PHILOSOPHICAL TRANSACTIONS B

royalsocietypublishing.org/journal/rstb

Research

Check for updates

Cite this article: Efford M, Taft S, Morin J, George M, George M, Speller C, Christensen V. 2025 Unsettling the record: modelling the devastating cumulative effects of selected environmental stressors and loss of human life caused by colonization in Burrard Inlet, Canada. *Phil. Trans. R. Soc. B* **380**: 20240040.
https://doi.org/10.1098/rstb.2024.0040

Received: 11 June 2024
Accepted: 20 November 2024

One contribution of 16 to a theme issue 'Shifting seas: understanding deep-time human impacts on marine ecosystems'.

Subject Areas:
ecology, ecosystem, environmental science

Keywords:
ecosystem modelling, archaeology, historical ecology, indigenous sovereignty, colonization, coastal change

Author for correspondence:
Meaghan Efford
e-mails: meaghan.efford@gmail.com; m.efford@oceans.ubc.ca

Electronic supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.7891699.

THE ROYAL SOCIETY PUBLISHING

Unsettling the record: modelling the devastating cumulative effects of selected environmental stressors and loss of human life caused by colonization in Burrard Inlet, Canada

Meaghan Efford[1], Spencer Taft[2], Jesse Morin[1], Micheal George[2], Michelle George[2], Camilla Speller[3] and Villy Christensen[1]

[1]Institute for the Oceans and Fisheries, The University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada
[2]Treaty, Lands & Resources, Tsleil-Waututh Nation, Vancouver, British Columbia V7H 2V6, Canada
[3]Department of Anthropology, The University of British Columbia, Vancouver, British Columbia V6T 1X8, Canada

ME, 0000-0001-5251-225X

In this paper we present a collaborative, transdisciplinary research project that explores the cumulative ecological and human impacts of colonization on the səl̓ilwət (Tsleil-Wat, Burrard Inlet) ecosystem in what is now known as British Columbia, Canada. səl̓ilwət is at the heart of the traditional and unceded territory of səl̓ilwətaɬ (Tsleil-Waututh), a Coast Salish Indigenous Nation. This research is conducted at the request and under the leadership of səl̓ilwətaɬ. Drawing on archaeology, historical ecology, historical/archival records, and səl̓ilwətaɬ science, we use Ecopath with Ecosim to model selected environmental stressors and the devastating loss of səl̓ilwətaɬ life caused by colonization, from 1750–1980 CE. We include European-introduced smallpox epidemics, the rise in the settler population and settler fishing pressure, the loss of shoreline habitat and the closure of bivalve harvesting owing to industrial and urban pollution. Our results show dramatic change in the ecosystem state following these events, with significant losses in biomass and degradation of ecosystem health during the 230 years that we assess. We demonstrate the ecological impact that smallpox had through loss of both human life and Indigenous stewardship. This research sits within the palaeoenvironmental, palaeoecological and environmental archaeological space of reconstructing past environments and human-to-environment relationships over deep time.

This article is part of the theme issue 'Shifting seas: understanding deep-time human impacts on marine ecosystems'.

1. Introduction

(a) Introduction and scope

səl̓ilwət has been the home to and origin of səl̓ilwətaɬ (Tsleil-Waututh), a Coast Salish First Nation, for millennia, and is the centre of the Nation's traditional and unceded territory [1–5]. səl̓ilwətaɬ specialises in managing and stewarding marine and tidal resources [1,3,5–9]. səl̓ilwət is a water system that wraps around and through what is now known as Metropolitan Vancouver, in British Columbia, Canada (see figure 1). It is home to the Port of Vancouver, the largest marine port in Canada, as well as numerous industrial, commercial, urban and recreational activities and interests, and over

2.5 million people. The səl̓ilwət ecosystem has experienced rapid and intense change and damage from colonization and urbanization of the area since European contact in approximately 1792 CE (Common Era, an alternative to AD or *Anno Domini*), with most changes occurring since the 1880s. In this research, we seek to answer the question: what are the cumulative impacts of selected environmental stressors caused by colonization on the ecosystem health of səl̓ilwət? For environmental stressors, we include 1) the impact of smallpox on the səl̓ilwətaɬ population and the resulting health of Səl̓ilwət; 2) the impact of settler fisheries, including Pacific salmon and Pacific herring as priorities; 3) the impact of settler hunting on terrestrial animals, including ungulates; and 4) the impact of urbanization on the health of the ecosystem. This research is led by the Nation and aims to combine Western scientific research and səl̓ilwətaɬ Indigenous science to inform and support stewardship activities, and to understand and mitigate the cumulative effects of industrial, commercial and urban development and activities brought by colonization and the growth of the surrounding cities [7,10–12].

(b) Research context and governance

This research is conducted through a collaborative partnership between səl̓ilwətaɬ Nation and the University of British Columbia under the səl̓ilwətaɬ data sovereignty and research governance. We model the cumulative effects of selected environmental stressors and loss of human life caused by colonization in səl̓ilwət (Tsleil-Wat, Burrard Inlet, British Columbia, Canada). The goals, priorities and direction of the work have been developed under the leadership of səl̓ilwətaɬ traditional knowledge experts, and this research has been done at the Nation's request. Representatives of səl̓ilwətaɬ approached V. Christensen to initiate and request this research, which led to the research team (co-authors) designing the research as part of a doctoral research project for M. Efford. When discussing the cumulative effects of colonization on an ecosystem, we must consider the human loss and pain felt by the communities who experienced it first-hand. This is not only an ecological story, but a human story that speaks to the wide-reaching impacts of colonization. In this paper, we discuss distressing topics, including smallpox epidemics, ecosystem and environmental damage and loss, and loss of and damage to herring and salmon populations. It is necessary to include these topics as some of the cumulative impacts of urbanization and colonization on the Səl̓ilwət ecosystem. However, we acknowledge that these topics are challenging and unsettling, and we encourage readers to seek support if they need it[1] . Text sections that discuss or mention loss of human life will be outlined with a box to ensure readers are aware of the areas within the text that can be the most challenging to read. Note that figure 2 includes reference to loss of human life.

(c) Modelling of past ecosystems

Palaeoenvironmental reconstruction has been an important component of environmental archaeology for decades, focusing in many cases on the ecology of human communities and the places they made their homes [13,14]. Understanding past environments aids in understanding how humans can live in and interact with those environments. Isolating the reconstructive modelling of past environments within a single discipline or data source, such as archaeology, can result in incomplete or incorrect reconstructions [14]. Hence the research framework of historical ecology, which has called for interdisciplinary approaches to understand human-to-environment relationships over deep time [15–18]. Palaeoecology specifically focuses on the reconstruction and analysis of past ecosystems. Archaeology focuses on the material remains of human culture in the past. By combining these two knowledge sources with Traditional Ecological Knowledge (TEK), we can better understand the relationships and influences between human communities and their environments [14,19]. TEK is Indigenous knowledge and science that encompasses local ecological principles and indicators, and that is passed down through generations as part of community relationships to and stewardship of place [20–25].

The use of ecological networks, which map the connections between species within an ecological community, benefits the reconstruction of past ecosystems by incorporating food webs [26]. Combining ecology, archaeology and səl̓ilwətaɬ science in environmental reconstructions allows for the analysis of landscape transformation over time, both owing to human activity and unrelated natural environmental change [27]. Incorporating archaeological, palaeoenvironmental and palaeoecological datasets and approaches into ecosystem modelling can create ecological networks of past ecosystems. This can include trophic interactions between components of the ecosystems, bringing the reconstruction to life in a way that is challenging to do otherwise. This incorporates the ecology of the ecosystem and the biology of any modelled plant and animals. Ecosystem models can be used to test scenarios and ask management questions. Additionally, this approach invites questions regarding what, owing to taphonomic processes, the archaeological record leaves invisible, under-represented or over-represented, as we require predator, prey and other biological interactions and parameters (discussed below) to balance the model. If parts of the ecosystem are under-represented or over-represented, the model may not balance, offering an opportunity to adjust to make the model of the ecosystem more realistic. There is precedent for the use of Ecopath in the modelling of past ecosystems in British Columbia, combining fisheries ecology, marine history, archaeology and economics to develop ecosystem models from past ecosystem states [28,29]. Ecopath with Ecosim (EwE) has been used in the modelling and analysis of ecosystems ranging from small lakes to the global ocean [30,31]. Our research is based on a static-state reconstruction of the Səl̓ilwət ecosystem set in 1750 CE as the starting point for the time-dynamic model we present here, which can be found on EcoBase [32] under the name 'Burrard Inlet, 1750–1980 CE' [10]. The selected environmental stressors from 1750–1980 CE are smallpox epidemics, settler fisheries and shoreline loss.

[1]The Lamathut 24/7 Crisis Line can be reached at 1 (800) 721-0066, and the Indian Residential School Survivors Society Elder and Cultural Support Line can be reached between 4:30-7pm PST, 7 days a week, at 1 (833) 414-4325.

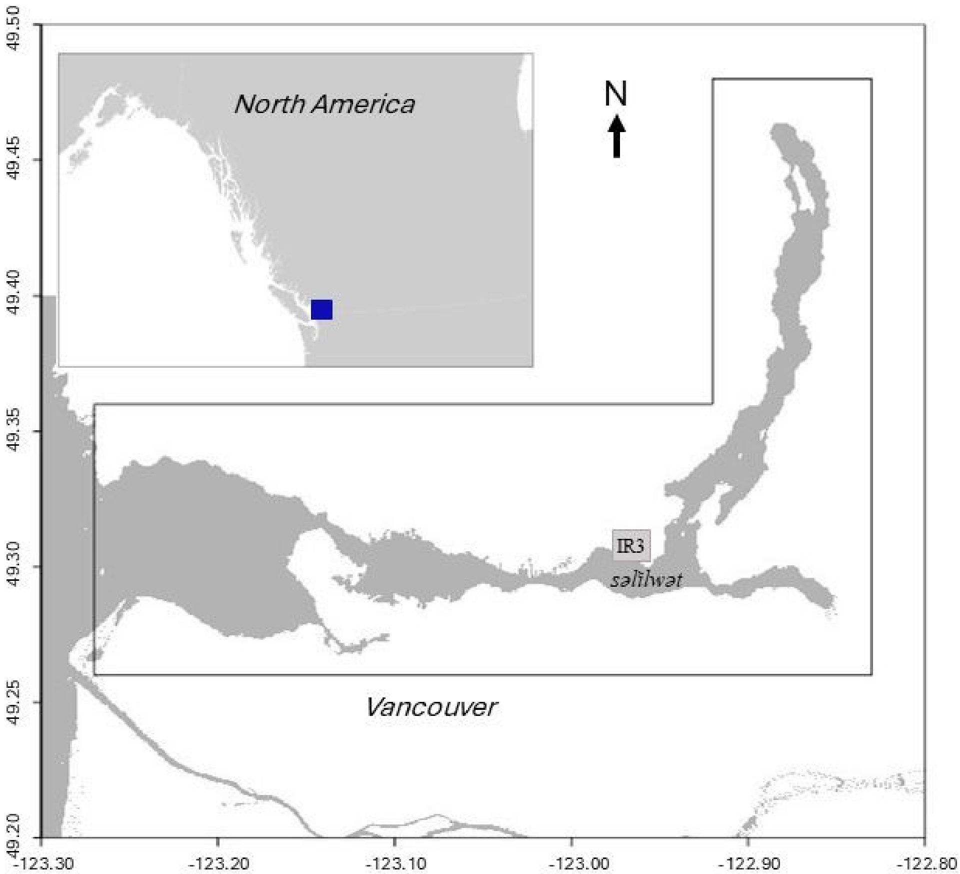

Figure 1. Map of səl̓ilwət (Burrard Inlet) with the study area of 443 km^2 outlined, including 103 km^2 of water and intertidal zone habitats. Burrard Inlet IR3 marked with grey box. Created by V. Christensen and M. Efford 2024.

(d) Addressing uncertainty with a transdisciplinary approach

Archaeological research and, by extension, the modelling of past ecosystems based on archaeological data, are inherently uncertain endeavours [33–35]. The interpretation of archaeological evidence is to speculate on the lived experiences and realities of past communities, and this speculation is inherently necessary to archaeological analyses [33–35]. Further, our approach to modelling of past ecosystems is to create a best-possible estimate based on the available data. However, by incorporating multiple lines of evidence and by incorporating the perspective and knowledge from səl̓ilwətaɬ co-authors, knowledge holders and co-creators of the research, our interpretation of our data is more robust and substantial, which therefore reduces uncertainty in our interpretation of our research results [36–38] . Together, this transdisciplinary approach focuses on the co-design, co-production and co-evaluation of research and offers a stronger, more complete picture of past ecosystems [36,37,39].

(e) Smallpox epidemics

Smallpox devastated Indigenous communities throughout North America [40–47] and it was an intentional tool of colonization in the Pacific Northwest [47,48]. The first wave of smallpox in this area—a virgin soil epidemic (first exposure of the disease to the area)—is estimated to have happened in 1782, before the ‘first contact’ with Europeans in the area in 1792 CE [41,43,44]. Captain George Vancouver, the person after whom the City of Vancouver is named, noted the impact of smallpox on the villages he saw during his travels (1792) in the Salish Sea a few years after this first wave, including deserted villages, skeletal Ancestral remains and scars characteristic of smallpox on those still living [41,43]. Prior to Vancouver’s ‘first contact’ with the area in 1792, Spanish Captain José María Narváez is reported to have visited the area in 1791, likely bringing European diseases like smallpox to the area [49]. Different reports assess the loss of life as between 50–90% of the communities, and others mention communities nearly being wiped out or villages completely deserted [41,43,44]. The second smallpox wave in 1862 was less devastating for Coast Salish peoples but resulted in further significant population loss [43,44]. It is important to consider how the loss of human life impacts their local ecosystems.

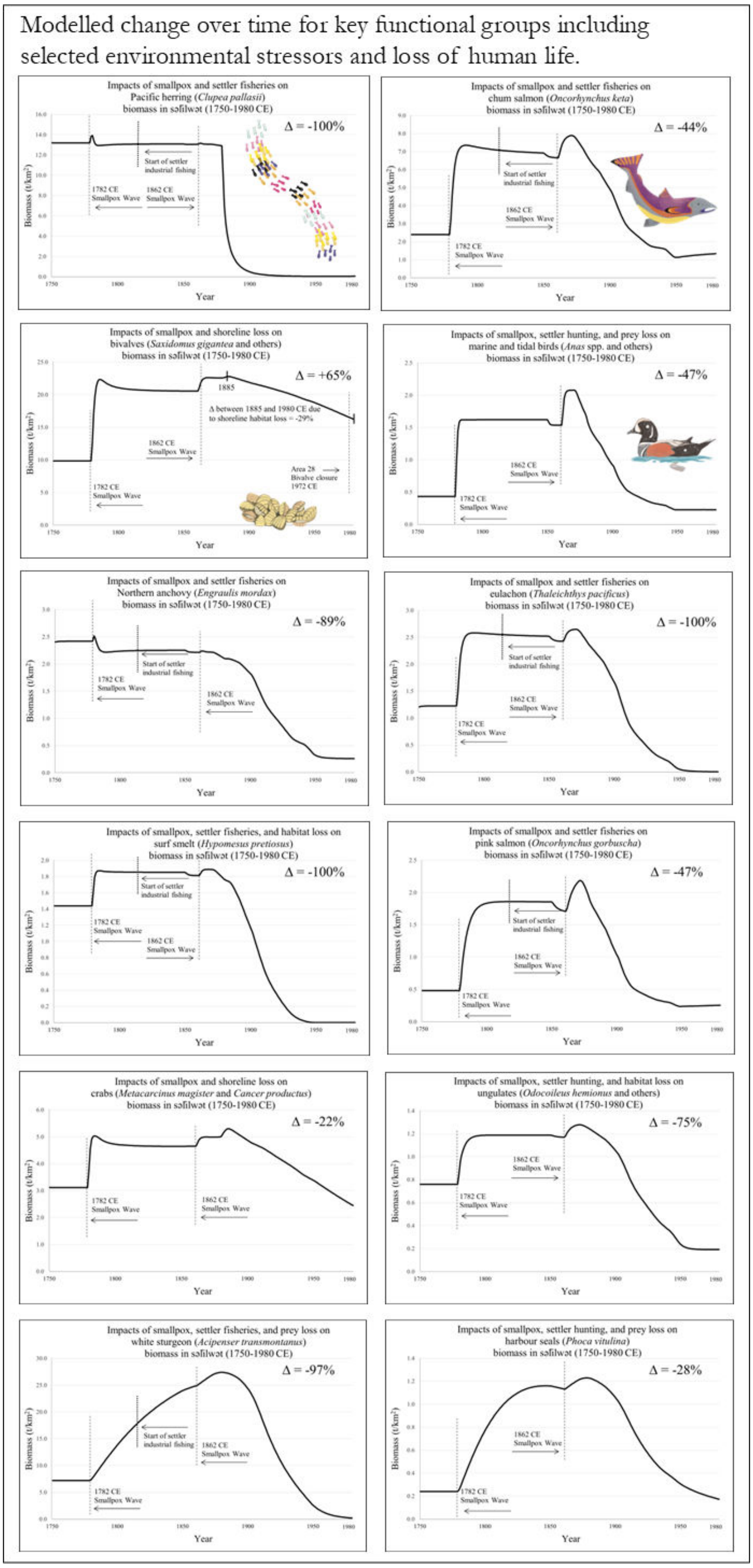

Figure 2. Modelled change over time in 12 key functional groups, including: Pacific herring (*Clupea pallasii*); chum salmon (*Oncorhynchus keta*); bivalves (*Saxidomus gigantea* and others); birds (*Anas* spp. and others); Northern anchovy (*Engraulis mordax*); eulachon (*Thaleichthys pacificus*); surf smelt (*Hypomesus pretiosus*); pink salmon (*Oncorhynchus gorbuscha*); crabs (*Metacarcinus magister*, *Cancer productus*); ungulates (*Odocoileus hemionus* and others); white sturgeon (*Acipenser transmontanus*); harbour seals (*Phoca vitulina*). Impacts to each functional group are included where relevant in graph titles, including smallpox, shoreline loss, settler fisheries, settler hunting and prey loss. See table 1 and electronic supplementary material, table S2 for data. Values are biomass in t km^{-2} year^{-1}. Artwork for the four pillars of Ancestral səl̓ilwətaɬ diets (Pacific herring, chum salmon, marine/tidal birds and bivalves) was commissioned from artist Irene de Jong for this project.

(f) Settler fisheries and the loss of herring

The rising settler population in Vancouver, British Columbia, Canada corresponded to a rise in capitalism and industrial development. This resulted in an increase in the capacity of fishing vessels and efficacy of equipment, also known as technological creep [50–53]. The industrialization of fishing in səl̓ilwət resulted in devastating losses in forage fish populations [54].

Table 1. Change in biomass (t/km^2) of key groups from 1750–1980 CE. Extracted Ecosim model results. Total area used to estimate loss in biomass is 103 km^2 for aquatic groups and 340 km^2 for the terrestrial group (ungulates). Total study area is 443 km^2 (see figure 1).

Group	1750 Biomass (t/km^2)	1880 Biomass (t/km^2)	1980 Biomass (t/km^2)	Total Δ in biomass (t/km^2) 1750–1980	Total Δ in biomass (tonnes) 1750–1980	Total % Δ in biomass
Pacific herring (*Clupea pallasii*)	13.200	9.862	0.049	−13.150	−1354.49	−100%
Chum salmon (*Oncorhynchus keta*)	2.400	7.126	1.334	−1.063	−109.47	−44%
Bivalves (*Saxidomus gigantea* and others)	9.840	22.780	16.261	+6.421	+661.32	+65%
Birds (*Anas* spp. and others)	0.432	1.668	0.228	−0.204	−21.02	−47%
Northern anchovy (*Engraulis mordax*)	2.405	2.105	0.260	−2.144	−220.85	−89%
Eulachon (*Thaleichthys pacificus*)	1.206	2.388	0.003	−1.203	−123.87	−100%
Surf smelt (*Hypomesus pretiosus*)	1.440	1.767	0.000	−1.440	−148.32	−100%
Pink salmon (*Oncorhynchus gorbuscha*)	0.480	1.851	0.255	−0.225	−23.20	−47%
Crabs (*Metacarcinus magister*, *Cancer productus*)	3.120	5.005	2.446	−0.673	−69.34	−22%
Ungulates (*Odocoileus hemionus* and others)	0.760	1.245	0.192	−0.568	−193.18	−75%
Harbour seals (*Phoca vitulina*)	0.240	1.228	0.173	−0.067	−6.88	−28%
White sturgeon (*Acipenser transmontanus*)	7.200	27.384	0.194	−7.006	−721.63	−97%
Totals	42.722	84.409	21.399	−21.323	−2,330.94	—

Herring was extirpated from səl̓ilwət by settler fisheries employing dynamite over 1885–1915, starting in the eastern end of the inlet and moving west [8,54]. This fishery, based in Coal Harbour, included Spratt's Oilery, a processing plant that processed herring into fish oil for the forestry industry for use as a lubricant for machinery. Pacific herring (*Clupea pallasii*), surf smelt (*Hypomesus pretiosus*), and eulachon (*Thaleichthys pacificus*) were devastated by commercial fishing and habitat loss in the 1880s–1920s [54]. Settler fishing practices reduced these populations by 99% [54]. This dramatic loss in herring, smelt and eulachon populations in the ecosystem happened before baseline states of Səl̓ilwət were established, so Western scientific understanding of the biodiversity of Səl̓ilwət has been based on a reduced state until very recently [54], a phenomenon known as shifting baseline syndrome [55,56]. Surf smelt spawn in the upper intertidal zone and are impacted by shoreline loss [57].

Pacific salmon have been important to settler fisheries since the beginning of colonization of the region in the 1820s, and decades of government reports include salmon as one of the most important resources in British Columbia fisheries [58–61]. The rapid increase in the settler population and the corresponding increase in industrialized salmon fishing and habitat change resulted in declines in salmon populations in the late 1800s [51,52,60,62,63]. Several canneries relied on the Səl̓ilwət salmon populations and likely səl̓ilwətaɬ fishing knowledge, including Bidwell Cannery (1928–1964), English Bay Cannery (1898–1905), Tulloch-Western Cannery (1946–unknown) and Great Northern Cannery (1900–1968), which saw increased success after focusing on chum salmon in the 1930s [64]. We model the growth of the settler fisheries using the settler population as a representation of and proxy for the industrialization of fishing methods, global trade and capitalism in addition to the settler population itself.

(g) Shoreline loss and the closure of bivalve harvesting

The development of the urban cities has caused extensive shoreline damage and change since the late 1800s, resulting in 55% loss of səl̓ilwət intertidal areas caused by urban, commercial and industrial development and change [65]. This reduces tidal habitat and impacts culturally and ecologically important plants, fish and animals, including eelgrass, clams, crabs, ducks and smelt, among many others [65]. The intertidal zone was also important for səl̓ilwətaɬ fishing methods, including the use of weirs and clam gardens [1,65]. The extensive shoreline change has reduced clam habitat significantly [65]. Many of the clam habitats in səl̓ilwət (sub area 28–6 to 28–14 as designated by the Department of Fisheries and Oceans) have been destroyed by urban, industrial and commercial development. Other clam habitats still exist but are unsafe to harvest owing to contamination from

Table 2. Ecopath fleet landings, including səlʼilwəta⊠ and settler fishing, hunting, harvesting, and ecosystem change. 'outside system' category includes prey species that are found outside of our study area, but provide necessary dietary contributions to migrating species included in the model. 'undergrowth' category includes the dense growth of plants found around trees, including saplings, shrubs, and other vegetation.

Functional Group	Fleets (landings in t km^{-2} year^{-1})					
	TWN Harvest (10 k pop)	Settler fishing	Settler herring	Settler hunting	Urbaniza tion	Total
Ungulates	0.225	—	—	0.000	—	0.225
Small terrestrial mammals	0.165	—	—	0.005	—	0.170
Berries	0.082	—	—	—	0.010	0.092
Root vegetables	0.082	—	—	—	0.010	0.092
Medicinal plants	0.082	—	—	—	0.002	0.084
Undergrowth	—	—	—	—	0.025	0.025
Eagles	—	—	—	—	—	—
Birds pelagic	—	—	—	—	—	—
Waterfowl	1.845	—	—	0.030	—	1.875
Whales/dolphins	0	—	—	—	—	—
Sea lions	0.137	—	—	0.005	—	0.142
Seals	0.031	—	—	0.000	—	0.032
Salmon shark	—	—	—	—	—	—
Dogfish	0.343	—	—	—	—	0.343
Sturgeon	0.399	0.010	—	—	—	0.409
Marine white fish	0.589	0.044	—	—	—	0.633
Flatfish	0.577	0.001	—	—	—	0.578
Anchovy	0.618	0.030	—	—	—	0.648
Eulachon	0.618	0.020	—	—	—	0.638
Surf smelt	0.618	0.023	—	—	—	0.640
Herring	2.678	—	0.087	—	—	2.768
Pink salmon	0.366	0.010	—	—	—	0.375
Chum salmon juv	—	0.0007	—	—	—	0.001
Chum salmon ad	1.969	0.035	—	—	—	2.004
Sockeye salmon	0.022	0.002	—	—	—	0.023
Coho salmon juv	—	0.020	—	—	—	0.020
Coho salmon ad	0.065	0.002	—	—	—	0.066
Chinook salmon juv	—	0.022	—	—	—	0.022
Chinook salmon ad	0.022	0.001	—	—	—	0.023
Salmonid	0.384	0.006	—	—	—	0.390
Surfperch	0.092	—	—	—	—	0.092
Rockfish	0.072	—	—	—	—	0.072
Sculpin	0.106	—	—	—	—	0.106
Stickleback	0.046	—	—	—	—	0.046
Misc. prey fish	—	—	—	—	—	—
Outside system	—	—	—	—	—	—
Zooplankton (carn)	—	—	—	—	—	—
Zooplankton (herb)	—	—	—	—	—	—
Jellyfish	—	—	—	—	—	—
Squids	0.058	—	—	—	0.000	0.058
Shrimp	0.092	—	—	—	—	0.092
Crabs	1.648	—	—	—	—	1.648

(*Continued.*)

Table 2. (*Continued.*)

Functional Group	Fleets (landings in t km^{-2} $year^{-1}$)					
	TWN Harvest (10 k pop)	Settler fishing	Settler herring	Settler hunting	Urbanization	Total
Bivalves	7.270	—	—	—	—	7.270
Echinoderms	0.177	—	—	—	—	0.177
Eelgrass	—	—	—	—	—	—
Other benthos	—	—	—	—	—	—
Phytoplankton	—	—	—	—	—	—
Macrophytes	—	—	—	—	—	—
Mushrooms	0.041	—	—	—	0.000	0.042
Terrestrial	—	—	—	—	—	—
Cultural shell deposit	—	—	—	—	—	—
Detritus	—	—	—	—	—	—
Sum	21.517	0.223	0.087	0.040	0.048	21.915

urban development starting in the late 1800s, with faecal coliform bacteria, persistent organic chemicals, heavy metals and/or seasonal marine biotoxins [65,66].

Water quality concerns, including stormwater and sewage overflows, widespread contamination from the fossil fuel industry and other water quality issues have all but eliminated safe shellfish harvesting in Səl̓ilwət intertidal habitats, and the Canadian government closed bivalve harvesting in 1972 [66–71]. Contamination from faecal coliforms, including *Escherichia coli* (*E. coli*), is a key concern regarding the safety of bivalve consumption [69,72]. The main source of faecal coliforms in Səl̓ilwət is the human population through wastewater [72,73]. Another concern is pollution and heavy metal poisoning from the fossil fuel industry. An analysis of chemical levels in shellfish in the study area found mercury, arsenic and lead in all samples of Dungeness crab (*Metacarcinus magister*), softshell clam (*Mya arenaria*) and the invasive varnish clam (*Nuttallia obscurata*), and both arsenic and lead are carcinogenic [67]. Cadmium, which is also carcinogenic, was found in all clam samples [67]. Those analyses were conducted within the context of evaluating the cumulative impacts of industrial chemical pollution from events such as oil spills and the contested Trans Mountain Pipeline expansion, which would increase the likelihood of oil spills and other environmental damage in Səl̓ilwət 0wing to increased pipeline capacity and the corresponding oil tanker traffic [5,67,74]. During the late 20th century, some səl̓ilwətaɬ community members continued to consume shellfish and other traditional foods from Səl̓ilwət after the bivalve harvest closure, which resulted in very high cancer frequency [11,67]. Industrial pollution poisoning traditional foods has been found to result in an increased risk of cancer both in marine and oil sands environments [11,67]. Varnish clams, manila clams (*Venerupis philippinarum*) and softshell clams are invasive to the area but established and abundant in Səl̓ilwət intertidal habitat, competing with the preferred and traditionally harvested butter clams (*Saxidomus gigantea*) and littleneck clams (*Protothaca staminea*) [75–79].

2. Methods

(a) Incorporating səl’ilwətaɬ science

An essential facet of this research is collaboration with səl̓ilwətaɬ knowledge holders and co-authors. Frequent collaborative review meetings with səl̓ilwətaɬ knowledge holders provided research guidance in addition to səl̓ilwətaɬ science. We chose collaborative review meetings rather than ethnographic interviews owing to the preference of səl̓ilwətaɬ contributors, and to include səl̓ilwətaɬ collaborators as co-creators of the research rather than interviewees. During initial review meetings, research questions were developed together to address specific questions of interest to səl̓ilwətaɬ. A draft research question based on available data was presented for refinement: ‘What are the cumulative impacts of colonization on the ecosystem health of səl̓ilwət?” This research question was refined to become: ‘What are the cumulative impacts of selected environmental stressors caused by colonization on the ecosystem health of Səl̓ilwət?’ Specific environmental stressors were chosen based on available data and səl̓ilwətaɬ research priorities, including 1) the impact of smallpox on the səl̓ilwətaɬ population and the resulting health of səl̓ilwət; 2) the impact of settler fisheries, including Pacific salmon and Pacific herring as priorities; 3) the impact of settler hunting on terrestrial animals, including ungulates; and 4) the impact of urbanization on the health of the ecosystem. In subsequent meetings, methods and results were presented to səl̓ilwətaɬ knowledge holders and staff for consideration and assessment. We focused discussions on 1) how səl̓ilwətaɬ is portrayed or discussed in the research; 2) the implications of this research for səl̓ilwətaɬ; and 3) next steps, including any questions the research leaves unanswered for səl̓ilwətaɬ. Finally, in editing the iterations of the reconstructed diet, səl̓ilwətaɬ collaborators aided in assessing the relative dietary contribution of each food group.

We held review meetings frequently over the research process, ensuring səl̓ilwətaɬ access and opportunity for assessment and questions. səl̓ilwətaɬ collaborators offered səl̓ilwətaɬ science and TEK to fill in the gaps that the archaeology and historical/archival records could not address. Additionally, səl̓ilwətaɬ collaborators and representatives conducted an official review process to ensure this research was completed in a good way and could be released with the consent of the Nation. This was an important component of this research as the research falls under səl̓ilwətaɬ data sovereignty and leadership and is conducted at the request of səl̓ilwətaɬ (Tsleil-Waututh Nation).

(b) Ecopath with Ecosim

Ecopath with Ecosim (EwE) [31,80] is an ecosystem modelling framework extensively employed in fisheries management, scenario assessment and ecological research, employing a mass-balanced approach. EwE facilitates the simulation of marine ecosystem dynamics and management scenarios by incorporating comprehensive data on species interactions, biomass distribution and fishing activities. While Ecopath furnishes a static portrayal of ecosystem structure and ecological relationships, Ecosim introduces a time-dynamic element by simulating temporal changes through modelled events in time series. This combined approach enables the assessment of fishing impacts, environmental fluctuations and other factors affecting ecosystems, along with the exploration of various scenarios.

Ecopath builds models around functional groups, which represent any group of organisms from the modelled system that can represent a single species, a group of related species or size or age groups within a species [31]. Ecopath requires a series of input data for the functional groups to create a model and define the system. These include a list of functional groups and their associated biomass (B) in the habitat area ($t\,km^{-2}$), production/biomass (P/B), consumption/biomass (Q/B) and Ecotrophic Efficiency (EE) [31,80]. P/B is the total production/biomass ratio of a functional group [31], or its total mortality (Z). Q/B is the relative annual consumption of food by a group relative to the group biomass, which expresses how much food the group will consume from the system, and it is determined based on the group's biology and their biomass in the modelled ecosystem. Ecotrophic Efficiency represents the fraction of a group's production that is used in the system (as described by the model) and it is thus a ratio between 0 and 1. The closer the fraction is to 1, the closer to maximum capacity of production used by the system. Only the first three of these four parameters must be entered: the model will automatically calculate the EE. For the present model, EE was estimated for all groups. Fisheries can be added with any number of 'fleets' to consider fishing (or hunting or harvesting) of functional groups, and the amount removed from the ecosystem in this way is measured in tonnes per square kilometre per year ($t\,km^{-2}\,year^{-1}$) [31].

Ecosim, which adds a time-dynamic dimension to the Ecopath framework, uses Ecopath for the initial parameterization and allows for simulation of time impacted by time series, vulnerability multipliers and forcing functions. A time series is a series of successive data points of observations of any studied biological or environmental parameter for the duration of the simulation. Vulnerability multipliers represent the relationship between predator biomass and prey mortality. They represent the maximum increase in predation mortality rate that a predator could cause to a prey group when the predator reaches its carrying capacity, with the default value set to 2.00 and a minimum possible value of 1.00 [31]. Forcing functions represent physical or other parameters that the model will enforce on the functional group to which it is applied [31]. For example, a loss in habitat can be modelled using a forcing function by applying a pattern of habitat loss over time (e.g. 50% over 10 years) to all functional groups that are in that habitat (e.g. the intertidal zone within the modelled ecosystem). This allows for habitat-specific changes to be modelled without the use of the spatial–temporal module of EwE, Ecospace [31,81].

(c) Modelling ecosystem change

We use EwE to model the historically documented changes to the Səl̓ilwət ecosystem (v. 6.7.0.18329, https://www.ecopath.com). EwE is a unique tool with which to assess the cumulative effects of development on an ecosystem [30,80,82–84]. We use EwE to model the cumulative effects of selected environmental stressors on Səl̓ilwət between 1750−1980 CE. The modelled area, outlined in figure 1, includes 443 km^2 with 103 km^2 of water, including marine, tidal and river habitats. We use a static state model set in 1750 CE as our starting baseline [10,12]. The static-state model establishes a sustainable ecosystem state and is based on archaeology, historical ecology, historical records, səl̓ilwətaɬ community knowledge and ecological data. We draw on primarily historical and archival data to establish the data points for the time series that represent the events we include in the model. The environmental stressors included in the model include: 1) the impact of smallpox on the səl̓ilwətaɬ population and the resulting health of Səl̓ilwə; 2) the impact of settler fisheries, including Pacific salmon and Pacific herring as priorities; 3) the impact of settler hunting on terrestrial animals, including ungulates; and 4) the impact of urbanization on the health of the ecosystem.

The static state model, which can be found on EcoBase, is named 'səl̓ilwət, Burrard Inlet, 1750−1980 CE' and it contains 52 functional groups spanning terrestrial, river, tidal and marine habitats (see electronic supplementary material, tables S3 and 4 for the basic input parameters and basic estimates [results] from this model) [10]. 'TWN' stands for Tsleil-Waututh Nation. The original 'fleet' focused on the səl̓ilwətaɬ hunting, harvesting and fishing within the ecosystem, with the landings representing the annual amount taken from the ecosystem and set to variable model population sizes, which was to test the maximum human carrying capacity of the ecosystem. The landings were calculated based on a pre-contact səl̓ilwətaɬ dietary reconstruction project that offers an estimated daily menu, averaged across a year and across a modelled pre-contact səl̓ilwətaɬ population of children, adults, elders and pregnant/lactating adults [11]. The calculations from the daily menu to the landings for the Ecopath model are reported in electronic supplementary material, table S5. Population sizes of 1000, 5000, 10 000, 15000 and 20 000 were tested and it was found that 10 000 was the largest population size the modelled ecosystem could sustain [10,12].

Based on this, we use the 10 000-person population size as the starting number of people, represented as a fleet in the time series (see table 2 for the Ecopath fleet landings and electronic supplementary material, tables S1, S3 and S4 for the Ecosim time series, Ecopath basic input parameters and Ecopath basic estimates (base model results), respectively). We include three more fleets in addition to the fleet that represents the səl̓ilwətaɬ population: (i) settler fishing, (ii) settler herring, (iii) settler hunting and (iv) urbanization, the last of which represents the replacement of habitat with urban development (see table 2 and electronic supplementary material, table S1). We modelled the settler herring fishery separately from the rest of the settler fisheries because of the well-documented eradication of herring caused by the dynamite herring fishery. To ensure that these 'fleets' do not start until the time series representing the settler population starts, we apply a negative biomass accumulation to each of the groups included in these three fleets corresponding to the landings multiplied by −1 [31]. For example, the landings for herring are 2.678 $t\,km^{-2}\,year^{-1}$ from settler fishing, so the biomass accumulation that we enter is −5.00. This way, the settler fleets do not initiate until the time series instructs it to do so (see electronic supplementary material, tables S1 and 4). We use a reduced vulnerability multiplier for the following groups to represent that they were closer to their carrying capacity before contact than is expressed with the default setting (of 2): pink salmon, with a vulnerability value of 1.10, and Waterfowl, with a vulnerability value of 1.20. To address exchange of biomass from migrating species, a functional group named 'Outside system' is included to provide prey to sturgeon and salmon groups. Immigration values of 1.5 for waterfowl and 0.13 for sea lions are also included to represent the immigration of additional biomass of these two migratory species. These two approaches to address exchange in and out of the study system help in modelling this small study area more accurately.

(d) Research parameters

We limit our analysis to the following events within our study period of 1750−1980 CE: two smallpox waves (1782 and 1862 CE); salmon and herring fisheries and canneries; the extirpation of herring; the change to and loss of shoreline; and the closure of bivalve harvesting. By including these selected environmental stressors, we model the impact of these events alone. We acknowledge that this does not represent all of the environmental stressors that impacted səl̓ilwət between 1750−1980 CE. Additionally, the loss of freshwater streams, which represents part of lost salmon spawning habitat, is not within the scope of this research. Finally, both the səl̓ilwətaɬ and settler populations are represented through fleets in the model. The səl̓ilwətaɬ fishery includes what is harvested, hunted, fished and gathered within our study area, and it does not include any imported or exported food goods. The growth of the settler population is determined using census data [85], represented through fleets, which does not include the change in gear, vessels, or commercial fishing techniques or regulations that very likely had an impact on fishing pressure and fleet efficacy. These research parameters establish the scope of this study.

(e) Smallpox epidemics and population size

Smallpox had such a significant impact on səl̓ilwətaɬ that the few remaining səl̓ilwətaɬ community members called on neighbouring xʷməθkʷəy̓əm (Musqueam) community members to assist with burials (Gabriel George, personal communication, March 2024). To model the impact of smallpox on səl̓ilwətaɬ, the səl̓ilwətaɬ population is represented in the model as a fleet, rather than as a functional group. This fleet includes all hunting, harvesting and fishing in the səl̓ilwət ecosystem by the səl̓ilwətaɬ population, and does not include any imported resources, which we assume would equal exports. We include two smallpox waves in the model, one in 1782 and the second in 1862 CE. Smallpox inflicted significant loss of life upon Coast Salish communities [40,41,43,44,86]. Reports vary regarding the extent of loss, ranging from 50–90% loss of life in communities affected, with some communities experiencing great loss and villages left deserted [40,41,43,44]. We use a time series to control the səl̓ilwətaɬ harvest fleet, decreasing by 80% (1782 CE) and a further 60% (1862 CE) for the two main smallpox waves, representing the depopulation and resulting decrease in fishing, hunting and harvesting pressure caused by these waves (see electronic supplementary material, table S1). We start with a value of 1.00 and reduce the value to 0.20 (i.e. 20% of that 1750 CE population) in 1782 and 0.12 (i.e. 12% of that 1750 CE population) in 1862 CE. It is difficult to calculate exactly what percentage of the səl̓ilwətaɬ community died in the first smallpox wave since it was before European census records, so we apply an estimate based on historical estimates of population loss. The 1862 CE smallpox wave would have hit a population that had already experienced at least one wave of the virus, and so may have had some immunity. We use a further reduction of 60% for the 1862 CE wave based on Robert Boyd's calculations [43]. Harris calculates an overall reduction in Coast Salish populations of 90% [41], and after both the 1782 CE and 1862 CE waves, our estimates result in a 92% loss. These reductions in population size are represented in the time series as reduced fishing pressure (see electronic supplementary material, table S1).

(f) Settler fisheries and shoreline change

We represent the extirpation of herring and the intense fishing of salmon, smelt and eulachon in the time series under the settler fishing fleet (see table 2 for landings and electronic supplementary material, table S1 for the time series). We increase the fishing pressure in accordance with the settler population and recorded landings, based on census data retrieved from Statistics Canada [85], and level off fishing pressure growth in the late 1940s (see electronic supplementary material, table S1). The intercensal growth in population is linked to the settler fishing pressure through the time series, under the three settler Fisheries: settler fishing, settler hunting and urbanization (see table 2 for landings). The settler fishing represents a modelled estimate of all settler commercial, industrial and small-scale fishing in the Səl̓ilwət ecosystem. We start the time series for these fisheries with a low starting value of 0.01 in 1820 and increase the value in accordance with the intercensal growth reported by Statistics Canada. In 1948, we maintain the value of 100.10 until 1980 to end the link between the population growth and the Fisheries (see electronic supplementary material, table S1).

A forcing function is applied to the following groups through the time series to represent the reduction of their intertidal habitat: surf smelt, crabs and bivalves. The forcing function is included in the time series (see electronic supplementary material, table S1). The loss of intertidal habitat is represented through a 1% loss per year until approximately 45% loss is attained by the mid–1940s, ending at 62% loss in 1980. While the overall shoreline loss for Səl̓ilwət is modelled at 55% between 1792–2020 CE, some of the local habitats faced more intense losses of >99% in False Creek Flats, and 80% in the Capilano River Estuary [65]. These two areas include essential intertidal habitat to the functional groups to which we apply this forcing function.

(g) Key functional groups for analysis

We focus our attention on the twelve functional groups that represent the top 80% of contributors to the pre-contact səl̓ilwətaɬ diet [11]. This includes the four pillars of the səl̓ilwətaɬ diet, representing 58% of the pre-contact səl̓ilwətaɬ diet: Pacific herring (*C. pallasii*), salmon (*Oncorhynchus* spp.), marine birds (*Anas* spp. and others) and bivalves (*Saxidomus gigantea* and others) [11]. The salmon species we include in this analysis are chum salmon (*Oncorhynchus keta*) and pink salmon (*O. gorbuscha*), which together contribute 93% of the salmon in the pre-contact diet from Səl̓ilwət [11]. An additional 22% of the diet comes from white sturgeon (*Acipenser transmontanus*), crabs (*M. magister, Cancer productus*), ungulates (*Odocoileus hemionus* and others), harbour seals (*Phoca vitulina*) and forage fish, including eulachon (*T. pacificus*), Northern anchovy (*Engraulis mordax*) and surf smelt (*H. pretiosus*). We do not include functional groups for which data are too sparse to be used for our study time period in this analysis.

3. Results

The model showed a dramatic change in ecosystem state as soon as the 1782 CE smallpox epidemic hits the ecosystem, reducing the səl̓ilwətaɬ population by 80%, from 10 000 to 2000 (see the impact of this human loss of life on 12 key functional groups in figure 2). The second wave in 1862 CE, represented as a loss of 60% of the səl̓ilwətaɬ population, had a less dramatic impact on the model as the fishing pressure was already significantly reduced. Following these epidemic events and massive reductions in the səl̓ilwətaɬ population, the settler population and environmental impacts increase and the biomass of the key functional groups on which we focused decreases significantly over 1900–1950 CE, when we stopped the link between settler population growth and fishing pressure. Key fish species were heavily impacted by settler fisheries from 1880–1980 CE. The biomass of forage fish was reduced significantly, with surf smelt reduced by 100% (148 tonnes lost between 1750–1980), eulachon reduced by 100% (124 tonnes), Northern anchovy reduced by 89% (221 tonnes) and Pacific herring reduced by 100% (1355 tonnes). Chum salmon was reduced by 44% (110 tonnes) and pink salmon by 47% (23 tonnes). The biomass of white sturgeon was reduced by 97% (722 tonnes). However, there was a more significant reduction in the biomass of many of the groups between 1880–1980 owing to settler fisheries, habitat loss and prey loss (see table 1). Surf smelt was reduced by 182 tonnes and eulachon by 246 tonnes. Chum salmon was reduced by 596 tonnes and pink salmon by 164 tonnes. Sturgeon experienced a loss of 2800 tonnes.

The shoreline of səl̓ilwət experienced dramatic change over the modelled time period and this is clear through the loss in the biomass of key intertidal functional groups. The biomass of bivalves initially increased owing to the lack of human harvesting pressure or clam garden management. However, the key concern with bivalves is the levels of contamination that make them unsafe to eat (see figure 2). While bivalves are still present and abundant, they are essentially inedible. Also marked on the bivalves graph in figure 2 is the inlet-wide bivalve closure in 1972 CE. However, from 1880–1980 CE, the bivalves experienced a rapid loss in shoreline habitat and their biomass is reduced by 29%, or 671 tonnes. Between 1750–1980, crabs experienced a loss of 22% or 71 tonnes, and marine and tidal birds a loss of 47% or 21 tonnes (see the respective graphs in figure 2). Between 1880–1980, crabs were reduced by 264 tonnes and marine and tidal birds by 148 tonnes. The biomass of harbour seals reduced by 28% [7 tonnes, see figure 2) between 1750–1980, and 109 tonnes between 1880–1980 CE. Ungulates, as the representative terrestrial functional group, reduced by 75% (193 tonnes, see figure 2) between 1750–1980 and 358 tonnes between 1880–1980. These percentages are the percent difference between the 1750 CE biomass value and the 1980 biomass value for each of the twelve functional groups that we analysed. Surf smelt was also impacted by the loss of intertidal zone habitat as upper-intertidal spawners [57].

The most important results are the trends in change over time. With the exception of bivalves, for which there are other concerns, the biomass of these groups that are key to səl̓ilwətaɬ traditional lifeways and diets are reduced significantly owing

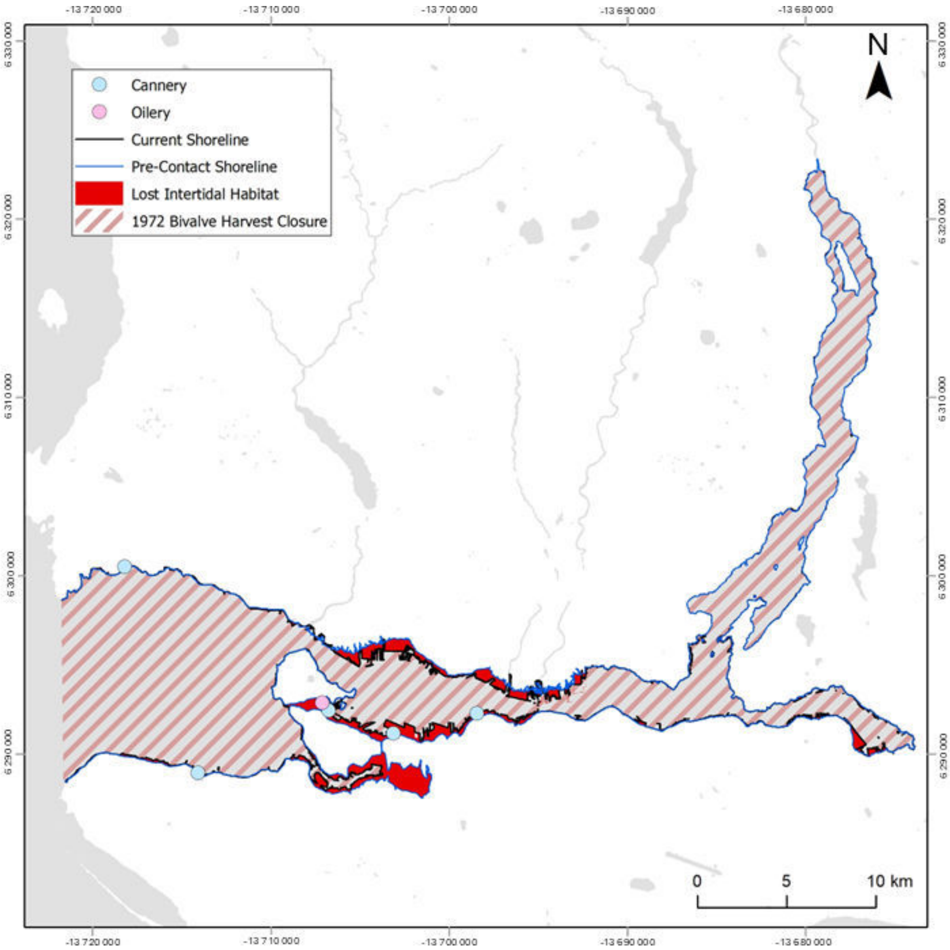

Figure 3. Map of səl̓ilwət including salmon canneries, Spratt's Oilery, the present-day shoreline, the pre-contact shoreline, the lost intertidal habitat and the area included in the 1972 bivalve harvest closure. By GIS & Information Management, Inlailawatash.

to settler-colonial fisheries and development activities. The loss of səl̓ilwətaɬ lives, resulting in reduced fishing, harvesting and hunting pressure, also has a significant impact on the biomass of most of the groups. Overall, our results show a significant loss in biomass from start to end of the model, with 21.32t km^{-2} of biomass lost over 1792–1980 CE and 63 t km^{-2} of biomass lost between 1880–1980 CE (see table 1). The 1750 total biomass across the twelve groups was 42.72 t km^{-2}, the 1880 biomass was 84.41 t km^{-2} and the 1980 total biomass was 21.50 t km^{-2}. As the available biomass of bivalves is unsafe to consume, we did not include it as edible biomass, and with this adjustment the total available 1980 biomass is 5.14 t km^{-2}. If the 1750 CE ecosystem state was able to sustain up to 10 000 people [10], a proportional decrease in carrying capacity would mean that only 1203 people could be sustained on the 1980 CE ecosystem, representing a human carrying capacity loss of 88% in the Səl̓ilwət ecosystem.

Pacific herring and Pacific salmon are culturally and ecologically keystone species in the Pacific Coast [87–89] and the loss of both herring and salmon impacts the people and animals that relied on them for food. As salmon, herring, shellfish and marine birds were the four pillars of the pre-contact səl̓ilwətaɬ diet [11], the significant loss of biomass of these groups especially would have had a substantial impact on the community. Our results show that settler-colonial fisheries and industrial/commercial development activities were primary contributors to the considerable reduction in biomass among key species crucial to səl̓ilwətaɬ traditional lifeways and diets.

4. Discussion

A quote shared frequently in discussions with səl̓ilwətaɬ knowledge holders during this research is 'when the tide went out, the table was set' [9]. This quote speaks to the essential role that Səl̓ilwət holds in sustaining səl̓ilwətaɬ communities. This is the first study quantifying the cumulative ecological loss caused by settler-colonial activity and commercial/industrial growth in Səl̓ilwət. To our knowledge, this is the first attempt to quantify the loss of biomass and food availability from pre-contact to the modern day. Our study area is 443 km^2, including 103 km^2 of marine and intertidal areas and 340 km^2 of terrestrial areas. Our results show that there was a loss of 21.50 t km^{-2} (see figure 2 and table 1). There was a total loss of 2331 tonnes of biomass over 1750–1980 CE. The loss in biomass between 1880 CE and 1980 CE was significantly more: the total biomass in 1880 for these twelve groups was estimated as 84.20t km^{-2} and the loss of biomass between 1880–1980 was 63.01 t km^{-2}, or 6740 tonnes. The key cause of this loss of biomass are the settler fisheries, which supplied the many canneries around the shores of Səl̓ilwət, including Bidwell Cannery, English Bay Cannery, Tulloch-Western Cannery and Great Northern Cannery [64], marked in blue, and Spratt's Oilery marked in pink on figure 3. This only represents the absolute loss in biomass, not the potential biomass lost by the eradication and devastation of key species, including herring, surf smelt, anchovy, eulachon, sturgeon and ungulates. The potential harvest of these species between the first smallpox wave in 1782 CE and the end of the model in 1980 CE is considerably higher and represents a considerable loss in traditional foods. For example, if səl̓ilwətaɬ had been able to continue harvesting the modelled 2.7 t km^{-2} of herring per year from 1782–1980 CE, a period of 198 years, this represents a loss of 534.6 t km^{-2}, or 55 064 tonnes of biomass.

The carrying capacity of the səl̓ilwət ecosystem was reduced by 88% by the modelled events over 1820–1980, a significant loss that increases the ecosystem's vulnerability to environmental stressors and reduces the overall biodiversity of the ecosystem. This study only modelled specific events: the smallpox waves of 1782 and 1862 CE, the settler fisheries including salmon and herring, the extirpation of herring and shoreline loss. We include a discussion of the pollution and contamination that resulted in the closure of the bivalve harvest in 1972 CE, but we do not model the contamination itself.

We did not include other events and environmental stressors, including the loss of streams, the forestry industry, or dams. Because of this, our estimates of loss are conservative and there was almost certainly more loss to biomass and ecosystem health during this time period that is outside the scope of this study. We also recognize that including other events would influence the trends presented in figure 2. The rapid increase in the settler population, driving a corresponding increase in their fishing, harvesting and hunting pressure on the ecosystem, caused dramatic loss in salmon, forage fish, white sturgeon and harbour seals. This relationship was modelled as a direct 1 : 1 relationship between the settler population and the fishing pressure from settler fisheries; however the settler population was used to also represent the industrialization of fishing methods, global trade and the introduction of capitalism. The loss of shoreline habitat, primarily caused by infilling of False Creek and Inner Harbour South [65], impacted bivalves, crabs and birds. Ungulates also suffered a dramatic reduction of their population, with settlers favouring the elk and deer meat [90–92]. Further, settlers hunted elk intensely and wiped out the herds that had once been abundant throughout the study area, with the last elk seen in 1881 CE nearby in Coquitlam [90–92]. Overall, there is a pattern of biodiversity and habitat loss as a casualty of industrial and commercial development and the creation of Metropolitan Vancouver.

We focused our analysis on the twelve functional groups we have included in our discussion. Given that the 1750 CE landings for the səl̓ilwətaɬ fleet could feed up to 10 000 people [10], and because we do not include the contaminated and inedible bivalves biomass, our results indicate that the modelled events left only enough food to sustain up to 1203 people by 1980. However, we do not suggest that 1,203 səl̓ilwətaɬ people were able to sustain themselves on the Səl̓ilwət over 1820–1980 CE, as səl̓ilwətaɬ food sovereignty, access, fishing, harvesting, and hunting were increasingly restricted and controlled, including competition from industrialized settler fisheries [93,94]. The Indian Reserve System was established in the 1830s, limiting Indigenous peoples into small pieces of land and restricting their access to their lands and resources [1,93,95]. Starting in 1869 CE, səl̓ilwətaɬ was forced to live on IR3 (Indian Reserve 3, or Burrard Inlet 3), marked on figure 1, and other Indian Reserves around Burrard Inlet, a very small part of their much larger traditional and unceded territory [96]. When considering impacts to the ecosystem beyond the scope of this study, the real carrying capacity in 1980 CE would be considerably lower. For example, other colonial and anti-Indigenous policies and infrastructure, including St. Paul's Indian Residential School opening in 1899 CE, are all impacts to the səl̓ilwətaɬ population that are outside of the scope of this study. For example, the Residential School System took thousands of children from Indigenous communities through violence and forced them to attend institutions that used abuse to attempt to 'kill the Indian in the child' [94,97,98]. Assault, poor hygiene, and poor diets resulted in the deaths of thousands of Indigenous children [94,97,98].

(a) Trophic impacts on biomass

One of the characteristics of ecosystem modelling in Ecopath is the diet compositions of functional groups, which is one of the mechanisms by which the model connects groups into a functioning ecosystem, an ecological network [31]. This is a key benefit to whole ecosystem modelling and demonstrates that the loss of the səl̓ilwətaɬ population and the rapid rise in settler population are both felt across the ecosystem. The model shows multiple stressors on all twelve groups, including loss of habitat, change in fishing mortality, change in predator biomass and change in available biomass of prey. Herring and salmon are two of the pillars of traditional səl̓ilwətaɬ diets [11] and the loss of herring and salmon biomass in the Səl̓ilwət ecosystem represents a loss to səl̓ilwətaɬ lifeways and food sovereignty.

A key example of trophic impacts to biomass is Pacific herring. Our results show a loss of 13.15 t km^{-2} of herring over 1880–1915 CE, which represents 1355 tonnes of herring biomass lost to settler overfishing and destructive fishing practices in səl̓ilwət in approximately 35 years. Herring is an ecological and cultural keystone species in the Pacific Northwest [87,89] and this loss is felt throughout the ecosystem. Within this analysis, we see this impact on birds and harbour seals; however, more broadly, herring are important contributors to the diets of salmon and seals. Both salmon and seals are key foods of the critically endangered Southern Resident Killer Whales (*Orcinus orca*) [99,100]. For the 2023/2024 season, the Canadian Department of Fisheries and Oceans set a maximum allowable harvest of 8058 tons (7310 tonnes, 1.075 t km^{-2}) of herring for the Strait of Georgia (total area, 6800 km^2), the arm of the Salish Sea in which səl̓ilwət is located [101]. səl̓ilwətaɬ was sustainably harvesting more than double that quantity, 2.678 t km^{-2} (278 tonnes per year) pre-contact. Herring, smelt and eulachon are all keystone species, and the devastation of these species in Səl̓ilwət has ripple effects throughout the ecosystem [89]. This demonstrates a transition from sustainable harvest to a devastating collapse in biomass to a long-term suppression of the population.

Another example of the trophic impacts to biomass is salmon. Chum salmon and pink salmon experience losses in biomass of 1.07 and 0.23 t km^{-2} respectively. This represents approximately 109.8 tonnes of chum salmon biomass and 23.24 tonnes of pink salmon biomass lost over 1880–1980, a period of 100 years. Salmon species are also ecologically and culturally keystone in the Pacific Northwest [88]. In this analysis, the loss of salmon biomass impacts harbour seals and white sturgeon. Additionally, salmon has an important role in the health of Səl̓ilwət aquatic and terrestrial ecosystems by providing nutrients and energy to forests and terrestrial systems as their carcasses decompose after spawning [102,103].

There are numerous environmental stressors to salmon, but we focus solely on the settler fisheries. The loss of spawning habitat, the forestry industry and the construction of dams are a few stressors on salmon that we do not model. There are numerous lost streams in the study area that were once salmon spawning habitat [65] and the loss of these streams would have likely further reduced the biomass of salmon in səl̓ilwət. The forestry industry has a negative impact on salmon populations by changing and damaging their spawning habitats [104,105]. Dams impact the life cycles and migration of salmon [106–108]. There is more to the story regarding the cumulative impacts of environmental stressors caused by colonization that can be modelled in future research.

(b) Ecological impact of disease

Our research highlights the connection between disease, loss of life in Indigenous communities, environmental change and reduction in ecosystem health. Previous work has studied the connection between loss of Indigenous lives and environmental change, but it focused on reforestation and was located in the Southwest of the United States [109]. Our results illuminate the ecological impact of the smallpox epidemics, resulting in not only a loss of human life, but also environmental change that is a direct result of the loss of səl̓ilwətaɬ lives. The model shows a balanced ecosystem in the period before the first smallpox wave. The modelled loss of 80% of the səl̓ilwətaɬ population in 1782 CE with the first wave of smallpox has a noticeable impact, showcasing the significance of the səl̓ilwətaɬ relationship with the ecosystem. The impact of the second smallpox wave in 1862 CE is more subtle, but still noticeable in all groups (see figure 2). səl̓ilwətaɬ had millennia-long resource management and exploitation practices that were sustainable and ecocentric [1,3,6,7,110,111]. Our results illuminate the sustainability of the intensive səl̓ilwətaɬ stewardship, fishing, harvesting and hunting in Səl̓ilwət pre-contact. The loss of səl̓ilwətaɬ life is felt across the ecosystem.

(c) Impact of fisheries and environmental change on biomass

Prior to the 1782 CE smallpox wave, the model is balanced (using the Ecopath mass balance process), representing a sustained ecosystem state. The loss of 80% of the səl̓ilwətaɬ population, simulated through their fishing and harvesting pressure on the ecosystem (table 2), results in an increase in biomass in all 12 modelled groups. The exploitation of fauna by the səl̓ilwətaɬ fleet exerts considerable pressure on biomass levels. However, the observed increase in biomass following an 80% reduction in the səl̓ilwətaɬ fleet is not necessarily ecologically beneficial, as it may lead to elevated mortality rates among prey species. The ecosystem's balance is disrupted, and due to rapidly increasing pressure from the rising settler population, it does not have a chance to recover. The 1862 CE smallpox wave, which is modelled as having a further 60% reduction in the səl̓ilwətaɬ population, appears to also have an impact on all twelve groups. However, there are compounding impacts during that period, including the increasing fishing pressure from the settler population.

Settler Fisheries have a significant impact on nine of the groups: chum salmon, pink salmon, Pacific herring, surf smelt, eulachon, Northern anchovy, white sturgeon, ungulates, and harbour seals experienced significant loss in biomass over 1900–1980 CE (see figure 2). The groups relying on the intertidal zone, including bivalves, crabs, and birds, are all significantly impacted by the loss of shoreline(see figure 2). Overall, the effect of Fisheries on the ecosystem is that of suppressing biomass, and this results in a complete extirpation in the cases of Pacific herring and eulachon and a near eradication in the biomass of Northern anchovy, surf smelt, and white sturgeon (figure 2). Settler fisheries dramatically reduced the overall health of the Səl̓ilwət ecosystem.

Bivalves are most impacted by shoreline change reducing their habitat and by industrial and commercial activities polluting səl̓ilwət. While we do not see as dramatic a collapse in the biomass of bivalves, the contamination with bacteria, viruses, chemicals, heavy metals and marine biotoxins have resulted in the bivalves that once provided sustenance for thousands of səl̓ilwətaɬ people being unsafe to consume [68,69,71]. The increase in bivalve biomass starting at 1782 CE is owing to the dramatic decrease in Səl̓ilwət harvesting pressure, caused by smallpox waves that reduced the Səl̓ilwət population. We do see a loss of 28% of the biomass of bivalves from 1885–1980 caused by shoreline change—representing a loss of 6.29 t km^{-2}, or 648 tonnes lost over 95 years—owing to loss of and damage to habitat. However, the loss of edible biomass is 100%: what is now present are primarily invasive species, and native species are preferred by səl̓ilwətaɬ harvesters [75]. Settler-colonial activities and the development of industrial and commercial interests in Səl̓ilwət have a significant negative impact on the health of the səl̓ilwət ecosystem. Settler fisheries have a significant impact on fished groups, dramatically reducing biomass over the study period. The loss of essential shoreline habitat further reduces the biodiversity and ecosystem health significantly.

5. Conclusions

This research sits within the palaeoenvironmental, palaeoecological and environmental archaeological space of reconstructing past environments and human-to-environment relationships over deep time. As far as we are aware, our study is novel in that it is the first attempt to quantify the cumulative impacts of colonization on an ecosystem. Through combining data sources across disciplines, this work avoids disciplinary silos and offers a holistic and robust model of the Səl̓ilwət ecosystem over time. It is essential to approach environmental reconstruction with transdisciplinary methods to bridge data and knowledge gaps [14,15,19,27]. Our analysis shows an overall pattern of loss of biodiversity and habitat, representing a severe reduction in ecosystem health starting with the first smallpox wave in 1782 CE.

In this research we establish a novel method to modelling the cumulative effects of urbanization and settler-colonization over time using Ecopath with Ecosim. While this modelling process offers a best estimate and overall biomass trends, rather than absolute accuracy, it is grounded in historical, archival, archaeological and ecological data, as well as firsthand accounts from səl̓ilwətaɬ experts. The model demonstrates the significant negative impacts of the modelled events on the səl̓ilwət ecosystem. səl̓ilwət experienced dramatic change over 1782–1980 CE, and this is keenly felt by səl̓ilwətaɬ today. Loss of biodiversity, the poisoning of important resources, loss of habitat and the horrific loss of human life have all had significant impact on səl̓ilwət and on səl̓ilwətaɬ. Collectively, the damage to and loss of habitat and biodiversity in Səl̓ilwət are devastating. The top twelve contributors to the pre-contact səl̓ilwətaɬ diet suffer from rapid increases in fishing and hunting pressure, as well as industrial pollution and loss of habitat. The considerable loss in available food, caused by the settler fishing industry and industrial activities, directly undermines səl̓ilwətaɬ food sovereignty.

This story is distressing, and there is no way to ignore the pain felt by Indigenous communities throughout what we now know today as Canada. However, səl̓ilwətaɬ has made important strides towards protecting, conserving and improving the health of Səl̓ilwət, and they continue to do so [8,9,75,93]. By modelling the impacts of these events on the ecosystem, we can better understand what has been lost to or damaged in the name of development and colonization, and this can be used by səl̓ilwətaɬ for future stewardship work. Additionally, this community-driven and transdisciplinary approach to the ecosystem modelling of past ecosystems and ecosystem change can be adapted and used in other communities and ecosystems.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. All relevant data is included in this submission, either in the manuscript itself, presented in submitted figures, or included in the supplemental tables.

Supplementary material is available online [112].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. M.E.: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, validation, visualization, writing—original draft, writing—review and editing; S.T.: conceptualization, methodology, resources, writing—review and editing; J.M.: conceptualization, methodology, resources, supervision, writing—review and editing; M.G.: conceptualization, resources, validation; M.G.: conceptualization, resources, validation; C.S.: conceptualization, methodology, supervision, writing—review and editing; V.C.: conceptualization, funding acquisition, project administration, supervision, validation, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

Funding. Funding for this research was provided through Mitacs Accelerate to M.E.

Acknowledgements. We would like to thank Tsleil-Waututh Nation for their leadership in this research. We would also like to thank Gabriel George, Director of Tsleil-Waututh Nation's Treaty, Lands and Resources Department, and Elder Carleen Thomas for their contributions and the knowledge they have shared throughout this research. Finally, we would like to thank the anonymous reviewers for their time and energy in providing constructive feedback, improving the manuscript significantly.

References

1. Morin J. 2015 Tsleil-Waututh Nation's history, culture and aboriginal interests in eastern Burrard Inlet (Public Redacted Version) https://twnsacredtrust.ca/wp-content/uploads/2015/05/Morin-Expert-Report-PUBLIC-VERSION-sm.pdf
2. Morin J. 2014 *The Burrard Inlet radiocarbon dating project: documenting pre-contact Tsleil-Waututh settlement patterns*. vol. **12**. North Vancouver, Canada: The Burrard Radiocarbon Dating Project.
3. Morin J, Lepofsky D, Ritchie M, Porčić M, Edinborough K. 2018 Assessing continuity in the ancestral territory of the Tsleil-Waututh-Coast Salish, southwest British Columbia, Canada. *J. Anthropol. Archaeol*. **51**, 77–87. (doi:10.1016/j.jaa.2018.04.004)
4. George L. 1991 Tsleil-Waututh place names. On file at Tsleil-Waututh's treaty, Lands and Resources Department. North Vancouver.
5. Tsleil-Waututh Nation. 2016 *Assessment of the Trans Mountain pipeline and tanker expansion proposal*. See https://twnsacredtrust.ca/wp-content/uploads/TWN_assessment_final_med-res_v2.pdf.
6. Morin J, Zhang H, Royle TCA, Speller C, Alcaide M, Morin R, Yang D. 2021 DNA-based species identification of ancient salmonid remains provides new insight into pre-contact Coast Salish salmon fisheries in Burrard Inlet, British Columbia, Canada. *J. Archaeol. Sci. Rep*. **37**, 102956. (doi:10.1016/j.jasrep.2021.102956)
7. Efford M *et al*. 2023 Archaeology demonstrates sustainable ancestral Coast Salish salmon stewardship over thousands of years. *PLoS ONE* **18**, 1–18. (doi:10.1371/journal.pone.0289797)
8. Tsleil-Waututh Nation. Sacred Trust Initiative. 2022 *The return of the herring population to Indian arm* . See https://twnsacredtrust.ca/the-return-of-the-herring-population-to-indian-arm/.
9. Tsleil-Waututh Nation's Treaty Lands and Resources Department. 2021 *Vignette 08: connection to place: indigenous leadership in səlilwət (burrard inlet)*, (eds C Thomas, A Rao, SD Santo, L Ogston, S Taft), pp. 88–91. Salish Sea Institute, Western Washington University, Bellingham. (doi:10.25710/vfhb-3a69)
10. Efford M, Morin J, George M, George M, Barber SB, Shaffer M. 2024 Archaeological investigations and ecological modelling into pre-contact (1792 CE) Tsleil-Waututh stewardship of Burrard Inlet, BC, Canada. In *Ecopath40 Conference: The Ecosystem Continuum: From Knowledge to Decisions*, Ostend, Belgium.
11. Efford M, George M, George M, Taft S, Morin J, de la Puente S. 2024 A fish-focused menu: reconstructing ancestral Tsleil-Waututh diets. *J. Ethnobiol.* **44**, 247–263. (doi:10.1177/02780771241261235)
12. Efford M *et al*. 2024 Archaeological investigations and ecological modelling into pre-contact (1792 CE) Tsleil-Waututh stewardship of Burrard Inlet, BC, Canada. PhD Thesis, Vancouver, Canada, University of British Columbia. https://open.library.ubc.ca/media/download/pdf/24/1.0445601/3.
13. Butzer K. 1982 *Archaeology as human ecology: method and theory for a contextual approach*. New York, NY: Cambridge University Press.
14. Dincauze D. 1987 Strategies for paleoenvironmental reconstruction in archaeology. *Archaeol. Method Theory* **11**, 255–336. https://www.jstor.org/stable/20210099
15. Crumley CL. 2021 Historical ecology: a robust bridge between archaeology and ecology. *Sustainability* **13**, 8210. (doi:10.3390/su13158210)
16. Armstrong CG *et al*. 2017 Anthropological contributions to historical ecology: 50 questions, infinite prospects. *PLoS One* **12**, e0171883. (doi:10.1371/journal.pone.0171883)
17. Beller E, McClenachan L, Trant A, Sanderson EW, Rhemtulla J, Guerrini A, Grossinger R, Higgs E. 2017 Toward principles of historical ecology. *Am. J. Bot*. **104**, 645–648. (doi:10.3732/ajb.1700070)
18. Balée W. 2006 The Research Program of Historical Ecology. *Annu. Rev. Anthropol.* **35**, 75–98. (doi:10.1146/annurev.anthro.35.081705.123231)
19. Crabtree SA, Dunne JA. 2022 Towards a science of archaeoecology. *Trends Ecol. Evol*. **37**, 976–984. (doi:10.1016/j.tree.2022.07.010)
20. Nelson MK, Shilling D. 2018 *Traditional ecological knowledge: learning from indigenous practices for environmental sustainability*. New York, NY: Cambridge University Press.
21. Turner NJ, Ignace MB, Ignace R. 2000 Traditional ecological knowledge and wisdom of aboriginal peoples in British Columbia. *Ecol. Appl*. **10**, 1275–1287. (doi:10.1890/1051-0761(2000)010[1275:tekawo]2.0.co;2)
22. Butler JRA, Tawake A, Skewes T, Tawake L, Mcgrath V. 2012 Integrating traditional ecological knowledge and fisheries management in the Torres Strait, Australia: the catalytic role of turtles and dugong as cultural keystone species. *Ecol. Soc* **17**, 4. (doi:10.5751/ES-05165-170434)
23. Turner N. 2014 *Ancient pathways, ancestral knowledge: ethnobotany and ecological wisdom of indigenous peoples of northwestern North America*. Montreal & Kingston, Canada: McGill-Queen's University Press. See https://www.jstor.org/stable/j.ctt7zt2k0 (accessed 12 December 2023).
24. Vilalta-Navas A, Beas-Luna R, Zetina-Rejón MJ, López-Ibarra GA, Malpica-Cruz L, Lorda J, Zepeda-Dominguez JA, Kluger LC. 2023 Coupling scientific and local ecological knowledge network models for temperate coastal ecosystems. *ICES J. Mar. Sci* **80**, 185–196. (doi:10.1093/icesjms/fsac225)
25. Bartlett C, Marshall M, Marshall A. 2012 Two-eyed seeing and other lessons learned within a co-learning journey of bringing together indigenous and mainstream knowledges and ways of knowing. *J. Environ. Stud. Sci*. **2**, 331–340. (doi:10.1007/s13412-012-0086-8)
26. Crabtree SA, Dunne JA, Wood SA. 2021 Ecological networks and archaeology. *Antiquity* **95**, 812–825. (doi:10.15184/aqy.2021.38)
27. Briggs JM, Spielmann KA, Schaafsma H, Kintigh KW, Kruse M, Morehouse K, Schollmeyer K. 2006 Why ecology needs archaeologists and archaeology needs ecologists. *Front. Ecol. Environ*. **4**, 180–188. (doi:10.1890/1540-9295(2006)004[0180:wenaaa]2.0.co;2)
28. Christensen V. 2001 *Ecosystems of the past: how can we know since we weren't there?*. Fisheries Impacts on North Atlantic Ecosystems: Models and Analyses Part 1: Analysis of Biomass Trends, pp. 26–34. Vancouver, BC: Fisheries Centre Research Reports. (doi:10.14288/1.0445601)
29. Ainsworth CH, Pitcher TJ, Heymans JJ, Vasconcellos M. 2008 Reconstructing historical marine ecosystems using food web models: northern British Columbia from pre-European contact to present. *Ecol. Model*. **216**, 6. (doi:10.1016/j.ecolmodel.2008.05.005)
30. Christensen V, Walters CJ. 2004 Ecopath with Ecosim: methods, capabilities and limitations. *Ecol. Model*. **172**, 109–139. (doi:10.1016/j.ecolmodel.2003.09.003)
31. Christensen V, Walters CJ. 2024 *Ecosystem modelling with EwE*. Vancouver, BC: University of British Columbia. (doi:10.14288/24d7-ab68)
32. Efford M. 2024 Burrard Inlet 1750-1980 CE. *EcoBase*. See https://ecobase.ecopath.org/php/protect/base_model.php?lang=&provenance=web&ident=&pass=&action=base&model=777.
33. Witmore C. 2015 Archaeology and the second empiricism. In *Debating archaeological empiricism* (eds C Hillerdal, J Siapkas), pp. 37–67. New York, NY: Routledge Press.
34. Sørensen TF, Marila MM, Beck AS. 2024 The mandate for speculation: responding to uncertainty in archaeological thinking. *Camb. Archaeol. J*. 1–16. (doi:10.1017/s0959774323000525)
35. Binford LR. 1968 Archaeological perspectives. In *New perspectives in archeology* (ed. S Binford), pp. 5–32. Chicago, IL: Aldine Publishing Co.
36. Wickson F, Carew AL, Russell AW. 2006 Transdisciplinary research: characteristics, quandaries and quality. *Futures* **38**, 1046–1059. (doi:10.1016/j.futures.2006.02.011)
37. Lawrence MG, Williams S, Nanz P, Renn O. 2022 Characteristics, potentials, and challenges of transdisciplinary research. *One Earth* **5**, 44–61. (doi:10.1016/j.oneear.2021.12.010)

38. Habu J, Fawcett C, Matsunaga JM. 2008 Introduction: Evaluating multiple narratives: beyond nationalist, colonialist, imperialist archaeologies. In *Evaluating multiple narratives: beyond nationalist, colonialist, imperialist archaeologies* (eds J Habu, C Fawcett, JM Matsunaga), pp. 1–11. New York, NY: Springer. (doi:10.1007/978-0-387-71825-5_1)
39. Grünhagen C, Schwermer H, Wagner-Ahlfs C, Voss R, Gross F, Riekhof MC. 2022 The multifaceted picture of transdisciplinarity in marine research. In *Transdisciplinary marine research: bridging science and society* (eds S Gómez, V Köpsel), pp. 3–26. London, UK: Routledge. (doi:10.4324/9781003311171-2)
40. Patterson KB, Runge T. 2002 Smallpox and the Native American. *Am. J. Med. Sci*. **323**, 216–222. (doi:10.1097/00000441-200204000-00009)
41. Harris C. 1994 Voices of disaster: smallpox around the Strait of Georgia in 1782. See https://www.jstor.org/stable/482767.
42. Rijn KV. 2006 "Lo! the poor Indian!" Colonial responses to the 1862–63 smallpox epidemic in British Columbia and Vancouver Island. *Can. Bull. Med. Hist*. **23**, 541–560. (doi:10.3138/cbmh.23.2.541)
43. Boyd R. 1994 Smallpox in the Pacific Northwest: the First Epidemics. *Anthropology Faculty Publications and Presentations* **141**, 5–40. https://pdxscholar.library.pdx.edu/anth_fac/141/
44. Boyd R. 1996 Commentary on early contact-era smallpox in the Pacific Northwest. *Ethnohistory* **43**, 307–328. https://about.jstor.org/terms
45. Dobyns HF. 1966 Estimating aboriginal American population: an appraisal of techniques with a new hemispheric estimate. *Curr. Anthropol*. **7**, 395–416. (doi:10.1086/200749)
46. Dobyns H, Swagerty W. 1983 *Their number become thinned: Native America population dynamics in eastern North America*. Knoxville, Canada: University of Tennessee Press.
47. Boyd R. 1999 *The Coming of the Spirit of Pestilence: Introduced Infectious Diseases and Population Decline among Northwest Coast Indians, 1774–1874*. Seattle, WA: University of Washington Press.
48. Lutz J, Carlson K. 2024 The smallpox chiefs: bioterrorism and the exercise of power in the Pacific Northwest. *West. Hist. Q* **55**, 87–104. (doi:10.1093/whq/whae001)
49. McDowell J. 2015 *Uncharted waters: the explorations of José Narváez (1768-1840)*. Vancouver, Canada: Ronsdale Press.
50. Pauly D, Watson R, Alder J. 2005 Global trends in world fisheries: impacts on marine ecosystems and food security. *Phil. Trans. R. Soc. B* **360**, 5–12. (doi:%2010.1098/rstb.2004.1574)
51. Muszynski A. 1988 Race and gender: structural determinants in the formation of British Columbia's salmon cannery labour forces. *Can. J. Sociol*. **13**, 103–120. https://about.jstor.org/terms
52. Stacey D. 1982 *Sockeye and tinplate: technological change in the Fraser River canning industry 1871–1912*. Victoria, Australia: British Columbia Provincial Museum.
53. Palomares MLD, Pauly D. 2019 On the creeping increase of vessels' fishing power. *Ecology & Society* **24**, 1–7. (doi:10.5751/es-11136-240331)
54. Morin J, Evans AB, Efford M. 2023 The rise of Vancouver and the collapse of forage fish: a story of urbanization and the destruction of an aquatic ecosystem on the Salish Sea (1885–1920 CE). *Hum. Ecol*. **51**, 303–322. (doi:10.1007/s10745-023-00398-w)
55. Jackson J, Alexander K, Sala E. 2011 *Shifting baselines: the past and the future of ocean fisheries*. Washington, DC: Island Press. (doi:10.5822/978-1-61091-029-3)
56. Pauly D. 1995 Anecdotes and the shifting baseline syndrome of fisheries. *Trends Ecol. Evol*. **10**, 430. (doi:10.1016/s0169-5347(00)89171-5)
57. Therriault TW, Mcdiarmid AN, Wulff W, Hay DE. 2022 *Review of surf smelt (Hypomesus pretiosus) biology and fisheries, with suggested management options for British Columbia*. Fisheries and Oceans Canada, Nanaimo. See https://publications.gc.ca/collections/collection_2015/mpo-dfo/Fs70-5-2002-115-eng.pdf.
58. Department of Marine and Fisheries. 1901 *Annual report of the department of marine and fisheries 1901*. Ottawa, Canada: Department of Marine and Fisheries.
59. Department of Marine and Fisheries Canada. 1888 *Annual report of the department of marine and fisheries 1888*. Ottawa, Canada: Department of Marine and Fisheries Canada.
60. Department of Marine and Fisheries Canada. 1875 *Annual report of the department of marine and fisheries (1875)*. Ottawa, Canada: Department of Marine and Fisheries Canada.
61. Department of Marine and Fisheries Canada. 1892 *Part II annual report of the department of marine and fisheries 1892*. Ottawa, Canada: Department of Marine and Fisheries Canada.
62. Tupper C. 1889 *Annual report of the department of fisheries, dominion of Canada, for the year 1888*. Ottawa, Canada: Department of Fisheries. See https://publications.gc.ca/collections/collection_2015/mpo-dfo/Fs1-1888-eng.pdf.
63. McAllister A. 1989 *Industrialization and aquaculture in the British Columbia salmon industry in the 1980s*. Ottawa, Canada: Carlton University. (doi:10.22215/etd/1989-01685)
64. From tides to tins. 2023 From tides to tins: Canneries. See https://tidestotins.ca/canneries/.
65. Taft S, Oldford G, Lilley P, Oetterich S, Morin J, George M. 2022 Reconstructing the pre-contact shoreline of Burrard Inlet (British Columbia, Canada) to quantify cumulative intertidal and subtidal area change from 1792 to 2020. *Fish. Cent. Res. Rep* **30**, 1–48. (doi:10.14288/1.0407075)
66. Fisheries and Oceans Canada. 2023 *BC tidal area 28 - Vancouver, Bowen Island, Indian Arm, Squamish: recreational fishing limits, openings and closures*. See https://www.pac.dfo-mpo.gc.ca/fm-gp/rec/tidal-maree/a-s28-eng.html.
67. Andrade-Rivas F *et al*. 2022 Industrialization and food safety for the Tsleil-Waututh Nation: an analysis of chemical levels in shellfish in Burrard Inlet. *Environ. Res*. **206**, 112575. (doi:10.1016/j.envres.2021.112575)
68. Sanchez M, LeNoble J, Rao AS. 2022 *Water quality assessment and proposed objectives for Burrard Inlet: Polychlorinated Biphenyls (PCBs), Dioxins (PCDDs) and Furans (PCDFs) technical report*. See https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/water-quality-objectives/burrard_inlet_water_quality_assessment_pcb_20220916.pdf.
69. Rao A, Sanchez M, Sutherland D, Lilley P. 2019 *Water Quality Assessment and Updated Objectives for Burrard Inlet: Introduction*. Prepared for Tsleil-Waututh Nation and the Province of B.C. See https://2020-03-31_biwqos_intro_appsdoc.pdf.
70. BC Centre for Disease Control, Fisheries and Oceans Canada. 2023 *Shellfish Webmap*. See https://maps.bccdc.ca/shellfish/.
71. Rao AS. 2022 *A review of Burrard Inlet water quality data to understand the impacts of contamination on Tsleil-Waututh Nation's safe harvesting practices.* Tsleil-Waututh NationTsleil-Waututh Nation Research Report. Vancouver, Canada: Treaty, Lands and Resources Department. See https://twnsacredtrust.ca/wp-content/uploads/2022/03/20220210_Contaminants-impacts-on-TWN_Formatted.pdf.
72. LeNoble JL, Lilley P, Rao A. 2021 *Water quality assessment and proposed objectives for Burrard Inlet: microbiological indicators technical report*. See https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/water-quality-objectives/burrard_inlet_water_quality_objectives_microbio_sept_15_2021.pdf.
73. Antony A, Hsu D, Chen E, Chen J, Sondergeld O. *Seasonal, spatial and source variation of E. coli counts in False Creek, British Columbia*. Report prepared for ENVR 400: Community Project in Environmental Science, University of British Columbia. See https://open.library.ubc.ca/media/download/pdf/52966/1.0074572/4.
74. George G, George-Wilson L. 2014 OH-001-2014: Trans Mountain Pipeline ULC: Trans Mountain Expansion Project. Hearing before the National Energy Board. Volume 6. See https://s3.wp.wsu.edu/uploads/sites/1974/2018/03/NEB-Trans-Mountain-Pipeline-Expansion-Hearing-Transcript-Vol-6-Oct.-6-2014-.pdf.
75. Guttmann M. 2022 'I'd like to see it come back': the revitalization of Tsleil-Waututh Nation clam tending in Burrard Inlet. Bachelor of Science Thesis. Burnaby, Canada: Simon Fraser University. https://summit.sfu.ca/item/35818.
76. Palacios R, Armstrong DA, Orensanz J (lobo). 2000 Fate and legacy of an invasion: extinct and extant populations of the soft-shell clam (*Mya arenaria*) in Grays Harbor (Washington). *Aquat. Conserv*. **10**, 279–303. (doi:10.1002/1099-0755(200007/08)10:43.3.co;2-9)

77. Gillespie GE, Bourne NF, Rusch B. 2004 *Exploratory intertidal bivalve surveys in British Columbia.... 2000 and 2001*. See https://www.researchgate.net/publication/321685719_Exploratory_Intertidal_Bivalve_Surveys_in_British_Columbia_2000_and_2001.
78. Bendell LI, Chan K, Crevecoeur S, Prigent C. 2014 Changes in ammonium and pH within intertidal sediments in relation to temperature and the occurrence of non-indigenous bivalves. *Open J. Mar. Sci*. **04**, 151–162. (doi:10.4236/ojms.2014.43015)
79. Dudas S, Dower J. 2006 Reproductive ecology and dispersal potential of varnish clam *Nuttallia obscurata*, a recent invader in the Northeast Pacific Ocean. *Mar. Ecol. Prog. Ser*. **320**, 195–205. (doi:10.3354/meps320195)
80. Pauly D. 2000 Ecopath, Ecosim, and Ecospace as tools for evaluating ecosystem impact of fisheries. *ICES J. Mar. Sci*. **57**, 697–706. (doi:10.1006/jmsc.2000.0726)
81. Kumar R, Surma S, Pitcher T, Varkey D, Lam M, Ainsworth C. 2016 An ecosystem model of the ocean around Haida Gwaii, Northern British Columbia: Ecopath, Ecosim and Ecospace. *Fish. Cent. Res. Rep* **24**, ii–76. (doi:10.14288/1.0354480)
82. Coll M, Bundy A, Shannon LJ. 2009 Ecosystem modelling using the Ecopath with Ecosim approach. In *Computers in fisheries research* (eds BA Megrey, E Moksness), pp. 225–291. Dordrecht, The Netherlands: Springer. (doi:10.1007/978-1-4020-8636-6_8)
83. Polovina J. 1984 An overview of the Ecopath model. *Fishbyte* **2**, 5–7.
84. Heymans JJ, Coll M, Link JS, Mackinson S, Steenbeek J, Walters C, Christensen V. 2016 Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. *Ecol. Model.* **331**, 173–184. (doi:10.1016/j.ecolmodel.2015.12.007)
85. Statistics Canada. Table 90-10-0017-01: Population and private dwellings occupied by usual residents and intercensal growth, 1851 to 2021 censuses. ()
86. Fenn E. 2022 Pox Americana: the great smallpox epidemic of 1775–82. *J. Am. Hist.* **89**, 1024–1025. (doi:10.2307/3092365)
87. Moss ML. 2016 The nutritional value of Pacific herring: an ancient cultural keystone species on the Northwest Coast of North America. *J. Archaeol. Sci*. **5**, 649–655. (doi:10.1016/j.jasrep.2015.08.041)
88. Garabaldi A, Turner N. 2004 Cultural Keystone Species: Implications for Ecological Conservation and Restoration. *Ecol. Soc.* **9**, 1. http://www.ecologyandsociety.org/vol9/iss3/art1/
89. Thornton TF. 2015 The ideology and practice of Pacific herring cultivation among the Tlingit and Haida. *Hum. Ecol*. **43**, 213–223. (doi:10.1007/s10745-015-9736-2)
90. Matthews M. 1955 Conversations with Khahtsahlano 1932–1954. See https://archive.org/details/ConversationsWithKhahtsahlano1932-1954_346/mode/2up.
91. Kennedy D, Bouchard R. 1987 Indian history of the Deer Lake and Burnaby Lake area. Appendix 2 for: Heritage Resource Studies at Deer Lake Park, Burnaby, B.C. Permit 1987-41
92. Pearson J, Reitz J. 1960 *Land of the Royal Kwantlen: a history of North Surrey*. (eds J Pearson, JM Reitz). Surrey, BC: Surrey Athletic Association.
93. George R, Simpson M. 2023 *It stops here: standing up for our lands, our waters, and our people*. Toronto, Canada: Penguin Random House Canada Ltd.
94. George S, Goldberg J, Belson L, MacPhee D, Wilson T. 2023 *The fire still burns: life in and after residential schools*. Vancouver, Canada: Purich Books, UBC Press.
95. Starblanket T. 2017 'Kill the Indian in the child': genocide in international law. In *Indigenous peoples as subjects of international law* (ed. I Watson), pp. 171–200. Abingdon, UK: Routledge. (doi:10.4324/9781315628318-9)
96. Government of Canada. 2021 Reserve/Settlement/Village Detail: Burrard Inlet 3. See https://fnp-ppn.aadnc-aandc.gc.ca/fnp/Main/Search/RVDetail.aspx?RESERVE_NUMBER=07903&lang=eng.
97. Truth and Reconciliation Commission of Canada. 2015 *Canada's residential schools: the history, part 1, origins to 1939*. vol. **1**. Montreal, Canada: McGill-Queen's University Press.
98. Milloy JS. 1996 *Suffer the little children: the Aboriginal residential school system*. Submitted to The Royal Commission on Aboriginal Peoples. See http://central.bac-lac.gc.ca/.redirect?app=rcap&id=443&lang=eng.
99. Hanson MB *et al*. 2021 Endangered predators and endangered prey: seasonal diet of Southern Resident killer whales. *PLoS One* **16**, e0247031. (doi:10.1371/journal.pone.0247031)
100. Ford J, Ellis G. 2006 Selective foraging by fish-eating killer whales *Orcinus orca* in British Columbia. *Mar. Ecol. Prog. Ser*. **316**, 185–199. (doi:10.3354/meps316185)
101. Department of Fisheries and Oceans Canada. 2024 *Pacific herring 2023-2024: Integrated fisheries management plan summary*. See https://www.pac.dfo-mpo.gc.ca/fm-gp/mplans/herring-hareng-ifmp-pgip-sm-eng.html.
102. Cederholm C, Kunze M, Murota T, Sibatani A. 1999 Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. *Fisheries* **24**, 6–15. (doi:10.1577/1548-8446(1999)024<0006:PSC>2.0.CO;2)
103. Wagner MA, Reynolds JD. 2019 Salmon increase forest bird abundance and diversity. *PLoS One* **14**, e0210031. (doi:10.1371/journal.pone.0210031)
104. Holtby LB. 1988 Effects of logging on stream temperatures in Carnation Creek British Columbia, and associated impacts on the coho salmon (*Oncorhynchus kisutch*). *Can. J. Fish. Aquat. Sci*. **45**, 502–515. (doi:10.1139/f88-060)
105. Cunningham D. 2022 Forestry influences on instream salmon habitat and the implications for watershed management. Master of Resource Management Thesis. Burnaby, Canada: Simon Fraser University.
106. Marschall EA, Mather ME, Parrish DL, Allison GW, McMenemy JR. 2011 Migration delays caused by anthropogenic barriers: modeling dams, temperature, and success of migrating salmon smolts. *Ecol. Appl*. **21**, 3014–3031. (doi:10.1890/10-0593.1)
107. Ferguson JW, Healey M, Dugan P, Barlow C. 2011 Potential effects of dams on migratory fish in the Mekong River: lessons from salmon in the Fraser and Columbia Rivers. *Environ. Manag*. **47**, 141–159. (doi:10.1007/s00267-010-9563-6)
108. Levin PS, Tolimieri N. 2001 Differences in the impacts of dams on the dynamics of salmon populations. *Anim. Conserv*. **4**, 291–299. (doi:10.1017/s1367943001001342)
109. Liebmann MJ, Farella J, Roos CI, Stack A, Martini S, Swetnam TW. 2016 Native American depopulation, reforestation, and fire regimes in the Southwest United States, 1492–1900 CE. *Proc. Natl Acad. Sci. USA* **113**, p. (doi:10.1073/pnas.1521744113)
110. Morin J, Royle TCA, Zhang H, Speller C, Alcaide M, Morin R. 2021 Indigenous sex-selective salmon harvesting demonstrates pre-contact marine resource management in Burrard Inlet, British Columbia, Canada. *Nature New Biol.* **11**, 21160. (doi:10.1038/s41598-021-00154-4)
111. Morin J, Evans A. 2022 Historical ecology in Burrard Inlet: summary of historic, oral history, ethnographic, and traditional use information. *Fish. Cent. Res. Rep* **30**, 64. (doi:10.14288/1.0407074)
112. Efford M, Taft S, Morin J, George M, George M, Speller C *et al*. 2025 Supplementary material from: Unsettling the record: modelling the devastating cumulative effects of selected environmental stressors and loss of human life caused by colonization in Burrard Inlet. Figshare. (doi:10.6084/m9.figshare.c.7891699)