“I’d like to see it come back”: The revitalization of Tsleil-Waututh Nation clam tending in Burrard Inlet

by

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Abstract

While the concept of social-ecological transformation is increasingly being invoked to guide ecologically safe and socially just pathways to sustainability, Indigenous communities have been transforming their social and ecological systems in the face of disturbance for millennia. Today, Indigenous Nations are reasserting their inherent and constitutionally protected rights – in Canada – to manage their relationship with the lands and sea, including coastlines that continue to be a major source of food, identity, and well-being. In collaboration with the Tsleil-Waututh Nation, we took a transdisciplinary approach to inform the revitalization of clam tending practices in Burrard Inlet, Canada. We 1) synthesized information on ancestral clam tending practices, 2) quantified the effect of environmental drivers on contemporary clam density, biomass, and species composition, and 3) facilitated a community knowledge exchange to envision future clam tending strategies. We found strong evidence that water flow was the dominant ecological variable driving native clam density and biomass. Moreover, we documented intergenerational knowledge sharing and experiential learning as key mechanisms to support the revitalization of clam tending practices. By centering research questions, methods, and actions that prioritized community objectives, participation, and relationships between people and place, our approach enhanced community understanding of contemporary drivers of change and possible future transformations.

Keywords: Indigenous Knowledges; Clam Tending; Tsleil-Waututh Nation; Social-Ecological Systems; Transformation

To the next generation of Tsleil-Waututh clam harvesters

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Positionality: My Relationship to this Research

As a non-Indigenous researcher doing research on Indigenous Lands, I have been guided by many different people and teachers throughout the course of this work. The use of “we” throughout this thesis illustrates the collective that guided and shaped this dialogue-rich research, and highlights that the work presented is much greater than my own. As research is a human endeavour, it is important to me to reflect on my own biases and positionality. I do so below by means of a story:

In the home where I was born, there was more than one language. Images of this home reside so clearly in my memory, and I know that I can never let them go. I can recall the carpeted staircase, how my tiny feet would carry me all the way to preschool, and especially the fierce love that I felt for my younger brother. At this point in my life, my understanding of home was a jumble of origins and belonging. This home reminded me that I belonged to many places. I can recall this home as clearly as I understood myself.

In my life now, I am bombarded every day with a conception of myself, and the clarity I felt at four years old has frayed. Throughout my experiences in academia, I’ve been encouraged on several occasions to write a ‘positionality statement’. I’ve written a few of these over the years, but these days thinking about positionality is especially hard. Throughout the past pandemic years, moments of shared everydayness where I previously understood my selfhood have transformed. Every day I am reminded of the complexity of personhood, and how positionality is always in flux.

With the power and privilege of an academic platform come the responsibility to ask oneself how our research process and outcomes can serve diverse audiences to which we are accountable. For me, reflecting on my settler positionality means reflecting on the privileges I have and take for granted every day. It means listening closely, being aware of the space I take up, knowing when to take a step back, and approaching questions collectively. It means making reparations and continually working to become aware of areas where further reflection is needed.

In the Tsleil-Waututh community where I work, I’ve always felt that I am taught from a place of love. I came to the Nation first as an employee. A couple of years later, I became a graduate student working towards the research outlined in this thesis. As a university researcher I found myself re-navigating existing relationships from a new position. In the summer months, together with colleagues now friends and teachers, we dig for clams. When somebody finds a particularly large clam, we howl with delight as we race to pull it from the sand. One day, we finish sampling early and wash our muddy field equipment in the water at Rocky Point Park. With muddy knees we trot over to the ice cream shop and celebrate the day with cones of butter pecan. Always, I am reminded to take delight and to giggle. Another day, we arrive to the field site early and need to wait for an hour for the tide to fall. We sit on the beach, watch the tankers, and wait for the clams to start squirting.

Not long ago I sat on the beach with a new friend. She was the first new friend from grad school that I met with in-person, and we were giddy. Her mother is from Ramallah, Palestine and she'd reached out with a direct message on zoom. I wanted to tell her about the taste of pomegranate juice sold on street corners in Tel Aviv, and about the persistence of plants in the desert. I wanted to tell her about the overwhelming shame that wells up when people ask where I'm 'really' from. I wanted to admit to her that sometimes I confuse nostalgia for my grandparent's kitchen with homesickness. I wanted to admit to her that although I've been within 15km of Ramallah, I've never been to the city itself. Instead, we sat in Stanley Park and talked about our professors, our childhoods, the pandemic, people we love, and intertidal ecology.

When I was 12 years old, I did a school project about my grandmother's life. I remember talking to her on the phone one evening as I cut out a poster board in the shape of Poland, and imagined she was shelling pecans from her tree as we chatted. The stories she told me were gentle. They were funny stories about her siblings that any twelve-year-old could relate to, but I still cry when I think about them. How do you explain the Holocaust to your twelve-year-old granddaughter who lives an ocean away? When we visit Israel, my grandparents squeeze me tight, and fill my pockets with pecans. When we drive from the airport to my grandparent's house, I always watch my mom's face as she looks out the window. My parents left Israel for reasons of political ideology. They brought with them two backpacks and a love for pecans.

From my position on the beach, waiting for the tide to fall and watching the tankers move through Burrard Inlet, I am reflecting on my own positionality. From my position on the beach, I can’t help but wonder about the tougher and more devastating question of who is afforded the dignity and grace to reflect on their position at all.

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Introduction

Social-Ecological Transformation

> *"Raven has never left this place, but sometimes it feels like she has been negligent, maybe even a little dense. Raven shaped us; we are built for transformation. Our stories prepare us for it. Find freedom in the context you inherit- every context is different: discover consequences and change from within, that is the challenge." (Maracle, 2004)*

Unprecedented human impacts driving global regime shifts call for radical social-ecological transformation (UNESCO 2013; Rockström et al., 2009; Steffen et al., 2015). How these changes are studied or imagined opens an exciting space for academics and practitioners. However, transformation means different things to different people, therefore, methodological, and conceptual questions persist around how to research or navigate transformation given questions of who frames the problems, who studies them, and who benefits from the results (O'Brien, 2012). By applying a transdisciplinary lens to support community engaged understandings of change, we aim to make room for different ways of knowing and being in the world.

Considerations of social-ecological system transformation emerged from resilience scholarship in the early 2000s and contributions to this body of thought have been rapidly growing in recent years (Biggs et al., 2012; Schultz et al., 2013; Fazey et al., 2018; Shah et al., 2018). Within this area of scholarship, the concept of 'transformation' typically refers to the emergence of fundamentally new social-ecological systems from existing ones that have crossed tipping points (Westley et al., 2011; Schultz et al., 2013). While transformation is generally seen to involve a fundamental change to key system parts and/or processes, there is little consensus as to what characterizes transformational processes and outcomes (Feola, 2015). Even as scholarship on social-ecological transformation grows, there is continued debate across disciplines about how fundamental change can be navigated, understood, and guided towards socially just, and ecologically safe outcomes (Shah et al., 2018).

How we embody and work with transformation influences the outcomes we create (Gram et al., 2022). Framing transformation as fundamentally good or bad, or not addressing issues of power, risks exposing vulnerable groups to harm (Blythe et al., 2018). Currently, a recognized gap in transformation research is in engaging with and reflecting the everyday experiences of diverse people (Shah et al., 2018), and pluralizing transformation discourse to make room for different ways of knowing and being in the world (Blythe et al., 2018).

Despite its relative newness in scholarly discourse of social-ecological resilience, here we assert that the concept of ‘transformation’ is not new. Within many Indigenous epistemologies, change is always happening in many forms including desirable or otherwise (Tuck & Yang, 2014). While change can be a result with discrete and measurable outcomes, it can also be a continuous and relational process (Tuck & Yang, 2014). Importantly, change exists in everyday acts, conversations, at kitchen tables, and on intertidal beaches (Corntassel, 2012). Contemporary manifestations of Indigenous stewardship approaches provide a tangible example of change achieved through ‘everyday acts of Indigenous resurgence’ (Corntassel, 2012). In this research we interpret social-ecological transformation as a broad concept concerning significant changes in linked social-ecological systems which result in shifts towards a fundamentally new system (Westley et al., 2011; Schultz et al., 2013). Given the inherent subjectivity of how significant change is experienced, interpreted, and brought about (Tuck & Yang, 2014), we do not identify this as a single agreed upon definition of ‘transformation’, but rather as a framework for discussion. This thesis then focuses on research questions, methods, and actions that prioritize Indigenous participation and nurture relationships between people and place, to support community-engaged understandings of change, and social-ecological transformations.

Indigenous Stewardship Systems

Coastal Indigenous Peoples have relied on marine ecosystems for thousands of years and – through observation, practice, and culturally transmitted learning – have developed locally-relevant management practices to sustain reciprocal relationships that support ecosystems and cultures that depend on them (Mathews & Turner, 2017; Atlas et al., 2021; Kobluk et al., 2021). However, following European contact and ongoing processes of colonization, severe ecosystem degradation and social-ecological impacts are impairing the opportunity for many Indigenous Nations to exercise their inherent and constitutionally protected rights to harvest and manage fisheries in accordance with ancestral governance protocols (Walter et al., 2000; Morin, 2015). While this is an issue throughout colonized territories, it is especially acute in areas with significant industrial and urban development.

Metropolitan regions are often sites of both drivers and impacts of changes to ecosystems and Indigenous social-ecological relationships (Andersson & Barthel, 2016). This convergence happens as many of today's urban centers are situated on lands and waters where Indigenous societies gathered and thrived such as at the confluence of major waterbodies. As the word's cities swell, there is severe stress, and change to urban waterbodies (Murphy et al., 2019). Through a myriad of social and ecological impacts, urbanization continues to encroach on cultural landscapes, and the lifestyles and stewardship practices that help maintain these landscapes (Andersson & Barthel, 2016). Despite the destructive impacts of colonization, Indigenous cultures and knowledges are resurgent, and there is growing recognition that Indigenous management systems contribute to not only maintaining but also restoring the productivity of aquatic ecosystems and fisheries (Berkes, 2006; Artelle et al., 2019; Salomon et al., 2019; Atlas et al., 2020).

Ancestral Clam Tending

For millennia, clams have continuously been a critical component to coastal First Nations' food security, food sovereignty, and cultural wellbeing. They are also a species that has been effectively managed through Indigenous enhancement strategies, access rights and responsibilities, and harvest restrictions (Lepofsky & Caldwell, 2013; Groesbeck et al., 2014; Jackley et al., 2016; Deur et al., 2019; Toniello et al., 2019). Since the early-Late Holocene, Indigenous communities have maintained and enhanced shellfish productivity through a variety of ecological and cultural management practices, including terracing and tilling. For example, clam gardens are rock-walled terraces built by people on soft-sediment beaches (Groesbeck et al., 2014; Lepofsky et al., 2015; Jackley et al., 2016; Deur et al., 2019; Toniello et al., 2019). Through the construction and care of these extensive intertidal features, Indigenous Peoples shape(ed) the seascape, and radically transform(ed) their food systems to support expanded settlements (Toniello et al., 2019; Holmes et al., 2022). A deep history of accumulated knowledge of how ecological conditions and social practices interact to affect the sustained use of resources over generations is key to the functioning of ancestral clam systems. Western science has further investigated the specific human-altered ecological mechanisms that drive the productivity of ancestral mariculture innovations (Groesbeck et al., 2014; Jackley et al., 2016; Salter, 2018). For example, research by Groesbeck et al., (2014) and Jackley et al., (2016) provides evidence for higher biomass and density of clams in ancestral clam gardens relative to unmodified beaches. These same trends are demonstrated in the archaeological record (Toniello et al., 2019). As a result of ongoing processes of colonization, in many contexts, these intertidal features may not have been tended for many generations. Nonetheless, their legacies continue to sustain increased shellfish productivity today, providing compelling evidence that clam gardens have provided reliable food sources for populations through time (Jackley et al., 2016; Holmes et al., 2022).

Culturally significant species are often at the center of social-ecological systems. Accordingly, patterns of resource use may transform, or be transformed by, shifts in species composition. Evidence suggests that these shifts can impact personal and generational perceptions of past, present, and future biological conditions (Soga & Gaston, 2002). In response to these realized impacts, many Indigenous communities are reviving and adapting traditional protocols to maintain and enhance the diversity of clam species, as well as the productivity of clam harvests (Augustine & Dearden, 2014). However, introduced clam species and the cumulative effects of industrial activities in urban centers are profoundly altering the relationship between clams and people (Turner & Spalding, 2013; Morin, 2015). Bringing together understandings of Indigenous-led ancestral clam tending practices, ecological studies of current conditions, and actions aimed at returning community to ancestral beaches, provides insights into strategies for the revitalization of Indigenous clam tending practices.

In collaboration with the Tsleil-Waututh Nation, the *People of the Inlet* who have long stewarded the lands and waters at heart of the now urbanized and colonized area known as Burrard Inlet in the City of Vancouver, British Columbia, we: 1) synthesized information on a suite of ancestral clam tending practices used throughout the Holocene; 2) quantified the effect of environmental drivers of clam density, biomass, and species composition in Burrard Inlet today; and 3) facilitated a community knowledge exchange to envision future clam tending strategies. Broadly this work seeks to fill important gaps in supporting more equitable approaches for social ecological transformation and ocean governance that are grounded in ancestral stewardship practices and reflect objectives emanating from Indigenous communities in urban areas.

Methods

Transdisciplinary Approach

We took a transdisciplinary approach to informing possible avenues towards the revitalization of Tsleil-Waututh clam tending practices in Burrard Inlet, British Columbia, Canada (Mauser et al., 2013). Our research questions and methods were guided by the information needs, priorities, and ancestral laws of the Tsleil-Waututh Nation (Tsleil-Waututh, 2015), all of which aim to actualize Tsleil-Waututh stewardship responsibilities in Burrard Inlet. To support this work, we: (1) synthesized a suite of possible Tsleil-Waututh clam tending practices in Burrard Inlet by means of a literature review; (2) examined possible environmental drivers of clam density, biomass, and species composition in Burrard Inlet through an ecological field study; and (3) created a space for experiential learning and intergenerational sharing by facilitating a community knowledge exchange on the beach. These research objectives and transdisciplinary approaches were each identified as essential elements of the collaboration with Tsleil-Waututh Nation. In addition to collaboratively designing research questions and methods, we signed a research agreement between researchers at Simon Fraser University and collaborators at Tsleil-Waututh Nation. This research agreement, created by the Nation, outlines objectives of the work, data stewardship expectations, and guidelines for conflict resolution. Additionally, we followed ethics protocols laid out by the Tri-Council (CIHR, NSERC, SSHRC).

Knowledge Co-production

This research was conducted in close collaboration with the Tsleil-Waututh Nation. The questions addressed in this thesis were identified by the Tsleil-Waututh Treaty, Lands and Resources Department as important to meeting broader objectives for revitalization and restoration of safe and abundant traditional foods in Burrard Inlet. Based on previous relationships between the university researchers and the Nation, the project's research questions and methodologies were collaboratively honed through continuous meetings. A successful joint funding application supported the implementation of the work, and a research agreement was signed between the Nation and the university researchers. Ecological field study sites were identified collaboratively, based on both Indigenous and western knowledges of local ecological conditions, and ecological fieldwork was conducted collaboratively. The objectives and methods used for the community Knowledge Exchange were co-created following a series of joint meeting and phone calls. The results of the work were shared and reviewed following a Tsleil-Waututh process. Together we honed results and our interpretations of them.

Study Area and Context

"My favorite place to dig is on the mudflats because it smells like home".

(Kalup George, Tsleil-Waututh Natural Resource Technician)

Fed by mountain streams, Burrard Inlet is a highly urbanized waterbody in the heart of the Greater Vancouver Regional District, British Colombia, Canada (Figure 2 A). Burrard Inlet, as a long narrow extension of the Salish Sea, consists of five major basins: the Outer Harbour, the Central Harbour, the Inner Harbour, Indian Arm, and Port Moody Arm (Tsleil-Waututh, 2015; Figure 2 A). From east-west Burrard Inlet is about 30 kilometers long, and Indian Arm extends northward approximately 20 kilometers. As a glacial fjord, Indian Arm is characterized by steep shorelines reaching tall mountains, conversely the Central Harbour supports large soft sediment beaches (Tsleil-Waututh, 2015). Some of the place names used in this thesis arise from Indigenous histories with these places (i.e., Salish), however others reflect colonial viewpoints (i.e., Indian Arm), or carry colonizers names (i.e., Vancouver).

Tsleil-Waututh People have lived along the shores of Burrard Inlet since time out of mind. Archaeological evidence demonstrates continuity of Tsleil-Waututh use and occupancy in Burrard Inlet dating back millennia (Morin et al., 2018). Tsleil-Waututh ancestors, who numbered in the many thousands, maintained villages around Burrard Inlet and intensively used a wide diversity of the natural resources (or relations) throughout their territory, especially marine and intertidal plants, and animals (Morin, 2015). Prior to contact, at least eight and as many as 14 villages existed in Burrard Inlet (Morin et al., 2018; Figure 2 A). "The Tsleil-Waututh subsistence economy was based on access to and stewardship of natural resources, especially marine resources, for both living community and ancestors" (Tsleil-Waututh, 2015).

Since the 1700s, the Inlet's productivity and abundant marine resources made it a destination for successive waves of human settlement and industrial development. Today over two million residents live in urban areas surrounding the inlet, and it is the largest port in Canada (Lilley, 2017; Figure 2 A). As a result of both indirect and direct contact with Europeans, the Tsleil-Waututh coalesced at three primary settlements in the mid-1800s which were designated as Indian Reserves by the Government of Canada via the Indian Act (Morin et al., 2018). Today, the Tsleil-Waututh Reserve on the north shore of the Central Harbour, occupying about 100 hectares of land and 100 hectares of adjacent marine water, is the primary settlement (Tsleil-Waututh, 2015). While the shoreline of Indian Arm remains relatively undeveloped, much of the Burrard Inlet shoreline is dominated by urban, commercial, and industrial activities (Taft et al., 2022).

European contact and ongoing processes of colonization have severely degraded the Burrard Inlet ecosystem with profound social-ecological implications starting as early as the mid-1800s (Morin, 2015). For example, by 1972, the Canadian Government had closed the shellfish fishery in Burrard Inlet due to pollution and the cumulative environmental effects of industrial development. Today, most of the Tsleil-Waututh subsistence economy has been eliminated, depleted, contaminated, or otherwise made unavailable for harvest (Morin, 2015).

The transformation that Tsleil-Waututh Nation has witnessed and experienced in Burrard Inlet over the last two centuries demonstrates that localized, individual incursions and losses can drive detrimental, ecosystem-wide transformation over many generations. However, the Nation believes that the opposite is also true, and that localized regenerative steps across generations can revitalize and restore the social-ecological health of a system. Therefore, the Nation is seeking to facilitate transformation through regenerative social-ecological programs and projects. For example, in 2016 the Pacific Regional Interdepartmental Shellfish Committee (PRISC) approved a portion of the shellfish waters in Indian Arm for harvesting and since then the Nation has held four annual community shellfish harvests. During these revitalized community harvests, the species collected is *Mya arenaria* (Fisheries and Oceans Canada, 2019), which are not native to Burrard Inlet, nor are they one of the many species that sustained Tsleil-Waututh for millennia. Nonetheless, they provide an important opportunity for community members to visit beaches and practice traditional food preparation and reinvigorate this community of practice.

Literature Review of Ancestral Clam Stewardship Practices

To inform alternative clam tending practices for restoration in Burrard Inlet and to relate them to Tsleil-Waututh Nation Knowledges and experiences, we reviewed the literature on ancestral clam tending practices by Indigenous communities along the West Coast of North America and the Tsleil-Waututh Nation Strength of Claim Report (Morin 2015). This Report outlines Tsleil-Waututh Knowledge alongside historical, archeological, and documentary records to describe Tsleil-Waututh history, culture, and interests in Eastern Burrard Inlet. It is important to note that some of these sources provide insight into Burrard Inlet's condition after settler activities began, and after much ecological change had already taken place in Burrard Inlet (Morin & Evans, 2022). As well, this report was written prior to any contemporary surveys for clam gardens in Burrard Inlet. Given this context, we aimed to learn from literature on clam tending practiced by other distinct Indigenous communities along the West Coast of North America. Here our intention was not to homogenize clam tending knowledge, but rather to inform a range of possible practices in Burrard Inlet where clam stewardship knowledges are being actively reawakened.

Ecological Field Survey

> *"I've always wondered why certain types of clams are at certain beaches, but not others. Especially the invasive clams. I think maybe it has something to do with temperature or sediment."*
>
> *(Charles (Charlie) George, Tsleil-Waututh Natural Resource Technician)*

To quantify the relative effects of environmental drivers on clam density, size, and species composition in Burrard Inlet, we worked together with a team of Tsleil-Waututh Natural Resource Technicians to survey 14 soft sediment intertidal sites from May to August 2021. Sites were specifically selected to reflect Tsleil-Waututh Nation priorities and capture a gradient in local and regional environmental conditions (Figure 2 A). At each site, we dug 15 randomly stratified plots (25 x 25 x 25 cm depth; volume = 0.0156 m^3) along a 30 m transect placed parallel to shore between 0.75m and 1.2m above chart datum. At each plot, we identified and measured all bivalves and collected sediment samples. We also deployed temperature and salinity loggers, as well as soluble carbonate blocks at each site. Quadrat-level biomass measurements were later estimated using an established Length-Weight regression (see Gillespie & Kronlund, 1999). We began and finished every survey with a group discussion of general observations. The observations ranged from the smell and the sound of the beach, to stories and experiences of field crew members on the beaches (as seen in quotes above).

Environmental Drivers

Environmental variables were selected based on what we hypothesized to be drivers of clam density, biomass, and species composition in Burrard Inlet. These hypotheses were based on literature on clam ecology, conversations with Tsleil-Waututh collaborators, and on previous research demonstrating human-altered ecological mechanisms related to clam tending. As such, diverse disciplines and knowledges underpin our hypotheses. Here, it is important to make explicit that while some of our hypotheses were based on Tsleil-Waututh experiences in Burrard Inlet, others were based on clam research conducted elsewhere following methods grounded in western science. Ongoing processes of colonization have caused profound social-ecological destruction in Burrard Inlet, and many associated barriers continue to limit Tsleil-Waututh Nation’s opportunities to develop and maintain knowledge of contemporary clam populations and the ecological mechanisms driving their distributions. It is within this context, that we sought learnings from research conducted elsewhere to inform our hypotheses in Burrard Inlet.

Temperature and Salinity. At each site, we measured ambient intertidal air and seawater temperature and salinity every 15 minutes during the summer growing season using integrated data loggers. These loggers were placed in a protective pipe and affixed to a rebar stake at the center of the transect, flush with the beach. We divided temperature and salinity data into exposed and sub-tidal time periods based on our estimates of when transects were submerged based on changes in salinity measurements. From these time series, we calculated several site-level metrics for sea water temperature and salinity (i.e., monthly mean, minimum, maximum and standard error). Then, checking model diagnostics, and using a variance inflation factor of three, we selected mean temperature as the metric to include in our global model (See Appendix A).

Relative Water Flow. Following methods adapted from (Salter, 2018), relative water flow was assessed as "the dissolution rate (g dissolved hour-1) of ice-cube sized gypsum blocks of similar weights (± 1 g) over 72 hours" to capture variations in current velocity, water retention, and submersion time (Thompson and Glenn 1994; Boizard & Dewreede, 2006).

Sediment Grain Size. Grain size (% by weight) was determined by sieving with a set of eight mesh sizes: 4.75 mm, 2 mm, 1 mm, 500 μm, 250 μm, 125 μm, 63 μm, and 4 μm (Folk, 1980). Sediment grain size processing was carried out by Pacific Soil Analysis Inc. Three of the fifteen sediment samples per sites were randomly selected to be processed and averaged as a site level mean.

Sediment Carbonate. Sediment carbonate content (g/cm^3) was determined for each sediment sample using sequential weight loss-on-ignition following methods adapted from (Wang & Li, 2011 and Salter, 2018). The same three sediment samples selected for grain size analysis were processed for sediment carbonate. We summarized these samples as a site mean.

Statistical Analysis

To determine the relative strength of evidence for the effect of each variable on clam biomass and density, we took an information theoretic approach. We selected individual predictor variables based on *a priori* hypotheses gleaned from previous research (spanning ecological and ethnographic disciplines) and Tsleil-Waututh Knowledge (See appendix for table of measured environmental covariates). To assess the fixed effects of temperature (°C), relative water flow (g/hr), sediment grain size (% by weight), and sediment carbonate (g/ cm3), on clam biomass (Kg clam/plot) and density (count/plot), we built a series of generalized linear mixed effects models, all including the random effect of 'site', using the 'glmmTMB' package in R (Brooks et al., 2017). We selected likelihood distributions and link functions to ensure that residuals of each global model met the assumptions of homogeneity of variances. We also checked for overdispersion using the 'DHARMa' package in R (Hartig, 2022). For models of bivalve density (count/plot), we used a negative binomial likelihood and log link function. For models of bivalve biomass (kg/plot), we used a Tweedie likelihood distribution and log link function. We assessed collinearity between predictors in our global model using variance inflation factors (VIFs), only permitting VIFs < 3 (Zuur et al., 2010). To facilitate comparison between fixed effects, we standardized predictor variables (centered and scaled by one standard deviation) (Schielzeth, 2010). To gain an understanding of how environmental parameters may vary between introduced and native species, we fit a global model including all predictor variables for each category of clam species. We also fit a global model to clam biomass and density for each species (See Appendix B and C).

Model selection and model averaging. For all response variables, we fit all subsets of the global models using the '*MuMin'* package in R (Barton, 2016). Models were assessed with Aikaike's Information Criterion corrected for small sample size (AICc) and ΔAICc. To assess the relative variable of importance (RVI) of each predictor, we compared all model subsets, and model averaged the set of candidate models with ΔAICc < 4 and W_i>0. We calculated regression coefficients using conditional averages and RVI using the sum of each model's Akaike weights in which each predictor variable was found (W_i) (Burnham and Anderson, 2002). All statistical analyses were conducted in R statistical computing software (R Core Team 2021).

Tsleil-Waututh Nation Vision

Literature Review

To understand Tsleil-Waututh's future visions for clam management in Burrard Inlet within the context of their broader environmental protocols, we reviewed five publicly available environmental management documents developed by Tsleil-Waututh Nation and a variety of collaborators. The documents included Tsleil-Waututh Nation's Marine Stewardship Plan (2005), Stewardship Policy (2009), Assessment of the TransMountain Pipeline (2015), Burrard Inlet Action Plan (2017), and Burrard Inlet Water Quality Objectives (2021). These documents highlight TWN legal governance responsibilities, relationships to land and marine territories enacted over millennia, and outline a larger vision for a healthier Burrard Inlet. We reviewed the documents using a keyword "clam" and "shellfish" to identify and summarize broad visions and specific directives pertaining directly to clams in Burrard Inlet. This process included an iterative dialogue with TWN technical staff, and two Cultural Advisors to identify and fill any gaps.

Knowledge Exchange

On October 7, 2021, we co-designed and hosted a day-long Knowledge Exchange to meet three specific objectives: 1) To bring Tsleil-Waututh Knowledge Holders, youth, and technical staff together on the beach to create a space for experiential learning; 2) To share knowledge of human-clam relationships and stewardship practices, past, present and future; and 3) To collaboratively envision future clam tending in Burrard Inlet that includes TWN and scientific environmental principles. Tsleil-Waututh Nation is at the forefront of many regenerative programs on their lands and waters, however opportunities for enacting clam tending practices and associated knowledge sharing protocols are continuously challenged by ongoing processes of colonization. It is within this context that the Knowledge Exchange was designed to create space for re-awakened knowledge and conversation. Two-way learning about clams in Burrard Inlet between Tsleil-Waututh community members and university scientists was also identified as important. To this end, we chose to invite a broad range of participants including members of the Elders Group, students and teachers from the Tsleil-Waututh Nation School, and technical staff from Tsleil-Waututh Nation’s Treaty, Lands and Resources Department. We approached each of these groups through pre-existing relationships, and following protocols suggested by Tsleil-Waututh Cultural Advisors. Given that the Knowledge Exchange had to be conducted in accordance with COVID-19 precautions, it was not opened to the entire community. We were able to safely accommodate a total of 30 participants.

In advance of the Knowledge Exchange, and in addition to meeting with Cultural Advisors, we held co-design meetings with teachers at the Tsleil-Waututh Nation School, the Elders Group, and technical staff. Through these meetings, we built ongoing relationships with Knowledge Exchange participants and ensured the exchange would be designed to meet their needs. As a result of the co-design process, we brought together several methodological approaches for the Knowledge Exchange, including storytelling, small group activities, field exploration, and youth-led video interviews of Elders. While we went into the Knowledge Exchange with preconceived notions about how the day would go, we found that prioritizing time for unstructured experiential learning and conversation was more important for meeting our collective objectives than strictly adhering to the initial plan. These adaptations were done with the guidance of

Cultural Advisors on the day of the Knowledge Exchange. The general structure of the Knowledge Exchange is described below.

Learning from the past – To learn about ancestral values and clam stewardship practices, we used intergenerational storytelling in small groups composed of technical staff, Elders and youth to discuss the question: "*How did Tsleil-Waututh ancestors harvest and steward clams and their habitats to sustain intertidal beaches?*" We selected the small group sizes based on guidance from Cultural Advisors on how to create space for meaningful cultural exchange.

Understanding the present – To generate a group understanding of current clam conditions, we spent time exploring the intertidal beach habitat together. Guided by TWN Cultural Advisors, and literature from Indigenous land-based pedagogy (Wildcat et al., 2014), we shifted from *talking* about clam harvesting in the intertidal to *engaging* in clam digging in the intertidal (Wildcat et al., 2014). Here, we centered the importance of unstructured play on the land and the experience of being there together. We provided the participants with the following prompts to discuss: "*Find four different clam species on the beach. You have likely found some species introduced from Europe and Asia. How do you value these species? Do these preferences differ among us? What actions should we take given the presence of these species?*"

Sharing Food – Lunch was provided by a caterer from the Tsleil-Waututh community. Together, we ate sandwiches and clam chowder. During this time, the participants had the option to share their vision for the future of TWN clam tending practices in an Indigenous youth-led video booth.

Visioning the future – To begin developing visions for future clam stewardship, small groups discussed the following questions: *"What clam stewardship practices do you hope to see on TWN beaches in the future? Where should these efforts be focused and why? What clam species should we focus on and why?"* Each group shared ideas and drew directly on a map of Burrard Inlet. At the end of the exercise, one member from each group was invited to share back with the broader group.

Closing – Following guidance from Tsleil-Waututh Cultural Advisors, we closed with a round of reflections to provide space for meaningful connection and sense-making. Together we spoke about what we had learned from the day, what we would remember, and our feedback for future workshops.

Data Collection and Thematic Analysis

Data was collected throughout the Knowledge Exchange in a variety of forms, including observer notes, poster boards and maps generated during the breakout groups described above. Observer notes were collected by four different technical staff (Tsleil-Waututh Nation employees) each of whom was stationed with a different group. Photos were taken, with permission, throughout the Knowledge Exchange by a TWN communications representative. Video booth interviews with Elders were transcribed. We conducted a thematic analysis of video transcripts, observer notes, poster boards, maps, and photos using NVivo 12 Qualitative Research Software (Released in March 2020). Here, we used themes following a framework of objectives used to gather qualitative community feedback in previous Tsleil-Waututh-led projects (Tsleil-Waututh, 2015). These themes included 1) Natural Resource Access and Use, 2) Cultural Work and Community Well-Being, 3) Environmental Stewardship Obligations, and 4) Control Over and Sharing of Resources according to Tsleil-Waututh and Coast Salish protocols.

Results

A Suite of Clam Tending Practices

Our review of peer reviewed literature reveals a diversity of ancestral clam tending practices along the Pacific Coast of North America which are embedded within a diverse portfolio of resource use and management strategies (Deur et al., 2015; Lepofsky et al., 2015), as well as specific ecological processes that are altered through these tending practices (Groesbeck et al., 2014; Jackley et al., 2016). Practices include rockwall construction and maintenance, tending and tilling of sediment, debris removal, addition of shell hash and gravel, size-selective clam harvesting, juvenile clam transplanting, and predator and debris removal (Figure 1 and described in detail below). While some of the literature we reviewed demonstrates what is known ethnographically about clam tending practices through deep time, other literature provides learnings on ancestral clam management based on ecological hypotheses/results investigated following methods in western science in the past 10 years.

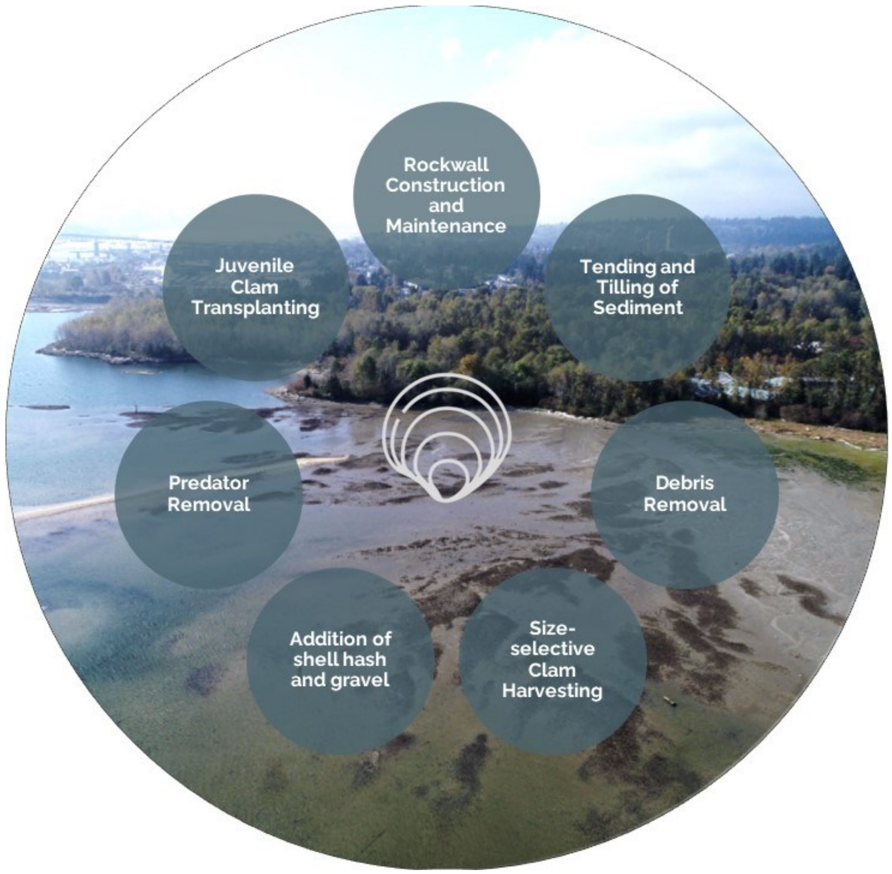

Figure 1. A suite of Ancestral Biophysical Clam Tending Practices

Rockwall Construction and Maintenance. Clam gardens are designed to take advantage of natural geomorphic and ecological processes and vary in their specific landscape modifications. They often consist of a rock wall at the low tide line that traps sediment and reduces the slope of a beach thus maximizing the intertidal habitat within the ideal tidal height for target clam species (Lepofsky & Cadwell, 2013; Groesbeck et al., 2014; Augustine & Dearden, 2014; Deur et al., 2015; Lepofsky et al., 2015; Jackley et al., 2016; Mathews & Turner, 2017; Toniello et al., 2019; Turner, 2020; Holmes et al., 2022).

Tending and Tilling of Sediment. Extensive research and stories tell of sediment being actively aerated and turned by Indigenous Peoples to improve clam growth and productivity by increasing access to oxygen (Groesbeck et al., 2014; Deur et al., 2015; Mathews & Turner, 2017; Lepofsky & Cadwell 2013; Toniello et al., 2019).

Debris Removal. Space is created for clams to grow by removing rocks and other debris from the beach. This space also allows harvester more ease when accessing the beach (Lepofsky & Cadwell, 2013; Groesbeck et al., 2014; Deur et al., 2015; Lepofsky et al., 2015; Turner et al., 2020).

Size-selective clam harvesting. "Shellfish are selectively harvested, leaving the smaller "seed" clams to continue to grow" (Turner, 2020).

Addition of shell hash and gravel. Ethnographic evidence describes the ancestral practice of returning discarded clam shells from harvests to managed shellfish beds (Deur et al., 2015; Lepofsky et al., 2015). Building on this, contemporary field studies have demonstrated that the addition of shell hash to offset sediment acidity (Doyle & Bendell, 2022) has been successful in aiding the recruitment and survival of juvenile clams (Greiner et al., 2018).

Predator removal. Recent large and small-scale field experiments demonstrate that excluding predators can have dramatic results in clam abundance (Beal et al., 2020).

Juvenile clam transplanting. Clam beaches may be seeded to boost their productivity. However, if intentional seeding takes place, it is important to ensure that the clam bed is tended to on a regular basis (WSANEC Clam Garden Restoration Report 2014-2020).

In accordance with Coast Salish Protocol, "Tsleil-Waututh acted under stewardship principles that maintained the health of their lands and the abundance of their resources. They actively managed stocks and modified the environment to promote the growth of desired species. This management included terrestrial and intertidal components" (Morin, 2015). We found evidence in the Strength of Claim Report for specific tending practices in Tsleil-Waututh territory, but not for all the tending practices described above (See Appendix B).

Ecological Field Survey

Clam Species Density and Biomass

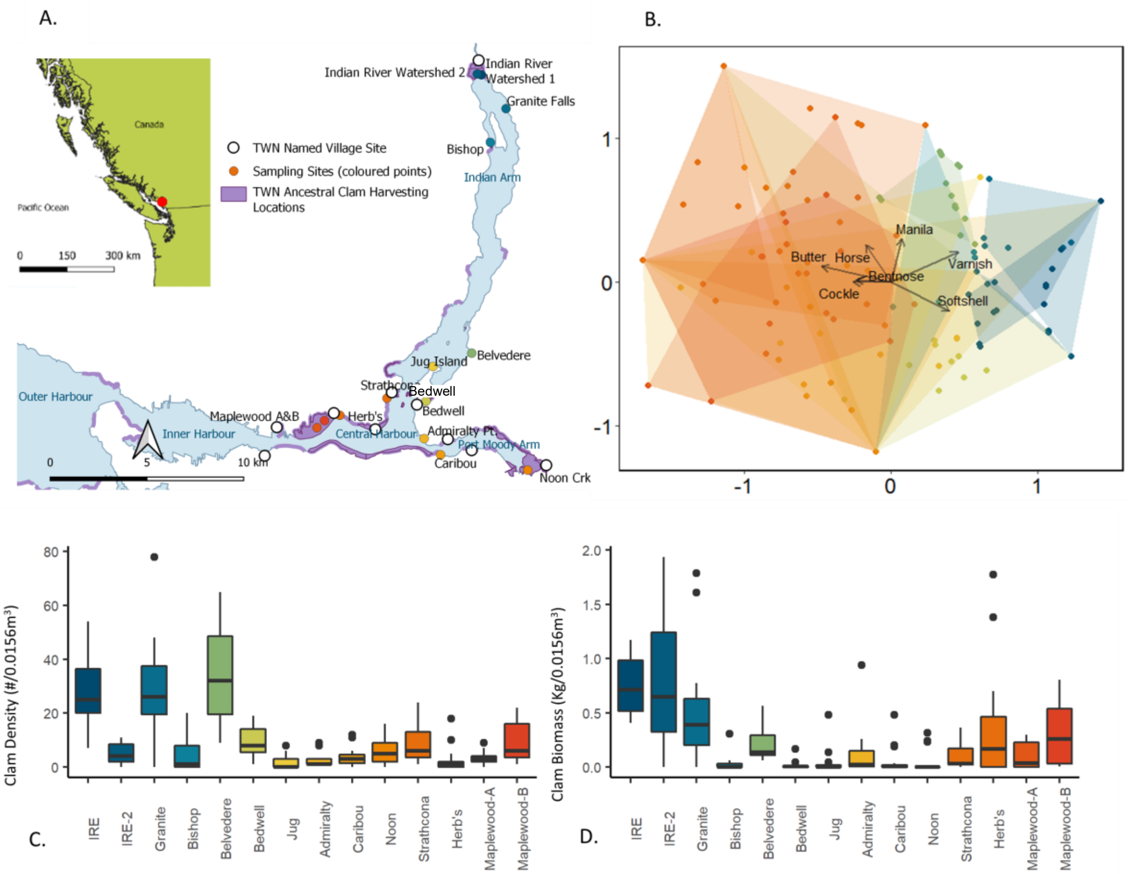

Figure 2. **(A) Tsleil-Waututh Nation's ancestral territory lies in Burrard Inlet, British Columbia (B.C.), on the pacific coast of Canada (inset). Clam survey locations (coloured dots), ancestral Tsleil-Waututh Nation clam harvest sites (purple polygons; Tsleil-Waututh, 2015) and named village sites (black outlined circles; Tsleil-Waututh, 2015; see Appendix E for Village Site Names) are shown in (A).The data used to inform ancestral harvesting locations and village sites originate from many sources and are presented without prejudice to Tsleil-Waututh Nation's rights, title, and interests (Tsleil-Waututh, 2015 (p.39)). (B) NMDS plot showing variation in clam species composition across sampling sites. Species composition is based on abundance at each site (Stress = 0.1). Points show quadrats (n=15) at each of the sampling sites outlined as polygons (n=14). Vectors show which species drive composition at each site. Total clam density (C) and biomass (D) in 15 quadrats across 14 sites. Site symbol colour is used only to represent geographic reference.**

We found important differences in clam density, biomass, and species composition across sites (Figure 2 B). Bivalve species assemblages differed spatially in their relative composition of native versus introduced species. Specifically, native species such as butter clams (*Saxidomus gigantea)*, cockles (*Clinocardium nuttalii)*, bentnose clams (*Macoma nasuta)* and horse clams (*Tresus nuttalii*) dominated sites closer to the Central Harbour where introduced species were rare. Conversely clam communities in Indian Arm towards the northern extent of Burrard Inlet (Figure 2 B) tended to be dominated by introduced species such as the varnish clam (*Nuttallia obscurata)*, manila clam (*Venerupis philippinarum)*, and softshell clam (*Mya arenaria*).

Clam density and biomass were highly variable both within and across sites (Figure 2 C &D) and followed similar spatial patterns with some distinctions. For instance, at sites in the Indian Arm located towards the head of the inlet we found a relatively high median density of clams per quadrat (Figure 2 C). Some sites located in the Indian Arm had as many as 60 times the density of clams, as those located in the Central Harbour. Conversely, at sites in the Central Harbour located closer to the mouth of the inlet, we found a relatively low density of clams (Figure 2 C).

Overall, the density and biomass of introduced clam species was higher than that of native species (Figure 3 A & B). However, this is not the case at every site. For instance, at Belvedere, a site located towards the head of the inlet we found a high density (32 clams/0.0156 m^3), but a relatively low biomass (0.14 Kg/0.0156 m^3) of clams (Figure 2 C & D). Here, clam species composition was driven by smaller Manila clams (Figure 2 B). Conversely, at sites in the Central Harbour such as Herb's we found a relatively low density of clams (1 clam/0.0156m^3), but a higher biomass (0.16 Kg/0.0156m^3) (Figure 2 C & D). Here, species composition seems to be driven by larger butter clams (Figure 2 B).

Environmental Drivers of Clam Species Density and Biomass

Table 1. Strength of evidence for alternative models predicting the effect of environmental variables on (A) native species density, (B) native species biomass, (C) introduced species density, (D) introduced species biomass. We report all models where $\Delta AIC_c < 4$. Note all models include the random effect of beach site.

Model:	df	logLik	AICc	deltaAICc	weight	Pseudo R2
A) Native Species Density (nbinom)						
Relative Water Flow	4	-246.11	500.43	0.00	0.26	0.35
Sediment Carbonate + Relative Water Flow	5	-245.45	501.22	0.79	0.18	0.35
Coarse Sand + Relative Water Flow	5	-245.92	502.16	1.73	0.11	0.35
Introduced Species Density + Relative Water Flow	5	-246.06	502.44	2.01	0.10	0.35
Mean Temp + Relative Water Flow	5	-246.11	502.54	2.11	0.09	0.35
Sediment Carbonate + Coarse Sand + Relative Water Flow	6	-245.31	503.06	2.63	0.07	0.35
Sediment Carbonate + Introduced Species Density + Relative Water Flow	6	-245.45	503.34	2.91	0.06	0.35
Sediment Carbonate + Mean Temp	6	-245.45	503.35	2.92	0.06	0.35
Coarse Sand + Introduced Species Density + Relative Water Flow	6	-245.88	504.20	3.76	0.04	0.35
Coarse Sand +Mean Temp + Relative Water Flow	6	-245.92	504.29	3.86	0.04	0.35
B) Native Species Biomass (tweedie)						
Relative Water Flow	5	-25.531	61.380	0.000	0.211	0.288
Sediment Carbonate + Relative Water Flow	6	-24.707	61.862	0.482	0.166	0.288
Coarse Sand + Relative Water Flow	6	-25.038	62.522	1.142	0.119	0.288
Sediment Carbonate + Coarse Sand + Relative Water Flow	7	-24.245	63.089	1.709	0.090	0.288
Mean Temp + Relative Water Flow	6	-25.486	63.418	2.038	0.076	0.288
Introduced Species Density + Relative Water Flow	6	-25.498	63.442	2.062	0.075	0.287
Sediment Carbonate + Mean Temp + Relative Water Flow	7	-24.676	63.951	2.571	0.058	0.288
Sediment Carbonate + Introduced Species + Relative Water Flow	7	-24.707	64.013	2.633	0.057	0.288
Coarse Sand+ Introduced Species + Relative Water Flow	7	-24.979	64.558	3.178	0.043	0.286
Coarse Sand+ Mean Temp + Relative Water	7	-25.013	64.624	3.244	0.042	0.288

Model:	df	logLik	AICc	deltaAICc	weight	Pseudo R2
Flow						
Sediment Carbonate+ Coarse Sand + Mean Temp + Relative Water Flow	8	-24.230	65.233	3.853	0.031	0.288
Sediment Carbonate + Coarse Sand + Introduced Species Density + Relative Water Flow	8	-24.239	65.253	3.873	0.030	0.287
C) Introduced species density (nbinom)						
Relative Water Flow	4	-443.14	894.49	0.00	0.14	0.67
Sediment Carbonate + Relative Water Flow	5	-442.17	894.66	0.18	0.13	0.67
Sediment Carbonate	4	-443.44	895.09	0.61	0.11	0.67
(1|Beach)	3	-444.62	895.38	0.89	0.09	0.67
Silt + Relative Water Flow	5	-442.69	895.70	1.21	0.08	0.67
Sediment Carbonate + Silt + Relative Water Flow	6	-441.71	895.87	1.38	0.07	0.67
Mean Temp + Relative Water Flow	5	-443.01	896.34	1.85	0.06	0.67
Sediment Carbonate + Mean Temp + Relative Water Flow	6	-442.08	896.60	2.11	0.05	0.67
Sediment Carbonate + Mean Temp	5	-443.17	896.65	2.17	0.05	0.67
Mean Temp	4	-444.32	896.85	2.37	0.04	0.67
Sediment Carbonate + Silt	5	-443.33	896.98	2.49	0.04	0.67
Silt	4	-444.53	897.28	2.79	0.04	0.67
Silt + Mean Temp + Relative Water Flow	6	-442.68	897.80	3.31	0.03	0.67
Sediment Carbonate + Silt + Mean Temp	6	-442.76	897.98	3.49	0.03	0.67
Sediment Carbonate + Silt + Mean Temp + Relative Water Flow	7	-441.71	898.01	3.53	0.02	0.67
Silt + Mean Temp +Mean Temp	5	-443.94	898.20	3.71	0.02	0.67
D) Introduced species biomass (tweedie)						
Sediment Carbonate	5	60.534	-110.750	0.000	0.158	0.540
(1|Beach)	4	59.452	-110.694	0.056	0.154	0.540
Relative Water Flow	5	60.288	-110.258	0.492	0.124	0.540
Sediment Carbonate + Relative Water Flow	6	61.183	-109.919	0.831	0.104	0.540
Sediment Carbonate + Mean Temp	6	60.795	-109.142	1.608	0.071	0.540
Mean Temp	5	59.727	-109.138	1.613	0.071	0.540
Sediment Carbonate + Silt	6	60.596	-108.746	2.004	0.058	0.540
Silt	5	59.487	-108.657	2.093	0.055	0.540
Mean Temp + Relative Water Flow	6	60.299	-108.151	2.600	0.043	0.540

Model:	df	logLik	AICc	deltaAICc	weight	Pseudo R2
Silt + Relative Water Flow	6	60.288	-108.129	2.621	0.043	0.540
Sediment Carbonate + Silt + Relative Water Flow	7	61.193	-107.786	2.964	0.036	0.540
Sediment Carbonate + Mean Temp + Relative Water Flow	7	61.184	-107.768	2.982	0.036	0.540
Silt + Mean Temp	6	59.729	-107.010	3.740	0.024	0.540
Sediment Carbonate + Silt + Mean Temp + Relative Water Flow	7	60.797	-106.995	3.756	0.024	0.540

Models with varying number of parameters were compared using small-sample bias corrected Akaike's Information Criterion (AICc), AICc differences (deltaAICc), normalized Akaike weights (weight), and the residual variance of the full model against the residual variance of the null model (Pseudo R2).

We found a positive effect of relative water flow on native clam species density and biomass (Figure 3 C & D: RVI =1, 1 respectively). While the effect of sediment carbonate on native clam density and biomass was also positive, the effect was imprecise and relatively less important (RVI=0.37, 0.43 respectively). Moreover, we found relatively little evidence for an effect of grain size, mean seawater temperature, and density of introduced species on native clam density and biomass (all RVIs < 0.5). While our measured environmental covariates explain some of the variability in clam density and biomass, much of the variability remains unexplained by our analysis (Figure 3; Table 1).

We found a moderate negative effect of relative water flow on the density and biomass of introduced species (Figure 3 E & F: RVI = 0.58, 0.4 respectively). The direction of this effect was opposite for native species (Figure 3). We also found a moderate negative effect of sediment carbonate on introduced species density and biomass (RVI= 0.5 and 0.49 respectively). We found relatively little strength of evidence for an effect of sediment grain size, and mean seawater temperature on the density and biomass of introduced clam species (all RVIs < 0.5).

We found more precise effects of our environmental covariates in our species-specific models (see Appendices C & D). We found a negative effect of mean temperature on butter clam density and biomass (RVI 0.84 and 1 respectively). Sediment carbonate and relative water flow both had positive effects on butter clam density and biomass. Conversely, relative water flow had a negative effect on softshell and varnish clam density and biomass (See butter clam, softshell clam, and varnish clam coefficient plots and RVIs, Appendices C & D).

When we qualitatively considered the spatial distribution of native clam species, we found that beaches of relatively high contemporary native clam density and biomass tended to be associated with Tsleil-Waututh village sites and known ancestral clam harvesting locations (Figure 2).

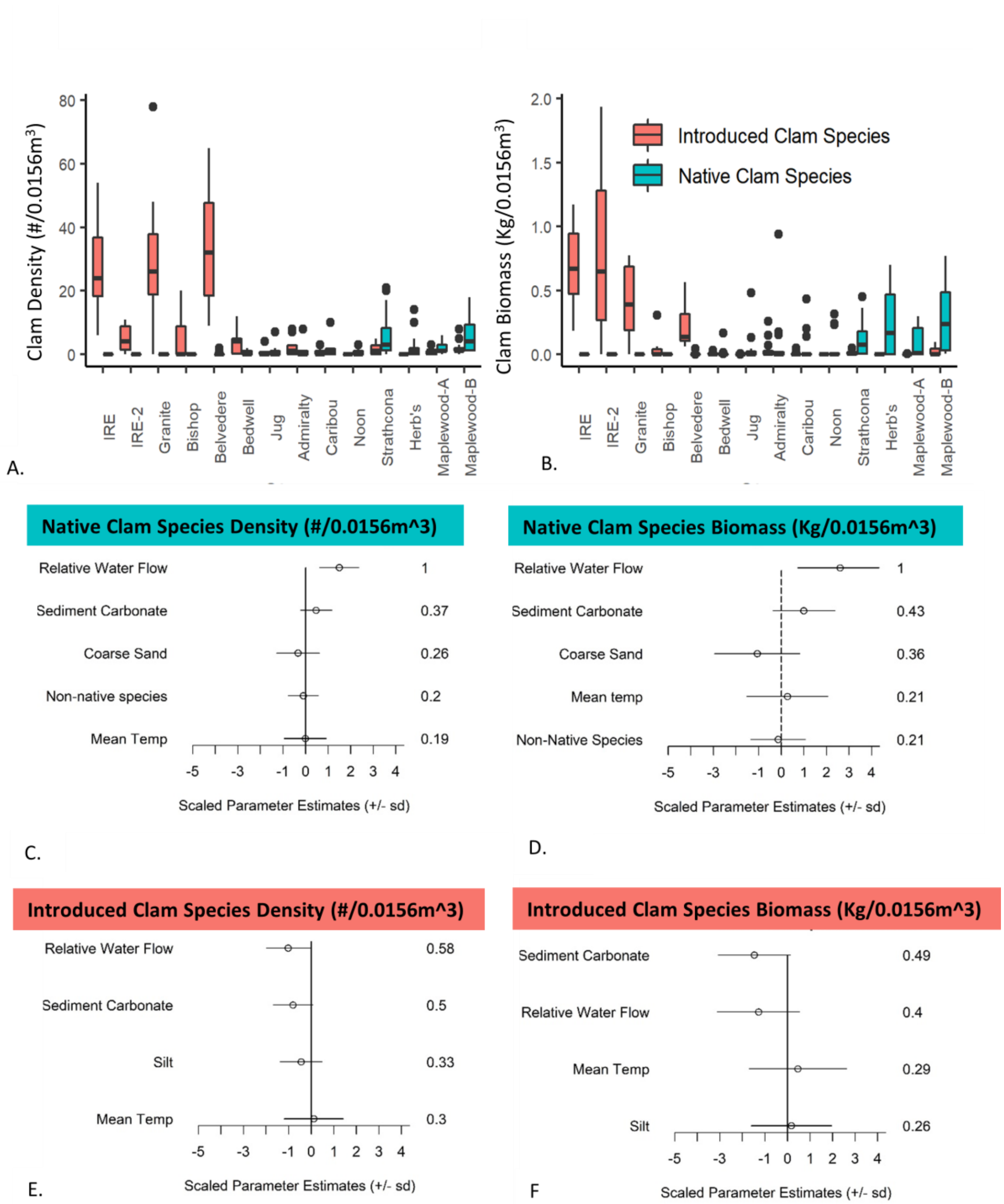

Figure 3. **Density (A) and Biomass (B) of introduced and native species across all sampling sites (n=14). Boxplots represent the distribution of 15 quadrats sampled at each of the 14 sites. Standardized parameter estimates, their 95% confidence intervals, and relative importance of environmental variables driving the density (C), and biomass (D) of native, and introduced clam species (E) and (F). Standardized parameter estimates and relative variable importance are calculated from Akaike's information criteria weights of top models ($\Delta AIC_c < 4$).**

Visions for Clam Stewardship in Burrard Inlet

The stewardship and restoration of Burrard Inlet's nearshore is a key priority among the many ways of exercising Tsleil-Waututh governance authority (Curran et al., 2020). Our review demonstrates the paramount importance of safe, abundant, and persistent clam harvesting to meet this priority (Table 2). Importantly, the Tsleil-Waututh Stewardship Policy which governs how the Nation assesses proposed activities and projects within their traditional territories, highlights a sacred responsibility to care for the territory's lands and waters:

> Our people are here to care for our land and water. It is our obligation and birthright to be the caretakers and protectors of our Inlet. Therefore, be it known far and wide that our Tsleil-Waututh Nation, the People of the Inlet, are responsible for and belong to our traditional territory (Tsleil-Waututh Nation, 2009).

Building on the Stewardship Policy, in May 2015 the Tsleil-Waututh Nation released the community's independent Assessment of the Trans Mountain Expansion Project (Tsleil-Waututh Nation 2015). This report is one of the most prominent contemporary applications of Indigenous law in Canada (Curran et al., 2020). Here, in accordance with the Tsleil-Waututh Nation Stewardship Policy, there is a specific shellfish directive:

> If conditions do not permit the harvest, use, sale, or trade of safe abundant wild foods such as salmon, herring, clams, or birds from Burrard Inlet, then the environmental integrity of the inlet is compromised, and cumulative effects have exceeded what is allowable under Tsleil-Waututh Law" (Tsleil-Waututh Nation 2015).

Tsleil-Waututh's 2017 Burrard Inlet Action Plan sets out a vision for a productive, resilient, and diverse Inlet (Lilley et al. 2017) where: "Being able to once again safely harvest traditional wild foods in Burrard Inlet, particularly bivalves like clams, is deeply important." These documents, and others, demonstrate Tsleil-Waututh Nation's historical and contemporary management authority in relation to clams, and visions for a healthier Burrard Inlet (Table 2).

Table 2. Five previously published resources developed or co-developed by TWN and collaborators. For each document we listed a description of the document (Column two), and an excerpt of the vision for shellfish in Burrard Inlet (Column three)

Document	Objective of document	Shellfish related directive
Marine Stewardship Plan (2005)	To support environmental improvement in Burrard Inlet, in 2005 Tsleil-Waututh developed a Marine Stewardship Program	» “Restoring Burrard Inlet to a condition where wild marine foods are abundant and safe to eat and a subsistence economy may be re-established » Restoring Burrard Inlet to a condition where cultural work may occur in clean water, without exposure to contaminated sediment, at sites that are physically intact and free from impaired views, violations of privacy, and noise intrusions"
TWN Stewardship Policy (2009)	Outlines the lenses through which TWN evaluates project proposal in their territories based on ancestral laws.	"We are the Tsleil-Waututh First Nation, the People of the Inlet. We have lived in and along our Inlet since time out of mind. We have been here since the Creator transformed the Wolf into that first Tsleil-Wautt and made the Wolf responsible for this land. We have always been here, and we will always be here. Our people are here to care for our land and water."
TWN Assessment of the Trans Mountain Pipeline (2015)	Assessment of the TMEX proposal in accordance with the TWN Stewardship Policy, history, culture, and governance.	"If conditions do not permit the harvest, use, sale, or trade of safe, abundant wild foods such as salmon, herring, clams, or birds from Burrard Inlet, then the environmental integrity of the inlet is compromised, and cumulative effects have exceeded what is allowable under Tsleil-Waututh law"
Burrard Inlet Action Plan (2017)	Provides guidance for a science-based, TWN-led initiative to improve the health of Burrard Inlet by 2025.	“Being able to once again safely harvest traditional wild foods in Burrard Inlet, particularly bivalves like clams, is deeply important to the Tsleil-Waututh Nation.” "There is a need to better understand both historic and current distribution of particular bivalve species relative to habitat conditions and human impacts, as well as the nature and extent of transition from native shellfish species like butter and littleneck clams to invasive introduced shellfish species like softshell and purple varnish clams, and how these species may be interacting."
Burrard Inlet Water Quality Objectives (2021)	To inform the management of water quality in Burrard Inlet in collaboration with the BC Ministry of Environment and Climate Change Strategy	"The document outlines long term and short-term water quality objectives for Burrard Inlet that reflect TWN’s aspiration to improve overall quality and restore access to traditional food."

Knowledge Exchange

“I would actually like to see it happen so that our kids can dig clams. So that they can experience what the Elders experienced in their time.”

Micheal George, shared during Oct 7th Knowledge Exchange

In total 30 people took part in the Knowledge Exchange including 6 Elders, 15 Tsleil-Waututh youth observers with two teachers, and 7 technical staff. While we were interested in learning about specific clam tending practices, the most important results for the community were gathering for intergenerational knowledge-sharing and experiential learning on the beach. The results presented below do not represent the entirety of the Tsleil-Waututh community, but rather the shared experiences of those who attended the October 7th Knowledge Exchange.

Stewardship Practices in Action

We found that conversations during the Knowledge Exchange contributed to and extended the previously established Tsleil-Waututh-led framework of objectives used to gather qualitative community feedback (Tsleil-Waututh, 2015). Importantly, we found that bringing people together on a clam beach allowed us to move beyond talking about objectives and toward small steps that enact and live them (Figure 4). In the section below, we outline some of the learning from the Knowledge Exchange organised according to the framework of the four previously established themes.

Figure 4. Dominant themes discussed and enacted during the Knowledge Exchange. These themes had been previously identified as important by the Tsleil-Waututh community and resonated within our work. Background photo is of Maplewood Mudflats, Burrard Inlet, Canada where the Knowledge Exchange took place. Each of the conversational themes is highlighted against the backdrop of a photo of the theme being lived and enacted during the Knowledge Exchange.

Cultural work and Community Well Being: Cultural work and youth education continue in ways that allow TWN to thrive as a community

"*…The youth coming out and helping harvest the clams, digging them. Learning from our kids how to make clam chowder (laughter). Yeah, I'd like to see the youth out there. It's good to see them with us today here learning*." (Stanley Thomas, Tsleil-Waututh Elder)

Through the Knowledge Exchange, we found that culturally important species such as clams provided an entry point for talking about broader community wellbeing. For example, talking about clams often led to remembering stories related to family and cultural protocol. Discussing culturally important species such as clams provided a powerful way for people to connect with their personal history. Importantly, the nature of conversations changed when we shifted from talking about clams to engaging with the beach. For example, when we moved to beach activities, participants began asking one another questions about specific clam species and their preferred environments. The laughter heard across the beach showed the playfulness and joy of coming together on the beach. Overall, these experiences highlight the importance of experiential learning on culturally important species such as clams and intergenerational knowledge exchange to cultural work and youth education.

Natural Resource Access and Use: The water in Burrard Inlet is clean, and natural resources are abundant, accessible, and safe to eat.

"I'd like to see it come back. Where we can dig from the beach and consume from the beach, the clam species. One of the smaller things that I would like to see is for access to happen. So that our Elders can go down to the beach and spend a day with their kids even if they can't harvest clams. I would say access... stairs down the rockwalls, trails to the beach where people are safe and not having to climb over obstacles." (Micheal George, Tsleil-Waututh Cultural Advisor)

Throughout the Knowledge Exchange, there was recognition that clams in Burrard Inlet are not currently accessible and safe to eat at desired locations due to contamination and shoreline change. This was demonstrated through reflections shared by workshop participants on the dramatic environmental changes that continue to take place across Tsleil-Waututh territory: "The shapes of the shells are different, even the same species have different shapes of shells" (Dennis Sisson, Tsleil-Waututh Elder), and "When I was young, you had to go way out further to dig for clams" (Doreen Parnel, Tsleil-Waututh Elder). Furthermore, during beach activities, participants primarily interacted with introduced species. Environmental changes such as these have profoundly disrupted opportunities for harvest, knowledge exchange, and associated cultural practices: "It would be cool if we could all eat the seafood again instead of having to go far to look for it or go buy it" (Lorelai Thomas, Tsleil-Waututh Elder). Nonetheless, as conversations moved into memories and personal experience, Elders shared recollections that were important to both their individual lives and visions of a healthier Burrard Inlet. These conversations highlight the importance of including memories, cultural context, and personal connections in objectives for natural resource access and use that strive to be equitable.

Environmental Stewardship Obligations: In accordance with TWN stewardship obligations, the health of Burrard Inlet is improving

One of the avenues for bringing about visions for the future is by exercising Tsleil-Waututh stewardship obligations. We found that rather than collaboratively developing strategies that we hypothesized would relate to the clam tending practices outlined in Figure 1 (A suite of Ancestral Biophysical Clam Tending Practices), the conversation focused on shared visions for enacting broad stewardship practices and spending time together as a community. While some participants noted specific tending practices such as the addition of shell hash, the creation of clam gardens, turning the sediment, the removal of undesirable species, the use of specific harvesting techniques, and the reduction of woodwaste, these practices were not discussed in detail. It is possible that this reflected a thinning of Tsleil-Waututh Knowledge of ancestral clam tending held by Knowledge Exchange participants following ongoing impacts of colonization in Burrard Inlet. We found that, while specific knowledge on Tsleil-Waututh clam tending was not shared, focusing on culturally significant species linked to other cultural knowledge being revived such as spirituality, cultural identity, language, connection to place, flavours, smells, and memories of those now-passed teachers. These conversations illustrate how stewarding the cultural connection to a single species or group of species such as clams, is as important as physically restoring the clams on the beach.

Control over and sharing of resources according to Tsleil-Waututh and Coast Salish protocols: Tsleil-Waututh's title and right to actively manage the territory in accordance with protocols to benefit past, present and future generations is respected

"Dig only in front of extended family houses, as long as they knew who you were and what family you came from." (Dennis Sisson, Tsleil-Waututh Elder)

Participants also highlighted the importance of carrying out stewardship obligations in accordance with Tsleil-Waututh protocols. For example, one participant described a system of Tsleil-Waututh land tenure regarding familial clam-digging beaches.

Discussion

We identified ancestral clam tending practices, current biophysical conditions driving clam abundance and composition, and facilitated actions aimed at bringing community back to the beaches to support the revitalization of Tsleil-Waututh clam tending practices in Burrard Inlet, Canada. We found that clam density varied by as much as 60 times across sites and that species composition varied significantly with sites at the head of the inlet dominated by introduced clams. We found strong evidence that water flow was the primary measured ecological variable driving native clam density and biomass. Our findings suggest that the ecological context of Burrard Inlet is substantially different from pre-contact conditions with the dominance of introduced species and relatively low median density (4 clams /0.0156 m^3) and biomass (26g /0.0156 m^3) of all clam species. While introduced species dominated numerically, this was only the case at the head of the Inlet. Sites towards the mouth of the Inlet had more native species. We found that themes that emerged from the Knowledge Exchange echoed previously identified stewardship principles that could be enacted to advance the revitalization of Tsleil-Waututh clam tending practices today. Importantly, the Knowledge Exchange we facilitated – while only one small step of many – provided a platform for intergenerational knowledge sharing, and experiential learning on the beach. Despite experiencing continually changing ecological conditions, Tsleil-Waututh Nation is finding and following new paths forward that are informed by land-based knowledge and ancestral practices.

Learning from Ancestral Clam Tending

Learning from distinct experiences navigating ecosystem change can enable communities to better plan for shocks and disturbances, ultimately contributing to adaptive capacity and conferring resilience (Folke et al., 2003; Armitage et al.,2011; Berkes, 2009; Burt et al., 2019). Many Indigenous peoples in Canada and elsewhere in the world are relearning and revitalizing ancestral stewardship practices (Joseph & Turner, 2020). By investigating and better understanding the diversity of ancestral clam tending practices that exist on what is known as the B.C. coast, we can inform a range of possible practices that could be applied to coasts around the globe. This knowledge and experience can offer inspiration for experimentation within other social-ecological contexts where clam stewardship knowledges are being reawakened (Figure 1).

Indigenous communities along the coast of the Pacific Northwest have long maintained and enhanced shellfish productivity through a variety of ecological and cultural management practices (Groesbeck et al., 2014; Lepofsky et al., 2015; Deur et al., 2015; Jackley et al., 2016). However, ongoing processes of colonization have impaired the opportunity for many Indigenous Nations to exercise their inherent and constitutionally protected rights (in Canada) to harvest and manage clams in accordance with ancestral governance protocols. Nonetheless, along the B.C. coast Indigenous Peoples continue to harvest and care for clams and clam beaches (Augustine & Dearden, 2014). Clam tending practices are being revitalized, and their application to contemporary management is of interest to several Nations along the B.C. coast (Augustine & Dearden 2014). For example, Hul'qumi'num- speaking and W̱SÁNEĆ Peoples alongside Parks Canada staff are restoring clam gardens and managing clam beaches, in and around the Gulf Islands National Park Reserve, guided by knowledge holders from these Coast Salish communities (H-GINPR Committee 2016). As another example, the Swinomish Indian Tribal Community recently built a rockwall for a new clam garden (Ryan, 2022). Other examples of such projects exist along the B.C. coast and around the Pacific Ocean (Pacific Sea Garden Collective, 2022). Our analysis of peer-reviewed literature illustrates a rich diversity of ancestral clam tending such as rockwall construction and maintenance, tending and tilling of sediment, debris removal, addition of shell hash and gravel, size-selective clam harvesting, juvenile clam transplanting, and predator and debris removal (Figure 1). The revitalization of these practices along the Pacific Northwest, demonstrates great potential for information exchange, and collectively cultivated capacity for transformation, as Indigenous communities from different ecosystems, colonial contexts, and present-day ecological conditions are in diverse stages of clam tending recovery. Recognizing that peer-reviewed literature offers only one lens into the rich Indigenous Knowledge on clam tending, we imagine that opportunities for learning extend far beyond what we have identified through this research.

The zooarchaeological record provides one important avenue for extending our understanding Tsleil-Waututh clam harvest and tending in Burrard Inlet prior to European contact. Understanding past species abundance and distribution can help us understand the social-ecological relationships which may have contributed to long-term human influence on species persistence or loss. In Burrard Inlet, several large archaeological sites in the Central Harbour hold cultural shell deposits that span a range of ecological settings and a diversity of pre-contact functions and hold evidence of Tsleil-Waututh-managed shellfish rich beaches (Pierson, 2011). The Tsleil-Waututh Strength of Claim Report provides evidence for some clam tending in Burrard Inlet, however only some of the specific biophysical practices identified in our literature review were described in the Tsleil-Waututh Traditional Use Study sources (Appendix B). It is important to note that these sources provide insight into Burrard Inlet's condition after settler activities began, and after much ecological change had already taken place in Burrard Inlet (Morin & Evans, 2022). As well, this report was written prior to any contemporary surveys for clam gardens in Burrard Inlet.

In her collaborative research on the restoration of lhásem with Squamish People, Leigh Joseph reflects on processes of knowledge renewal:

> If we speak as though traditional knowledge is lost, it implies that our ancestors were unable to maintain their knowledge through the hardships endured since colonization. This is not the case. There are threads of knowledge, some big and some small, which have been carried on, and will be carried forward into the future. The task at hand is to weave these threads of knowledge together by renewing traditional practice in Indigenous communities (Joseph, 2012, p.101).

Learning from tending practices implemented by other Indigenous Peoples alongside historical documentation led by Tsleil-Waututh Nation offers threads of knowledge for the revitalisation of Tsleil-Waututh clam tending practices that build on past teachings and knowledge and are rooted within cultural context. These threads create space for community-driven contributions and priorities.

Ecological Limitations and Possibilities in Burrard Inlet

A multitude of historical and ongoing drivers of change have affected clam populations along the Pacific Coast, particularly in urban centers. Ecological degradation due to resource extraction, port and industrial development, and urbanisation have had profound impacts on clam beaches across North America broadly and in Burrard Inlet specifically (Morin & Evans 2022, Taft et al., 2022, Rao 2022). Over the past 150 years, native clam populations in Burrard Inlet have undergone massive reductions in abundance and changes to species composition. Some of the factors driving clam declines have been habitat loss, invasive species, and contamination documented as early as 1912 CE (Thompson 1913, Morin & Evans, 2022). Many of the circumstances driving ecological degradation continue today.

In 1972, the Canadian Government closed Burrard Inlet to bivalve harvest due to contamination (Morin and Evans, 2022). In 2016, Tsleil-Waututh Nation conducted its first sanctioned harvest since the initial closure. This opening followed years of work led by Tsleil-Waututh Nation to ensure clams are safe to eat. The Nation continues to carry out rigorous and ongoing sampling adherent to Canadian Shellfish Sanitation Program standards to support an annual harvest opening of 1-3 days at a single remote beach. Outside this brief window, all marine waters in TWN territory, remain closed to shellfish harvesting by the Government of Canada. The species harvested is an introduced species (softshell clam – *Mya arenaria*) that is dominant at the harvesting site.

Since the harvesting closure in Burrard Inlet was instituted in 1972, many barriers limit Tsleil-Waututh Nation's opportunities to develop and maintain knowledge of contemporary clam populations. Since 1792 CE, 949 ha of intertidal area in Burrard Inlet has been effectively lost, via infilling, dredging and hard armouring, and no longer support clams (Taft et al. 2022). Indeed, these changes limited the sites that were available for this study. Contemporary ecological surveys do not represent, or even approach, historical or pre-contact conditions. Rather, they represent conditions after extensive social and ecological change has already occurred (Morin & Evans, 2022).

Building an understanding of the current drivers of clam density, biomass, and species composition in Burrard Inlet, may help inform the revitalization of ancestral harvesting and tending practices. The results of our ecological surveys reflect high variability in contemporary clam abundance and biomass as well as the strong prevalence of introduced species. Nonetheless, they also provide indication as to where native clam species persist, and the environmental variables that may be driving clam abundance, biomass, and species composition in Burrard Inlet. These environmental variables may be mediated by the tending practices discussed in the previous section and offer potential ways forward as Tsleil-Waututh Nation continues to assert their rights to access safe and persistent clam harvests into the future.

Consistent with studies elsewhere along the coast (Gillespie et al., 2004) we found a high variability in clam biomass and density both within and across sites. Nonetheless, our results suggest that contemporary density and biomass of native clam species in Burrard Inlet are 6-12 times lower than numbers reported elsewhere along the B.C. coast. For example, Gillespie (2004) found a range of 116-192 butter clams/m^2, and 64-256 Pacific littleneck clams/m^2 at beaches on the north coast of B.C. (Gillespie, 2004). Tsleil-Waututh's Traditional Use Studies indicate that clams were a staple for Tsleil-Waututh people in the early-to-mid-twentieth century (Morin and Evans, 2022) and archaeological evidence indicates that they were central to people's lives for millennia (Pierson, 2011). Tsleil-Waututh's Traditional Use Studies describe increasing pollution in the 1960's at a clam bed in the Central Harbour dissuading people from harvest. Indeed, descriptions of pollution from oil refining activities destroying local clam population in Burrard Inlet exist as early as 1912 (Thompson, 1913).

In accordance with other recent field surveys in Burrard Inlet (Dudas & Dower, 2006), we identified a relatively high abundance of introduced clam species at our sampling sites. Specifically, we found introduced varnish, manila, and softshell clams all of which have different histories of introduction. For example, the introduction of soft-shell clams to the Pacific Northwest can be traced back to the mid-1800's where they likely arrived to San Franciso Bay mixed in shipments of eastern oyster (Palacios et al., 2000). Conversely, manila clams were intentionally introduced to the B.C. coast for commercial reasons. Following their introduction in the 1960's, manila clams have spread throughout the Strait of Georgia and along the west coast of Vancouver Island (Gillepsie 2004; Bendell et al., 2014). Today manila clams are dominant on a variety of beach habitats throughout the south coast of B.C. (Gillepsie 2004; Bendell et al., 2014). Conversely, the varnish clam, which is native to Southeast Asia, is a relatively recent introduction. Varnish clams are thought to have been unintentionally transported as larvae in ballast waters to Vancouver Harbour in the early 1990s. Since their introduction, they have spread at densities up to four times greater than those of non-invasive species to a northern limit in Smith Sound, B.C. and to, Oregon in the south (Dudas & Dower, 2006).

Our findings contrast with species assemblages found in zooarchaeological records in Burrard Inlet. For example, while Pierson (2011) found Pacific littleneck, Nuttal's cockle and butter clams to dominate midden assemblages in Burrard Inlet, we found a high occurrence of introduced species. Importantly, we found a strong pattern in the spatial distribution of introduced clam species. In our surveys, clams up Indian Arm and towards the northern extent of Burrard Inlet tended to be dominated by introduced species, while those closer to the Central Harbour were dominated by native species (Figure 2). While environmental drivers such as relative water flow and sediment carbonate explain some of the variability in the contemporary density and biomass of distinct clam species, much of the variability remains unexplained by our analysis (Table 1). This requires us to consider other factors that may drive the geographically variable distribution of clam species.

It is possible that some geographic variability of species assemblages could be due to longstanding human care and stewardship. This leads us to hypothesize that Tsleil-Waututh ancestors settled near habitat that was good for native clam species. As an alternative but non mutually exclusive hypothesis, we surmise that legacies of ancestral clam tending may have increased beach resilience to invasion by improving habitat quality for native clam species. While it is difficult to exclude alternative drivers of change such as contamination, history of invasions, and larval dispersal, our findings point to possible interactions between clam tending practices and invisibility of exotic clam species. The experimental implementation of Tsleil-Waututh tending practices on beaches could help tease apart other detailed mechanisms driving the spatial distribution of introduced clam species in Burrard Inlet while the archaeological record could reveal the spatial distribution of clams through deep time.

We found evidence that higher relative water flow, drove a higher density and biomass in native clam species (Figure 3). Previous evidence from clam gardens elsewhere in B.C. has demonstrated that higher relative water flow drove higher clam densities at clam gardens compared to non-walled beaches (Salter, 2018). Greater water residency may increase the delivery and deposition of clam larva to beaches, increase food delivery (Jorgenson, 1966), and moderate ambient temperature (Salter, 2018). Moreover, waterflow moderates dissolved oxygen concentration which is known to play an important role in clam growth and survival (Bayne, 1971). Other work from Burrard Inlet has demonstrated how narrow passages have a strong influence on water flow, as water accelerates when it is forced through constricting narrows (Meijers, 2021). In Burrard Inlet, site specific characteristics such as relative water flow may help inform future Tsleil-Waututh clam tending.

We found moderate evidence that greater sediment carbonate on the beach drove a higher biomass and density of native clam species. Previous research demonstrates how sediment carbonate can enhance larval settlement, and the post recruitment growth of calcifying organisms (Green et al. ,2013; Waldbusser et al., 2013). Specifically, the taphonomic feedback hypothesis (Kidwell & Jablonski, 1983) suggests a relationship between shell remains, and living bivalve populations. When bivalves reach the end of their lives, their shells add more mineral calcium carbonate to the sediment. This accumulation of carbonate shells in the sediment provides a hard substrate where larvae settle in a positive feedback loop. Moreover, as shells break down on the beach dissolved carbonate in porewater is available for calcifying organisms to turn into shells, potentially supporting more rapid shell growth.

Evidence from clam gardens on Quadra Island demonstrates how greater sediment carbonate, supplied by a dense accumulation of crushed shell, drove higher clam density, biomass, and growth rates of experimentally transported clams (Salter, 2018). Indeed, ethnographic accounts tell of Indigenous communities creating conditions to promote shell hash (i.e., sediment carbonate), through the construction of clam gardens, or returning clam shells from harvests to managed clam beds (Deur et al., 2015; Lepofsky et al., 2015). Once larvae have settled, the quality of porewater plays a significant role in the survivorship of juvenile clams (Green et al., 2009). In Burrard Inlet, the application of shell hash to offset porewater acidification has been shown to be highly site dependent due to the spatial heterogeneity of other urban impacts such as woodwaste (Doyle & Bendell, 2022). For example, processes of eutrophication could act in concert with acidification and create conditions unsuitable for larvae settlement and development (Doyle & Bendell, 2021).

When taken together, our results suggest that beaches with high sediment carbonate in Burrard Inlet reflect an enduring legacy of Indigenous clam tending, and we hypothesize that the legacy of this tending supports a greater density and biomass of native clam species. Moreover, it is possible that native clam species are more sensitive to decreases in sediment carbonate, while introduced clam species can tolerate a wider range of conditions, and therefore occupy a different environmental niche. This hypothesis suggests an ecological mechanism explaining why we observed a greater density and biomass of native clam species adjacent to ancestral Tsleil-Waututh settlements and important clam harvesting locations. Importantly, this may suggest that legacies of Indigenous clam tending practices continue to benefit native clam species in Burrard Inlet today.

While we did not find strong evidence for the effect of sediment grain size, and temperature on clam density, biomass and species composition, literature suggests that these are important drivers. Temperature is an important variable effecting growth and survival of clams given its implications for metabolic performance (Houghton & Moore, 1977). Where stable temperatures enhance growth, temperature extremes induce physiological stress (Bernard, 1983). One limitation of our study is in its spatial and temporal extent. While we measured temperatures throughout the summer growing season, research from elsewhere has demonstrated that clam die-offs in response to extremely high summer temperatures often do not occur until the following winter (Cronin, 1968). This temporal extent would not have been captured in our study. Furthermore, our study was limited in its spatial extent. Future studies considering the effects of temperature on the biomass, density, and species composition of clams in Burrard Inlet could consider a larger spatial extent of sampling sites to capture a wider range in temperature variability.

Learning from the Beaches

> *"[w]e have found ways to connect to the land and our stories and to live our intelligences no matter how urban or how destroyed our homelands have become." (Simpson 2017, p. 173)*

As others have shown, bringing a tending practice back to an Indigenous community has significance beyond biophysical manipulations, and ecological enhancements (Joseph, 2018; Lepofsky et al., 2017; Thom, 2005; Wickham et al., 2022). Clams are emblematic of relationships to place and stewardship obligations, supporting cultural identities and wellness that extends far beyond nutritional needs (Augustine and Dearden, 2014). Our findings from the Knowledge Exchange echo this, indicating that intertwined in the process of reconnecting with clam tending practices are reawakened conversations about relationships to place, cultural practices, language, and stewardship responsibilities– each of which are critical elements of Indigenous resurgence (Figure 4).

The Knowledge Exchange highlighted the importance of experiential learning and intergenerational knowledge sharing on the beach. “Land-based pedagogy and practices can act as a catalyst for regenerating Indigenous social, spiritual, and physical land-connection” (Wildcat et al., 2014). Shawn Wilson (2008) reflects on the importance of reawakening responsibilities to more-than-human relations as essential to healing and resurgence. Indigenous land-based pedagogy is an important aspect of achieving this (Corntassel & Hardbarger, 2019). In their work focused on the perpetuation of Indigenous Knowledges, Jeff Corntassel and Tiffanie Hardbager reflect on how and why community resurgence takes place:

> When considering how and why community resurgence takes place, it is important to examine these actions through an everyday lens while also taking into account how land, water, ceremonial life, language, food and sacred living histories shape the responsibilities and sense of/gadugi [working together as a group for a common goal] that promote our collective and individual health and well-being. These aspects must be taken into account when contemplating how best to foster “land-centred literacies” that connect us to our past, ground us in our present realities and prepare us for the future generations that will face new and dynamic challenges. (Corntassel and Hardbager, 2019).

The results of our Knowledge Exchange echo rich work from elsewhere that articulates the importance of exchanging knowledge not only with one another, but also with the land, the waters, and more-than-human relations. Knowledge exchange processes are influenced by context, pre-existing relationships individual experience and values (Fazey et al., 2013). Importantly, culture and context influence the way people engage with knowledge and ideas (Fazey et al., 2013). Future knowledge exchange practices could further reflect the complexities and nuances of Indigenous-land based education and think further about how we can “practice and foster reciprocity with communities to create land-based sites of education” (Wildcat et al., 2014).

As Tsleil-Waututh Nation works to heal from the ongoing impacts of colonization, while facing continued social and environmental challenges, the mobilization of ancestral knowledge may take many forms and benefit from many types of support (Table 2). We offer this work as threads of evidence and momentum toward ongoing efforts to revitalize Tsleil-Waututh clam tending practices in Burrard Inlet.

Transformation in Social-Ecological Systems

Tsleil-Waututh Nation is at the forefront of rapid social and ecological change. Their efforts to transform untenable conditions in ways that sustain ecosystems and social-ecological relationships can inform other communities facing similar challenges, as well as decision-makers and researchers in positions to influence change and key leverage points. The importance of envisioning transformations based on community priorities and rooted in the renewal of social-ecological relationships, cannot be underestimated. Such visioning requires collective imagining, ecological understandings, intergenerational communication, and systemic shifts in institutional underpinnings (Corntassel, 2012; Sellberg et al., 2017; Simpson, 2004)

Among scientists, there is a growing focus on co-production, participation, collaborative dissemination, and application of knowledge to increase the likelihood of transformation and improvement of management decisions (Salomon et al., 2018; Hakkarainen et al., 2020; Reid et al., 2021). A core challenge in transformation scholarship involves reflecting the lived challenges and aspirations of diverse peoples, and in identifying opportunities for disrupting systemic power structures and imbalances. Experiments to create spaces for social-ecological transformation are gaining increased traction (Charli-joseph et al., 2018). There are emerging methodological approaches where participatory spaces are used to generate intentional bottom-up transformations (Charli Joseph et al., 2018). Nonetheless, there is a growing consensus among scholars that the specific methods developed to create conditions for transformation are contingent on context and relationships (Falardeau et al., 2019).

Even within efforts toward co-production, when engaging in science the power relations that underpin the discipline do not serve all people equally. Increasingly scientists are asking “how may we change the way science is done?” (Liboiron, 2021). Where participatory and place-based methodologies follow principles of inclusivity, participation, cooperation, and knowledge exchange, we must continue to ask ourselves “how do our disciplines and research methods benefit from access to Indigenous land, life, and knowledge?” (Liboiron, 2021). And what do Indigenous land, life, and knowledge stand to gain or lose from our research methods? These questions guide us towards many ongoing learnings, examined relationships, and guiding principles, including principles of ethical and reciprocal exchange.

While holding undoubted value, it is unlikely that disciplinary knowledge on its own will be enough to enable the fundamental changes that may lead to ecologically safe and socially just transformation (Abson et al., 2017). By taking a transdisciplinary approach to understanding possible avenues towards the revitalization of Tsleil-Waututh clam tending practices in Burrard Inlet, we seek to fill important gaps in supporting approaches social-ecological transformation towards equitable ocean governance that are grounded in ancestral stewardship practices and reflect contemporary community objectives.

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Appendix A.

Measured Environmental Covariates

Table A.1. Table of measured environmental covariates. Predictor variable (column a), field method (column b), rational (column c), metric included in the quantitative model (column d), and reference (colomn e).

Predictor Variable	Field Method	Mechanism	Metric	References
Water Temperature	Temperature loggers were installed at each site in the center of each transect. Measurements were made every 15 minutes throughout the growing season.	Temperature is an important variable affecting metabolic performance, growth and survival of clams. Stable temperature enhances growth while temperature extremes induce physiological stress.	Mean temperature throughout the growing season.	Bernard 1983
Introduced Species Density	All Species in every quadrat were counted, ID and measured.	Introduced exotic species can dominate communities and replace native species. Resistance to invaders posed by native species assemblages is generally weak, and invaders tend to have greater competitive effects on native species than vice versa.	Quadrat level introduced species count.	Sousa et al., 2009
Relative Water Flow	The dissolution rate (g dissolved hour-1) of ice-cube sized gypsum blocks of similar weights (± 1 g) over 72 hours was measured.	Increased water residency may drive higher clam biomass by moderating ambient temperature. Increased water residency may also increase densities by increasing the delivery of clam larva to the beaches and enhancing food supply and oxygen generation.	Dissolution rate of gypsum blocks of similar weight over 72 hour period (weight lost/72hours).	Thompson and Glenn 1994, Boizard and DeWreede 2006
Sediment Grain Size	Collected in the field from the center of each quadrat. Grain size (% by weight) was determined by dry sieving with a set of seven grain sizes.	Coarse sediments generally provide suitable habitat for filter feeding clam species.	Silt and Coarse Sand	Quayle and Bourne 1972, Groesbeck et al. 2014

Sediment Carbonate Content	Sediment carbonate content (g/cm3) was determined using sequential loss-on-ignition following methods adapted from Wang et al. (2011).	Carbonate conditions within beach sediments have been found to contribute to species-sediment preferences. Sediment carbonate may enhance larval bivalve settlement and post-recruitment growth.	% weight of carbonate	Kidwell and Jablonski 1983, Green et al.2009

Appendix B.

A suite of Ancestral Clam Tending Practices

Table B.1. A suite of Clam Tending Practices (Column 1) described in published literature, and investigated through Indigenous Ways of Knowing and Western Science (Column 2). Column three, describes whether these practices have been articulated in any TWN Traditional Use Study.

A suite of tending practices	**Method and Benefit articulated in peer reviewed literature**	**Information from TWN Strength of Claim (Morin, 2015)** ***Note that this study was conducted prior to any clam garden surveys being conducted in Burrard Inlet**
Rockwall Construction and Maintenance	Clam gardens are designed to take advantage of natural geomorphic and ecological processes and vary in their specific landscape modifications. They often consist of a rock wall at the low tide line that traps sediment and reduces the slope of a beach thus maximizing the intertidal habitat within the ideal tidal height for target clam species (Groesbeck et al. 2014, Jackley et al. 2016	"While clam gardens have not been reported from the Study Area, much of the suitable shoreline here has been heavily modified, and they would have likely been destroyed."
Tending and tilling of sediment	Extensive research and stories tell of "sediment being actively aerated by Indigenous people who turned the sediment using a digging stick and rolled rocks to garden boundaries. Aeration improved clam growth and productivity by increasing access to oxygen (Deur et al., 2015; Groesbeck et al., 2014).	"The Tsleil-Waututh TUS data explicitly describes a decay of the rich shellfish beds in front of Sleil-Waututh IR No.3 due to pollution. (Tsleil-Waututh 2000; 2011). In the late 1960s, the eel grass and seaweeds on the beach in front of Sleil-Waututh disappeared and the sediments of the beach became increasingly foul-smelling."
Debris Removal	Space is created for clams to grow by removing rocks and other debris from the beach. This space also allows harvester more ease when accessing the beach (Deur et al., 2015; Groesbeck et al., 2014; Lepofsky et al., 2015).	"There are what appear to be beaches that have been purposefully cleared of boulders in the Study Area (personal observation), but it is unknown if these are pre-contact in origin."

A suite of tending practices	Method and Benefit articulated in peer reviewed literature	Information from TWN Strength of Claim (Morin, 2015) *Note that this study was conducted prior to any clam garden surveys being conducted in Burrard Inlet
Selective clam harvesting	"Shellfish are selectively harvested, leaving the smaller "seed" clams to continue to grow" (Turner, 2020).	"… This selective harvesting of large and older individuals allows the smaller younger clams to fully develop and reduces competition for habitat. Similar selective harvesting of shellfish should be anticipated among all Coast Salish shell middens, including the Tsleil-Waututh."
Addition of shell hash and gravel	Previous studies have demonstrated that the addition of shell hash to offset sediment acidity has been successful in aiding the recruitment and survival of juvenile clams (Greiner et al., 2018, Jackley et al., 2016).	Not directly referenced
Predator removal	Recent large and small-scale field experiments demonstrate that excluding predators can have dramatic results in clam abundance (Beal et al., 2020).	Not directly referenced
Juvenile clam transplanting	Seeding beaches in addition to adequate care could boost clam bed production levels effectively. However, if intentional seeding takes place it is important to ensure that the clam bed is tended to on a regular basis (WSANEC Clam Garden Restoration Report 2014-2020).	Not directly referenced

Appendix C.

Model Selection Tables

Table C.1. Strength of evidence for alternative models predicting the effect of environmental variables on (A) Butter clam density, (B) Butter clam biomass, (C) Varnish clam density, (D) Varnish clam biomass, (E) Softshell clam density, (F) Softshell clam biomass. We report all models where $\Delta AIC_c < 4$. Note all models include the random effect of beach site.

Model:	df	logLik	AICc	deltaAIC	weight	PseudoR2
A) Butter Density (nbinom)						
Sediment Carbonate + Mean Temp + Relative Water Flow	6	-128.43	269.30	0.00	0.18	0.19
Sediment Carbonate + Coarse Sand + Mean Temp + Relative Water Flow	7	-127.69	269.98	0.68	0.13	0.19
Sediment Carbonate + Mean Temp	5	-129.92	270.16	0.85	0.12	0.20
Mean Temp + Relative Water Flow	5	-130.40	271.12	1.82	0.07	0.20
Sediment Carbonate + Introduced Species Density + Mean Temp + Relative Water Flow	7	-128.31	271.21	1.91	0.07	0.19
Sediment Carbonate + Relative Water Flow	5	-130.53	271.37	2.07	0.06	0.20
Coarse Sand + Mean Temp + Relative Water Flow	6	-129.58	271.60	2.29	0.06	0.20
Mean Temp	4	-131.82	271.86	2.55	0.05	0.20
Sediment Carbonate + Coarse Sand + Introduced Species Denstiy + Mean Temp + Relative Water Flow	8	-127.63	272.03	2.72	0.05	0.19
Sediment Carbonate + Coarse Sand + Mean Temp	6	-129.86	272.17	2.86	0.04	0.20
Sediment Carbonate + Introduced Species Density + Mean Temp + Relative Water Flow	6	-129.92	272.28	2.97	0.04	0.20
Relative Water Flow	4	-132.10	272.41	3.11	0.04	0.20
Sediment Carbonate + Introduced Species Density + Relative Water Flow	6	-130.27	272.99	3.69	0.03	0.20
Sediment Carbonate + Coarse Sand + Relative Water Flow	6	-130.31	273.06	3.76	0.03	0.20
Introduced Species Density + Mean	6	-130.40	273.25	3.94	0.03	0.20

Temp + Relative Water Flow						
B) Butter Biomass (Tweedie)						
Sediment Carbonate + Mean Temp + Relative Water Flow	7	-50.98	116.56	0.00	0.30	0.23
Sediment Carbonate + Coarse Sand + Mean Temp + Relative Water Flow	8	-50.63	118.04	1.48	0.14	0.23
Sediment Carbonate + Mean Temp	6	-52.87	118.18	1.62	0.13	0.24
Sediment Carbonate + Introduced Species Density + Mean Temp + Relative Water Flow	8	-50.96	118.69	2.13	0.10	0.23
Mean Temp + Relative Water Flow	6	-53.35	119.15	2.59	0.08	0.24
Sediment Carbonate + Introduced Species Denstiy + Mean Temp + Relative Water Flow	7	-52.81	120.21	3.65	0.05	0.23
Sediment Carbonate + Coarse Sand + Introduced Species Denstiy + Mean Temp + Relative Water Flow	9	-50.63	120.23	3.67	0.05	0.23
Mean Temp	5	-54.97	120.27	3.70	0.05	0.24
Coarse Sand + Mean Temp + Relatvie Water Flow	7	-52.84	120.28	3.72	0.05	0.24
Sediment Carbonate + Coarse Sand + Mean Temp + Relative Water Flow	7	-52.87	120.33	3.77	0.05	0.24
C) Varnish Density (nbinom)						
Silt + Relative Water Flow	5	-236.34	482.99	0.00	0.23	0.62
Sediment Carbonate + Silt + Relative Water Flow	6	-235.53	483.52	0.53	0.18	0.62
Silt + MeanTemp + Relative Water Flow	6	-236.00	484.45	1.47	0.11	0.62
Relative Water Flow	4	-238.24	484.70	1.71	0.10	0.62
Silt +Sediment Carbonate + Mean Temp + Relative Water Flow	7	-235.24	485.07	2.09	0.08	0.62
Mean Temp + Relative Water Flow	5	-237.41	485.14	2.15	0.08	0.62
Sediment Carbonate + Relative Water Flow	5	-237.44	485.19	2.20	0.08	0.62
Sediment Carbonate + Mean Temp + Relative Water Flow	6	-236.66	485.77	2.78	0.06	0.62
Sediment Carbonate	4	-238.96	486.13	3.14	0.05	0.62
(1|Beach)	3	-240.06	486.25	3.27	0.04	0.62
Varnish Biomass (Tweedie)						
Mean Temp+ Relative Water Flow	6	16.87	-21.29	0.00	0.30	0.49
Sediment Carbonate + Mean Temp + Relative Water Flow	7	17.13	-19.67	1.62	0.13	0.49

Relative Water Flow	5	14.92	-19.53	1.76	0.13	0.49
(1|Beach)	4	13.74	-19.26	2.03	0.11	0.49
Silt + Mean Temp + Relative Water Flow	7	16.88	-19.16	2.13	0.10	0.49
Silt + Relative Water Flow	6	15.29	-18.13	3.16	0.06	0.49
Sediment Carbonate	5	14.19	-18.06	3.23	0.06	0.49
Sediment Carbonate + Relative Water Flow	6	15.21	-17.98	3.31	0.06	0.49
Silt +Sediment Carbonate + Mean Temp + Relative Water Flow	8	17.14	-17.50	3.79	0.05	0.49
Softshell Density (nbinom)						
Relative Water Flow	4	-220.69	449.58	0.00	0.33	0.39
Silt + Relative Water Flow	5	-220.24	450.80	1.22	0.18	0.39
Mean Temp + Relative Water Flow	5	-220.33	450.97	1.39	0.16	0.39
Sediment Carbonate + Relative Water Flow	5	-220.60	451.51	1.93	0.12	0.39
Silt + Mean Temp + Relative Water Flow	6	-220.10	452.64	3.06	0.07	0.39
Sediment Carbonate + Mean Temp + Relative Water Flow	6	-220.13	452.71	3.13	0.07	0.39
Sediment Carbonate + Silt + Relative Water Flow	6	-220.15	452.74	3.16	0.07	0.39
Softshell Biomass (Tweedie)	**df**	**logLik**	**AICc**	**delta**	**weight**	**CalculatedR2**
Relative Water Flow	5	-5.27	20.85	0.00	0.23	0.56
Sediment Carbonate + Relative Water Flow	6	-4.34	21.12	0.27	0.20	0.56
Sediment Carbonate + Silt + Relative Water Flow	7	-3.57	21.73	0.88	0.15	0.56
Silt + Relative Water Flow	6	-4.71	21.86	1.01	0.14	0.56
Mean Temp + Relative Water Flow	6	-5.20	22.85	2.00	0.08	0.56
Silt + Mean Temp + Relative Water Flow	7	-4.25	23.10	2.25	0.07	0.56
Sediment Carbonate + Mean Temp + Relative Water Flow	7	-4.33	23.25	2.40	0.07	0.56
Sediment Carbonate + Silt + Mean Temp + Relative Water Flow	8	-3.25	23.28	2.43	0.07	0.56

Models with varying number of parameters were compared using small-sample bias corrected Akaike's Information Criterion (AICc), AICc differences (deltaAICc), normalized Akaike weights (weight), and the residual variance of the full model against the residual variance of the null model (Pseudo R2).

Appendix D.

RVI plots

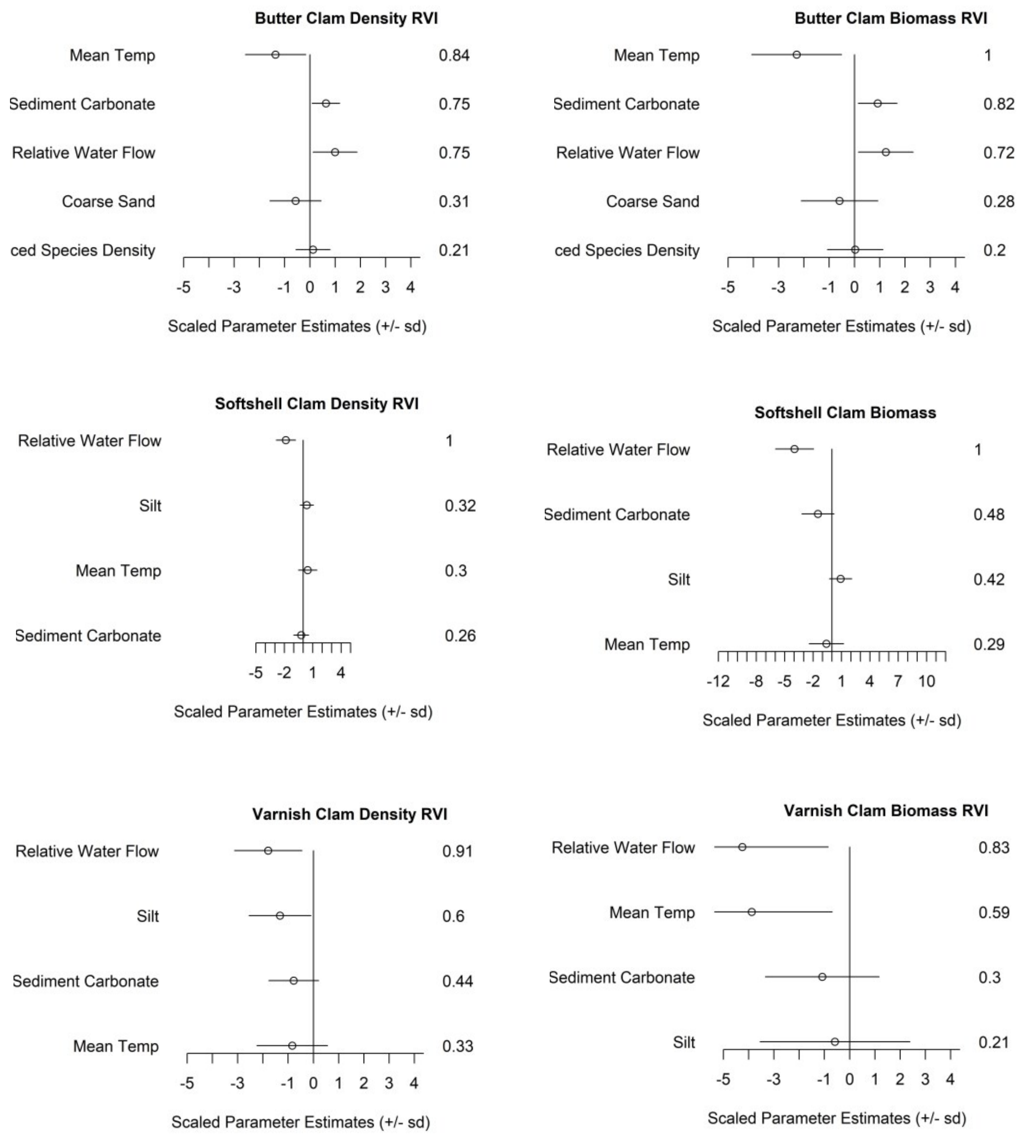
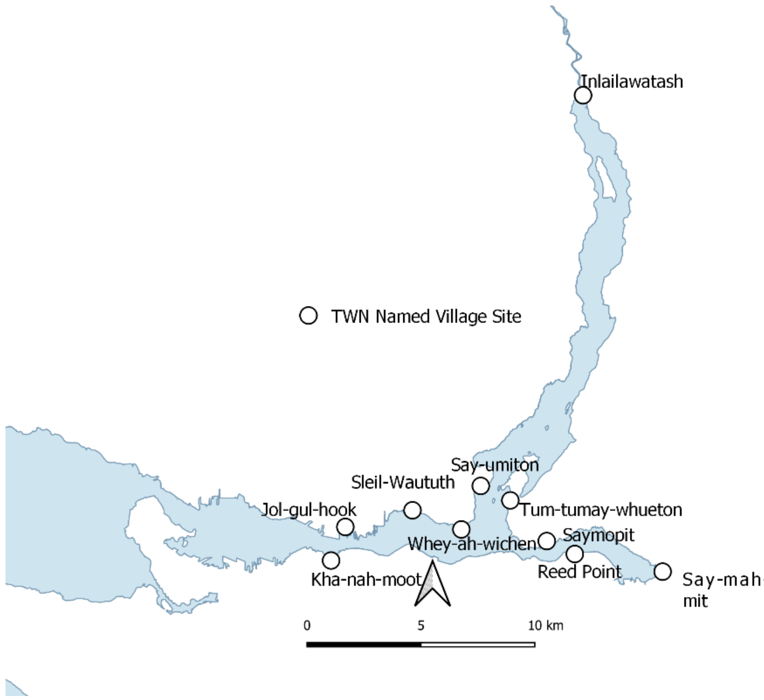


Figure D.1. Standardized parameter estimates, their 95% confidence intervals, and relative importance of environmental variables driving the density of butter, softshell and varnish clams. Standardized parameter estimates and relative variable importance are calculated from Akaike's information criteria weights of top models ($\Delta AIC_c < 4$).

Appendix E.

Tsleil-Waututh Named Village Sites



Appendix E.1 **Tsleil-Waututh Nation's ancestral territory lies in Burrard Inlet, British Columbia (B.C.), on the pacific coast of Canada. Tsleil-Waututh named village sites are represented by black outlined circles (Tsleil-Waututh, 2015). The data used to produce this map originate from many sources and are presented without prejudice to Tsleil-Waututh Nations rights, title and interests (Tsleil-Waututh, 2015 (p.17)).**