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Ancient Anthropogenic Clam Gardens of the Northwest Coast Expand Clam Habitat

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Abstract

Clam gardens are ancient mariculture features developed by Indigenous Peoples of the Northwest Coast of North America that create shallow sloping intertidal shelves where clam productivity is enhanced. We quantify the area of clam habitat created by constructing rock-walled clam gardens terraces in northern Quadra Island, British Columbia, Canada. We combined modelling, high-resolution mapping, beach sampling, and a comprehensive survey of the shoreline to document the location and areal extent of clam habitat in clam gardens today. We divided our analysis into three classes of clam gardens, which differ in substrate and thus the amount of clam habitat created. We found that Indigenous People built clam garden walls on 35% of the shoreline and that about 112,979 m^2 of flat beach terrace were created by clam garden construction. Collectively, the three classes of clam gardens increased clam habitat area between 26 and 36%. About 35% of the area of clam habitat in clam gardens was constructed de novo on bedrock shelves and rocky slopes where no clam habitat existed previously. Furthermore, about 12.0% of clam gardens are smaller than 30 m^2, reflecting the effort put into creating enhanced food production wherever possible. Our analysis demonstrates that clam management in the form of clam gardens was extensive prior to colonization and that these features still have a significant impact on today's intertidal ecosystems. Clam habitat expansion facilitated by clam garden construction encouraged a sustainable and abundant food source in the past and could do so again in today's changing environmental conditions.

Key words: Clam garden; Mariculture; Traditional resource management; Indigenous; Northwest Coast; Anthropogenic ecosystems.

Highlights

- Anthropogenic clam gardens dramatically increase the quantity and quality of clam habitat.
- About one-third of clam gardens created clam habitat where there was none before.

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- Increasing the area of clam habitat allowed for intensive yet sustainable harvesting of clams.

Introduction

Over the past few decades, there have been several fundamental shifts in ecological discussions that have resulted in increasing recognition by natural scientists of the deep ecological knowledge and practice of Indigenous Peoples. These shifts include rethinking of the concept of wilderness (for example, Cronin 1996; see Day 1953 for a much earlier discussion), the explosion of social-ecological systems thinking (for example, Schoon and van der Leeuw 2015), and the burgeoning of the field of conservation biology. Similarly, ecologists are awakening to the realization of the extent to which Indigenous Peoples altered their landscapes in the past, and the legacy of those interactions today (for example, Ross 2011; Fisher and others 2019; Odonne and others 2019).

Collectively, these shifts in thinking are evident today in a blossoming literature that calls for western scientists to work with and learn from Indigenous Peoples. This literature reflects recognition not only of the potential for more robust, but also more just science (for example, Ban and others 2018; Salomon and others 2018). Encompassed with this discussion is the increasing recognition that long-term, place-based ecological knowledge of Indigenous Peoples (''traditional ecological knowledge''; TEK; Turner and others 2000; Berkes 2018), including traditional management practices, can be used as the basis of local restoration and conservation efforts today (for example, Senos and others 2006; Joseph 2012).

A necessary step towards including traditional management practices in current restoration and conservation is evaluating both the extent and the efficacy of those practices in the past and the legacy of those practices in current ecosystems. For instance, recent research has demonstrated that the building of rock-walled clam gardens—one of the several ancient mariculture techniques used by Indigenous Peoples of the Northwest Coast of North America to enhance clam productivity (Deur and others 2015; Lepofsky and others 2015; Moss and Wellman 2017)—still increases littleneck (*Leukoma staminea*) and butter clam (*Saxidomus gigantea*) productivity today up to 2–4 times (Groesbeck and others 2014; Jackley and others 2016). We are just beginning to understand the mechanisms involved in this increase in productivity in the past and the present (Salter 2018; Toniello and others 2019), but we do know that beginning at least 3500 years ago (Smith and others 2019), Indigenous Peoples of the Northwest Coast constructed these intertidal rock-walled beach terraces in a range of foreshore habitats to increase the production of culturally important intertidal foods.

In this paper, we further explore the ways in which clam gardens increased the production of clams in the past and in doing so had a major impact on the coastal ecosystems of the Northwest Coast of North America. In particular, we assess the extent to which the construction of clam gardens—that is, the building of rock walls in the lower intertidal and the subsequent infilling of the terrace with sediments—expanded the area of littleneck and butter clam habitat. Through detailed surveys of the shorelines of Kanish and Waiatt Bays, northern Quadra Island, BC (Figure 1), examination of high-resolution aerial images, and GIS analyses, we find that anthropogenic expansion of clam habitat was extensive, substantial, and occurred in a range of geomorphological settings. This paper adds to the growing body of literature about the extent and legacy of ancient ecosystem manipulation by Indigenous Peoples and provides baseline data that could be the foundation for clam management going forward.

Methods

Study Area

We focus our analysis of clam garden habitat on Kanish and Waiatt Bays, on northern Quadra Island, BC, within the traditional territories of the southern Kwakwaka'wakw (Laich-kwil-tach) and northern Coast Salish First Nations (Figure 1). Our study is part of a larger research program on clam gardens on northern Quadra (Groesbeck and others 2014; Lepofsky and others 2015; Neudorf and others 2017; Salter 2018; Smith and others 2019; Toniello and others 2019), which is in turn nested in a network of projects aimed at understanding the social-ecological context of clam gardens throughout the Northwest Coast (https://clamgarden.com/).

We choose Kanish Bay and Waiatt Bay as study sites because of their abundance of clam gardens. Our archaeological and ecological surveys elsewhere on the British Columbia coast suggest the high density of clam gardens in our study area is not necessarily typical of all other regions. In any particular region, the density of clam gardens is due to some combination of foreshore geomorphology, the ''natural'' abundance of clams, and a myriad of

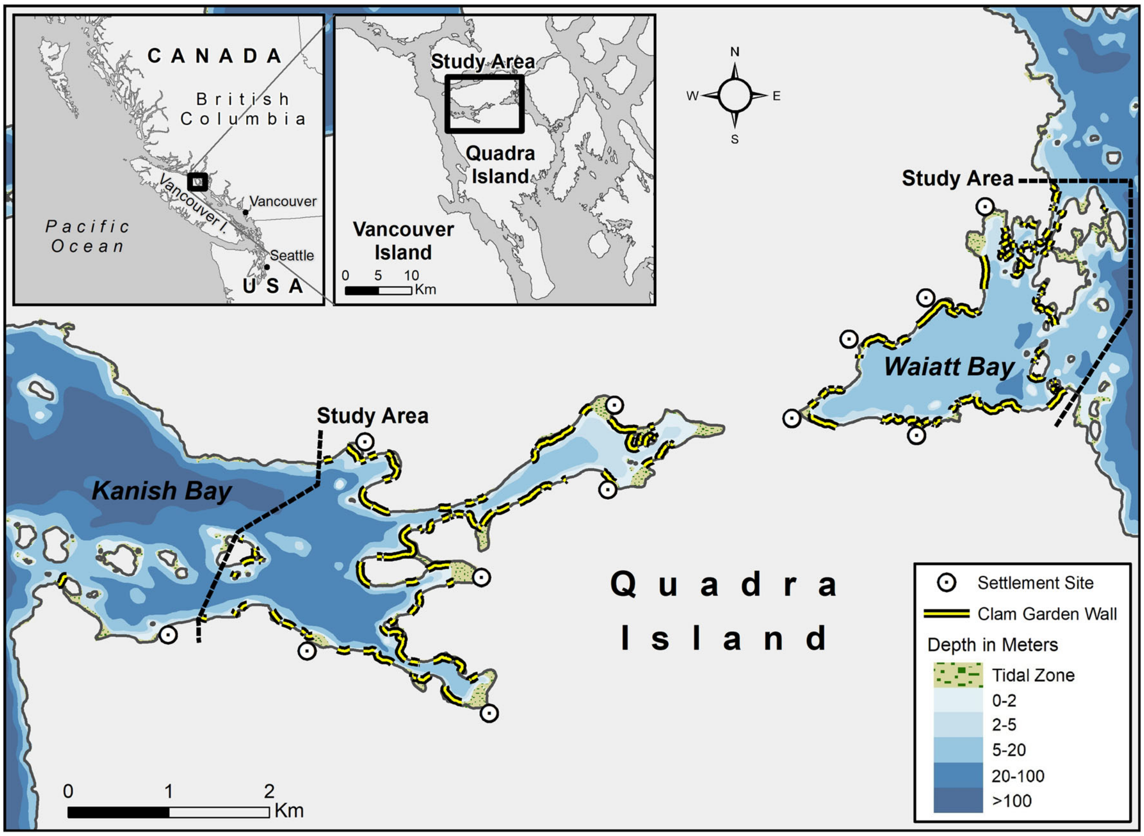

Figure 1. Study area on northern Quadra Island, BC, Canada, showing the location of clam garden walls and major ancient settlement sites. Aerial imagery was not collected for much of outer Kanish Bay and thus was excluded from the study area.

cultural factors. Although the cultural-ecological role of clam gardens has not been fully researched in most other parts of the coast, it is clear that clams played an important role in all regions (Moss 1993; Augustine and Dearden 2014; Deur and others 2015; Lepofsky and others 2015) and that clam gardens were part of a portfolio of management strategies embedded in many First Nations long-term interactions with their landscapes (Lepofsky and Caldwell 2013; Deur and others 2015; Lepofsky and others 2015; Jackley and others 2016).

The shorelines of both Kanish and Waiatt Bays are rocky and crenulated with many smaller protected embayments ideally suited for building clam gardens. Our surveys demonstrate that there is a constructed rock wall in almost all possible foreshore areas, including on soft-sediment beaches that already provided some clam habitat, and on bedrock outcrops and rocky slopes with no clam habitat prior to the construction of a rock-walled terrace (Figure 1; Smith and others 2019). The only foreshore areas that do not have clam gardens are sheer rock faces and a few of the fine sediment beaches at the mouths of major streams. The rocky outcrops bookending these fine sediment beaches, however, are often modified with a rock-walled clam garden terrace. The extent of clam gardens in Kanish and Waiatt Bays gives us an opportunity to study different aspects of clam gardens in a relatively small geographic and ecologic reach.

The remains of ancient settlements, some as old as 9000 years BP, are found throughout the study area (Figure 1; Crowell 2017). The archaeological shell middens, some up to 5 metres deep, are overwhelmingly dominated by littleneck and butter clams. These sculpted middens reflect both the continual terraforming of the landscape by Indigenous Peoples and the central importance of mollusks in the diet. Based on project radiocarbon dates of the ancient settlements in Kanish Bay, approximately 3500 years ago there was an increase in human population contemporaneous with the initiation of clam gardens (unpublished data, Lepofsky).

Clam Gardens and Clam Ecology

Indigenous Peoples built and maintained clam gardens by rolling or placing beach rocks at the lowest low tide mark to both ''keep the beach clean'' and to form a rough rock wall (Figure 2; Deur and others 2015; Lepofsky and others 2015). Over time, the rock wall increased in height and girth, and sands, silts, and broken shell (''shell hash'') accumulated upslope of the wall to create a relatively flat terrace to the height of the wall (Figure 3; Neudorf and others 2017; Smith and others 2019). Inland of the flat clam garden terrace there is a break in topography where the slope increases to that of the pre-clam garden beach (Figure 3). The lateral edges of distinct clam gardens are often defined by a break in topography, such as a bedrock outcrop, or the outer limits of an embayment (Figure 4). However, because the configuration of the wall along its length is largely dependent on local topography, delineating individual clam gardens can be somewhat subjective. Identifying discrete clam gardens is complicated further by the fact that we have little idea of how ancient tenure systems dictated the partitioning of what we might call a single garden today.

Despite the fact that clam gardens were not recognized by western scientists until relatively recently, these features are easy to spot from the air, water, or land during the appropriate tides due to

Figure 2. Examples of clam gardens in Kanish and Waiatt bays at low–low tides. **A** Class 1 clam garden, built on soft-sediment beach that previously supported clam habitat, with rock wall in the foreground, anthropogenic terrace behind the wall, and grass-covered shell midden associated with ancient settlement in the background. **B** Class 1 clam garden with three terraces at different tidal heights, each associated with a previously higher sea level. **C** Class 1 clam garden showing major terrace associated with higher previous sea level and very low, unfinished rock wall terrace in the foreground associated with current sea level. Low, unfinished walls like these are found in a few clam gardens in the study area. Given their positioning relative to current sea levels, we surmise that their construction was disrupted by the introduction of European diseases; **D** Class 2 clam garden built on a small shelf of bedrock that would not have provided clam habitat prior to the building of the rock wall terrace. Photographs by Dana Lepofsky (**A**, **C**), Nicole Smith (**B**), and Joanne McSporran (**D**).

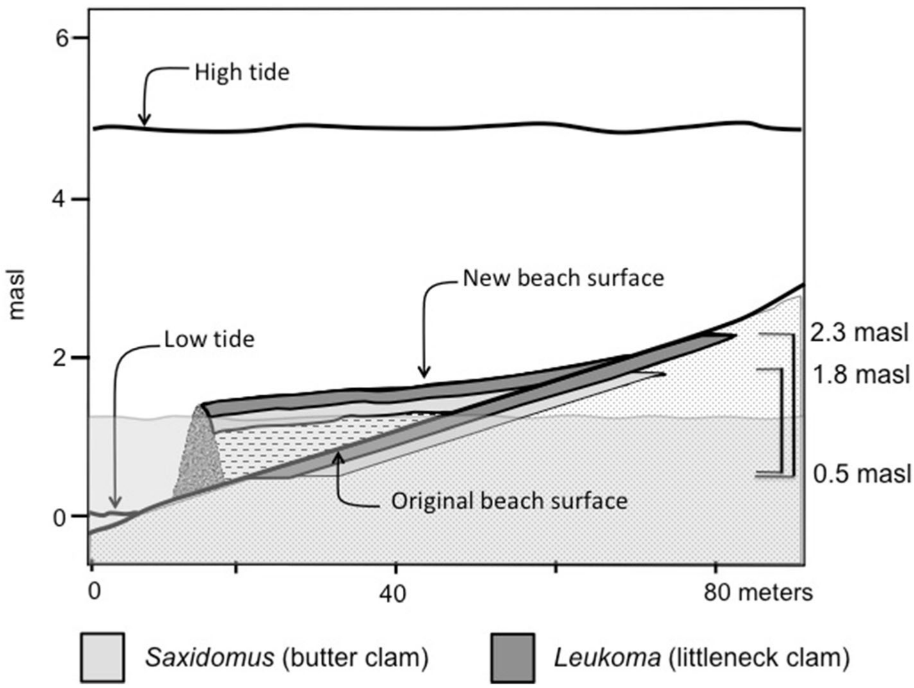

Figure 3. Cross section of Class 1 clam garden flooded at 1.2 m tide, showing beach surface before and after building the terrace wall, and the extent of ideal butter and littleneck clams habitat (butters = 0.5–1.8 masl; littlenecks = 0.5–2.3 masl). The thickness of the bands representing clam habitat in both the pre- and post-clam garden beaches reflects the maximum burrowing depth of each species (butters = 35 cm; littlenecks = 15 cm). The building of the clam garden wall in this scenario results in a small increase in overall clam habitat; however, the differences in the *x*- and *y*-scales (10:1) exaggerate the appearance of the magnitude of this increase. The significant advantage of building a wall on this beach is the increase in accessible clam habitat at moderate tide levels (for example, 1.2 masl). Cross section based on survey of clam garden depicted in Figure 2A.

the characteristic rock wall and associated flat terrace (Figs. 2, 4). In areas where sea level has been rising due to tectonic activity since the middle Holocene, only the very tops of the walls are visible during today's lowest low tides. In our study area, however, where sea level is dropping (Crowell 2017; Fedje and others 2018), the walls and associated terraces are clearly visible in the daylight during the lowest tide windows in each of May–August. In most of the clam gardens in our study area, it seems that over the millennia, people moved the wall's position towards the ocean by rolling the rocks downslope as sea level dropped. Thus, the majority of garden terraces today approximate the terrace extent at the time when European-introduced diseases in the late 1700s led to dramatic losses of Indigenous populations (Harris 1994) and thus a decline in traditional mariculture practices (Toniello and others 2019). In a few larger beaches, where the clam garden terraces do not front a settlement, abandoned walls did not impede access to settlements on land, and multiple walls of different ages are visible on the beach today (Figure 2B, C; Smith and others 2019). In this study, we aim to estimate the amount of current clam habitat that was created by clam gardens. That is, we exclude from our analysis the few terraces that are positioned relative to older, higher sea levels and thus do not support native clam habitat today.

Our previous research indicates that within the general clam garden form, there are three more specific forms (classes) of clam gardens, distinguished by the underlying substrate on which the garden was created (Smith and others 2019). These classes are distinguishable in aerial images and through on-the-ground surveys. In Class 1 clam gardens (Figures 2A–C, 4A), the pre-clam garden terrain is characterized by a soft-sediment beach (with variable amounts of boulders interspersed) that in some cases naturally provided productive clam habitat since the middle Holocene (Toniello and others 2019). Class 2 (Figures 2D, 4B) and Class 3 clam gardens (Figure 4C) are built on bedrock or rocky slopes, respectively, which would have provided minimal to no clam habitat prior to the construction of the clam garden by Indigenous

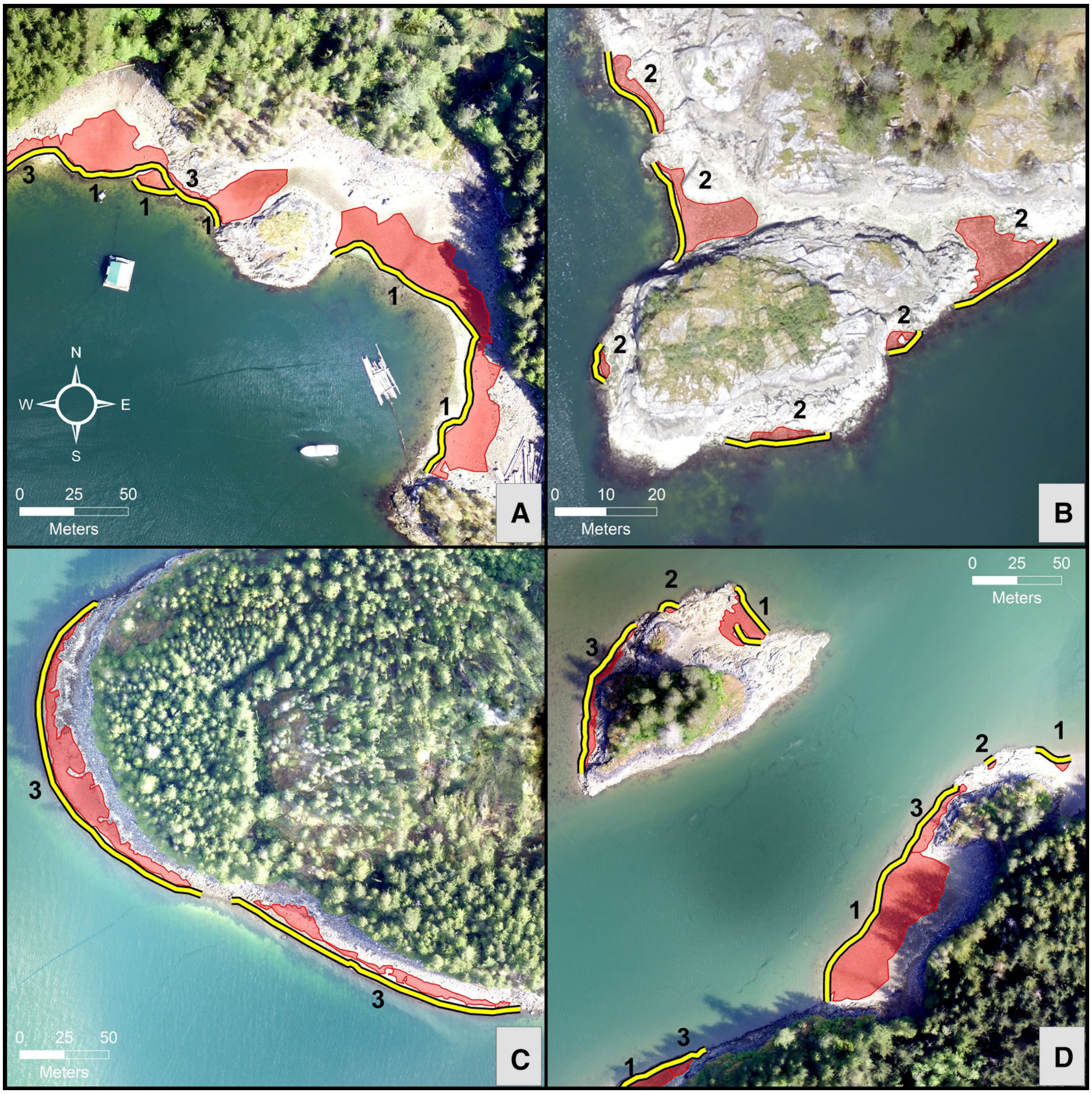

Figure 4. Aerial imagery showing examples of three clam garden classes. Red shading represents clam garden habitat; yellow line follows clam garden wall. **A** Class 1 with a few small Class 3 beaches; **B** Class 2; **C** Class 3; **D** beaches with all three classes.

Peoples. Thus, in the latter two cases, building a clam garden on these substrates essentially created clam habitat de novo. Most of the larger beaches are composed of Class 1 clam gardens in the centre and Class 2 and/or 3 clam gardens along the sides (Figure 4D).

Researchers in our team have made great strides in understanding the ways in which clam gardens alter marine ecosystems and increase clam productivity. Indigenous community members and field studies indicate that clam gardens created habitat for many lower intertidal organisms, including sea cucumbers and barnacles, and attracted animals such as water fowl, raccoons, mink, and river otters (Deur and others 2015; Cox and others 2019). However, the primary reason for creating these features seems to have been to increase the abundance of butter clams and littleneck clams. This is indicated by the knowledge shared by Indigenous Elders (for example, Deur and others 2015), that clam gardens are many times more productive for these species than neighbouring non-walled beaches (Groesbeck and others 2014; Jackley and others 2016), and that these two bivalves overwhelmingly dominate the matrix of the local archaeological record (unpublished data, Lepofsky). Other bivalves species are found in clam gardens, but other native species thrive at different tidal ranges (for example, horse clams) or prefer finer substrates (for example, cockles); introduced species largely thrive above the intertidal zone created by clam gardens.

Several mechanisms have been identified that enhance butter and littleneck clam productivity within clam gardens. Building the rock-faced terrace creates a wedge of sediment that encompasses the preferred tidal range (littleneck = ~ 2.3–0.5 m, butter = 1.8–0.5 m LLWLT) and burrowing depths of these species (littleneck = 15 cm, butter = 35 cm; Figure 3). Within the created terrace, increasing shell hash and coarse sediments (Salter 2018; Toniello and others 2019; Cox and others 2019) and moderating seasonal water temperatures (Salter 2018) have a positive effect on clam productivity. These factors would have also been augmented by a range of traditional management practices, such as tilling, selective harvests, and keeping the beach clean of predators and rocks (Deur and others 2015; Lepofsky and others 2015). This paper addresses the extent to which building clam gardens increased clam habitat at the landscape scale.

Quantifying Littleneck and Butter Clam Habitat in Clam Gardens

We use the surface area of clam habitat as a proxy measure of the amount of clam habitat created by building a clam garden. Of course, the total amount of habitat created by building a clam garden is actually a volumetric measure. However, because we do not know the depth of the created habitat in any given beach, we cannot calculate volume. Consequently, our calculations are underestimates of the actual created habitat.

Archaeological and Ecological Surveys

To document the extent of clam gardens in the study area, we ground surveyed 100% of the shoreline in Kanish and Waiatt Bays, recording the location, extent, and geomorphic context of every clam garden in the study area. In addition, as part of our palaeoecological and ecological studies (Groesbeck and others 2014; Groesbeck unpublished data; Toniello and others 2019), we conducted in-ground sampling of 34 clam gardens and non-walled beaches that informed our understanding of the extent and abundance of littleneck and butter clams. These surveys' as well as published data (Chew and Ma 1987), are the foundation for our inference that butter clam and littleneck habitat extends up the beach to about 1.8 and 2.3 m LLWLT, respectively. Although both of these species can be found seaward of the clam garden terrace at lower tidal levels, this is beyond the zone where they thrive and are not considered in this study.

GIS Analyses

In addition to the results of our field testing of gardens, we considered three lines of evidence to create polygons of clam habitat area in each clam garden. These are high-resolution aerial imagery, slope models derived from aerial imagery, and the upper elevational extent of the preferred habitat of butter and littleneck clams. Each line of evidence sequentially delimitated and refined the area we calculated as built clam garden habitat (Figure 5).

The foundation for our analysis is more than 3000 high-resolution (8–10 cm) drone images of Kanish and Waiatt Bays that show clearly the clam gardens and the surrounding topography (Figure 4). In addition, we created < 3 cm resolution aerial imagery and elevation models of eight of the more complex clam gardens (examples in Figure 5A). Because poor weather conditions prevented imaging much of the western extent of Kanish Bay, this area has been excluded from our analysis (Figure 1). Our field surveys and examination of Google Earth imagery indicate that this area includes at least 13 unmeasured clam gardens. Thus, our total estimate of the area of clam habitat in Kanish Bay is a significant underestimate.

Our first step was to classify each clam garden beach (or beach section) into one of the three clam garden classes (Smith and others 2019) based on geomorphic setting visible in the high-resolution imagery (Figures 4, 5A) and our in-field observations. Using the high-resolution imagery, we then created ArcGIS editor line and polygon layers to trace wall segments and create preliminary polygons of the clam habitat created by building the clam garden wall. In general, the clam garden beaches are visible on the aerial images as areas relatively free of boulders as a result of infilling of sediment and the clearing of rocks by Indigenous People. We did not include beaches where we suspected there was a clam garden, but taphonomic factors (siltation, logging) prevented us from being certain.

The type of clam garden class influenced the decisions about where to draw the preliminary polygons. For all three classes, the landward side of the clam garden wall formed the lower limit of each polygon. The upper limit of most Class 2 and Class 3 clam gardens and some Class 1 clam gardens were easily determined by the presence of bedrock out-

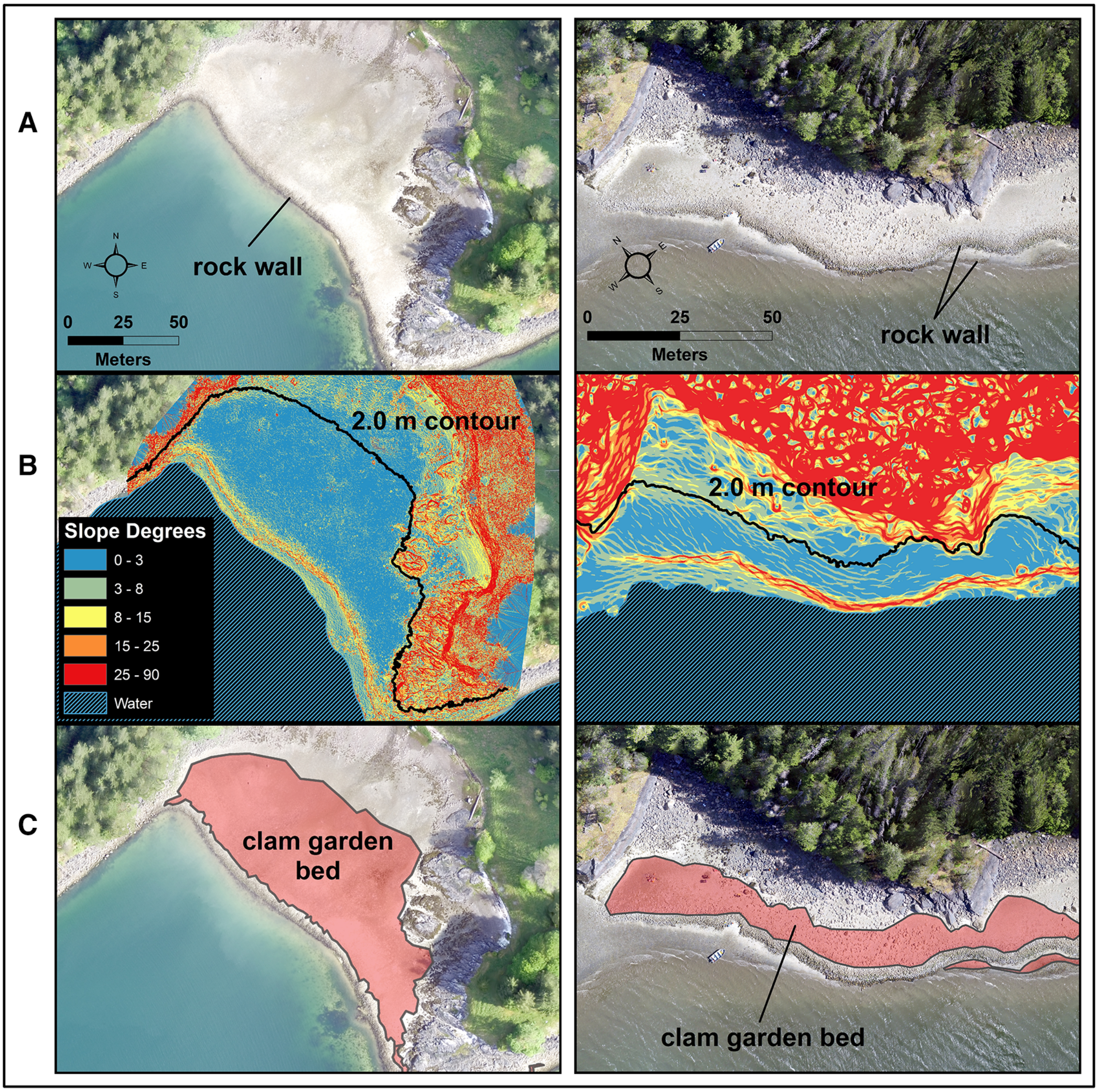

Figure 5. Steps for calculating extent of clam habitat in two Class 1 gardens (left and right panels). **A** High-resolution aerial images (< 3 cm resolution examples) on which the polygons of clam habitat are based; **B** slope model showing the correspondence between the level clam garden beach (0–3° slope, blue) and the upper (conservative) extent of clam habitat (2.0 m contour, black line); **C** final polygons depicting created clam habitat based on high-resolution image, slope model, topographic lines, and field observations. Image on left is the garden depicted in Figure 2A; image on right is the garden depicted in Figure 2C.

crop, edge of beach, or increased density of boulders and cobbles (Figure 5A). However, delineating the upper boundary of most Class 1 clam gardens (and a few Classes 2 and 3 clam gardens) was more difficult because of the unclear transition between what was the ''built'' beach of the terrace and natural beach slope on the landward side.

Defining this upper limit in these cases required crosschecking with field data and the creation of slope models based on the drone imagery. In particular, the slope models helped us delineate terrain with less than 3° slope—that is, relatively flat terrain created by the building of the terrace wall. Furthermore, the mapping software used for the slope model was able to extract data points from unclear areas in the aerial imagery (for example, due to overexposure), so we could more fully visualize and define the clam terrace. To create the slope model, the drone imagery was first processed using structure from motion methods to generate 3D products including elevation models (in Pix4D software). These elevation models were produced by using identifiable key features in overlapping drone images along with surveyed targets throughout the study area. The resulting elevation models were then imported into ARC GIS surface spatial analysis software to produce slope models that allowed us to identify areas of 3 or less degrees slope in all clam gardens in the study area (Figure 5B, blue zone). These relatively flat areas roughly delineate the flat beach terrace created by building the clam garden wall.

Our final refinement of built clam habitat polygons was to ensure that none of our clam gardens exceeded the 2.0 m topographic line—that is, the line just below the maximum upper extent of littleneck clams today (that is, 2.3 masl; Figure 5B). This line was determined based on the eight Class 1 clam gardens for which we have less than 3 cm resolution imagery and a coarser 2.0 m model created for the whole study area shoreline. In fact, because most of the walls in Class 1 clam gardens are considerably less than 2.0 m in height (measured from their base at $\sim$ 0 m LLWLT), the terrace created by infilling is below 2.0 m LLWLT (Figure 3). In the vast majority of cases, the initial clam habitat polygons based on the high-resolution images and slope models corresponded well with the boundaries indicated for clam habitat.

There were a small number of Class 1 beaches where using the aerial imagery and slope model but not the 2.0 m topographic line would have overestimated the extent of clam habitat today had we not have familiarity with the geomorphic contexts of all clam gardens. These are beaches that we identified in the field as having walls and terraces located at higher tidal heights than the current zones of butter and littleneck clam habitat; we believe these are the remains of clam gardens built and used during higher former sea levels (for example, Figure 2B, C; Smith and others 2019). We presume that other equally old walls on other beaches were dismantled in the past and refurbished downslope following declining sea levels. Even though these remnant upper terraces were built to expand clam habitat several millennia ago, we excluded them from our analyses because they did not fit our criteria for estimating created clam habitat in relation to current sea levels. Ultimately, any estimate of clam habitat created by clam gardens should not be taken to be exact, but rather representative of the kinds and magnitude of habitat creation resulting from clam garden construction.

Enumerating Clam Gardens and Clam Habitat

Finally, to estimate the area of clam habitat in the three classes of clam gardens, we tallied the total area in the polygons in each class and counted the total number of polygons in each class. To calculate the area of clam habitat created by building a clam garden, we assumed a minimum and maximum per cent increase by class. In Classes 2 and 3 clam gardens, that had little or no clam habitat prior to building of the clam gardens, we assume that the increase in habitat was between 75 and 100% per clam garden. Our minimum estimate of 75% reflects the recognition that some clams may have established in the bedrock crevices and in between boulders in these locations.

For Class 1, where there was naturally occurring clam habitat prior to building a clam garden, we assume that building the wall and the subsequent accumulation of sediment on the terrace increased the area of clam habitat anywhere from 0 to 10%. The upper end of this per cent increase is realized in beaches where the wall is built below the lower limit of ideal clam habitat (that is, 0.5 m LLWLT). In such cases, there is an incremental increase in habitat adjacent to the wall (Figure 3). Lower per cent increases occur when the wall base is higher in the intertidal and thus covers previously available clam habitat. In such cases, the rolling of rocks downslope and the infilling with sands and silts would have offset any small amounts of habitat lost to the footprint of the wall. Important to remember is that our calculations are measures of increase in *quantity* of habitat; we do not take into account the increase in *quality* resulting from various management techniques and the improved growing conditions afforded by the substrate and wall microenvironment (Groesbeck and others 2014; Deur and others 2015; Lepofsky and others 2015; Salter 2018).

Furthermore, we make no assumptions about the relative productivity of the clam habitat within our clam garden polygons. Our research indicates that the productivity of clam beaches today is often a poor reflection of past productivity when the clam gardens were tended and prior to industrial logging (Toniello and others 2019). In addition, we have observed considerable variation in clam productivity today within and between beaches. For instance, we observe that Classes 2 and 3 are much more productive than Class 1 beaches. This is because Class 1 clam gardens often trap silts from logging, and because the lack of harvesting on these beaches results in thick accumulations of *Ulva* sp. that in turn creates anoxic sediments. Thus, although we have detailed survey data on the relative abundance of clams on some Class 1 beaches (Groesbeck and others 2014), it is over-stepping the data to apply this level of precision to other beaches today or to estimate past productivity.

Results

Stretched end to end, clam garden walls in the study area extend for around 15 km, covering about 35% of the shoreline (total shoreline of study area = 42.7 km) in Kanish and Waiatt Bays. We delineated 209 clam garden polygons in each of the three classes (Figure 6); together they encompass a total of 112,978.9 m^2 of clam habitat. Individual clam gardens (that is, polygons) within the study area range in size from 4.7 to 6319.6 m^2 (mean = 540.56 ± 911.6 m^2), with about half of the clam gardens being less than 200 m^2 (Figure 6). All of the clam gardens built on bedrock (Class 2) are small, whereas the other two classes represent the full range of sizes (Class 1 = 1076.7 ± 1312.2 m^2, total N = 68; Class 2 = 63.4 ± 58 m^2, total N = 59; Class 3 = 439.3 ± 538.2 m^2, total N = 82). Classes 2 and 3 clam gardens make up 35% of the total area in clam garden which means that about one-third of the clam habitat was created on substrate where there was little to no prior clam habitat. This result combined with the fact that about 12.0% of

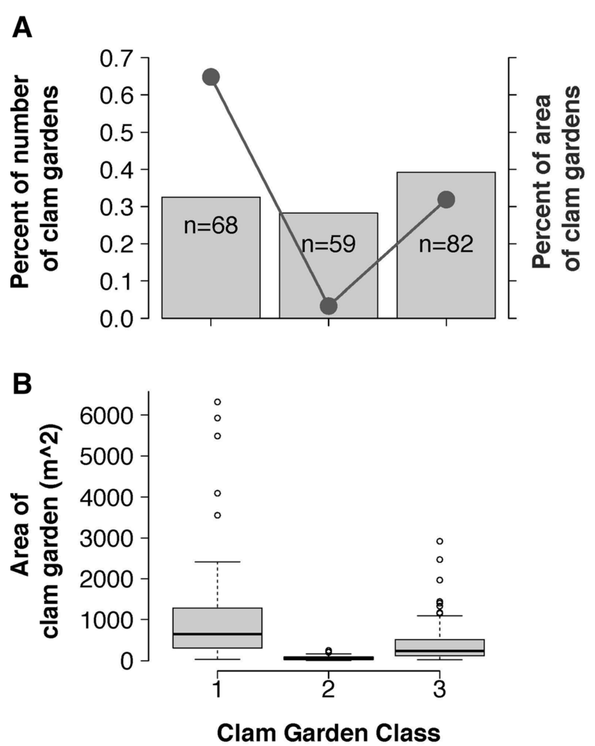

Figure 6. **A** Per cent abundance of number (bar chart) and area (trend line) of each garden class of the total number and area of clam gardens in Kanish and Waiatt Bays. Right and left *y*-scales are the same. A number of clam gardens in each class are the number of polygons delineated (N = 211). Total area of clam habitat in all clam gardens = 112,124.9 m^2. **B** Area of each clam garden class.

clam gardens are quite small (< 30 m^2) reflects both the effort put into creating enhanced food production wherever possible and the dramatic influence of ancient mariculture on the intertidal ecosystem.

By tallying the minimum and maximum per cent increase in each of the three classes, we estimate that the total increase in clam habitat attributed to the building clam gardens is somewhere between 26 and 35% or 29,375–39,543 m^2. The greatest increase in habitat was the result of building Class 3 clam gardens on rocky slopes, where pre-clam habitat was nearly non-existent. In addition, some of the Class 3 clam gardens measured in this study were large in size (Class 1 total = 73,216.5 m^2 × 0% increase; × 10% increase = 0–7321.7 m^2; Class 2 total = 3739.1 m^2 × 75% increase; × 100% increase = 2804.4–3739.1 m^2; Class 3 total = 36,023.2 m^2 × 75% increase; × 100% increase = 27,017.4–36,023.2 m^2). Even our minimum estimate of habitat increase reflects the significant effect that building clam gardens had on the amount and quality of clam habitat in Kanish and Waiatt Bays. If we consider that our area calculations are conservative, that they do not take into account increases in habitat quality, and that we calculate increases in area rather than volume, our estimates of amount of habitat created are even more impressive.

Discussion

The construction of clam gardens in Kanish and Waiatt Bays over the past three millennia resulted in dramatic changes to the abundance and distribution of productive clam habitat as well as the nature of the foreshore environment. By increasing clam habitat through the building of intertidal rock walls and adjusting the walls as needed to accommodate changes in tide and sea level (Smith and others 2019), or through ongoing clam garden maintenance (Deur and others 2015), First Nations people ensured a more consistent supply of a staple food, despite ongoing increases in human population and harvesting pressure. At the site level, the construction of clam gardens expanded the available area in which clams live and thrive, ultimately increasing clam productivity. At the landscape level, the sheer number of constructed clam gardens along the shoreline not only greatly increased clam habitat, but also had a huge effect on the biotic and abiotic processes of coastal ecosystems.

Although our results of absolute habitat *increase* are impressive, it is important to remember that they are in fact gross underestimates of habitat *en-*

hancement. That is, we focused our assessments of ecosystem change on the easier to quantify area of clam habitat created, rather than on quantifying the degree to which clam habitat was enhanced. In fact, we now know that as a result of the abiotic changes in substrate and water temperature associated with clam gardens, the ecosystem created by a clam garden has a strong positive effect on clam production (Groesbeck and others 2014; Jackley and others 2016; Salter 2018; Toniello and others 2019). Thus, the increase in improved clam habitat would be significant in all clam garden classes, not just in the newly created Classes 2 and 3 beaches. Another unquantifiable but important factor when considering habitat enhancement is that the beach in clam gardens was likely more intensively managed by a range of now-invisible techniques (for example, tilling, weeding, harvesting restrictions), and thus more productive than their pre-clam garden counterparts. Finally, although we do not quantify accessibility of these beaches, it is important to remember that these more productive, terraced beaches are available to clam diggers for more tidal windows than unwalled beaches (Figure 3).

Relatedly, we made no attempt to quantify the relative or absolute increase in clam productivity within or between different beaches or classes of beaches. Based on our field surveys and testing, however, our strong impression is that the most productive clam gardens are the many small Class 2 clam gardens in Waiatt Bay. In those clam garden beaches, the butter clams are so dense that there is surprisingly little substrate between the clams. Furthermore, counter to common understanding of butter clam natural history (for example, Quayle and Bourne 1972), the zone of abundant, healthy, mature butter clams in these clam gardens begins on the surface and extends to the maximum depth of the garden sediment—which is sometimes only $\sim$ 20 cm deep. These created beaches were recognized in the mid-twentieth century as the best butter clam habitat in the traditional territory of one of the local First Nations (Williams 1997, 2006). We do not know how this current abundance translates into the deeper past prior to declines in the Indigenous population, when on the one hand, traditional management practices were flourishing, but on the other, harvesting was much more intensive.

In many ways, the marine ecosystems created by the Indigenous Peoples of Kanish and Waiatt Bays are similar to that encompassed within traditional terrestrial cultivation systems from around the world. That is, the use of terracing to capture sediments is a global practice among traditional agriculturalists and is widely recognized as a means to promote engineered ecosystems that are healthy and can be sustained with tending (Wilken 1987). Archaeologists studying these agricultural systems recognize that such systems provided long-term services to ecosystems and to people of the past (for example, Lepofsky and Kahn 2011; Londoño and others 2017).

Like ancient terraced agricultural systems on steep hillsides, the beaches of Kanish and Waiatt Bay bear the legacy of long-term management by Indigenous Peoples. However, unlike the terrestrial agricultural systems, marine management systems on the Northwest Coast, and the ecological knowledge embedded within, are largely invisible to most people. One reason for this is the fact that clam garden walls are usually underwater and visible for approximately only 80 daylight hours every year. Without the visibility of the rock wall itself, it is easy to assume that any given beach was unmodified. Additionally, and perhaps most significantly, is that most non-Indigenous people are unaware of the extent to which Indigenous Peoples of this region actively managed their landscape to maintain or increase important resources (Deur and Turner 2005; Turner 2014; Lepofsky and others 2017).

The erasure of Indigenous peoples from the marine landscape has important implications for Indigenous rights and title. In particular, as long as beaches are seen as "natural" or "wild"—despite the clear evidence of human presence indicated by several-metre high shell middens adjacent to such beaches—First Nations will be denied their traditional rights to practice mariculture on these beaches (Joyce and Canessa 2009; Joyce and Satterfield 2010; Augustine and Dearden 2014; Silver 2014). Similar restrictions created for "wild" versus tended resources have limited First Nations access to other culturally important foods (for example, Deur and Turner 2005; Deur and others 2013). Despite widespread documentation of traditional resource and environmental management practices (for example, Fowler and Lepofsky 2011), modern managers often embrace such practices only after western science confirms their viability (Hunn and others 2003; Lertzman 2009). The current move among many coastal First Nations to reclaim and restore clam gardens in their traditional territories (for example, https://www.pc.gc.ca/en/pn-np/bc/gulf/nature/restauration-restoration/parcs-a-myes-clam-gardens) not only actively reconnects communities to their seascapes, but is pushing the dominant society towards a system of resource and ecosystem management that is more expansive, socially just, and respectful.

The building of clam gardens and the subsequent creation of clam habitat was the first of two major periods of anthropogenic changes to the foreshore ecosystems of Kanish and Waiatt Bays. The second period is associated with the deposition of massive amounts of fine sediments downslope as a result of logging of adjacent hill slopes in the early twentieth century (Taylor 2009). The resulting changes in beach substrates, combined with the absence of traditional management techniques (for example, clearing the beach of rocks, tilling, removal of predators; Deur and others 2015; Lepofsky and others 2015), have had a significant negative impact on the productivity of clam populations in this region (Toniello and others 2019).

Around the world, the integrity of intertidal ecosystems is at risk from ongoing industrial activities, increased tourism, and climate change. Ancient clam gardens are an example of traditional management techniques that encourages the protection of intertidal ecosystems and supports resilient clam populations. Furthermore, this type of intertidal management created rock wall armoured beaches that are less susceptible to sediment erosion caused by increasingly high storm tides associated with climate change. Traditional intertidal management practices, such as clam garden construction, can inform modern management practices to move towards sustainable intertidal management techniques. A first step in incorporating this knowledge into current management, however, is recognizing the extent of these practices in the past and their legacies on the landscape today.

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Compliance with Ethical Standards

Conflict of interest The authors declare that we have no conflict of interest.

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