interaction with Olympia oysters	Does the evidence in this thesis support this?	Source(s)
Archaeological				
Management & Cultivation	Increase in relative frequency of oysters at Kosapsom over time. Gradual increase in Olympia oyster size since ~1800 cal BP. Limited locations in protect waterways near pocket estuaries or lagoons.	Slight increase and overall stability in size despite more intensive harvesting as a likely sign of management and potentially cultivation Rarer resource more likely to be controlled and managed	Yes	Chapter 3, this thesis Chapter 2, this thesis
Nearby site in the Gorge Waterway: DcRu-5	A site with many Olympia oysters that dates back approximately 4100 cal BP Located in the Gorge narrows adjacent to where "Camossung" was turned to stone.	Illustrates the longevity and interconnectedness of Olympia oysters in the Gorge.	Yes	Keddie 1992:10; Keddie 1991:6
Cultural-Environmental Interactions				
Fire	Increased anthropogenic burning after 2000 BP on southern Vancouver Island	Could have indirect effects on oysters through increased post-fire sedimentation	Tentative	Brown & Hebda 2002a:7
Tsunami Response	Tsunami evidence in Port Angeles across the Strait of Juan de Fuca at Číx^{w}icən around ~1250 BP resulted in reconfiguration of nearshore habitats subsistence strategies and decrease in human population.	In between time periods analyzed for this study at Kosapsom	No	Butler et al. 2019; Hutchinson et al. 2019

Other Factors to Consider	Evidence	Interaction with Olympia oysters	Does the evidence in this thesis support this?	Source(s)
Tsunami Response Continued	Evidence of an earthquake ~2000 BP, interpreted as causing a hiatus in occupation at the Maplebank Village site and shift to different food sources after reoccupation	Earthquake could overlap with oldest period analyzed for this thesis, which others have argued resulted in people moving to Kosapsom from Maplebank (DcRu-12)	Equivocal: radiocarbon dates from Kosapsom show near continuous occupation over the past 3000 years	Blais-Stevens et al. 2011: Figure 5; Stewart et al. 2020
Physical Environmental Change				
Sea Surface Temperature (SST)	SST fluctuates between 8.5°C and 13.5°C on average in the Saanich Inlet throughout the Holocene on a 100-year time scales. Smaller changes undetectable due to error estimates	More local undetectable fluctuations may affect oyster growth on smaller time scales	Tentative, further research needed	McQuoid & Hobson 2001: Figure 6
Sea Level Rise	Sea levels of 0.5 m lower at ~2000 and gradually rising afterwards in the Gulf Islands. Marine signature as early as ~5000 BP in Portage Inlet (near Kosapsom in the Gorge), sea levels need to be 4 m lower to avoid marine inundation.	Lower sea levels could suggest less water flow and too much freshwater input in the Gorge which could negatively impact oyster growth or lower sea levels could create warmer temperatures which would create better reproductive opportunities for oysters	Tentative, further research needed	Fedje et al. 2009:Figure 3 Clague et al. 1982
Salinity Levels	Salinity fluctuates between 28.5 and 30.5 ppt during the Holocene on a 100-year average in the Saanich Inlet. Smaller changes are undetectable due to error estimates	Proximate record may not represent salinity levels in the Gorge, but does give an idea that salinity is not changing dramatically in the region	Tentative, further research needed	Hobson et al. 2001; McQuoid & Hobson 2001: Figure 6
Air Temperature	~2000 BP and onwards temperatures are cooler.	Cooling happens before the time periods represented in this study.	No	Hebda 1995:62

Other Factors to Consider	Evidence	Interaction with Olympia oysters	Does the evidence in this thesis support this?	Source(s)
Air Temperature Continued	Roman Warm Period ~2000-1500 BP Little Ice Age ~500 BP	Warmer temperature could mean better growing conditions or die offs during low tides during the day in the summer; Kosapsom oysters are smallest on average at ~1800 BP. Little Ice Age could mean worse growing conditions, but oysters are larger on average.	Tentative, further research needed	Hutchinson et al. 2019: Figure 6
Precipitation	Wetter after ~3400-2000 BP	Shift to wetter climate happens before time periods represented in this study.	No	Brown & Hebda 2002b: 369
Indigenous Knowledge				
Proprietorship	System based on 1) rights of access and valuable resource sites were controlled as property 2) "Proprietorship was contingent on proper management of the property" 3) System of ethics defined proper and improper use of land 4) System of reciprocity 5) "Enforcement of reciprocity rules were totally public" 6) "Rules about the behavior of chiefs provided a system of governance that could maintain the other five elements and allow modifications as needed"	Proprietorship incentivized sustainable management. As productive Olympia oyster beds were likely managed and owned as property by families, their continued proprietorship depended on managing the oysters sustainably.	Yes	Trosper 2002:323-333

Other Factors to Consider	Evidence	Interaction with Olympia oysters	Does the evidence in this thesis support this?	Source(s)
Indigenous Oral History	Recounted by Songhees chief Jimmy Fraser discussing the Tillicum Narrows in the Gorge: *"After the Flood when Raven, Mink, and the Transformer Hayls (xɛ̓ls) were travelling around teaching the people how things were to be done, they came to this place, and found a young girl and her grandfather. The girl, q'amaʹsəŋ [Camossung] sitting in the water, crying. "Why are you crying?" asked xɛ̓ls. "My father is angry with me, and won't give me anything to eat." "What would you like?" he asked, "sturgeon?" "No". "Berries?" "No". She refused a lot of things, and that is why these are not found along the Gorge. "Ducks?" "Herrings?" "Cohoes?" "Oysters?" These she accepted, and that is why they are plentiful here."* *"You will control all of these things for your people", said xɛ̓ls. Then he turned her into stone, sitting there under the water, looking up the narrows. Her grandfather's name was Snukaymelt (snək'ɛ́məlt) "diving". Since she liked her grandfather to be with her, he was also turned to stone, as if jumping in carrying a rock to take him to the bottom."*	Explanation for why oysters are plentiful in the Gorge.	Yes	Jimmy Fraser in Duff 1969:36
Potlatches and Feasting	Most durable of potlatch goods obtained in exchanges with food Need to feed guests and rare foods are appreciated	Rare resource valued as exchangeable for goods, incentivized distribution of oysters at potlatches as a rare food source	Yes	Kennedy and Bouchard 1990:448; Perodie 2001:194; Snyder 1975:156; Suttles and Lane 1990:497

Conclusions

This chapter developed a method to evaluate the size of fragmentary archaeological oysters and demonstrated there is a strong predictable relationship between the thickness of the hinge and the total length of Olympia oysters. This method has a reasonable rate of accuracy in that 86% of the variability in shell length is captured in this hinge-length regression model. With access to low-cost digital calipers, this effective measurement technique can now be used to estimate the length of Olympia oysters from fragmentary remains in other archaeological deposits in the Salish Sea where they occur.

I then applied this method to an archaeological assemblage from Kosapsom, a settlement in Greater Victoria known to contain high frequencies of Olympia oysters spanning 3000 years and one of a few sites in the Salish Sea with a hyperabundance of this species. The increase in abundance and size of Olympia oysters at Kosapsom indicates traditional management practices were likely in place to maintain and grow the oyster population throughout the occupation of the village and to ensure that overharvesting did not occur. Specific management practices and how regional values likely influenced Olympia oyster management are discussed in more detail in a section above. This research contributes to the growing recognition of Indigenous shellfish management practices on the Northwest Coast and beyond.

When the archaeological size estimates from Kosapsom are compared with modern data from restoration projects, it appears that Olympia oyster populations are still recovering following overharvesting beginning in the late 19th century (cf. Kirby 2004; Toft and Peabody 2021). This ability to estimate size from archaeological data is important for examining human-shellfish relationships and the current condition of coastal ecosystems and estuaries in the Salish Sea. Understanding past size is useful in extending ecosystem baselines that include size because

larger oysters produce more offspring and are integral in maintaining and growing populations in the Salish Sea.

Chapter 4 Conclusions: Under Recognized Variability in Coast Salish Shellfish Harvesting Through the Lens of Oysters and Historical Ecology

The study of shellfish from archaeological sites on the Northwest Coast has much to offer to better understand ancient Indigenous shellfish fisheries, human-shellfish relationships, and changing environments. Studying ancient shellfish provides pre-industrial baselines that are valuable for modern management because archaeology offers the ability to better understand the millennia-long interactions between people and environments (Rick 2023) and the past state of ecosystems (Balée 2006; Jackson 2001; Jackson et al. 2001). This thesis has sought to address the continued relevance of shellfish through the exploration of Olympia oysters in the Salish Sea. In this Chapter, I review the research questions I asked in Chapter 1 and summarize how they are answered in Chapters 2 and 3. Following this, I examine future research options. I end by discussing how Olympia oysters fit into archaeological research on the Northwest Coast and the implications for future management strategies.

Review of Research Questions

1. *How does archaeological Olympia oyster abundance vary in the Salish Sea and compare with modern Olympia oysters in the Pacific Northwest?*

In Chapter 2, I compiled data from 42 archaeological sites in the Salish Sea to explore archaeological Olympia oyster abundance and identified variation Focusing on archaeological sites with comparable systematic data recovery, 17 sites with Olympia oysters had relative

frequency data reported and of these only four (23.5%) have relative frequency values above fifteen percent, by either Minimum Number of Individuals (MNI) or weight (Figure 4). I interpret this to indicate that there were only a few locations with large and readily accessible Olympia oyster populations in proximity to these archaeological sites. The unique locations of the sites with high oyster abundance are in shallow protected waterways near pocket estuaries or lagoons, habitats ideal for oyster growth (Figure 5; Figure 6).

As my research indicates, Olympia oysters have specific habitat requirements that lead to them being especially abundant in a few locations. As a spatially clustered resource, Olympia oysters appear to have been valued as a food resource and may even have been exchanged between Coast Salish communities. This, in turn, may have influenced the maintenance of affinal ties between family relatives, communities, and even language groups. Marriage ties and family connections offered a long-term advantage whereby trust and care established between villages and households in different areas enabled access to rarer resources and helped buttress against times of potential scarcity (Kennedy 1995; Suttles [1960]1987). Additionally, trading oysters could have been a way for people with access to maintain reciprocal obligations and accrue prestige. At places where Olympia oysters are unusually abundant, Olympia oysters may have additionally been a feasting food, especially if the hosts were known for their unique local specialty foods. As at Kosapsom, locally abundant but otherwise relatively rare species such as Olympia oysters were likely fed to visitors by communities who controlled access to them. Affinal ties and wealth sharing suggest that Olympia oysters (as a comparatively rare resource) may have been positively strengthening and upholding these relationships. Considered over the timescales of centuries and even millennia, the persistence of a well-managed abundant oyster habitat may reflect this investment in place-based associations with food.

By comparing archaeological, historical, and modern Olympia oyster locations in the Salish Sea, I found that archaeological locations correspond with both historic and modern locations with few exceptions (Figure 2). However, in some areas where there are historic and/or modern Olympia oysters there are no archaeological sites with Olympia oysters nearby. This could be due to a lack of sampling effort and/or a lack of comprehensive analysis and description (e.g., Lyman 1995). This is especially the case in areas such as Southern Puget Sound and Hood Canal where historic and/or modern occurrences are abundant. Similarly, in a few instances, there are archaeological sites with no historic or modern recorded locations nearby, which could indicate a lack of surveying effort, local extirpation, and/or transport of oysters from areas with highly productive beds. Further research and scrutiny of primary reports and future research and sampling effort will help address this uncertainty, but this review of existing data suggests strong variability in oyster abundance that connects to the broader role of maintaining family relations in the Coast Salish world discussed by Suttles (1987) and shared publicly by many knowledgeable Salish elders.

2. *How does the size distribution of Olympia oysters at Kosapsom compare to modern size distributions in the Salish Sea?*

In Chapter 3, I developed a method for estimating ancient Olympia oyster size-at-harvest at the Kosapsom Village site. To do this I developed a size-based estimation method using regression that can accurately estimate the total length from the fragmentary left hinges (Figure 8). I then applied this method to hinges from deposits in Kosapsom to generate a size profile at the site as a whole and in chronologically separate deposits. I compare these human harvest records to the ecological samples of oysters at two modern restoration sites in the Salish Sea. I

found that Olympia oysters in the Gorge waterway are on average 7.6 mm smaller today than at Kosapsom. However, the estimated size distribution from Kosapsom is like the restoration site in Fidalgo Bay, where millions of Pacific oyster shells were distributed into the water over the past few decades and where Olympia oyster spat have begun to settle onto indicating that restoration is possible with sufficient resources. Having larger oysters in the population is important because larger oysters produce more offspring (Steele 1957). The substantial observed size difference in Olympia oysters between ancient Kosapsom and the modern Gorge waterway today suggests that other factors are limiting Olympia oyster restoration in the Gorge. It is notable that without this baseline, such contrasts would not be known. This thesis has demonstrated the possibility of obtaining size data from ancient samples and its potential to consider contemporary Olympia oyster restoration and population health. To determine the Indigenous harvest profile of oysters more broadly in the Salish Sea, future research efforts will need to generate measurement data from other archaeological collections. Additionally, it will be important to discuss results with communities and restoration ecologists to better understand the possibility that larger oysters were more common in the past relative to today.

3. *What do oyster abundance and size distributions at Kosapsom indicate about Indigenous harvesting practices and cultivation techniques?*

Throughout this thesis, I have sought to consider how Olympia oyster abundance and size may relate to Indigenous harvesting and cultivation techniques. In Chapter 2, I examined how Olympia oyster locations and frequency relate to how Olympia oyster harvesting may have been used for trade exchange and transplantation in the past. Olympia oysters occur in high frequencies in archaeological sites that are located near microhabitats conducive to oyster

growth. The spatially concentrated nature of Olympia oysters may have led to community-based management and harvesting restrictions. In Chapter 3, I explored how changing size frequencies at Kosapsom may relate to different harvesting and cultivation strategies. The increase in abundance and slight yet statistically significant increase in size of Olympia oysters at Kosapsom over 1800 years would have benefited from structured harvest and cultivation strategies to maintain harvests for generations, as unstructured harvesting would predict declines in both abundance and size. The nature of the Gorge Waterway and the proximity of Kosapsom to known Olympia oyster populations suggests that very little harvesting would have been possible without the permission of the proprietors. Long-term sustainability would have necessitated active management to maintain Olympia oyster population levels and sizes, suggesting that even no change in size over time would indicate active management. The increases in size (Figure 13) and relative abundance (Table 5) over time at Kosapsom seem highly unlikely in the absence of structured harvesting.

Future Research

Archaeological projects need to more frequently recognize the value of collecting and analyzing shellfish, especially in coastal sites where they are often ubiquitous within sites, but where they also may occur in low frequencies except for a few specific locations. This also means that archaeological consulting and cultural resource management projects need to ensure that shellfish analysis is built into basic budget line items for any project involving 'shell midden' deposits. In Chapter 2, I explore archaeological occurrence and abundance data for Olympia oysters. However, 60% of the 42 examined sites with oysters did not even report the relative frequency of shellfish and instead only have species lists (cf. Lyman 2015). This

illustrates a need for archaeologists to prioritize systematic collecting and quantitative analysis of shellfish from 'shell midden' deposits. Controlled volume samples (i.e., column samples, augers, bulk samples, etc.) represent an effective sampling solution that does not require bringing an entire site back to the lab (only a few dozen litres). Revisiting existing archaeological collections in repositories and making efforts to measure oyster valves to generate size estimates would greatly improve our understanding of precolonial Olympia oyster size. Making such elementary shellfish analysis a habitual part of future coastal excavations would greatly enhance our understanding of the enduring relationships between shellfish and people on the Northwest Coast.

In conjunction with collecting and reporting relative frequency of shellfish from archaeological sites, archaeologists can also measure them to understand past harvesting strategies and expand baselines. In Chapter 3, I develop a regression to estimate past Olympia oyster size. Other sites with high frequencies of Olympia oysters in the Salish Sea (Figure 3) are great candidates for applying this regression to other sites. Applying this to regression to the sites, particularly in Southern Puget Sound, Fidalgo Bay, Sinclair Inlet, and Hood Canal would expand the understanding of Indigenous harvesting practices and potential management strategies in the Salish Sea. Identifying additional details available in historical literature will provide further insight into changes over time and the timing of collapse in various areas within the Salish Sea. This would also contribute to baselines prior to European colonization and overharvesting which would be additionally useful for current and future restoration projects.

Additional modern Olympia oysters could be measured and added to the regression presented in Chapter 3 to explore regional variation and expand the size range. Measuring complete Olympia oysters from other areas of the Salish Sea from entirely natural populations

would provide the ability to improve the applicability of the method. Measuring more oysters would also expand the size range to include more larger and smaller oysters. Currently, estimation from the model is constrained to oysters between 21.7 and 56.9 mm long. Expanding the size range would increase the accuracy of the model in estimating Olympia oyster size outside of that size range.

Examining archaeological oyster shells in the Salish Sea could expand biological knowledge about specific parasites. Recently, Martinelli et al. (2020) determined the presence of a shell-boring parasite *(Polydora websteri*) in Washington State, however, they are unsure whether it is an introduced species or native to the region. Morphological examination of archaeological oyster shells could also be examined to potentially confirm the historic occurrence of *Polydora websteri* as a factor influencing the size and health of oyster populations observed in the past and today.

Evidence for Indigenous Olympia oyster cultivation could also be strengthened by calculating the ratio of right and left oyster valves from archaeological sites as has been done in other areas of the world (cf. Jenkins 2017; Winder 2017). If the ratio of right to left valves is not even, it may suggest one side of the shell was systematically returned to the water to provide oyster larvae something to attach to and increase productivity (cf. Augustine et al. 2022; Groesbeck et al. 2014). If this is found at archaeological sites in the Salish Sea, it could be additional evidence of cultivation, especially when paired with other lines of potential evidence discussed in this thesis.

Additionally, answering whether or not Olympia oysters formed reefs may be addressed by examining archaeological material for proof of attachment scars and the presence of many oysters growing in clumps. By clumps, I refer to two or more oysters growing together. Over

generations, these clumps may grow together to form 3-D habitats referred to as "oyster beds" (Blake and Bradbury 2012). The occurrence of these attributes could be quantified by counting them and creating a percentage based on the MNI of oysters within the same volume examined as has been done with attachment scars in Atlantic oysters (cf. Jenkins 2017; Jenkins and Gallivan 2020). If the percentage of oysters with attachment scars or oysters growing in clumps is high, it would be additional evidence of Olympia oysters forming reefs.

Implications for Restoration, Management, and Reconciliation

The near extirpation of Olympia oysters in some areas of the Salish Sea following overharvesting by Europeans in the 1800s, and the dramatic decrease in other areas, is further evidence of the need for acknowledging the loss of ecosystem health and for working towards reconciliation with Indigenous peoples. Archaeological evidence from the Kosapsom village site presented in Chapter 3 suggests that Olympia oyster populations increased over 1800 years as represented by increases in both proportional abundance and absolute size over time (Table 6; Table 5; Figure 13; Figure 14). To sustain this increase would have necessitated structured harvesting methods and community-based resource management practices. A more in-depth discussion of sustainable harvesting at Kosapsom is presented in the Chapter 3 section titled "Implication of cultivation, management and sustainable harvesting." Additionally, Olympia oysters are not growing as large as they did in the past in the Gorge Waterway (*see* Chapter 3), even in the absence of human harvesting pressure. British Columbia Olympia oyster harvesting in closed as of 2007 (Department of Fisheries and Oceans Canada 2009) and in Washington oyster harvest size requirements in so large that virtually no Olympia oysters can be harvested legally (Washington State Department of Fish & Wildlife 2023). A consequence of this is that

the access by Indigenous peoples to harvest a cultural food is limited (e.g., Gavenus et al. 2023). Management decisions and restoration plans should include archaeological evidence and Indigenous knowledge and foster relationships with local communities (Alleway et al. 2023; Grenz and Armstrong 2023; Hatch et al. 2023; Reeder-Myers et al. 2022).

The ancient harvest size profiles constructed in Chapter 3 of this thesis provide an extended baseline for Olympia oysters prior to European colonization. Such data could be utilized in restoration projects as an additional metric to assess the health of Olympia oyster populations. Larger oysters are known to produce more offspring (Hopkins 1937; Steele 1957) and this is consistent with a host of organisms including fish (Birkeland and Dayton 2005). Comparisons to modern Olympia oysters imply that modern oysters are not always reaching sizes found in the past. At the long-term Fidalgo Bay restoration site, oysters are similar in size to those from Kosapsom likely due to the large-scale nature of the restoration project and the resources that have been devoted to it. At the Gorge restoration site, Olympia oyster sizes are smaller than Kosapsom oysters. This has consequences for population health that restoration efforts should address by focusing on ways to keep Olympia oysters alive long enough to reach larger sizes.

This thesis is part of a broader effort to include Indigenous histories and environmental records as part of ecosystem management tools. As my coauthors and I argued (Reeder-Myers et al. 2022) and the data presented in this thesis further indicate, oyster histories should be used to guide future oyster management and in addition to the health of local bays and waterways, help restore the persistent and ongoing relationships between Indigenous peoples and the enduring food to the Salish Sea and beyond. Archaeological datasets offer the opportunity to better

understand past human-environmental relationships and should be used alongside other forms of Indigenous knowledge to help guide future restoration and management.

Appendix A: Supplementary Information for Chapter 3

Overview

Appendix A provides the measurement data of complete modern Olympia oysters used to generate the regression model presented in Chapter 3. It also includes the R Script created to generate this regression and predict new data points from measured left hinges. This can be used as a resource for estimating Olympia oyster size from other archaeological sites in the Salish Sea.

Table 11: Modern Olympia oyster measurements used to develop a regression to predict Olympia oyster size. All oysters were harvested in December of 2021. For raw data in .xlsx or .csv format please contact the author. Asterisk indicates unmeasurable hinges (incomplete).

Catalogue Number	Common Name	*Taxonomic Name*	Age Notes[8]	Paired	Dorsal Length	Hinge Thickness Left Valve	Hinge Thickness Right Valve
1	Olympia Oyster	*Ostrea lurida*	HS	Yes	53.65	9.87	7.47
2	Olympia Oyster	*Ostrea lurida*	HS	Yes	48.26	6.37	6.66
3	Olympia Oyster	*Ostrea lurida*	HS	Yes	52.20	7.43	6.39
4	Olympia Oyster	*Ostrea lurida*	HS	Yes	53.22	7.67	6.56
5	Olympia Oyster	*Ostrea lurida*	HS	Yes	44.73	7.62	5.67
6	Olympia Oyster	*Ostrea lurida*	HS	Yes	54.74	8.26	6.51
7	Olympia Oyster	*Ostrea lurida*	HS	Yes	50.05	8.16	5.67

[8] HS = Harvest Size; S19G = Summer 2019 Ground; F19GB = Fall 2019 Grow Bag; S20GB = Summer 2020 Grow Bag

Catalogue Number	Common Name	*Taxonomic Name*	Age Notes[8]	Paired	Dorsal Length	Hinge Thickness Left Valve	Hinge Thickness Right Valve
8	Olympia Oyster	*Ostrea lurida*	HS	Yes	48.66	8.10	5.74
9	Olympia Oyster	*Ostrea lurida*	HS	Yes	47.32	8.41	5.68
10	Olympia Oyster	*Ostrea lurida*	HS	Yes	54.29	8.89	6.55
11	Olympia Oyster	*Ostrea lurida*	HS	Yes	52.65	7.33	5.77
12	Olympia Oyster	*Ostrea lurida*	HS	Yes	54.58	8.46	5.94
13	Olympia Oyster	*Ostrea lurida*	HS	Yes	56.11	9.88	8.00
14	Olympia Oyster	*Ostrea lurida*	HS	Yes	56.87	11.06	7.76
15	Olympia Oyster	*Ostrea lurida*	HS	Yes	52.31	9.96	9.26
16	Olympia Oyster	*Ostrea lurida*	HS	Yes	53.28	9.23	6.92
17	Olympia Oyster	*Ostrea lurida*	HS	Yes	50.00	8.63	6.87
18	Olympia Oyster	*Ostrea lurida*	HS	Yes	53.82	7.89	5.42
19	Olympia Oyster	*Ostrea lurida*	HS	Yes	51.58	7.37	*
20	Olympia Oyster	*Ostrea lurida*	HS	Yes	51.44	8.85	7.30
21	Olympia Oyster	*Ostrea lurida*	HS	Yes	45.94	7.95	7.22
22	Olympia Oyster	*Ostrea lurida*	HS	Yes	52.03	7.85	5.55
23	Olympia Oyster	*Ostrea lurida*	S19G	Yes	45.50	6.73	6.00
24	Olympia Oyster	*Ostrea lurida*	S19G	Yes	42.70	6.41	4.57
25	Olympia Oyster	*Ostrea lurida*	S19G	Yes	45.32	6.96	4.22
26	Olympia Oyster	*Ostrea lurida*	S19G	Yes	40.07	5.81	3.81
27	Olympia Oyster	*Ostrea lurida*	S19G	Yes	40.06	5.96	5.44
28	Olympia Oyster	*Ostrea lurida*	S19G	Yes	45.44	6.00	4.72
29	Olympia Oyster	*Ostrea lurida*	S19G	Yes	40.57	6.02	5.01
30	Olympia Oyster	*Ostrea lurida*	S19G	Yes	35.98	5.55	4.32
31	Olympia Oyster	*Ostrea lurida*	S19G	Yes	37.63	5.76	4.67
32	Olympia Oyster	*Ostrea lurida*	S19G	Yes	41.30	5.83	4.42

Catalogue Number	Common Name	*Taxonomic Name*	Age Notes[8]	Paired	Dorsal Length	Hinge Thickness Left Valve	Hinge Thickness Right Valve
33	Olympia Oyster	*Ostrea lurida*	S19G	Yes	42.38	5.58	4.52
34	Olympia Oyster	*Ostrea lurida*	S19G	Yes	44.66	5.81	4.27
35	Olympia Oyster	*Ostrea lurida*	S19G	Yes	41.53	6.56	6.18
36	Olympia Oyster	*Ostrea lurida*	S19G	Yes	43.55	7.28	4.95
37	Olympia Oyster	*Ostrea lurida*	S19G	Yes	40.14	6.15	4.47
38	Olympia Oyster	*Ostrea lurida*	S19G	Yes	34.19	5.68	4.46
39	Olympia Oyster	*Ostrea lurida*	S19G	Yes	39.50	6.12	5.35
40	Olympia Oyster	*Ostrea lurida*	S19G	Yes	42.85	5.81	4.38
41	Olympia Oyster	*Ostrea lurida*	S19G	Yes	40.86	5.27	4.03
42	Olympia Oyster	*Ostrea lurida*	S19G	Yes	40.39	5.43	4.51
43	Olympia Oyster	*Ostrea lurida*	S19G	Yes	49.37	5.81	4.07
44	Olympia Oyster	*Ostrea lurida*	S19G	Yes	44.94	6.31	4.32
45	Olympia Oyster	*Ostrea lurida*	S19G	Yes	33.50	5.34	4.57
46	Olympia Oyster	*Ostrea lurida*	S19G	Yes	38.73	6.14	4.20
47	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	44.73	5.84	4.43
48	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	49.87	5.96	5.20
49	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	40.68	5.03	2.90
50	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	48.48	6.28	4.35
51	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	50.92	6.95	5.52
52	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	48.07	6.04	3.77
53	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	46.05	5.86	5.18
54	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	45.78	6.90	3.48
55	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	37.74	5.91	4.73
56	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	43.41	6.28	4.97
57	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	42.13	6.12	5.06

Catalogue Number	Common Name	*Taxonomic Name*	Age Notes[8]	Paired	Dorsal Length	Hinge Thickness Left Valve	Hinge Thickness Right Valve
58	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	45.26	6.37	4.63
59	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	41.08	6.71	5.56
60	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	43.20	5.72	3.79
61	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	42.29	5.65	4.96
62	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	48.00	6.63	5.94
63	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	53.32	6.40	6.46
64	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	47.76	6.12	4.84
65	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	46.91	6.87	5.59
66	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	42.41	5.14	4.67
67	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	51.79	6.49	*
68	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	31.39	4.54	2.88
69	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	37.46	5.15	4.86
70	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	47.20	6.67	5.35
71	Olympia Oyster	*Ostrea lurida*	F19GB	Yes	41.49	6.22	4.57
72	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	33.74	5.37	5.07
73	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	41.05	6.35	5.18
74	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	48.63	5.96	5.99
75	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	39.60	6.02	3.85
76	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	41.35	5.97	4.86
77	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	41.98	6.81	*
78	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	39.74	6.80	4.26
79	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	40.92	6.06	4.56
80	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	34.08	4.93	4.10
81	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	39.10	5.33	3.47
82	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	40.05	5.14	4.87

Catalogue Number	Common Name	*Taxonomic Name*	Age Notes[8]	Paired	Dorsal Length	Hinge Thickness Left Valve	Hinge Thickness Right Valve
83	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	37.75	5.36	4.07
84	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	37.60	5.12	*
85	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	39.06	6.46	4.42
86	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	41.90	6.35	3.95
87	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	41.92	7.21	5.16
88	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	43.71	5.49	3.47
89	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	38.80	5.98	3.98
90	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	38.95	5.56	4.78
91	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	43.44	5.68	4.26
92	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	41.29	5.80	4.04
93	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	39.41	5.44	3.50
94	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	37.18	4.90	4.47
95	Olympia Oyster	*Ostrea lurida*	S20GB	Yes	46.82	6.48	5.16
96	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	27.27	3.82	3.44
97	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.91	5.06	3.92
98	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	21.72	3.29	3.11
99	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.09	3.63	2.81
100	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.77	4.61	3.12
101	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	24.57	3.99	3.69
102	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	23.96	3.09	1.95
103	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	21.68	2.88	2.06
104	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.24	3.53	3.08
105	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	26.05	4.13	2.98
106	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.50	4.32	3.15
107	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.09	3.91	3.41

Catalogue Number	Common Name	*Taxonomic Name*	Age Notes[8]	Paired	Dorsal Length	Hinge Thickness Left Valve	Hinge Thickness Right Valve
108	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.15	3.29	*
109	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	24.32	3.50	2.48
110	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	24.21	3.21	2.74
111	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	24.65	3.90	3.05
112	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	23.56	3.23	3.05
113	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.52	3.42	2.65
114	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	27.17	3.97	2.68
115	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	22.91	3.49	3.37
116	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	26.48	3.34	3.22
117	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	26.26	3.44	*
118	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	26.01	3.70	2.02
119	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	23.25	3.10	3.13
120	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	22.26	3.94	3.08
121	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.14	3.68	3.05
122	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	26.14	3.44	2.41
123	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	22.57	3.39	2.08
124	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	25.31	3.34	3.03
125	Olympia Oyster	*Ostrea lurida*	< 1 Year	Yes	28.71	3.57	2.82

R Script

```
#Log Hinge Width Regressions and Predictions
#Taylor Vollman
#Start Date: 28 Feb 2022
#Last Updated: 6 Dec 2023

library(tidyverse)
library(car) #for crPlots()
library(nortest) #for ad.test()
library(readr)
library(ggplot2)

options(digits = 4) #limits to 4 significant figures

#Load dataset
#set working directory Session>Set Working Directory>Choose Directory
library(readxl)
OlyMeasurements <- read_excel("OlyMeasurements.xlsx")


#Make Dorsal_Length Continuous
OlyMeasurements$Dorsal_Length <-
        as.numeric(as.character(OlyMeasurements$Dorsal_Length))
#Make Hinge_Thickness_Left_Valve Continuous
OlyMeasurements$Hinge_Thickness_Left_Valve <-
        as.numeric(as.character(OlyMeasurements$Hinge_Thickness_Left_Valve))

#add logs for hinge width
OlyMeasurements$logH <- log(OlyMeasurements$Hinge_Thickness_Left_Valve)


#Bivariate Plot w/ Log values
ggplot(OlyMeasurements, aes(logH, Dorsal_Length)) +
        geom_point() +
        scale_color_manual() +
        xlab("log Hinge Thickness (mm)") +
        ylab("Dorsal Length (mm)") +
        theme() +
        xlim(0,3) +
        ylim(0,60)

####Create Regression model####
X <- OlyMeasurements$Hinge_Thickness_Left_Valve
Y <- OlyMeasurements$Dorsal_Length
```

```
# lm fit
Oly.LogH.Regression <- lm(Y ~ log(X))
#To view the ANOVA table:
anova(Oly.LogH.Regression)

#To just view the slope and y-intercept coefficients:
Oly.LogH.Regression

#Summary of Oly model 2
#Residuals, R^2, p-value
summary(Oly.LogH.Regression)

#See Residuals
#Plot Residuals
plot(Oly.LogH.Regression, which = 1) #Residuals vs Fitted
plot(Oly.LogH.Regression, which = 2) #Q-Q Plot
plot(Oly.LogH.Regression, which = 3) #Scale-Location
plot(Oly.LogH.Regression, which = 5) #Residuals vs Leverage
crPlots(Oly.LogH.Regression)

#Normality of residuals
ad.test(Oly.LogH.Regression$residuals)

####CI, PI, and Predicting New Observations####
#CI of the Coefficients
confint(Oly.LogH.Regression, level = 0.95)
#Gives up and lower limits of 95% CI

#Adding Prediction Interval
#Add PI to model first
Pred.Oly <- predict(Oly.LogH.Regression, interval = "prediction")
Plot.Oly <- cbind(OlyMeasurements, Pred.Oly)

#Plot of Regression Line with CI & PI
ggplot(Plot.Oly, aes(Hinge_Thickness_Left_Valve, Dorsal_Length)) +
        geom_point(shape = 1) +
        stat_smooth(method = "lm", formula = y ~ log(x), col = "blue") +
        geom_line(aes(y = lwr), color = "red", linetype = "dashed") +
        geom_line(aes(y = upr), color = "red", linetype = "dashed") +
        xlim(0,12) +
        ylim(0,80) +
        xlab("Left Valve Hinge Thickness") +
        ylab("Dorsal Length (mm)") +
        theme_classic()
```

```
#####Predicting Dorsal Length####
#> new.data <- data.frame(x_variable = c(newx1, newx2, ...etc.))
#> or Import .xlsx or .csv of Left Valve Hinge Measurements

#Make Hinge_Thickness_Left_Valve Continuous
YOURDATAFRAMENAME$Hinge_Thickness <-
        as.numeric(as.character(YOURDATAFRAMENAME$Hinge_Thickness))

#Convert Hinge to Log
#add logs for hinge width
YOURDATAFRAMENAME$logH <- log(YOURDATAFRAMENAME$Hinge_Thickness)


#Predict
predict(Oly.LogH.Regression, newdata = YOURDATAFRAMENAME, interval = "prediction")


#Save predicts as object
pred.new.Hinge_Thickness <- predict(Oly.LogH.Regression, newdata =
        YOURDATAFRAMENAME, interval = "prediction")

#Export as .csv
write.csv(pred.new.Hinge_Thickness, "Prediction Lengths.csv")
```

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