Diversity and Resilience of Sea Gardens Across the Pacific Ocean

by

Jacqui Levy

B.Sc., University of Washington, 2015

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Resource Management

in the
School of Resource and Environmental Management
Faculty of Environment

SIMON FRASER UNIVERSITY
Spring 2023

Declaration of Committee

Name:	**Jacqui Levy**
Degree:	**Master of Resource Management**
Title:	**Diversity and Resilience of Sea Gardens Across the Pacific Ocean**
Committee:	**Chair: Pascal Haegeli** Associate Professor, Resource and Environmental Management
	Anne Salomon Supervisor Professor, Resource and Environmental Management
	Dana Lepofsky Committee Member Professor, Archaeology
	Melissa Poe Committee Member Social Science Lead Washington Sea Grant
	Chelsea Armstrong Examiner Assistant Professor, Indigenous Studies

Abstract

In a time of rapid global environmental change, it is important to identify the practices that promote resilient social-ecological systems. Indigenous systems of stewardship offer insight into social-ecological resilience given that they reflect long-term use and adaptation over periods of environmental change. To gain insight onto what practices can support resilient food systems, we analyzed twenty-one Indigenous mariculture innovations from around the Pacific Ocean. We examined the extent to which latitudinal patterns in species diversity influence the diversity of species harvested within these systems. We also assessed the diversity of life history traits, trophic groups, modes of reproduction, migration strategies, and population growth strategies that exist among the species cultured within these innovations and the diversity of management strategies used to maintain them. Lastly, we compared these social-ecological attributes of mariculture diversity to contemporary commercial aquaculture practices. We found that globally, Indigenous mariculture systems cultivate a diversity of species with a range of ecological and life history traits, unlike contemporary commercial industrial mariculture systems which rely on fewer species and are thus less biologically diverse. We also found that the diversity of species cultivated across the Pacific Ocean was not driven by a latitudinal gradient in species diversity suggesting that these biodiverse food systems are not incidental, but rather are the result of intentional stewardship rooted in a diversity of management practices informed by observations and experimentation and honed over many generations. Our research demonstrates the importance of biodiversity in resilient social-ecological systems, and that building resilient and biodiverse coastal food systems must include the lived knowledge and leadership of Indigenous People.

Keywords: Social-ecological resilience; Indigenous stewardship; Marine food systems; Marine ecology; Mariculture; Aquaculture

Acknowledgments

My graduate work was made possible by the wisdom and work of the many practitioners, stewards, and knowledge holders in the Pacific Sea Garden Collective. I feel humbled by the breadth and depth of this knowledge, and I am grateful to have had access to this body of knowledge. Thank you to the members of the Pacific Sea Garden Collective for sharing your wisdom to help guide this project- without it, this project would not have been possible.

I am lucky to have had the support, insight, and generosity of so many people.

A huge thank you to my supervisory committee for your mentorship and support: Anne Salomon, Dana Lepofsky, and Melissa Poe. I am incredibly lucky to have learned from such intellectual forces and such strong, vibrant, inspiring women! I have learned so much from you. Thank you, Anne, from the bottom of my heart for taking me on, for your patience, guidance, and support, and for teaching me so much.

Thank you to my CMEC labmates for your kindness, insight, wisdom, authenticity, and laughter: Hannah Kobluk, Kelsey Miller, Kim-Ly Thompson, Skye Augustine, Maya Guttmann, Sarah Gutzmann, Alyssa Allchurch, Emily Spencer, Meredith Fraser, and Desiree Lawson. You conduct your work with such open hearts, and I admire all of you. I am lucky to have crossed paths with you.

Thank you, to my chosen family in Squamish: Tyla, Arad, Ryka, Selina, Roger, and Pepper. I wouldn’t be here without you. Thanks for loving me, encouraging me, and for helping me take life a little less seriously. You are all such ridiculous and wonderful beings.

I am also grateful for the financial support from the NSERC Discovery Grant and NSERC CGS-M, and for the support of SFU’s graduate fellowship. This support allowed me the privilege to learn, grow, and further my education.

Statement of Positionality and Identity

I am a non-Indigenous person with mixed European ancestry, and a settler. I grew up in what is called the United States, on land stolen from Indigenous Peoples. I was educated in Western, capitalist, and colonial paradigms under patriarchy and white supremacy. White supremacy explicitly and implicitly grants privilege and power to Whiteness while discriminating against and devaluing the knowledge of non-Western cultures. This has biased my beliefs, understanding and assumptions about the world, and I still have a great deal of unlearning to do.

As a non-Indigenous person conducting research about Indigenous systems of management, I am lucky and privileged to be part of this conversation. I hope that my research advances agendas of decolonization and revitalization by pointing to the lived knowledge, experiences, and authority of the Indigenous stewards of these places.

Table of Contents

List of Tables

List of Figures

Introduction

In a time of accelerating loss of ocean biodiversity and global environmental change, there is a need to identify the practices and strategies that promote biodiverse and resilient social-ecological systems (Folke et al., 2021; Hughes et al., 2013). It is well-established that diversity is a key characteristic of social-ecological resilience because it facilitates greater adaptive capacity under changing conditions (Biggs et al., 2012; Kotschy et al., 2015; Nyström et al., 2019). For example, in marine systems, diverse fisheries portfolios allow harvesters to adapt to ecological and social disturbances, and more biologically diverse ecosystems allow for a more stable delivery of ecosystem functions (Cline et al., 2017; Isbell et al., 2015). Studying diversity within resilient social-ecological systems can help identify what practices are more likely to sustain productivity when a system is confronted with change (Lepofsky & Salomon, In Press).

Resilience refers to the ability of a system to recover from unexpected change and to maintain its functioning and identity by adapting to a disturbance (Biggs et al., 2012; Liggs et al., 2015). Specifically, a resilient social-ecological system adapts to disturbance and reorganizes to retain vital ecosystem functions that support human well-being (Biggs et al., 2015; Chapin et al., 2010; Folke et al., 2016; Poe et al., 2016; Walker & Salt, 2012). Social-ecological resilience emphasizes the embedded and linked human-nature system.

Social-ecological systems are considered self-organizing and complex adaptive systems that exhibit non-linear behavior and emergent properties between components (Biggs et al., 2012; Levin, 1998). Interactions between the components of complex adaptive systems can feed back and influence subsequent interactions, adding uncertainty and non-linearity to the system (Levin, 1998; Mahon et al., 2008) Diversity confers social-ecological resiliency because it provides heterogeneity, and thus more pathways to adapt and recover from unexpected perturbations within a complex system (Kotschy et al., 2015).

A hallmark of Indigenous stewardship of food systems is diversity, which encompasses species diversity as well as a variety of management strategies along a continuum of habitats (Armstrong et al., 2021; Hoffman et al., 2021; Marshall et al., 2018; Schuster et al., 2019). For example, on the Oregon coast, fishing weirs were operated year-round and targeted both resident and migratory species in estuaries, rather than solely relying on salmon for food (Byram, 2002; Tveskov & Erlandson, 2003). In Hawaii, Indigenous Hawaiians employed complex food intensification strategies across a variety of habitats in terrestrial and aquatic environments (Winter et al., 2020). Fish were cultivated along a salinity gradient; from inland freshwater ponds (loko i'a kalo) within taro fields to help reduce pests and promote soil enrichment for taro, all the way to large seawater ponds (loko kuapa) along the coast (Costa-Pierce, 1987). This diversification of species and cultivation techniques across different habitats promotes resiliency by providing the ability to adapt during unexpected environmental changes (Berkes, 2007). Understanding how humans have secured food production while encouraging environmental feedbacks that promote productivity is important in the context of global food security. Studying systems that are diverse and socially-ecologically resilient can provide insight and innovation to promote resiliency in other regions.

Western conservation science typically considers human-altered environments a recent and destructive phenomenon on an otherwise pristine and unaltered planet (Bliege-Bird & Nimmo, 2018; Williams et al., 2020). This perspective ignores the stewardship of landscapes by many Indigenous Peoples, who have long been selectively transforming and enriching local biodiversity and ecosystems in complex and enduring ways (Armstrong et al., 2021; Hoffman et al., 2021; Jackley et al., 2016a; Marshall et al., 2018). Multiple lines of evidence demonstrate that Indigenous Peoples all over the world have been stewards and engineers of ecosystems for millennia, and have engaged in management to increase the productivity of the local environment (Armstrong et al., 2022; Balée et al., 2023; Jackley et al., 2016a; Lepofsky et al., 2021; Palace et al., 2017). These management actions are part of larger goals and objectives, and can be understood as a spectrum of human influence, with a gradient of intensity and influence on the environment (Lertzman, 2009). In these management systems, people were not passive recipients of the environment but are active engineers of ecosystem processes and drivers of local diversity (Boivin et al., 2016). For example, in Australia, Indigenous fire stewardship creates greater landscape diversity and heterogeneity, leading to greater abundance of a keystone lizard species despite high harvest pressure (Bird et al., 2013). On the Atlantic coast of North America, pre-contact shell middens elevated soil nutrients and increased local plant species richness (Cook-

Patton et al., 2014). Along the Pacific coast of North America, clam gardens double the productivity and abundance of edible clam species by expanding and enriching ideal intertidal clam habitat (Groesbeck et al., 2014). In these contexts, humans have been in relationship with their local environment for millennia, altering and managing it to increase productivity and produce a stable food supply despite environmental and social change.

Indigenous systems of stewardship offer insight into social-ecological resilience given that they are built on generations of accumulated knowledge and wisdom and have persisted through times of environmental change (Berkes et al., 2000; Turner & Reid, 2022). Along the Pacific coast, Indigenous Peoples have maintained intricate relationships and management practices with local intertidal environments for millennia, and these practices have helped enable a predictable and long-term food supply (Gauvreau et al., 2017; Jackley et al., 2016; Kobluk et al., 2021; Reeder-Myers et al., 2022). Some of these strategies include mariculture innovations: coastal technologies such as tidal fish traps, fish weirs or sea gardens which are embedded within a suite of cultural, spiritual and governance practices (Lepofsky & Caldwell, 2013a; Mathews & Turner, 2017). Archaeological evidence has shown that these innovations lasted through changes in sea level, changes in temperature, and other environmental variability (Holmes et al., 2022; Toniello et al., 2019).

Global patterns of species richness and biodiversity are the result of ecological, evolutionary, and climatic processes over hundreds of thousands of years. Notable biogeographical patterns like the latitudinal diversity gradient describe the striking increase in species richness for all taxa from the Earth’s poles to the equator (Hillebrand, 2004). Additional studies have shown that in marine environments, warmer sea surface temperatures are associated with higher biodiversity (Gagné et al., 2020; Tittensor et al., 2010). Studying the patterns between global biodiversity and the environmental mechanisms that drive it can provide perspective for conservation and management, especially in the face of global climate change.

Understanding how humans have secured and managed marine resources in the past is important in building resilient food systems during environmental change. To lend insight into what makes for resilient resource management systems, we analyzed twenty-one Indigenous mariculture innovations from around the Pacific Ocean (Figure 1)

(*Sea Gardens Across the Pacific*, 2022). We investigated how global patterns in the natural environment might influence biodiversity within these mariculture innovations. We assessed the diversity of life history and ecological traits amongst the species cultivated, as well as the diversity of management strategies within these management systems. Finally, we assessed the species richness of these innovations compared to the species richness in commercial industrial mariculture. We asked the following questions: 1) Does the diversity of species cultivated within Indigenous mariculture innovations follow global patterns of marine biodiversity driven by latitude and sea surface temperature? 2) What is the diversity of trophic levels, reproductive guilds, migratory strategies, population doubling time, thermal ranges, and management strategies amongst the species cultivated? And 3) How does the species diversity within Indigenous mariculture systems compare to that of commercial industrial mariculture today? We predicted that there would be weak evidence for an effect of latitude and sea surface temperature on the diversity of species cultivated. For question two, among ancestral mariculture innovations, we also expected relatively more low trophic level species with less complex reproductive needs, non-migratory species, and/or species with lower population doubling times. Alternatively, given that these systems are part of a linked social-ecological system, we also predicted there maybe evidence for a broad range of species cultivated from each of these categories. Finally, due to the values of longevity of harvest and sustainability within many Indigenous management systems, we predicted that there would be a higher number of species cultivated in Indigenous mariculture systems compared to commercial industrial mariculture (Atlas et al., 2021b). This synthesis of resilient management systems, which span thousands of years and thousands of kilometers of coastline, shed light onto what practices can support resilient food systems into the future.

Methods

Study Area

The mariculture innovations examined in this study represent a Pacific-wide compilation of mariculture technologies. They encompass innovations located from 58N (Intertidal Fish Traps of Southeast Alaska) to 55S (Corrales de Pesca of the Chiloé archipelago in Patagonia) (*Sea Gardens Across the Pacific*, 2022). The locations of unique innovation sites span the breadth of temperate, subtropical, and tropical climates, and currently experience average sea surface temperatures ranging from 10°C-29°C. The source collection by no means represents all mariculture innovations across the Pacific. However, they collectively reflect a diversity of technologies across many marine environments.

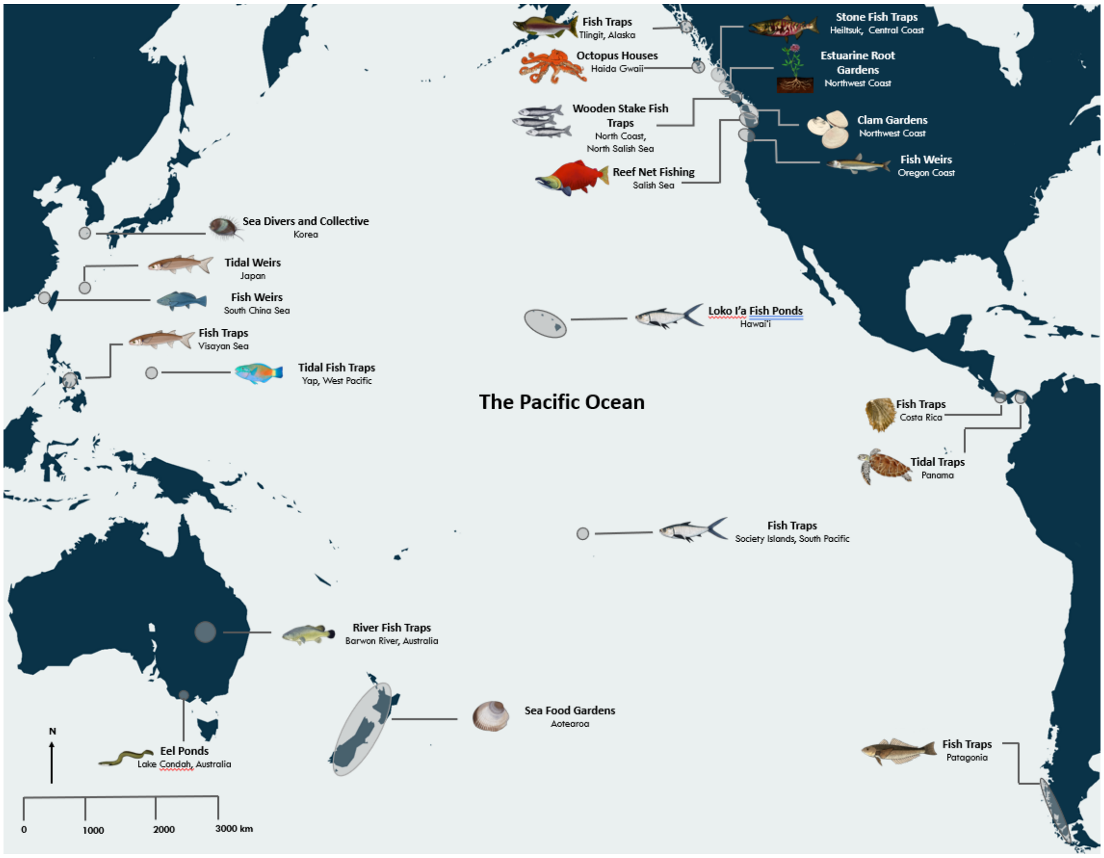


Figure 1 **Locations of the 21 Indigenous mariculture innovations across the Pacific Ocean from which this analysis was based.**

Data Collection

Species Richness

To classify the species harvested in each mariculture technology, we conducted a systematic review of published papers, books, and government reports (n = 282) gathered by experts from the Pacific Sea Garden Collective (2022). These included natural and social science researchers and practitioners, both Indigenous and non-Indigenous. We made one record for each species, family, or class explicitly stated as being currently or previously stewarded using the innovation technology. In areas where there is a limited published ethnographic record or remaining knowledge holders (e.g., Costa Rica, Panama), we included species that were observed within the mariculture innovations by researchers today and present in the nearby (<50km) archaeological record. We recognize, however, that faunal remains represented in the archaeological record will likely encompasses marine species not influenced by the Indigenous mariculture innovation studied. We calculated gamma species richness per innovation by summing the number of species found to be associated with each unique innovation.

Species Traits and Spatial Data

For each species documented, we gathered species-specific ecological and biological information using global fish database FishBase (Froese and Pauly, 2023) and global invertebrate database SeaLifeBase (Palomares and Pauly, 2022). Specifically, we gathered data on each species' trophic level, migratory strategies, population doubling time, reproductive guild, preferred thermal ranges (Table A1).

Spatial Data

For each unique mariculture innovation, we calculated a latitudinal midpoint and sea surface temperature. The latitudinal midpoint was calculated from spatial polygons, which encompassed the range within which each unique innovation exists. These ranges come from published maps from the same body of literature as the species dataset, and we prioritized Indigenous territory maps over those of colonial government systems. Latitudinal midpoints (N-S/2) were calculated from these spatial polygons.

We acquired sea surface temperature data from the European Space Agency to calculate the average monthly mean sea surface temperature from 1990-2010 (Merchant et al., 2019). We used the same spatial polygons as the species richness dataset.

Industrial Mariculture

We retrieved industrial mariculture data from 1980-2009 using the Sea Around Us database (Pauly, Zeller, Palomares, 2020). Industrial mariculture data is defined as “production that is commodity-driven and export-based”, with a minimum 1 tonne per year of total wet weight (Pauly, Zeller, and Palomares, 2020; Campbell & Pauly, 2013). This database excludes artisanal and subsistence mariculture, freshwater aquaculture, and kelp production. We used similar spatial parameters as the Indigenous mariculture data. Since the industrial mariculture data on the Sea Around Us database is by region, province, or state whereas our dataset is by Indigenous territory, there are a total of n = 14 sites for industrial mariculture compared to n = 21 for Indigenous mariculture.

We chose to compare Indigenous and industrial mariculture owing to their similarities in technologies and methods; these similarities among mariculture approaches were better pairings than industrial fishing and Indigenous mariculture, for example.

Management Practices Within Mariculture Systems

To assess the diversity of management practices within the Indigenous mariculture innovations, we pooled management categories using Indigenous marine resource management literature from the Northwest Coast of North America (Lepofsky et al., 2017; Lepofsky & Caldwell, 2013b; Mathews & Turner, 2017). We chose this body of literature because these systems have been extensively studied and include multiple lines of evidence (ethnographic, archaeological, and paleo-ecological). We created a table of management strategies and asked experts from the Pacific Sea Garden Collective to fill in “yes”, “no”, or “no information” regarding the strategies used in each mariculture technology (Table B1).

To explore the types of innovations within our dataset, we further classified each innovation as “pond”, “garden”, or “fish traps/weirs”. A pond refers to the construction of pools and channels to breed and grow different species for later harvest (Costa-Pierce, 1987). We defined fish traps or weirs as structures built into rivers or intertidal environments to block, direct, catch, or strand fish (Moss, 2012). Gardens are intertidal areas constructed or altered to extend and enhance available habitat, often with joined tending and cultivation practices (Deur et al., 2015).

Publication Bias

Publication bias refers to research in the published literature not representing the population of completed studies. Some mariculture innovations are more thoroughly documented in published literature than others. To ensure that our study did not measure higher species richness in mariculture innovations with published literature, we quantified the relative amount of research effort for each mariculture innovation using the number of papers published for each unique innovation. We included “number of published papers” as a covariate in our model determining the relative effect of latitude and sea surface temperature on species richness.

Biases, Assumptions, and Limitations

Data Sources

Additional bias in our data sources exists. We used available published literature written in English, often by western ethnographers, which may exclude the lived knowledge of current and past stewards. For transparency we recorded the types of data sources we drew upon and acknowledge that our data provide a snapshot of and likely an underestimation of the species harvested and of the techniques used in mariculture innovations.

Management Systems

We acknowledge that the classification of mariculture innovations as “gardens”, “ponds”, or “weirs”, or by different management strategies is a heuristic device created by non-Indigenous researchers. Innovations placed in one category could also be placed in another category, and these classifications may not encompass the full suite of their role in a broader management system. For example, holding ponds might also be built into fish traps to extend harvest periods (White, 2011). A distinguishing characteristic of Indigenous mariculture innovations is that they are part of an embedded system. Separating out these mariculture technologies risks overgeneralizing or overlooking their broader contexts and roles within an integrated social, cultural, spiritual, and government system.

Species Naming

Western scientific (Linnean) nomenclature is used here as one avenue to explore ecological diversity, and we acknowledge that that these innovations are places of biocultural diversity. There are many ways that taxonomy is reflected in Indigenous languages and practices. An Indigenous name for an animal, plant, or alga, might refer to a group of species in Linnean classification, or to a single life history stage (Gillman & Wright, 2020). In our case, we chose to use Western science nomenclature because it allowed us consistency in comparing species use across cultural contexts.

Statistical Analysis

To determine the relative effect of latitude, sea surface temperature and number of papers published on the number of species associated with Indigenous mariculture innovations, we fit generalized linear models with a negative binomial likelihood and log link function. We selected this likelihood distribution because it best described the discrete nature of our response variable and ensured that model residuals met assumptions of linearity, homoscedasticity, normality, and independence. Given that latitude co-varied with sea surface temperature, and some innovations did not have known sea surface temperature data, we chose latitude as a covariate in this model over sea surface temperature.

Using a model selection approach, we compared all candidate models including a null model using Δ AIC$_c$ values and weights (Burnham, 2015; Burnham & Anderson, 2002). Models were built in R using the MASS package and model comparison was conducted in the MuMin package in R (Bartoń, 2022; Ripley et al., 2023).

Results

Drivers of Species Richness

We found no evidence for an effect of latitude, sea surface temperature, or number of papers published on species richness across the mariculture innovations (Figure 2, Table 1). Model averaging results revealed relative variable of importance for latitude to be less than 0.4 (sum of Akaike weights = 0.28) (Burnham, 2015).

Analyses using sea surface temperature yielded similar results. Sea surface temperature was second to the null model, with Δ AIC_c of 2.04 (Figure C3, Table C3). Model averaging revealed relative variable of importance for SST to be less than 0.4 (sum of Akaike weights = 0.25) (Burnham, 2015).

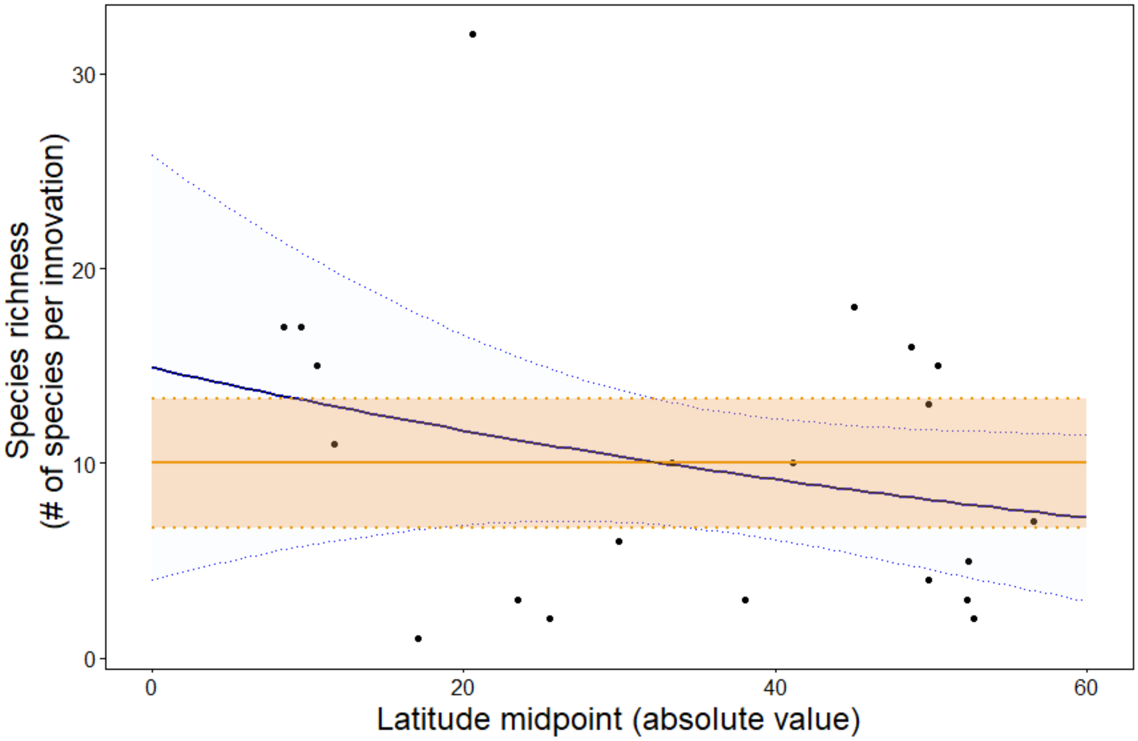


Figure 2 Diversity of species associated with Indigenous mariculture innovations. Null model (orange line) vs latitude model (blue line) with 95% confidence intervals (shaded areas). Black dots represent raw data points. The predictor line for latitude is almost fully within the confidence intervals of the null model.

Table 1 Strength of evidence for alternative models predicting the effect of latitude and number of papers published on species richness.

Model	N	LL	AIC_c	ΔAIC_c	R^2 adj	Weight
Response variable - Distribution						
Species Richness – Negative Binomial						
Null	21	-68.5	141.8	0.0	0.000	.52
Latitude Midpoint	21	-67.8	143.0	1.20	0.071	.28
Number of Papers Published	21	-68.5	144.4	2.67	0.004	.14
Number of Papers Published + Latitude Midpoint	21	-67.8	146.0	4.26	0.073	.06

Species Life History and Ecological Traits

Trophic Groups

We found that 44% of the species associated with Indigenous mariculture innovations across the Pacific were secondary consumers (n = 92, Figure 3A). Examples include sockeye salmon (*Onchorhynchus nerka*), Pacific herring (*Clupea pallasi*) and many species of Jack or Trevally (papi'o, amaka and ulua) from the Carangidae family. Primary consumers made up the next largest trophic group (n = 61, 29%) and include bivalve species like toheroa clams (*Paphies ventricosa*), butter clams (*Saxidomus gigantea*) and rabbitfish (garmiy, daruy, limreq, biywod) from the Siganidae family. Tertiary consumers like coho salmon (*Oncorhynchus kisutch*) make up the third largest group (n = 40, 19%). Very few species were primary producers (n = 17, 8%) (N=210 species). Examples of primary producers include feather boa kelp (*Egregia menziesii*) or springbank clover (*Trifolium wormskioldii*).

Migratory Strategies

We found that non-migratory species were the primary group of species used in these mariculture innovations (n = 138, 69%, Figure 3B). This number includes sedentary invertebrates such as butter clams (*Saxidomus gigantea*), and kelp species. We observed that the total number of migratory species is still relatively high (n = 61, 31%), and that there are diverse migratory strategies including species that are: anadromous (n = 24), oceanodromous (n = 18), amphidromous (n = 8), catadromous (n = 6), and potadromous (n = 5) (N = 199). Examples of anadromous species include pink salmon (*Oncorhynchus gorbuscha*) or green sturgeon (*Acipenser medirostris*). Oceanodromous species include honu (sea turtles, Hawaiian).

Population Doubling Time

Most species in these mariculture innovations have an average population doubling time of 1.4-4.4 years (n = 67, 64%, Figure 3C), such as róbalo (*Eleginops maclovinus*), and eulachon (*Thaleichthys pacificus*). Species like black rockfish (*Sebastes melanops*) with 4.5-14 years' doubling time were relatively less common (n = 21, 20%). Very few species with a population doubling time of less than 15 months were represented (n = 17, 16%) (N = 105) (Figure 3C). Examples include nehu (anchovy, *Encrasicholina purpurea*) or parrotfish (taroeq, choy or marib, *Chlorurus spilurus*). (N= 105 species).

Reproductive Guild

Most species used in these mariculture innovations belong to the non-guarder reproductive guild (n = 161, 81%), followed by bearers (n = 25, 12%) and guarders (n = 14, 7%) (N = 200) (Figure 3D). In the non-guarder guild, most species are broadcast spawners (87%), such as venus clams (*Venus antigua*) or California sea cucumbers (*Apostichopus californicus*). Within the guarder guild, 67% of species are nest spawners such as green sea turtles (*Chelonia mydas agassizi*), and 33% are substratum choosers. In the bearers' guild, most species are external bearers (80%) such as sea catfishes (Ariidae) followed by internal live bearers (20%) like sharks (Carcharhinidae, 17%). Out of N = 210 species, there were 10 species whose main reproductive guild (guarder, non-guarder, or bearer) were unknown or not applicable (pollinators).

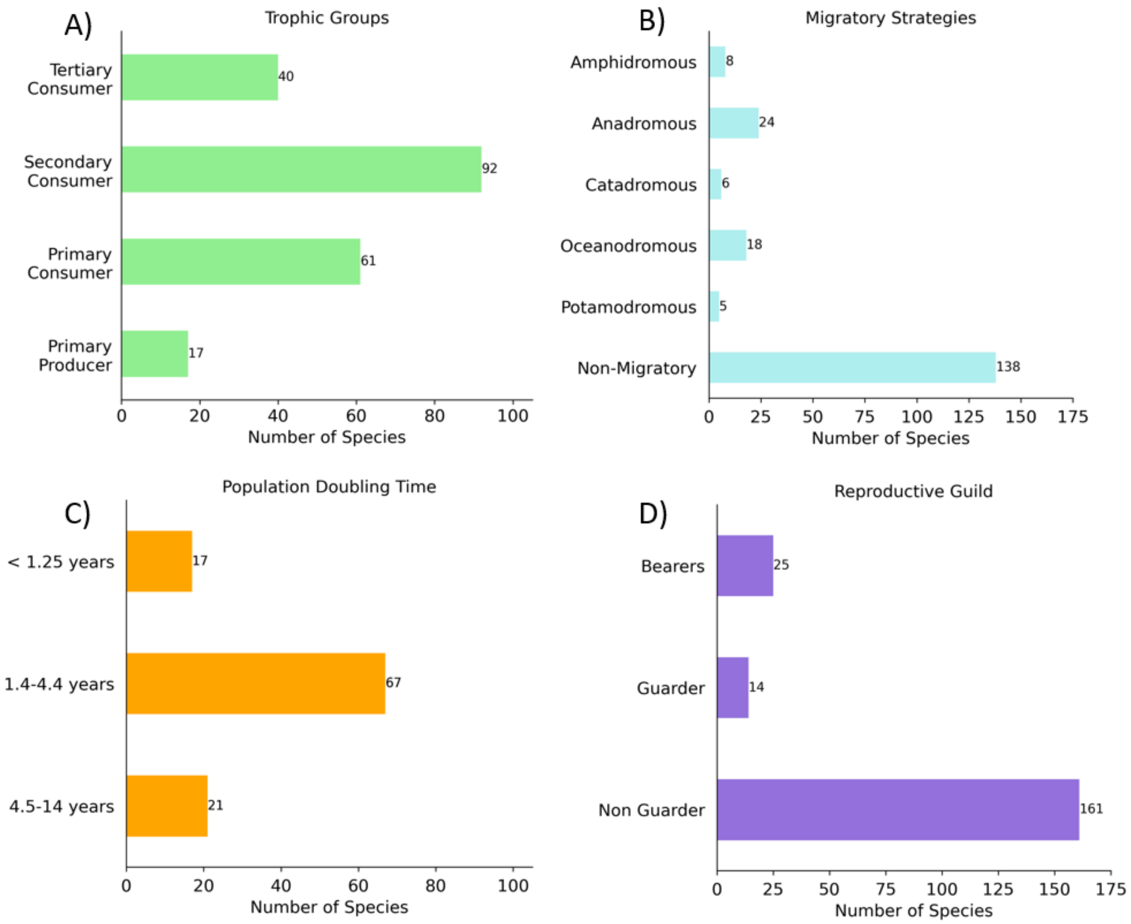


Figure 3 **The diversity of traits for species in Indigenous mariculture innovations, shown by different trophic groups (A), unique migratory strategies (B), variety of population doubling times (C), and reproductive guilds (D). Harvesting species from a variety of ecological niches means stewardship of many environments, which might be one way that diversity contributes to social-ecological resilience.**

Thermal Preferences

The preferred thermal range for fish species within the mariculture innovations varied from 0°C - 35°C (N = 123) (Figure 4). While latitude and sea surface temperature did not explain species richness (Figure 2), we did see that species with a diversity of temperature ranges were cultivated within these innovations.

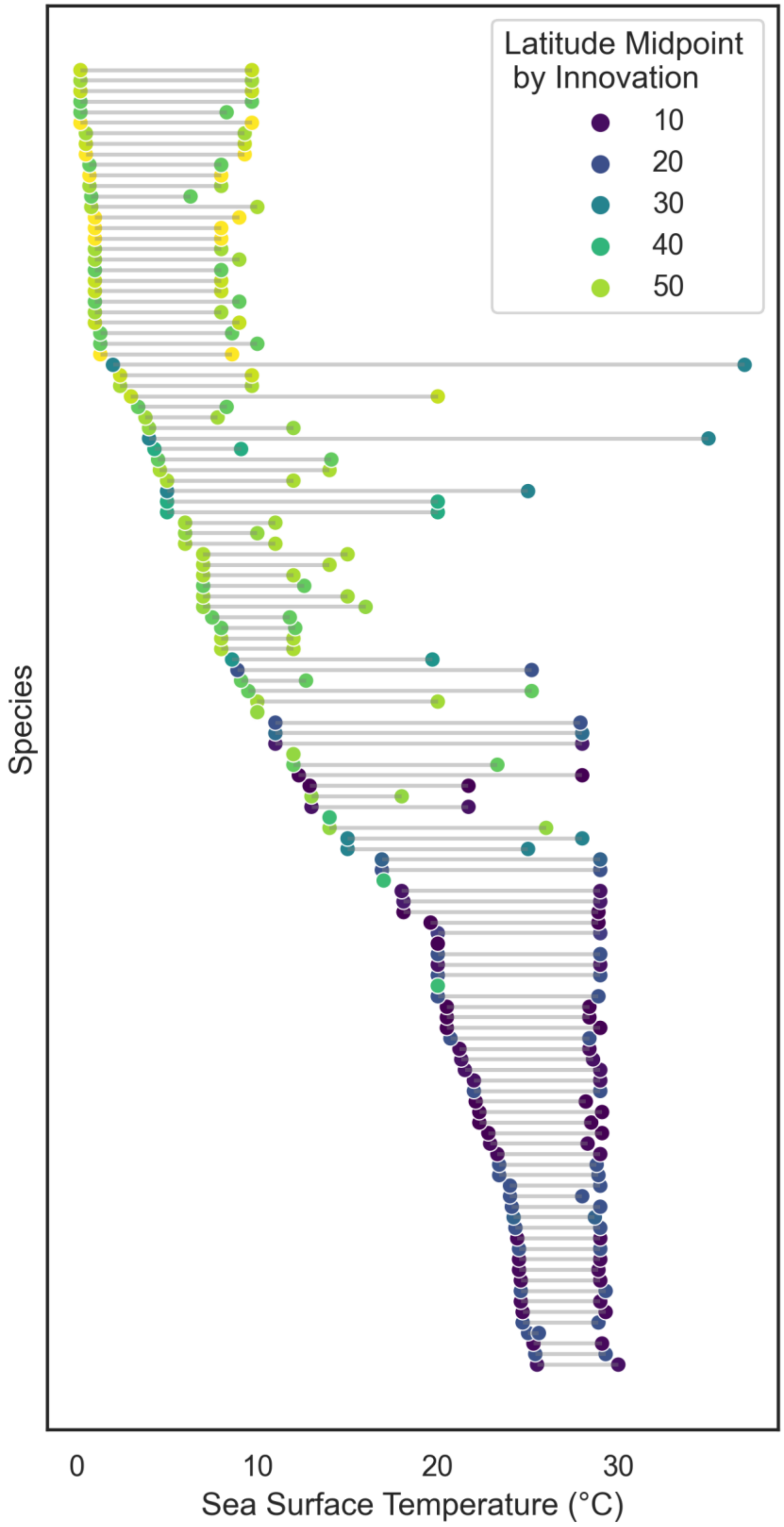
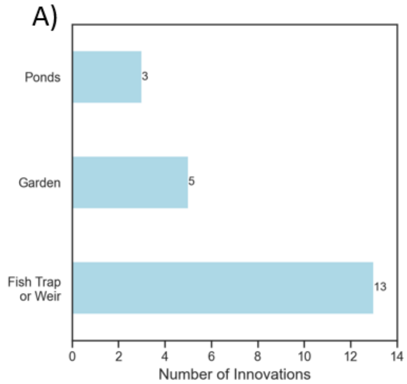


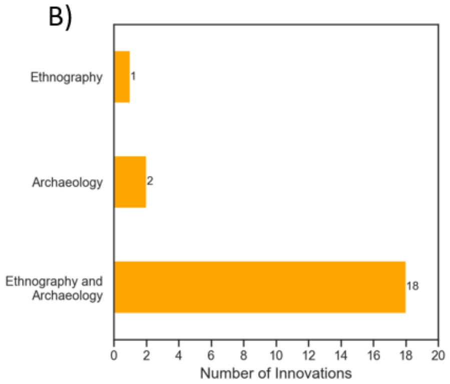
Figure 4 Thermal ranges for species within mariculture innovations. Each connected line is the temperature range for a species. N = 123

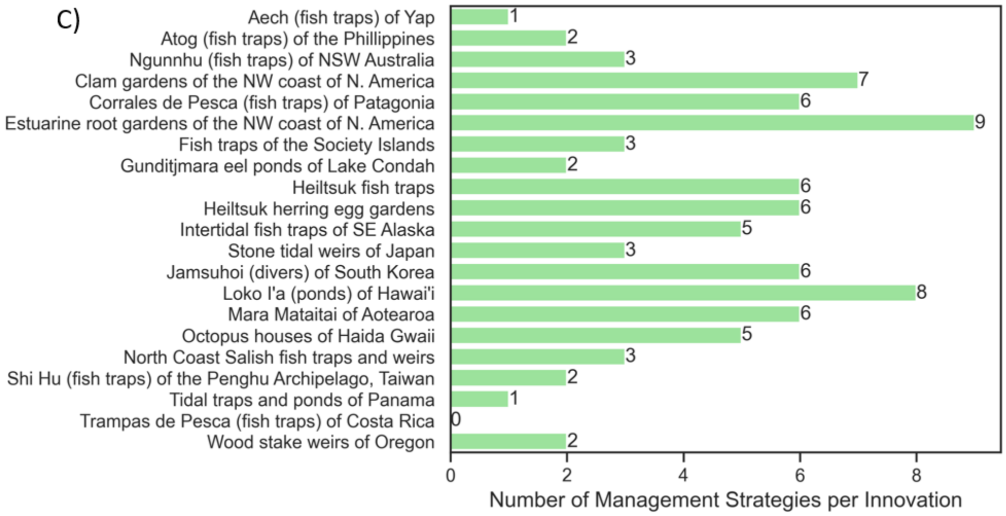
Management Systems

While there is a range in the number of management strategies employed in the mariculture innovations, the majority have at least 3 unique management strategies (mean = 4.0, +/- 3.0) (Figure 5C). Most of these innovations were classified as fish traps or weirs (13), followed by gardens (5) and ponds (3) (Figure 3A). We found that most of our data sources came from both ethnographic and archaeological data (18), and relatively fewer innovations were informed by archaeological data (2) or ethnographic data (1) (Figure 5B, Table D1).

We found that there was a variety of management strategies used in these innovations (Figure 3D). The top two categories were tenure systems and selective harvest (16). Documented evidence of tenure systems existed for 16 of the 21 mariculture innovations, and there was a lack of evidence for the remaining 6. The next most used practices in these innovations were clearing or cleaning of habitat (13) and terracing or ditching (13).


A)
Ponds
3
Garden
5
Fish Trap or Weir
13
0
2
4
6
8
10
12
14
Number of Innovations


B)
Ethnography
1
Archaeology
2
Ethnography and Archaeology
18
0
2
4
6
8
10
12
14
16
18
20
Number of Innovations


C)
Aech (fish traps) of Yap
1
Atog (fish traps) of the Phillippines
2
Ngunnhu (fish traps) of NSW Australia
3
Clam gardens of the NW coast of N. America
7
Corrales de Pesca (fish traps) of Patagonia
6
Estuarine root gardens of the NW coast of N. America
9
Fish traps of the Society Islands
3
Gunditjmara eel ponds of Lake Condah
2
Heiltsuk fish traps
6
Heiltsuk herring egg gardens
6
Intertidal fish traps of SE Alaska
5
Stone tidal weirs of Japan
3
Jamsuhoi (divers) of South Korea
6
Loko I'a (ponds) of Hawai'i
8
Mara Mataitai of Aotearoa
6
Octopus houses of Haida Gwaii
5
North Coast Salish fish traps and weirs
3
Shi Hu (fish traps) of the Penghu Archipelago, Taiwan
2
Tidal traps and ponds of Panama
1
Trampas de Pesca (fish traps) of Costa Rica
0
Wood stake weirs of Oregon
2
0
2
4
6
8
Number of Management Strategies per Innovation

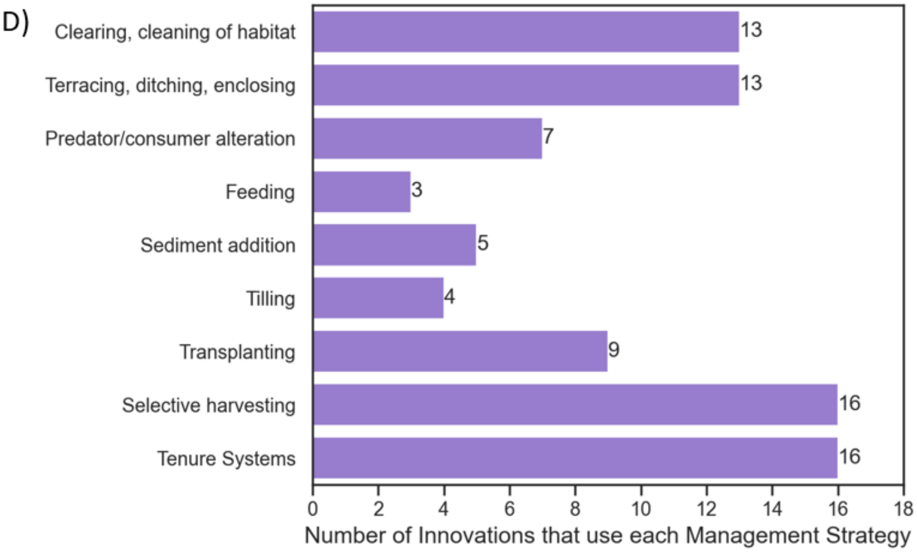

D)
Clearing, cleaning of habitat
13
Terracing, ditching, enclosing
13
Predator/consumer alteration
7
Feeding
3
Sediment addition
5
Tilling
4
Transplanting
9
Selective harvesting
16
Tenure Systems
16
0
2
4
6
8
10
12
14
16
18
Number of Innovations that use each Management Strategy

Figure 5 **Management practices of Indigenous mariculture technologies. (A) Number of different types of innovations in this study, (B) Types of data used to collect management data, (C) Number of management strategies by innovation (mean = 4.0, standard deviation +/- 3.0) and (D), Number of innovations that employ each management strategy, as sourced from experts in the Pacific Sea Garden Collective.**

Industrial Mariculture

Total Species Richness

From 1990- 2009, across the Pacific Ocean, the total species richness number for industrial mariculture was 113, compared to 210 for Indigenous mariculture (Figure 6A). This is 46% more total species richness for mariculture innovations compared to industrial mariculture.

Trophic Groups

Most species from industrial mariculture since 1980 are primary consumers (n = 50, 45%, Figure 6B), such as the Pacific cupped oyster (*Crassostrea gigas*) or White leg shrimp (*Litopenaeus vannamei*). Next are secondary consumers (n = 41, 37%), such as White spotted grouper (*Epinephelus coeruleopunctatus*) followed by tertiary consumers (n = 21, 19%) like Atlantic salmon (*Salmo salar*) (N = 113 species). This is a different order than the trophic groups used in Indigenous mariculture, which were: secondary consumers (44%), followed by primary consumers (29%), tertiary consumers (19%), and primary producers (8%).

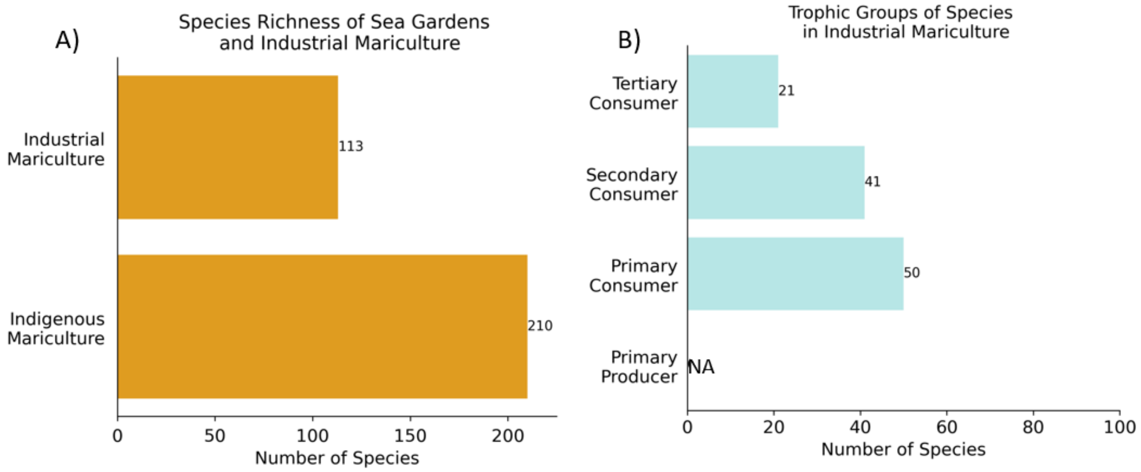


Figure 6 **A) Species richness for mariculture innovations and industrial mariculture, and B) the trophic groups of species within industrial mariculture. Industrial mariculture data does not include primary producers like kelp or seaweed. Data retrieved from the Sea Around Us from 1980-2009.**

Discussion

Our research provides additional evidence of the importance of biodiversity in promoting resilient social-ecological systems and the importance of recognizing diverse cultural practices influencing these systems. Globally, Indigenous mariculture systems support a diversity of species with a range of life history and reproductive traits (Figure 3), while commercial industrial mariculture systems rely on fewer species and are thus less biologically diverse (Figure 6). We found that latitude does not drive the diversity of species stewarded via Indigenous mariculture, suggesting that a biodiverse food system is not incidental, but is the result of intentional and transformative stewardship (Figure 2). This stewardship is rooted in a diversity of management practices informed by environmental observations and experimentation and honed over many generations (Figure 5) and during changes in environmental conditions. Indigenous mariculture systems are embedded in dynamic place-based societies and intertwined with diverse spiritual, cultural, and government systems and many practices that drive their resilience and persistence. A compelling attribute of these social-ecological systems is their relationship to a diversity of species.

Diversity as an Attribute of Indigenous Mariculture

Globally, Indigenous management systems support biodiversity (Brondízio et al., 2021; Fa et al., 2020). Across terrestrial landscapes, Indigenous-led management helps to protect biodiversity and key ecosystem functions (Estrada et al., 2022; Fa et al., 2020; Garnett et al., 2018; Schuster et al., 2019). Our results lend support for this in coastal environments, as we found that across the Pacific Ocean, using mariculture systems, Indigenous Peoples cultivate species with a diversity of trophic levels, reproductive guilds, migratory strategies, population doubling times, and temperature ranges.

At first glance, our findings about the diversity of trophic levels stewarded within these innovations might seem surprising, as they contradict our original hypothesis. We predicted that there would be a preference towards species that require less energy to maintain, such as those in lower trophic levels. Instead, we found that secondary consumers made up a relatively higher amount of the species stewarded, and that the percentages for primary, secondary, and tertiary consumers (44%, 29%, and 19%, respectively) were not radically uneven. This evenness across trophic groups suggests niche redundancy, which allows adaptation under change and a continuity of species-specific ecosystem functions. Cultivating a diversity of species in similar trophic levels may increase the stability of the food web, as stability is highest in systems with multiple species harvested in each trophic level (Gross et al., 2009). In contrast, large levels of harvest at a single trophic level can have reverberating consequences through the food web (Smith et al., 2011). Furthermore, cultivating a diversity of species in similar trophic niches might also allow the substitution when environmental or social disturbances might reduce the availability of one of these species. It was not surprising to see that relatively more of the species cultivated in these mariculture innovations are secondary consumers, as there are many instances of Indigenous People selectively altering the local trophic environment to enhance the productivity of certain species (Table B2). For example, in the northeast Pacific Ocean, sea otter populations were held below carrying capacity for millennia, in order to increase the availability and size of California mussels for human consumption (Slade et al., 2022). Building sustainability and resilience in marine food systems means increasing adaptive capacity, through diverse harvest portfolios with multiple species in each trophic group.

We found that 31% of the species stewarded in these Indigenous mariculture systems were migratory, and 69% of the species were non-migratory. This seems like a relatively high proportion of migratory species, which require complex management, as they use multiple habitats and require specific environmental conditions at each life history stage. However, Indigenous stewardship is rooted in values of reciprocity, respect, and fundamental sustainability practices, and many Indigenous fisheries have continually harvested migratory species without the overharvest and population collapses often seen in industrial fishing (Atlas et al., 2021). Indigenous fisheries have been able to harvest migratory species at high intensities, such as salmon (Turner & Mackie, 2006). The harvest of species with both migratory and non-migratory strategies might confer more resiliency to the system than the harvest of either alone. For example, migratory species spend their growth period in environments external to the nearshore system where these innovations are located. Their return to their natal environment results in an allochthonous transport of biomass and a provision of nutrients and biomass to the nearshore food system, without as much direct ecological competition for resources with local species. Additionally, because migratory and non-migratory species occupy different habitats for much of their lives, they are exposed to different disturbances and experience population fluctuations at a different cadence. These differences in exposure to different disturbances, as well as in the timing of migration patterns relative to local species' growth and reproduction patterns allows for year-round access to food. Our research suggests that promoting redundancy and diversity through the cultivation of both migratory and non-migratory species confers diversity and resiliency to local food systems.

Furthermore, we found that multiple species were harvested across the life history categories in this study. We chose to examine migratory strategies, reproductive guilds, trophic levels, and population parameters because each of these categories represents a diversity of niches from different ecological perspectives. The presence of multiple species in each of these categories within Indigenous mariculture demonstrates functional redundancy. Across ecosystems, functional redundancy allows a mechanism for adaptation and can confer community stability during disturbance, allowing for the continued provision of key ecosystem functions (Biggs et al., 2020; van der Plas, 2019). Several mariculture innovations in this study managed or altered ecosystem functions. For example, 5 out of 21 of the innovations added sediment, nutrients, or fertilizer to the system, and 7 out of 21 added species to provide predation or herbivory functions as needed (Figure 5D). In Hawaiian mariculture systems, some species were cultivated in the Loko i'a (ponds) to enhance ecosystem functions for other species: such as intentional addition of species that filter water, reduce algal growth, or add fertilizer, like honu (sea turtles) (Keala et al., 2007). A diversity of niches, functional groups, and ecological groupings confers social-ecological resiliency in mariculture systems.

People Enhanced and Maintained Diversity

We did not see evidence for an effect of latitude on the diversity of species in Indigenous mariculture systems, and the results follow our hypothesis. Our null result suggests that in these systems, the natural environment alone is not the driver of the species that are being cultivated in these mariculture innovations. A diverse food system is not incidental, and the stewards of these systems were and are active contributors and co-participants in the environmental system, enacting intensification techniques to enhance biodiversity and productivity. This perspective re-affirms the deep reciprocal relationship with and stewardship of place that is present in Indigenous stewardship.

Management Systems

As expected, we see that Indigenous mariculture systems employ a diverse range of practices that contribute to a resilient food system. We found that most mariculture innovations are associated with at least 3 management strategies, with selective harvest being the most common. Selective harvest refers to only taking a portion of a plant, some individuals from a population, or allowing individuals at a specific size or life history stage to return to spawn (Lepofsky et al., 2017; Lepofsky & Caldwell, 2013b; Mathews & Turner, 2017). Many Indigenous stewardship practices embody principles of reciprocity, respect, and conservation, so it was not unexpected to find that selective harvest was a common practice (Lyver et al., 2017; Oliveira, 2014; White (Xanius), 2006). Only 16 of the 21 innovations had documented evidence for tenure systems, however, it is likely that all these systems were associated with some form of tenure, for which evidence has yet to be found.

Most of our data sources came from both ethnography and archaeology, while fewer innovations were informed solely by archaeological data or ethnographic data. Source diversity in studying these systems is important, as data sources shape what can be inferred about management and can contribute a diversity of evidence about people's connection with and enhancement of the local ecosystem. Source diversity does not compensate for researcher biases, but joining multiple lines of evidence together can create a more complete picture of how landscapes were managed to enhance diversity, and help to reinvigorate past examples of resilient management practices (Armstrong & Veteto, 2015; Lepofsky et al., 2017).

Industrial and Indigenous Mariculture

We found 46% more species diversity in Indigenous mariculture systems compared to that of industrial mariculture, indicating that Indigenous mariculture builds social-ecological resilience in part by cultivating a diversity of species. Literature in industrial aquaculture supports our result, and higher species diversity can be associated with higher rates of production and resilience (Dumont et al., 2020; Metian et al., 2020; Oboh, 2022; Thomas et al., 2021). A reliance on a diversity of local species reduces the ecosystem consequences from the introduction of non-native species, but there are other well-documented negative ecological outcomes from industrial mariculture (De Silva et al., 2009; Herbeck et al., 2013; Quiñones et al., 2019). Over the last 50 years, industrial mariculture has dramatically increased in production, but is trending towards less species diversity, in addition to a variety of harmful ecological outcomes (Campbell & Pauly, 2013; Troell et al., 2014). In contrast, Indigenous systems have harvested over several thousand years without the extraordinary environmental consequences often seen in industrial mariculture (Atlas et al., 2021a; Reeder-Myers et al., 2022). Promoting social-ecological resilience in mariculture means fostering biodiversity and redundancy, as well as centering the knowledge and wisdom of Indigenous People.

Future Management and Revitalization

The deep time scale and broad spatial dimensions of our data demonstrate that Indigenous systems were managed to include a wide variety of diverse species with redundant ecological roles. We see evidence for diverse harvest portfolios, and species with complex and spatially broad ecosystem niches. Indigenous management systems are embedded within social, cultural, and spiritual frameworks that drive the social-ecological resilience of these systems. Globally, the revitalization of Indigenous management confers social-ecological resilience (Brondízio et al., 2021; Reyes-García et al., 2019). For example, across multiple continents, land managed by Indigenous communities has higher rates of vertebrate biodiversity compared to conventional protected areas (Schuster et al., 2019). Indigenous Peoples have broad tenure across ecologically valuable land, and Indigenous knowledge systems hold critical pieces to preserving global biodiversity. (Garnett et al., 2018; O'Bryan et al., 2021). Building resilient and biodiverse social-ecological systems must promote the revitalization of Indigenous systems of management and center the perspective and leadership of Indigenous stewards.

References

Armstrong, C. G., Earnshaw, J., & McAlvay, A. C. (2022). Coupled archaeological and ecological analyses reveal ancient cultivation and land use in Nuchatlaht (Nuu-chah-nulth) territories, Pacific Northwest. *Journal of Archaeological Science*, *143*, 105611. https://doi.org/10.1016/j.jas.2022.105611

Armstrong, C. G., Miller, J. E. D., McAlvay, A. C., Ritchie, P. M., & Lepofsky, D. (2021). Historical Indigenous Land-Use Explains Plant Functional Trait Diversity. *Ecology and Society*, *26*(2), art6. https://doi.org/10.5751/ES-12322-260206

Armstrong, C., & Veteto, J. (2015). Historical Ecology and Ethnobiology: Applied Research for Environmental Conservation and Social Justice. *Ethnobiology Letters*, *6*. https://doi.org/10.14237/ebl.6.1.2015.313

Atlas, W. I., Ban, N. C., Moore, J. W., Tuohy, A. M., Greening, S., Reid, A. J., Morven, N., White, E., Housty, W. G., Housty, J. A., Service, C. N., Greba, L., Harrison, S., Sharpe, C., Butts, K. I. R., Shepert, W. M., Sweeney-Bergen, E., Macintyre, D., Sloat, M. R., & Connors, K. (2021a). Indigenous Systems of Management for Culturally and Ecologically Resilient Pacific Salmon (Oncorhynchus spp.) Fisheries. *BioScience*, *71*(2), 186–204. https://doi.org/10.1093/biosci/biaa144

Atlas, W. I., Ban, N. C., Moore, J. W., Tuohy, A. M., Greening, S., Reid, A. J., Morven, N., White, E., Housty, W. G., Housty, J. A., Service, C. N., Greba, L., Harrison, S., Sharpe, C., Butts, K. I. R., Shepert, W. M., Sweeney-Bergen, E., Macintyre, D., Sloat, M. R., & Connors, K. (2021b). Indigenous Systems of Management for Culturally and Ecologically Resilient Pacific Salmon (*Oncorhynchus* spp.) Fisheries. *BioScience*, *71*(2), 186–204. https://doi.org/10.1093/biosci/biaa144

Balée, W., Swanson, T., Zurita-Benavides, M. G., & Ruiz Macedo, J. C. (2023). Evidence for Landscape Transformation of Ridgetop Forests in Amazonian Ecuador. *Latin American Antiquity*, 1–15. https://doi.org/10.1017/laq.2022.94

Bartoń, K. (2022). *MuMIn: Multi-Model Inference* (1.47.1). https://CRAN.R-project.org/package=MuMIn

Berkes, F. (2007). Understanding uncertainty and reducing vulnerability: Lessons from resilience thinking. *Natural Hazards*, *41*(2), 283–295. https://doi.org/10.1007/s11069-006-9036-7

Berkes, F., Colding, J., & Folke, C. (2000). Rediscovery of Traditional Ecological Knowledge as Adaptive Management. *Ecological Applications*, *10*(5), 1251–1262. https://doi.org/10.2307/2641280

Biggs, C. R., Yeager, L. A., Bolser, D. G., Bonsell, C., Dichiera, A. M., Hou, Z., Keyser, S. R., Khursigara, A. J., Lu, K., Muth, A. F., Negrete Jr., B., & Erisman, B. E. (2020). Does functional redundancy affect ecological stability and resilience? A review and meta-analysis. *Ecosphere*, *11*(7), e03184. https://doi.org/10.1002/ecs2.3184

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C. (2012). Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, *37*(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Biggs, R., Schlüter, M., & Schoon, M. L. (Eds.). (2015). *Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems*. Cambridge University Press. https://doi.org/10.1017/CBO9781316014240

Bird, R. B., Tayor, N., Codding, B. F., & Bird, D. W. (2013). Niche construction and Dreaming logic: Aboriginal patch mosaic burning and varanid lizards (Varanus gouldii) in Australia. *Proceedings of the Royal Society B: Biological Sciences*, *280*(1772), 20132297. https://doi.org/10.1098/rspb.2013.2297

Bliege Bird, R., & Nimmo, D. (2018). Restore the lost ecological functions of people. *Nature Ecology & Evolution*, *2*. https://doi.org/10.1038/s41559-018-0576-5

Boivin, N. L., Zeder, M. A., Fuller, D. Q., Crowther, A., Larson, G., Erlandson, J. M., Denham, T., & Petraglia, M. D. (2016). Ecological consequences of human niche construction: Examining long-term anthropogenic shaping of global species distributions. *Proceedings of the National Academy of Sciences*, *113*(23), 6388–6396. https://doi.org/10.1073/pnas.1525200113

Brondízio, E. S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M. F., Galvin, K., Reyes-García, V., McElwee, P., Molnár, Z., Samakov, A., & Shrestha, U. B. (2021). Locally Based, Regionally Manifested, and Globally Relevant: Indigenous and Local Knowledge, Values, and Practices for Nature. *Annual Review of Environment and Resources*, *46*(1), 481–509. https://doi.org/10.1146/annurev-environ-012220-012127

Burnham, K. (2015). *Multimodel Inference: Understanding AIC relative variable importance values*. https://www.semanticscholar.org/paper/Multimodel-Inference%3A-Understanding-AIC-relative-Burnham/5a516fbc642c4e2d70986d56e8dcd185b16dc49e

Burnham, K. P., & Anderson, D. R. (Eds.). (2002). Formal Inference From More Than One Model: Multimodel Inference (MMI). In *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach* (pp. 149–205). Springer. https://doi.org/10.1007/978-0-387-22456-5_4

Byram, R. S. (2002). *Brush fences and basket traps: The archaeology and ethnohistory of tidewater weir fishing on the Oregon coast* [Ph.D., University of Oregon]. http://www.proquest.com/docview/251827722/abstract/69B445FAF76B4277PQ/1

Campbell, B., & Pauly, D. (2013). Mariculture: A global analysis of production trends since 1950. *Marine Policy*, *39*, 94–100. https://doi.org/10.1016/j.marpol.2012.10.009

Chapin, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., Olsson, P., Smith, D. M. S., Walker, B., Young, O. R., Berkes, F., Biggs, R., Grove, J. M., Naylor, R. L., Pinkerton, E., Steffen, W., & Swanson, F. J. (2010). Ecosystem stewardship: Sustainability strategies for a rapidly changing planet. *Trends in Ecology & Evolution*, *25*(4), 241–249. https://doi.org/10.1016/j.tree.2009.10.008

Cline, T. J., Schindler, D. E., & Hilborn, R. (2017). Fisheries portfolio diversification and turnover buffer Alaskan fishing communities from abrupt resource and market changes. *Nature Communications*, *8*(1), Article 1. https://doi.org/10.1038/ncomms14042

Cook-Patton, S. C., Weller, D., Rick, T. C., & Parker, J. D. (2014). Ancient experiments: Forest biodiversity and soil nutrients enhanced by Native American middens. *Landscape Ecology*, *29*(6), 979–987. https://doi.org/10.1007/s10980-014-0033-z

Costa-Pierce, B. A. (1987). Aquaculture in Ancient Hawaii. *BioScience*, *37*(5), 320–331. https://doi.org/10.2307/1310688

De Silva, S. S., Nguyen, T. T. T., Turchini, G. M., Amarasinghe, U. S., & Abery, N. W. (2009). Alien Species in Aquaculture and Biodiversity: A Paradox in Food Production. *Ambio*, *38*(1), 24–28.

Deur, D., Dick, A., Recalma-Clutesi, K., & Turner, N. J. (2015). Kwakwaka'wakw "Clam Gardens": Motive and Agency in Traditional Northwest Coast Mariculture. *Human Ecology*, *43*(2), 201–212. https://doi.org/10.1007/s10745-015-9743-3

Dumont, B., Puillet, L., Martin, G., Savietto, D., Aubin, J., Ingrand, S., Niderkorn, V., Steinmetz, L., & Thomas, M. (2020). Incorporating Diversity Into Animal Production Systems Can Increase Their Performance and Strengthen Their Resilience. *Frontiers in Sustainable Food Systems*, *4*. https://www.frontiersin.org/articles/10.3389/fsufs.2020.00109

Estrada, A., Garber, P. A., Gouveia, S., Fernández-Llamazares, Á., Ascensão, F., Fuentes, A., Garnett, S. T., Shaffer, C., Bicca-Marques, J., Fa, J. E., Hockings, K., Shanee, S., Johnson, S., Shepard, G. H., Shanee, N., Golden, C. D., Cárdenas-Navarrete, A., Levey, D. R., Boonratana, R., Volampeno, S. (2022). Global importance of Indigenous Peoples, their lands, and knowledge systems for saving the world's primates from extinction. *Science Advances*, *8*(32), eabn2927. https://doi.org/10.1126/sciadv.abn2927

Fa, J. E., Watson, J. E., Leiper, I., Potapov, P., Evans, T. D., Burgess, N. D., Molnár, Z., Fernández-Llamazares, Á., Duncan, T., Wang, S., Austin, B. J., Jonas, H., Robinson, C. J., Malmer, P., Zander, K. K., Jackson, M. V., Ellis, E., Brondizio, E. S., & Garnett, S. T. (2020). Importance of Indigenous Peoples' lands for the conservation of Intact Forest Landscapes. *Frontiers in Ecology and the Environment*, *18*(3), 135–140. https://doi.org/10.1002/fee.2148

Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, *21*(3). http://www.jstor.org/stable/26269981

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S. R., Chapin, F. S., Seto, K. C., Weber, E. U., Crona, B. I., Daily, G. C., Dasgupta, P., Gaffney, O., Gordon, L. J., Hoff, H., Levin, S. A., … Walker, B. H. (2021). Our future in the Anthropocene biosphere. *Ambio*, *50*(4), 834–869. https://doi.org/10.1007/s13280-021-01544-8

Froese, R. and D. Pauly. Editors. (2023). FishBase. Version 2/2023. World Wide Web electronic publication. www.fishbase.org

Gagné, T. O., Reygondeau, G., Jenkins, C. N., Sexton, J. O., Bograd, S. J., Hazen, E. L., & Houtan, K. S. V. (2020). Towards a global understanding of the drivers of marine and terrestrial biodiversity. *PLOS ONE*, *15*(2), e0228065. https://doi.org/10.1371/journal.pone.0228065

Garnett, S. T., Burgess, N. D., Fa, J. E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C. J., Watson, J. E. M., Zander, K. K., Austin, B., Brondizio, E. S., Collier, N. F., Duncan, T., Ellis, E., Geyle, H., Jackson, M. V., Jonas, H., Malmer, P., McGowan, B., Sivongxay, A., & Leiper, I. (2018). A spatial overview of the global importance of Indigenous lands for conservation. *Nature Sustainability*, *1*(7), Article 7. https://doi.org/10.1038/s41893-018-0100-6

Gauvreau, A. M., Lepofsky, D., Rutherford, M., & Reid, M. (2017). “Everything revolves around the herring”: The Heiltsuk–herring relationship through time. *Ecology and Society*, *22*(2). http://www.jstor.org/stable/26270079

Gillman, L. N., & Wright, S. D. (2020). Restoring indigenous names in taxonomy. *Communications Biology*, *3*(1), 609. https://doi.org/10.1038/s42003-020-01344-y

Groesbeck, A. S., Rowell, K., Lepofsky, D., & Salomon, A. K. (2014). Ancient Clam Gardens Increased Shellfish Production: Adaptive Strategies from the Past Can Inform Food Security Today. *PLoS ONE*, *9*(3), e91235. https://doi.org/10.1371/journal.pone.0091235

Gross, T., Rudolf, L., Levin, S. A., & Dieckmann, U. (2009). Generalized Models Reveal Stabilizing Factors in Food Webs. *Science*, *325*(5941), 747–750. https://doi.org/10.1126/science.1173536

Herbeck, L. S., Unger, D., Wu, Y., & Jennerjahn, T. C. (2013). Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China. *Continental Shelf Research*, *57*, 92–104. https://doi.org/10.1016/j.csr.2012.05.006

Hillebrand, H. (2004). On the Generality of the Latitudinal Diversity Gradient. *The American Naturalist*, *163*(2), 192–211. https://doi.org/10.1086/381004

Hoffman, K. M., Davis, E. L., Wickham, S. B., Schang, K., Johnson, A., Larking, T., Lauriault, P. N., Quynh Le, N., Swerdfager, E., & Trant, A. J. (2021). Conservation of Earth's biodiversity is embedded in Indigenous fire stewardship. *Proceedings of the National Academy of Sciences*, *118*(32), e2105073118. https://doi.org/10.1073/pnas.2105073118

Holmes, K., Lepofsky, D., Smith, N. F., Crowell, T. D., & Salomon, A. K. (2022). Ancestral sea gardens supported human settlements for at least 3,800 years on the Northwest Coast of North America. *Frontiers in Earth Science*, *10*. https://www.frontiersin.org/articles/10.3389/feart.2022.988111

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., & Walker, B. (2013). Multiscale regime shifts and planetary boundaries. *Trends in Ecology & Evolution*, *28*(7), 389–395. https://doi.org/10.1016/j.tree.2013.05.019

Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., Bezemer, T. M., Bonin, C., Bruelheide, H., de Luca, E., Ebeling, A., Griffin, J. N., Guo, Q., Hautier, Y., Hector, A., Jentsch, A., Kreyling, J., Lanta, V., Manning, P., Eisenhauer, N. (2015). Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, *526*(7574), Article 7574. https://doi.org/10.1038/nature15374

Jackley, J., Gardner, L., Djunaedi, A. F., & Salomon, A. K. (2016). Ancient clam gardens, traditional management portfolios, and the resilience of coupled human-ocean systems. *Ecology and Society*, *21*(4), art20. https://doi.org/10.5751/ES-08747-210420

Keala, G., Hollyer, J., & Castro, L. (2007). *Loko I'A - A Manual on Hawaiian Fishpond Restoration and Management*. College of Tropical Agriculture and Human Resources, University of Hawaiʻi at Mānoa. https://www.ctahr.hawaii.edu/oc/freepubs/pdf/Loko%20I'a%20Full%20Publication.pdf

Kobluk, H. M., Gladstone, K., Reid, M., Brown, K., Krumhansl, K. A., & Salomon, A. K. (2021). Indigenous knowledge of key ecological processes confers resilience to a small-scale kelp fishery. *People and Nature*, *3*(3), 723–739. https://doi.org/10.1002/pan3.10211

Kotschy, K., Biggs, R., Daw, T., Folke, C., & West, P. C. (2015). Principle 1 –Maintain diversity and redundancy. In M. Schlüter, M. L. Schoon, & R. Biggs (Eds.), *Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems* (pp. 50–79). Cambridge University Press. https://doi.org/10.1017/CBO9781316014240.004

Lepofsky, D., Armstrong, C. G., Greening, S., Jackley, J., Carpenter, J., Guernsey, B., Mathews, D., & Turner, N. J. (2017). Historical Ecology of Cultural Keystone Places of the Northwest Coast. *American Anthropologist*, *119*(3), 448–463. https://doi.org/10.1111/aman.12893

Lepofsky, D., & Caldwell, M. (2013a). Indigenous marine resource management on the Northwest Coast of North America. *Ecological Processes*, *2*(1), 12. https://doi.org/10.1186/2192-1709-2-12

Lepofsky, D., & Caldwell, M. (2013b). Indigenous marine resource management on the Northwest Coast of North America. *Ecological Processes*, *2*(1), 12. https://doi.org/10.1186/2192-1709-2-12

Lepofsky, D., A.K. Salomon. In Press. Clam gardens across generations and places support social-ecological resilience to global change. In: Climatic and ecological change in the Americas: A perspective from historical ecology. Edited by J.A. Whitaker, C. G. Armstrong, and G. Odonne. Taylor and Francis Group. London. UK.

Lepofsky, D., Toniello, G., Earnshaw, J., Roberts, C., Wilson, L., Rowell, K., & Holmes, K. (2021). Ancient Anthropogenic Clam Gardens of the Northwest Coast Expand Clam Habitat. *Ecosystems*, *24*(2), 248–260. https://doi.org/10.1007/s10021-020-00515-6

Lertzman, K. (2009). The Paradigm of Management, Management Systems, and Resource Stewardship. *Journal of Ethnobiology*, *29*(2), 339–358. https://doi.org/10.2993/0278-0771-29.2.339

Levin, S. A. (1998). Ecosystems and the Biosphere as Complex Adaptive Systems. *Ecosystems*, *1*(5), 431–436. https://doi.org/10.1007/s100219900037

Liggs, R., Schlüter, M., & Schoon, M. L. (2015). An introduction to the resilience approach and principles to sustain ecosystem services in social–ecological systems. In M. Schlüter, M. L. Schoon, & R. Biggs (Eds.), *Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems* (pp. 1–31). Cambridge University Press. https://doi.org/10.1017/CBO9781316014240.002

Lyver, P. O., Timoti, P., Gormley, A. M., Jones, C. J., Richardson, S. J., Tahi, B. L., & Greenhalgh, S. (2017). Key Māori values strengthen the mapping of forest ecosystem services. *Ecosystem Services*, *27*, 92–102. https://doi.org/10.1016/j.ecoser.2017.08.009

Mahon, R., McConney, P., & Roy, R. N. (2008). Governing fisheries as complex adaptive systems. *Marine Policy*, *32*(1), 104–112. https://doi.org/10.1016/j.marpol.2007.04.011

Marshall, F., Reid, R. E. B., Goldstein, S., Storozum, M., Wreschnig, A., Hu, L., Kiura, P., Shahack-Gross, R., & Ambrose, S. H. (2018). Ancient herders enriched and restructured African grasslands. *Nature*, *561*(7723), Article 7723. https://doi.org/10.1038/s41586-018-0456-9

Mathews, D., & Turner, N. (2017). *Ocean Cultures: Northwest Coast Ecosystems and Indigenous Management Systems* (pp. 169–199).

Merchant, C. J., Embury, O., Bulgin, C. E., Block, T., Corlett, G. K., Fiedler, E., Good, S. A., Mittaz, J., Rayner, N. A., Berry, D., Eastwood, S., Taylor, M., Tsushima, Y., Waterfall, A., Wilson, R., & Donlon, C. (2019). Satellite-based time-series of sea-surface temperature since 1981 for climate applications. *Scientific Data*, *6*(1), Article 1. https://doi.org/10.1038/s41597-019-0236-x

Metian, M., Troell, M., Christensen, V., Steenbeek, J., & Pouil, S. (2020). Mapping diversity of species in global aquaculture. *Reviews in Aquaculture*, *12*(2), 1090–1100. https://doi.org/10.1111/raq.12374

Moss, M. L. (2012). *Fishing Traps and Weirs on the Northwest Coast of North America New Approaches and New Insights*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199573493.013.0020

Nyström, M., Jouffray, J.-B., Norström, A. V., Crona, B., Søgaard Jørgensen, P., Carpenter, S. R., Bodin, Ö., Galaz, V., & Folke, C. (2019). Anatomy and resilience of the global production ecosystem. *Nature*, *575*(7781), Article 7781. https://doi.org/10.1038/s41586-019-1712-3

Oboh, A. (2022). Diversification of farmed fish species: A means to increase aquaculture production in Nigeria. *Reviews in Aquaculture*, *14*(4), 2089–2098. https://doi.org/10.1111/raq.12690

O’Bryan, C. J., Garnett, S. T., Fa, J. E., Leiper, I., Rehbein, J. A., Fernández-Llamazares, Á., Jackson, M. V., Jonas, H. D., Brondizio, E. S., Burgess, N. D., Robinson, C. J., Zander, K. K., Molnár, Z., Venter, O., & Watson, J. E. M. (2021). The importance of Indigenous Peoples’ lands for the conservation of terrestrial mammals. *Conservation Biology: The Journal of the Society for Conservation Biology*, *35*(3), 1002–1008. https://doi.org/10.1111/cobi.13620

Oliveira, K.-A. R. K. N. (2014). *Ancestral Places: Understanding Kanaka Geographies*. Oregon State University Press. https://muse.jhu.edu/pub/205/monograph/book/36681

Pacific Sea Garden Collective. (2022). *Sea Gardens Across the Pacific: Reawakening Ancestral Mariculture Innovations. Version 1.* Washington Sea Grant at the University of Washington. https://doi.org/10.6069/ZJB9-CG30

Palace, M. W., McMichael, C. N. H., Braswell, B. H., Hagen, S. C., Bush, M. B., Neves, E., Tamanaha, E., Herrick, C., & Frolking, S. (2017). Ancient Amazonian populations left lasting impacts on forest structure. *Ecosphere*, *8*(12), e02035. https://doi.org/10.1002/ecs2.2035

Palomares, M.L.D. and D. Pauly. Editors. (2022). SeaLifeBase. Version 12/2022. World Wide Web electronic publication. www.sealifebase.org

Pauly D., Zeller D., Palomares M.L.D. Editors. (2020). Sea Around Us Concepts, Design and Data seaaroundus.org.

Poe, M. R., Donatuto, J., & Satterfield, T. (2016). “Sense of Place”: Human Wellbeing Considerations for Ecological Restoration in Puget Sound. *Coastal Management*, *44*(5), 409–426. https://doi.org/10.1080/08920753.2016.1208037

Quiñones, R. A., Fuentes, M., Montes, R. M., Soto, D., & León-Muñoz, J. (2019). Environmental issues in Chilean salmon farming: A review. *Reviews in Aquaculture*, *11*(2), 375–402. https://doi.org/10.1111/raq.12337

Reeder-Myers, L., Braje, T. J., Hofman, C. A., Elliott Smith, E. A., Garland, C. J., Grone, M., Hadden, C. S., Hatch, M., Hunt, T., Kelley, A., LeFebvre, M. J., Lockman, M., McKechnie, I., McNiven, I. J., Newsom, B., Pluckhahn, T., Sanchez, G., Schwadron, M., Smith, K. Y., … Rick, T. C. (2022). Indigenous oyster fisheries persisted for millennia and should inform future management. *Nature Communications*, *13*(1), Article 1. https://doi.org/10.1038/s41467-022-29818-z

Reyes-García, V., Fernández-Llamazares, Á., McElwee, P., Molnár, Z., Öllerer, K., Wilson, S. J., & Brondizio, E. S. (2019). The contributions of Indigenous Peoples and local communities to ecological restoration. *Restoration Ecology*, *27*(1), 3–8. https://doi.org/10.1111/rec.12894

Venables WN, Ripley BD (2002). *Modern Applied Statistics with S*, Fourth edition. Springer, New York. https://www.stats.ox.ac.uk/pub/MASS4/

Schuster, R., Germain, R. R., Bennett, J. R., Reo, N. J., & Arcese, P. (2019). Vertebrate biodiversity on indigenous-managed lands in Australia, Brazil, and Canada equals that in protected areas. *Environmental Science & Policy*, *101*, 1–6. https://doi.org/10.1016/j.envsci.2019.07.002

Slade, E., McKechnie, I., & Salomon, A. K. (2022). Archaeological and Contemporary Evidence Indicates Low Sea Otter Prevalence on the Pacific Northwest Coast During the Late Holocene. *Ecosystems*, *25*(3), 548–566. https://doi.org/10.1007/s10021-021-00671-3

Smith, A. D. M., Brown, C. J., Bulman, C. M., Fulton, E. A., Johnson, P., Kaplan, I. C., Lozano-Montes, H., Mackinson, S., Marzloff, M., Shannon, L. J., Shin, Y.-J., & Tam, J. (2011). Impacts of Fishing Low–Trophic Level Species on Marine Ecosystems. *Science*, *333*(6046), 1147–1150. https://doi.org/10.1126/science.1209395

Thomas, M., Pasquet, A., Aubin, J., Nahon, S., & Lecocq, T. (2021). When more is more: Taking advantage of species diversity to move towards sustainable aquaculture. *Biological Reviews*, *96*(2), 767–784. https://doi.org/10.1111/brv.12677

Tittensor, D. P., Mora, C., Jetz, W., Lotze, H. K., Ricard, D., Berghe, E. V., & Worm, B. (2010). Global patterns and predictors of marine biodiversity across taxa. *Nature*, *466*(7310), 1098–1101. https://doi.org/10.1038/nature09329

Toniello, G., Lepofsky, D., Lertzman-Lepofsky, G., Salomon, A. K., & Rowell, K. (2019). 11,500 y of human–clam relationships provide long-term context for intertidal management in the Salish Sea, British Columbia. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(44), 22106–22114. https://doi.org/10.1073/pnas.1905921116

Troell, M., Naylor, R. L., Metian, M., Beveridge, M., Tyedmers, P. H., Folke, C., Arrow, K. J., Barrett, S., Crépin, A.-S., Ehrlich, P. R., Gren, Å., Kautsky, N., Levin, S. A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B. H., Xepapadeas, T., & de Zeeuw, A. (2014). Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences*, *111*(37), 13257–13263. https://doi.org/10.1073/pnas.1404067111

Turner, N. J., & Reid, A. J. (2022). “When the Wild Roses Bloom”: Indigenous Knowledge and Environmental Change in Northwestern North America. *GeoHealth*, *6*(11), e2022GH000612. https://doi.org/10.1029/2022GH000612

Turner, N., & Mackie, Q. (2006). *12,000+ years of change: Linking traditional and modern ecosystem science in the Pacific Northwest*. https://www.academia.edu/35424463/12_000_years_of_change_Linking_traditional_and_modern_ecosystem_science_in_the_Pacific_Northwest

Tveskov, M. A., & Erlandson, J. M. (2003). The Haynes Inlet weirs: Estuarine fishing and archaeological site visibility on the southern Cascadia coast. *Journal of Archaeological Science*, *30*(8), 1023–1035. https://doi.org/10.1016/S0305-4403(02)00291-1

van der Plas, F. (2019). Biodiversity and ecosystem functioning in naturally assembled communities. *Biological Reviews*, *94*(4), 1220–1245. https://doi.org/10.1111/brv.12499

Walker, B., & Salt, D. (2012). Preparing for Practice: The Essence of Resilience Thinking. In B. Walker & D. Salt (Eds.), *Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function* (pp. 1–25). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-231-0_1

White, (Xanius) E. (2011). Heiltsuk stone Fish Traps on the Central Coast of British Columbia. In: The Archaeology of North Pacific Fisheries, edited by Madonna L. Moss, and Aubrey Cannon, University of Alaska Press, 2011. ProQuest Ebook Central, http://ebookcentral.proquest.com/lib/sfu-ebooks/detail.action?docID=1820976

White (Xanius) E. (2006). *Heiltsuk stone fish traps: Products of my ancestors' labour* [Thesis, Department of Archaeology - Simon Fraser University]. http://summit.sfu.ca/item/4240

Williams, B. A., Venter, O., Allan, J. R., Atkinson, S. C., Rehbein, J. A., Ward, M., Di Marco, M., Grantham, H. S., Ervin, J., Goetz, S. J., Hansen, A. J., Jantz, P., Pillay, R., Rodríguez-Buriticá, S., Supples, C., Virnig, A. L. S., & Watson, J. E. M. (2020). Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems. *One Earth*, *3*(3), 371–382. https://doi.org/10.1016/j.oneear.2020.08.009

Winter, K., Lincoln, N., Berkes, F., Alegado, R., Kurashima, N., Frank, K., Pascua, P., Rii, Y., Reppun, F., Knapp, I., McClatchey, W., Ticktin, T., Smith, C., Franklin, E., Oleson, K., Price, M., McManus, M., Donahue, M., Rodgers, K., … Toonen, R. (2020). Ecomimicry in Indigenous resource management: Optimizing ecosystem services to achieve resource abundance, with examples from Hawai‘i. *Ecology and Society*, *25*(2). https://doi.org/10.5751/ES-11539-250226

Appendix A – Life History Trait Definitions

Table A.1. Definitions for life history traits from FishBase (Froese and Pauly, 2023).

Category	Definition	Subcategory	Definitions of Subcategory
Migratory Type	Relocation to from one body of water to another, usually for reproductive purposes. Generally cyclical and predictable in nature.	Oceanodromous	Migration between feeding and spawning areas within ocean. Cyclical, predictable, covers >100km
		Anadromous	Organism that ascends rivers to spawn
		Catadromous	Migration down from freshwater to sea to spawn. Cyclical, predictable, covers >100km
		Amphidromous	Migrating to and from freshwater/sea at some life stage but not for breeding
		Potamodromous	Migratory in freshwater. Cyclical, predictable, covers > 100km
		Non-migratory	No migratory behavior for spawning
Reproductive Guild	Organisms within each guild display similar reproductive strategies, like parental care, nest building, or spawning/egg dispersal adaptations.	Non-guarder	No parental care provided for eggs after spawning.
		Guarder	Some parental care provided for eggs after spawning.
		Bearer	Fertilized eggs retained in/on body for part or all of the developmental period

Trophic Group	The position an organism occupies in a food web, based on the food it consumes.	Primary Producer	Consumes primary producers and detritus.
		Primary Consumer	Consumers of primary producers and detritus. (herbivore/detritivore).
		Secondary Consumer	Consumers of herbivores (carnivore)
		Tertiary Consumer	Consumers of primary or secondary consumers (carnivore).
Population Doubling Time	How long it takes a population to double in size, based on model estimations.	< 1.25 years	Less than 15 months.
		1.4 - 4.4 years	Between 1.4 and 4.4 years.
		4.5 - 14 years	Between 4.5 and 14 years.

Appendix B – Management Strategies

Table B.2 Management strategies and descriptions (Lepofsky et al., 2017; Lepofsky & Caldwell, 2013b; Mathews & Turner, 2017).

Management Strategy	Description
Clearing or cleaning of habitat	Manual removal of large rocks, driftwood, seaweed, debris, etc. from estuaries, fish ponds, clam beaches, spawning areas, to enhance productivity.
Terracing, ditching, enclosing	Creating new habitats through rock and log terracing, ditching, etc., to extend available habitat, or to create holding ponds for later harvest.
Predator/consumer removal or addition	Applying knowledge of predation and consumer interactions to enhance productivity of the desired species. E.g, removing predators who compete with or consume the target species, introducing herbivores to control algal growth
Feeding	Providing food for growing fish; or putting fishguts, bones, and dead salmon back into the river to nourish young fish, crabs, etc.
Sediment addition	Adding nutrients or moisture retaining materials to soil, or nutrients to water, or other materials E.g, adding shell hash to clam gardens.)
Tilling	Aerating soil or substrate to enhance moisture penetration, recycle nutrients, etc.
Transplanting	Moving young fish, larvae, root fragments, etc. from one location to another, including transplanting salmon eggs, spawning herring, shellfish spat, or rhizomes
Selective harvesting	Includes selective, partial, rotational, or nondamaging harvesting: Taking only a portion of a plant, or only some individuals from a population, allowing individuals to return to spawn, selectively harvesting males or females, or other selection practices to maintain and promote population growth.
Tenure systems	Laying of plot boundaries or establishing borders and site-specific ownership and management. E.g, in estuarine root gardens, crabapple trees, edible red laver seaweed picking areas, clam gardens.

Appendix C – Model with Sea Surface Temperature and Species Richness

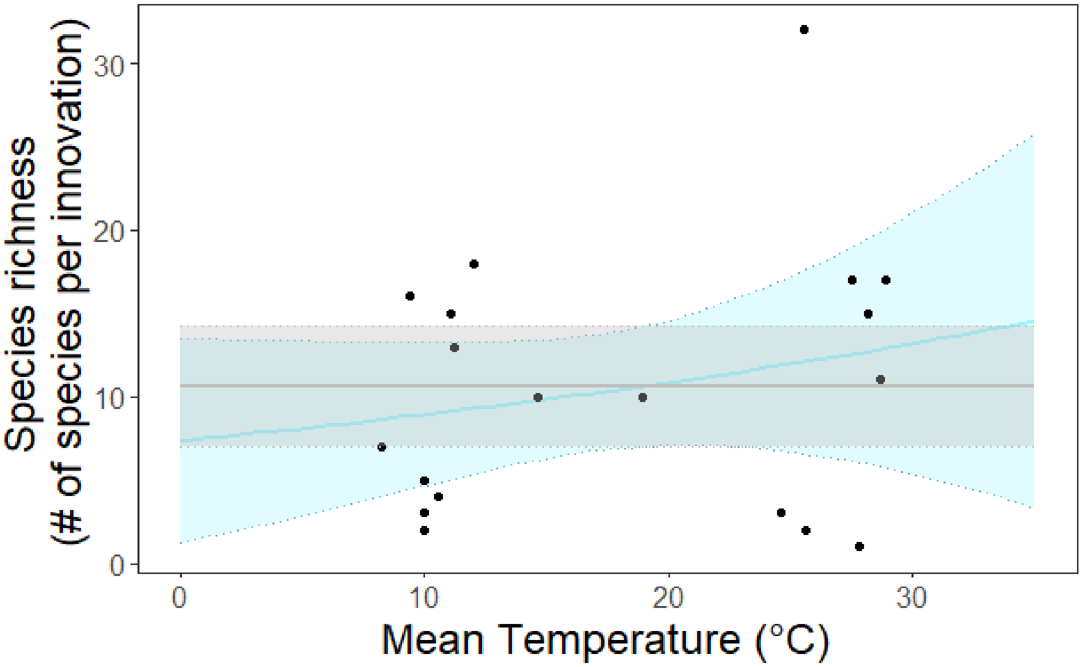


Figure C1 **Diversity of species associated with Indigenous mariculture innovations vs mean sea surface temperature. Null model (grey line) vs temperature model (blue line) with 95% confidence intervals (shaded areas). The predictor line for sea surface temperature is almost fully within the confidence intervals of the null model.**

Table C1 **Strength of evidence for alternative models predicting the effect of SST and number of papers published on species richness**

Model	N	LL	AIC_c	ΔAIC_c	R^2 adj	Weight
Response variable - Distribution						
Species Richness – Negative Binomial						
Null	19	-63.0	130.8	00.0	0.000	0.58
Sea Surface Temp	19	-62.6	132.8	2.04	0.042	0.21
Number of Papers Published	19	-62.8	133.3	2.51	0.017	0.17
Number of Papers Published + Sea Surface Temp	19	-62.6	136.0	5.22	0.046	0.04

Appendix D – Management Strategy Responses

Table D1 Expert responses to about which management strategies are used within each mariculture innovation.

Innovation Name	Clearing, cleaning of habitat	Terracing, ditching, enclosing	Predator or consumer alteration	Feeding	Sediment addition	Tilling	Transplant-ing	Selective harvesting	Tenure Systems
Aech (fish traps) of Yap	No information	No information	No information	No information	No information	No information	No information	Yes	No information
Atog (fish traps) of the Philippines	Yes	No	No information	No information	No	No information	No information	No information	Yes
Ngunnhu (fish traps) of NSW Australia	No information	Yes	No information	No information	No information	No information	No information	Yes	Yes
Clam gardens of the NW coast of N. America	Yes	Yes	Yes	No information	Yes	Yes	No information	Yes	Yes
Corrales de Pesca (fish traps) of Patagonia	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes
Estuarine Root Gardens of the NW coast of N. America	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fish traps of the Society Islands	Yes	Yes	No information	No information	No information	No information	No information	No information	Yes
Gunditjmara eel ponds of Lake Condah	No information	Yes	No information	No information	No information	No information	No information	Yes	No information
Heiltsuk fish traps	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
Heiltsuk herring egg gardens	Yes	Yes	Yes	No information	NA	NA	Yes	Yes	Yes
Intertidal fish traps of SE Alaska	No	Yes	No	No	Yes	No	Yes	Yes	Yes
Stone tidal weirs of Japan	Yes	Yes	No	No information	No information	No	No	Yes	No information
Jamsuhoi (divers) of South Korea	Yes	No information	Yes	Yes	No information	No information	Yes	Yes	Yes

Loko I'a (ponds) of Hawai'i	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Mara Mataitai of Aotearoa	Yes	No information	Yes	No information	Yes	No information	Yes	Yes	Yes
Octopus houses of Haida Gwaii	No information	Yes	Yes	No information	No information	No information	Yes	Yes	Yes
North Coast Salish fish traps and weirs	Yes	No	No information	No information	No information	No information	No information	Yes	Yes
Shi Hu (fish traps) of the Penghu Archipelago, Taiwan	No information	Yes	No information	No information	No information	No information	No information	No information	Yes
Tidal traps and ponds of Panama	Yes	No information	No information	No information	No information	No information	No information	No information	No information
Trampas de Pesca (fish traps) of Costa Rica	No	No	No	No	No	No	No	No	No
Wood stake weirs of Oregon	No information	No information	No	No information	No information	No information	No	Yes	Yes