Indigenous Aquaculture: A Tool to Support Food Security

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June 3, 2020

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Abstract

Fears of food insecurity are a reality for vulnerable island nations and coastal communities, especially with impending climatic and environmental disasters. The 2020 breakout of SARS-CoV-2 further highlighted fundamental problems with the current centralized food system, inspiring more people to value local, community-produced options. Restoring indigenous aquaculture systems, such as Pacific Northwest clam gardens and Hawaiian *loko iʻa* (fishponds), holds great promise in helping small coastal communities adapt to a changing climate. Their integrated, low trophic level models increase natural seafood production without feeds or antibiotics. In turn, they increase the health of their surrounding ecosystem as well as the physical and mental health of those who utilize them. To do so, the systems rely on hyper-local traditional ecological knowledge (TEK) accumulated over centuries. But indigenous aquaculture is only a solution if it can function in climate change. Here we explore how the TEK embedded in indigenous aquaculture can withstand climate changes, while helping communities adapt to and mitigate the associated challenges.

Introduction

Discussions for sustainably feeding a growing population have often centered around large-scale solutions. The onset of the recent global pandemic, however, highlighted something small communities have long appreciated: local food production. While it is premature to understand the implications of the disease on food supply chains, depending solely on a large centralized food system now appears unsustainable. As a result, early consumer behavior shows an uptick in locally sourced foods, which are less vulnerable to supply chain disruptions (Hobbs 2020).

Climate change and its expected extreme weather events will only further threaten food security (Campbell et al. 2016, Lindholm 2019, Vermeulen et al. 2012), especially in vulnerable coastal communities (Barnett 2010, IPCC 2001). Indigenous aquaculture (systems utilizing traditional ecological knowledge (TEK) to enhance the natural production of seafood while nurturing their surrounding environment) can be part of the solution. Governments are increasingly being advised to incorporate TEK into risk management and contingency plans (Vinyeta and Lynn 2013). Article 7.5 of the Paris Agreement, for example, calls for community-focused solutions and "co-management of natural resources using best available science and local, traditional knowledge" (Conference of the Parties 2015). In the five years since, the number of scientific papers mentioning TEK are on the rise **(See Figures 1 and 2)**, but TEK is still rarely suggested as an applied solution for food security, and indigenous aquaculture is practically non-existent. In a dedicated search of scientific literature, only one paper could be found **(See Figure 3)**.

Having successfully weathered centuries of floods, frosts, droughts, disease, and famines (Watson 2019), indigenous aquaculture can set a precedent of how regional food systems can be sustainable and adaptable, even in times of crisis. But indigenous aquaculture can only do so with continual funding and systematic research, which many institutions are hesitant to give due to worries about how these systems will withstand unprecedented ecological changes. Thus, this paper explores: 1) the functionality of indigenous aquaculture systems, specifically Pacific Northwest clam gardens and Hawaiian *loko iʻa* (fishponds) in climate change; 2) their ability to help communities adapt to and mitigate climate change; 3) what Western science stands to lose if we do not study or utilize these technologies; 4) the identification of research that can lead to a better understanding of the past, present, and potential future of these systems.

Figure 1.
Total number of TEK papers published per year. Data was found entering “traditional ecological knowledge” into Web of Science. The term TEK was not used because of the crossover with the TEK (tyrosine kinase) gene. Early access papers are included in the count. A total of 3,189 entries were identified, and all were included.

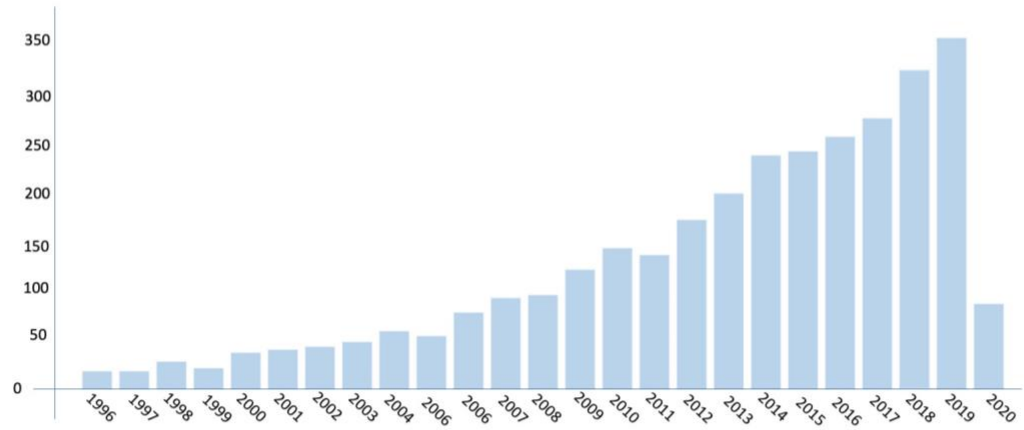


Figure 2.
Number of citations per year of the 3,189 traditional ecological knowledge papers shown in Figure 1, not including self-citations.

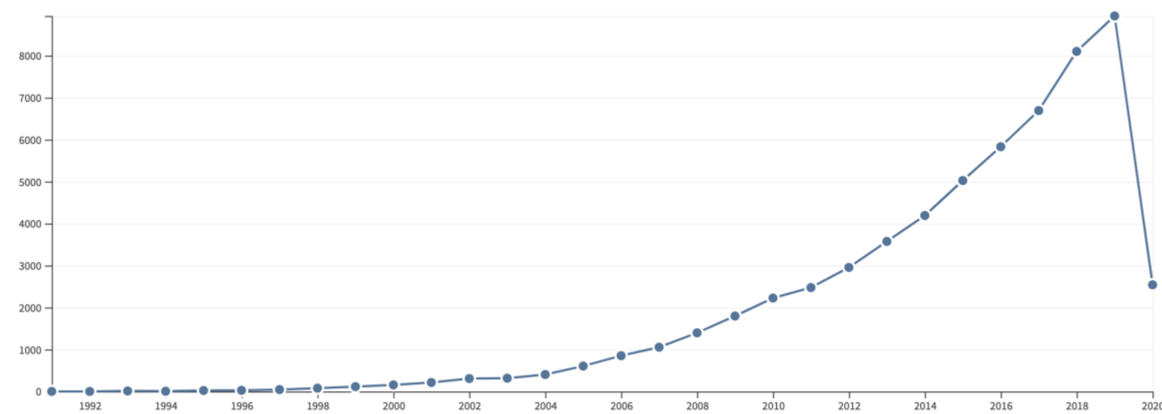


Figure 3.
The total 3,189 entries from Figure 1 were refined in Web of Science using the term “food security”. The following are the 124 remaining papers. Highlighted in blue is the only aquaculture paper. Highlighted in yellow is the only indigenous aquaculture paper, which served as part of the literature review for the clam garden case study.

ID	Author(s)	Publication Year	Title	Web of Science Category
1	Abbas et al.	Early access: March 2020	Traditional wild vegetables gathered by four religious groups in Kurram District, Khyber Pakhtunkhwa, North-West Pakistan	Genetic Resources and Crop Evolution
2	Ahmed et al.	2010	Increased Market Integration, Value, and Ecological Knowledge of Tea Agroforests in the Akha Highlands of Southwest China	Ecology and Society
3	Alonso et al.	2018	Culture and Food Security	Global Food Security-Agriculture Policy Economics and Environment

4	Altieri	2004	Linking ecologists and traditional farmers in the search for sustainable agriculture	Frontiers in Ecology and the Environment
5	Alves	2012	Relationships between fauna and people and the role of ethnozoology in animal conservation	Ethnobiology and Conservation
6	Atreya et al.	2018	Factors Contributing to the Decline of Traditional Practices in Communities from the Gwallek-Kedar area, Kailash Sacred Landscape, Nepal	Environmental Management
7	Avakoudjo et al.		Local Knowledge, Uses, and Factors Determining the Use of Strychnos spinosa Organs in Benin (West Africa)	Economic Botany
8	Barboza et al.	2016	The role of game mammals as bushmeat In the Caatinga, northeast Brazil.	Ecology and Society
9	Berner et al.	2016	Adaptation in Arctic circumpolar communities: food and water security in a changing climate.	International Journal of Circumpolar Health
10	Bharucha et al.	2010	The roles and values of wild foods in agricultural systems.	Philosophical Transactions of the Royal Society B-Biological Sciences
11	Brown et al.	2011	Traditional agricultural landscapes and community conserved areas: an overview	Management of Environmental Quality
12	Busse et al.	2017	Participatory Assessment of Factors Influencing Nutrition and Livelihoods in Rural Ethiopia: Implications for Measuring Impacts of Multisector Nutrition Programs.	Food and Nutrition Bulletin
13	Bussmann et al.	2017	Plant and fungal use in Tusheti, Khevsureti, and Pshavi, Sakartvelo (Republic of Georgia), Caucasus	Acta Societatis Botanicorum Poloniae
14	Campbell, J.R.	2015	Development, global change and traditional food security in Pacific Island countries	Regional Environmental Change
15	Carlson et al.	2018	Peruvian anchoveta as a telecoupled fisheries system.	Ecology and Society
16	Cilliers et al.	2018	Garden ecosystem services of Sub-Saharan Africa and the role of health clinic gardens as social-ecological systems.	Landscape and Urban Planning
17	Cohen et al.	2015	Community-Based, Co-management for Governing Small-Scale Fisheries for the Pacific: A Solomon Islands’ Case Study	Interactive Governance for Small-Scale Fisheries: Global Reflections
18	Coppock et al.	2017	Rangeland Systems in Developing Nations: Conceptual Advances and Societal Implications	
19	De Gisi et al.	2014	History and Technology of Terra Preta Sanitation	Sustainability
20	De Grenade et al.	2017	Anticipatory Capacity in Response to Global Change Across an extreme elevation gradient in the Ica Basin, Peru	Regional Environmental Change
21	Dey, P.	2011	Revisiting indigenous farming knowledge of Jharkhand (India) for conservation of natural resources and combating climate change	
22	Didar-UI Islam et al.	2016	Impact scenarios of shrimp farming in coastal region of Bangladesh: an approach of an ecological model for sustainable management	
23	Eighani et al.	2019	Introducing nearshore fish aggregation devices (FAD) to artisanal persian Gulf fisheries: A preliminary study.	Fisheries Research
24	Falkowski et al.	2019	More than just corn and calories: a comprehensive assessment of the yield and nutritional content of a traditional Lacandon Maya milpa.	Food Security

25	Fauchald et al.	2017	Transitions of social-ecological subsistence systems in the Arctic.	
26	Filous et al.	2020	Population dynamics of roundjaw bonefish Albula glossodonta at a remote coralline Atoll inform community-based management in an artisanal fishery	Fisheries Management and Ecology
27	Foale et al.	2011	Tenure and taboos: origins and implications for fisheries in the Pacific	Fish and Fisheries
28	Friedlander, A. M.	2018	Marine conservation in Oceania: Past, present, and future	Marine Pollution Bulletin
29	Garay et al.	2011	Relational knowledge systems and their impact on management of mountain ecosystems Approaches to understanding the motivations and expectations of traditional farmers in the maintenance of biodiversity zones in the Andes.	Management of Environmental Quality
30	Gartaula et al.	2020	Indigenous knowledge of traditional foods and food literacy among youth: Insights from rural Nepal.	
31	Gaudin	2015	Facilitators and Barriers to Traditional Food Consumption in the Cree Community of Mistissini, Northern Quebec	Ecology of Food and Nutrition
32	Gerlach	2013	Rebuilding northern foodsheds, sustainable food systems, community well-being, and food security.	
33	Gnonlonfoun et al.	2019	New indicators of vulnerability and resilience of agroforestry systems to climate change in West Africa.	Agronomy for Sustainable Development
34	Golden et al.	2015	"Blue-ice": framing climate change and reframing climate change adaptation from the indigenous peoples' perspective in the northern boreal forest of Ontario, Canada	Climate and Development
35	Gonzalez-Marin et al.	2017	Regaining the traditional use of wildlife in wetlands on the coastal plain of Veracruz, Mexico: ensuring food security in the face of global climate change.	Regional Environmental Change
36	Goerg et al.	2014	Engaging Local Knowledge in Biodiversity Research: Experiences from Large Inter- and Transdisciplinary Projects.	Interdisciplinary Science Review
37	Gouwakinnou et al.	2011	Folk perception of sexual dimorphism, sex ratio, and spatial repartition: implications for population dynamics of Sclerocarya birrea (A. Rich) Hochst populations in Benin, West Africa.	Agroforestry Systems
38	Gregory et al.	2017	The Marginalisation and Resurgence of Traditional Knowledge Systems in India: Agro-Ecological 'Islands of Success' or a Wave of Change?	
39	Gurdak et al.	2019	*Evidence of Recoveries from Tropical Floodplain Fisheries: Three Examples of Management Gains for South American Giant Arapaim.*	
40	Hagstrum et al.	2017	Evolution of Stored-Product Entomology: Protecting the World Food Supply	
41	Hosen et al.	2020	Adaptation to Climate Change: Does Traditional Ecological Knowledge Hold the Key?	Sustainability
42	Huambachano, M.	2018	Enacting food sovereignty in Aotearoa New Zealand and Peru: revitalizing Indigenous	Agroecology and Sustainable Food Systems

			knowledge, food practices and ecological philosophies	
43	Hudson et al.	2016	Social Practices of knowledge mobilization for sustainable food production: nutrition gardening and fish farming in the kolli hills of India.	Food security
44	Isaacs et al.	2016	Assessing the value of diverse cropping systems under a new agricultural policy environment in Rwanda	Food Security
45	Jackley et al.	2016	Ancient clam gardens, traditional management portfolios, and the resilience of coupled human-ocean systems.	Ecology and Society
46	Jacobi et al.	2018	Operationalizing food system resilience: An indicator-based assessment in agroindustrial, smallholder farming, and agroecological contexts in Bolivia and Kenya.	Land Use Policy
47	Jasmine et al.	2016	Traditional knowledge systems in India for biodiversity conservation.	
48	Jenkins et al.	2018	My Island home: place-based integration of conservation and public health in Oceania.	Environmental Conservation
49	Kittinger et al.	2013	Human Dimensions of Small-Scale and Traditional Fisheries in the Asia-Pacific Region.	Pacific Science
50	Kong et al.	2017	Green Revolution: China North Eastern Plains.	
51	Kremen et al.	2012	Diversified Farming Systems: An Agroecological, Systems-based Alternative to Modern Industrial Agriculture.	Ecology and Society
52	Lara et al.	2019	Flipping the Tortilla: Social-Ecological Innovations and Traditional Ecological Knowledge for More Sustainable Agri-Food Systems in Spain. *Sustainability*	Sustainability
53	Lemahieu et al.	2018	Local Perceptions of environmental changes in fishing communities of southwest Madagascar.	Ocean and Coastal Management
54	Lunga et al.	2016	Exploiting indigenous knowledge commonwealth to mitigate disasters: from the archives of vulnerable communities in Zimbabwe.	
55	Luo et al.	2019	Diversity and use of medicinal plants for soup making in traditional diets of the Hakka in West Fujian, China.	
56	Machalaba et al.	2015	Climate Change and Health: Transcending Silos to Find Solutions.	
57	Mahapatra et al.	2012	Wild edible fruit diversity and its significance in the livelihood of indigenous tribals: Evidence from eastern India.	Food Security
58	Marchi et al.	2018	Agro-Forest Management and Soil Degradation in Mediterranean Environments: Towards a Strategy for Sustainable Land Use in Vineyard and Olive Cropland.	Sustainability
59	Marin et al.	2016	Re-localizing 'legal' food: a social psychology perspective on community resilience, individual empowerment and citizen adaptations in food consumption in Southern Italy.	Agriculture and Human Values
60	Mellado et al.	2014	Use of local knowledge in marine protected area management.	Marine Policy
61	Menendez-Baceta et al.	2017	Trends in wild food plants uses in Gorbeialdea (Basque Country).	Appetite

62	Meriwether et al.	2018	Restoring near-shore marine ecosystems to enhance climate security for island ocean states: Aligning international processes and local practices.	Marine Policy
63	Min et al.	2020	Research Progress in the Conservation and Development of China-Nationally Important Agricultural Heritage Systems (China-NIAHS).	Sustainability
64	Min et al.	2016	Responding to common questions on the conservation of agricultural heritage systems in China.	
65	Mishra et al.	2009	Dynamics of Adi Women's Traditional Foods and Livelihoods in Varying Socio-ecological Systems of Arunachal Pradesh: A Source of Learning and Inspiration. New Cultures of Food: Marketing Opportunities from Ethnic, Religious and Cultural Diversity	
66	Molares et al.	2020	Traditional mycological knowledge and processes of change in Mapuche communities from Patagonia, Argentina: A study on wild edible fungi in Nothofagaceae forests.	Mycologia
67	Mosepele et al.	2007	Indigenous knowledge and fish utilisation in the Okavango Delta, Botswana: implications for food security.	
68	Mutungi et al.	2019	Postharvest processes of edible insects in Africa: A review of processing methods, and the implications for nutrition, safety and new products development.	Food Science And Nutrition
69	Negi et al.	2013	Socio-Ecological and Religious Perspective of Agrobiodiversity Conservation: Issues, Concern and Priority for Sustainable Agriculture, Central Himalaya.	
70	Okolle et al.	2016	An evaluation of smallholder farmers' knowledge, perceptions, choices and gender perspectives in vegetable pests and diseases control practices in the humid tropics of Cameroon.	
71	Ong et al.	2017	The role of wild edible plants in household food security among transitioning hunter-gatherers: evidence from the Philippines.	Food Security
72	Orsini et al.	2013	Urban agriculture in the developing world: a review.	Agronomy for Sustainable Development
73	Padmavathy et al.	2011	Alternative Farming Techniques for Sustainable Food Production	
74	Parlee et al.	2012	Well-being and environmental change in the arctic: a synthesis of selected research from Canada's International Polar Year program.	Climatic Change
75	Parraguez-Vergara et al.	2018	Does indigenous and campesino traditional agriculture have anything to contribute to food sovereignty in Latin America? Evidence from Chile, Peru, Ecuador, Colombia, Guatemala and Mexico.	
76	Parrotta et al.	2015	*The Historical, Environmental and Socio-economic Context of Forests and Tree-based Systems for Food Security and Nutrition*.	

77	Peterson et al.	2019	Understanding Canoe Making as a Process of Preserving Cultural Heritage.	
78	Petropoulou et al.	2007	Indigenous resource management and environmental degradation: southern Greece.	
79	Pieroni et al.	2019	Ethnic and religious affiliations affect traditional wild plant foraging in Central Azerbaijan.	Genetic Resources and Crop Evolution
80	Pitcher et al.	2010	Fishful Thinking: Rhetoric, Reality, and the Sea Before Us.	Ecology and Society
81	Pokorny et al.	2013	From large to small: Reorienting rural development policies in response to climate change, food security and poverty.	Forest Policy and Economics
82	Powell et al.	2015	Improving diets with wild and cultivated biodiversity from across the landscape.	Food Security
83	Proverbs et al.		Social-Ecological Determinants of Access to Fish and Well-Being in Four Gwich'in Communities in Canada's Northwest Territories.	Human Ecology
84	Rivero-Romero et al.	2016	Traditional climate knowledge: a case study in a peasant community of Tlaxcala, Mexico.	
85	Roe et al.	2016	Becoming ecological citizens: connecting people through performance art, food matter and practices.	Cultural Geographies
86	Roux et al.	2019	Small-scale fisheries in Canada's Arctic: Combining science and fishers knowledge towards sustainable management.	Marine Policy
87	Sangakkara et al.	2016	Characteristics of South Asian rural households and associated home gardens - A case study from Sri Lanka.	Tropical Ecology
88	Savo et al.	2017	Impacts of climate change for coastal fishers and implications for fisheries.	Fish and Fisheries
89	Saxena et al.	2020	Community Self-Organisation from a Social-Ecological Perspective: 'Burlang Yatra' and Revival of Millets in Odisha (India).	Sustainability
90	Schemmel et al.	2016	The codevelopment of coastal fisheries monitoring methods to support local management.	Ecology and Society
91	Shumskys et al.	2014	Understanding the contribution of wild edible plants to rural social-ecological resilience in semi-arid Kenya.	Ecology and Society
92	Singh, A et al.	2007	Cultural Significance and diversities of ethnic foods of Northeast India.	
93	Singh, R.K. et al.	2012	"Tinni" Rice (Oryza rufipogon Griff.) Production: An Integrated Sociocultural Agroecosystem in Eastern Uttar Pradesh of India.	Environmental Management
94	Singh, R et al.	2019	Challenges and opportunities for agricultural sustainability in changing climate scenarios: a perspective on Indian agriculture.	Tropical Ecology
95	Singh, R et al.	2017	Human Overpopulation and Food Security: Challenges for the Agriculture Sustainability	
96	Sipos et al.	2009	NON-TRADITIONAL PEDAGOGIES IN ADVANCED EDUCATION: ENGAGING HEAD, HANDS & HEART FOR	

			ENVIRONMENTAL AND EDUCATIONAL BENEFIT	
97	Sowerwine et al.	2019	Enhancing Indigenous food sovereignty: A five-year collaborative tribal-university research and extension project in California and Oregon.	
98	Spiegelaar et al.	2013	Impact of Euro-Canadian agrarian practices: in search of sustainable import-substitution strategies to enhance food security in subarctic Ontario, Canada.	Rural and Remote Health
99	Stinchcomb et al.	2019	A Review of Aircraft-Subsistence Harvester Conflict in Arctic Alaska.	Arctic
100	Suma et al.	2017	Exclusions in inclusive programs: state-sponsored sustainable development initiatives amongst the Kurichya in Kerala, India.	Agriculture and Human Values
101	Takahashi et al.	2016	Roles of forests in food security based on case studies in Yunnan, China.	
102	Tamou et al.	2018	Understanding roles and functions of cattle breeds for pastoralists in Benin.	Livestock Science
103	Tewksbury et al.	2014	Natural History's Place in Science and Society.	Bioscience
104	Thorkildsen et al.	2014	Social-Ecological Changes in a Quilombola Community in the Atlantic Forest of Southeastern Brazil.	Human Ecology
105	Thrupp et al.	2000	Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture.	International Affairs
106	Thurstan et al.	2018	Aboriginal uses of seaweeds in temperate Australia: an archival assessment.	
107	Tiwari et al.	2010	Forest Management Practices of the Tribal People of Meghalaya, North-East India.	Tropical Forest Science
108	Tomaselli et al.	2018	Iqaluktutiaq Voices: Local Perspectives about the Importance of Muskoxen, Contemporary and Traditional Use and Practices.	Arctic
109	Torres-Vitolas et al.	2019	The Socio-Ecological Dynamics of Food Insecurity among Subsistence-Oriented Indigenous Communities in Amazonia: a Qualitative Examination of Coping Strategies among Riverine Communities along the Caqueta River, Colombia.	Human Ecology
110	Trosper et al.	2018	The Unique Character of Traditional Forest-Related Knowledge: Threats and Challenges Ahead	Traditional Forest-Related Knowledge: Sustaining Communities, Ecosystems and Biocultural Diversity
111	Turner et al.	2018	Springtime in the Delta: the Socio-Cultural Importance of Muskrats to Gwich'in and Inuvialuit Trappers through Periods of Ecological and Socioeconomic Change.	Human Ecology
112	Uprety et al.	2012	Diversity of use and local knowledge of wild edible plant resources in Nepal.	
113	Van Rensburg et al.	2015	Delving in the past: unearthing the diversity of traditional vegetables in South Africa	

114	Walter et al.	2012	Educational alternatives in food production, knowledge and consumption: The public pedagogies of Growing Power and Tsyunhehkw.	
115	Watts et al.	2017	Inuit food security in canada: arctic marine ethnoecology.	Food Security
116	Wendiro et al.	2019	Identifying indigenous practices for cultivation of wild saprophytic mushrooms: responding to the need for sustainable utilization of natural resources.	
117	Wheeler et al.	2019	Identifying key needs for the integration of social-ecological outcomes in arctic wildlife monitoring.	Conservation Biology
118	Whitney et al.	2018	Ethnobotany and Agrobiodiversity: Valuation of Plants in the Homegardens of Southwestern Uganda.	Ethnobiology Letters
119	Yiridoe et al.	2005	Garden Production systems and food security in Ghana: Characteristics of traditional knowledge and management systems.	Renewable Agriculture and Food Systems
120	Zapico et al.	2015	Biocultural Diversity of Sarangani Province, Philippines: An Ethno-Ecological Analysis.	Rice Science
121	Zhang et al.	2016	Ethnobotanical study of traditional edible plants used by the Naxi people during droughts.	
122	Zhao et al.	2018	Research on the cooperative innovation mechanism of agricultural science and technology in Chongqing three gorges reservoir area based on supply-side reform.	
123	Ziker et al.	2016	Indigenous Siberians solve collective action problems through sharing and traditional knowledge.	Sustainability Science
124	Zimmer et al.	2013	The compatibility of agricultural intensification in a global hotspot of smallholder agrobiodiversity (Bolivia).	

Material and Methods

This study builds on centuries of ancestral knowledge and advances a collective movement to document and revitalize various, culturally appropriate forms of indigenous aquaculture. Over 150 participants gathered for an unprecedented indigenous aquaculture meeting at 800-year-old He‘eia fishpond on the east side of O‘ahu. Participants included Native Hawaiians and *kama‘āina* (locals*;* literally person of the land); 13 Pacific Northwest tribal nations across Alaska, British Columbia, and Washington; four Māori tribes from Aotearoa New Zealand’s North Island; and native peoples from Micronesia and California. The gathering crossed over between several projects, including Simon Fraser University’s Resilience of Social-Ecological Systems class; The Clam Garden Network; the Hui Mālama Loko I‘a network; and the Cross-Pacific Indigenous Aquaculture Collaborative Hub, which was created by Alaska, Hawai‘i and Washington Sea Grants with the help of a three-year National Oceanic and Atmospheric Administration (NOAA) grant.

Through this gathering, subsequent Zoom meetings, and an in-depth literature review, we provide preliminary research and well-informed proxies that can advise how indigenous aquaculture can perform in the future and what further research is needed. Scientific and grey literature was sourced from Google Scholar; University of California, San Diego Library; and Web of Science. We also obtained an (Institutional Review Board) IRB exemption through

University of California, San Diego as an act of good faith and a Western academic symbol of the cross-cultural communication and reciprocal sharing of knowledge that the indigenous aquaculture community purposefully embodies.

As for terminology, this paper uses indigenous aquaculture because it is consistent with Hui Mālama Loko Iʻa, the NOAA-funded Collaborative Hub, and the current IUCN Motion 55, which calls for a global database of indigneous aquaculture knowledge. This paper acknowledges that all forms of historic aquaculture do not fit under the term indigenous and that some of the systems are referred to as mariculture. We conceptionally recognize them all, including those technologies currently unknown and undocumented to the scientific community. The term clam gardens is also used here to be consistent with The Clam Garden Network, although sea gardens has recently been designated as a more accurate term, recognizing new research that the walled beach terraces cultivated more than clams (Augustine, S. and Stocks, A., Class lecture, May 6, 2020; Caldwell et al. 2012; and Deur et al. 2015).

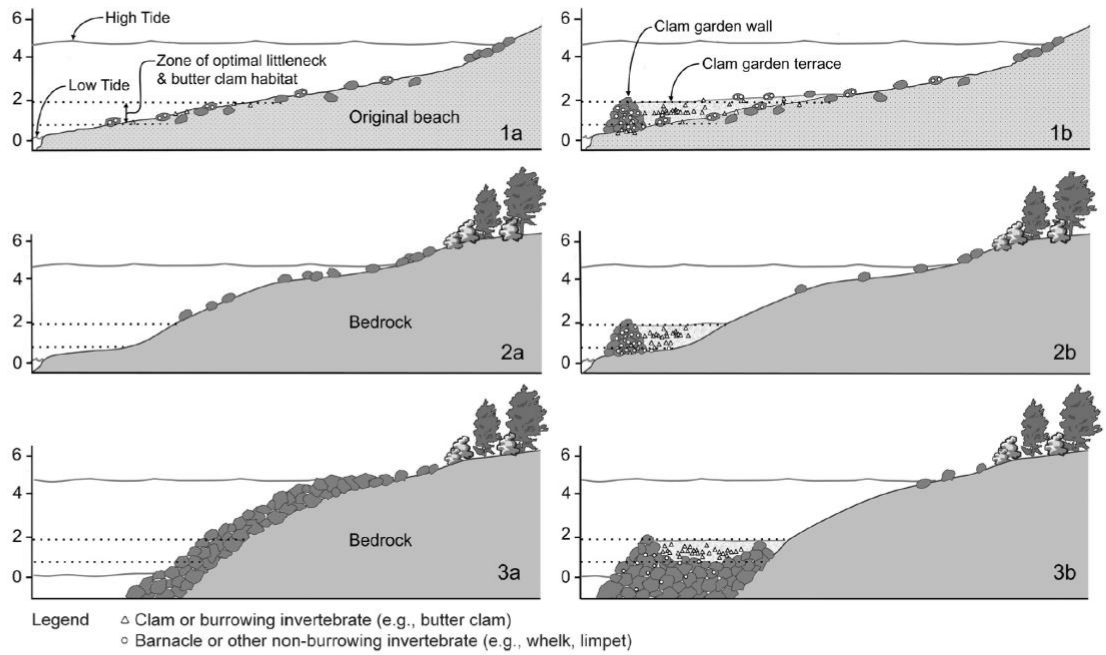
Background

Clam Gardens

Mink was unhappy. The tide would not go down to the level of his food. He stole wolf's tail and held it to the fire. Wolf called out: "Hey! Stop that. What do you want?"
Mink hollered, "I want the tide to go down further."
"Okay," says Wolf, "I'll make it go down to the barnacles."
Mink wasn't satisfied and held the tail closer to the fire.
"Okay, okay!" says Wolf. "I'll make it go down to where the cockles grow."
"No way," Mink said, "I want it to go down to the lo xwi we," and he held Wolf's tail right in the middle of the fire.
"Ooh, Owwwh!" howled Wolf, and he made the tide go down to the lowest level of the beach where the lo xwi we was built.
(Recorded by Franz Boas 1906 as mentioned in Cardinal et al. 2005. Also, Williams 2006)

Mink and other predators still scavenge *lo xwi we* (clam gardens) at low tide. The Kwak'wala word (belonging to the British Columbian Kwakiutl people) means rolled together or low tide mark (Cardinal et al. 2005 and Deur et al. 2015). That is because for thousands of years First Nations and Native Americans would gather on beaches along the edges of bays and semi-protected inlets in Alaska, British Colombia, and Washington State (Harper et al. 1995) to roll rocks to the lowest low tide line. The walls consistently built at this mark have been radiocarbon dated to at least 3,500 years old, and they show evidence of being consistent with changing sea levels (Smith et al. 2019) over time. These walls extended about 0.7 to 1.3m above chart datum (Groesbeck 2014). Sediment would then accumulate on the beach side of the wall, creating a flatter terrace that retains more water and submerges clams in a protected, nutrient-rich environment ideal for spawning events and larval clam recruitment and settlement (**See Figure 4**). Overall, clam gardens contained 4 times as many butter clams (*Saxidomus giganteus*) and over twice as many Pacific littlenecks (*Leukoma staminea*) than local non-walled beaches (Groesbeck 2014). Both species also grow 1.7 times faster in clam gardens than in non-walled beaches (Groesbeck 2014, Jackley et al. 2016, and Smith et al. 2019).

Figure 4.
Smith et al. 2019. 3500 years of shellfish mariculture on the Northwest Coast of North America.

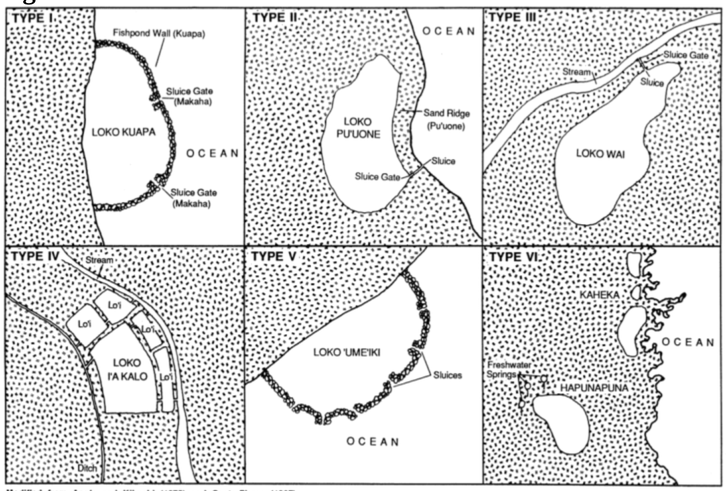


Loko I'a

> Kuʻula-kai had a human body, but was possessed with *mana kupua* (supernatural powers), in directing and controlling the fish of the sea. While Kuʻula and his wife [Hina-puku-iʻa, goddess of fishermen] were living at Lehoʻula on the island of Maui, he devoted all his time to his chosen vocation of fishing. His first work was to construct a *loko iʻa* (fishpond) handy to his house, but near the shore where the surf breaks, and he stocked this pond with all kinds of fish. Upon a rocky platform, he also built a house, which he called by his own name, Kuʻula, to be sacred for the fishing *kapu* (laws and regulations; literally forbidden). Here he offered the first fish caught to the fish god, and because of his observances, fish were *laka loa* (obedient) to him; all he had to do was to say the word, and fish would appear.

Some scientists suggest this *moʻolelo* (story; literally succession of speech) of the first loko iʻa is more than folklore. Kuʻula could have been a real person who used empirical observation and repetitive field experience to develop a deep understanding of oceanography and coastal ecology, including water chemistry, fish behavior, and tidal flows (McDaniel 2018).

Figure 5.



Modified from Apple and Kikuchi (1975) and Costa-Pierce (1987).

It is this scientific ingenuity that made loko i‘a a critical part of Hawai‘i’s complex and sustainable natural resource management system. As the research of Simon Fraser’s resiliency class and the Collaborative Hub is confirming, numerous cultures herded and trapped fish using rock walls in estuaries and shallow tidal areas (Also Costa Pierce 1987). However, the ingenuity of the six types of loko i‘a (**See Figure 5**) show a uniquely deep understanding of engineering, hydrology, ecology, biology, and agriculture, all of which were holistically and communally managed within *ahupua‘a* (watershed-scale land divisions) (Costa Pierce 1987, Keala et al. 2007, and Kikuchi 1976). In Hawaiian communities, reviving this knowledge, and therefore the spirit of Ku‘ula, is an essential part of the collaborative movement to restore loko i‘a.

Researchers estimate that prior to James Cook’s arrival in 1778, there were 488 loko i‘a reliably producing about 300 pounds of herbivorous fish per acre per year (Chang et al. 2019 and Costa-Pierce 1987) (DHM, 1990). By 1901, only 99 of them were commercially active, producing 680,000 pounds of fish per year, including 485,000 pounds of *‘ama‘ama* (striped mullet; *Mugil cephalus*) and 194,000 pounds of *‘awa* (milkfish; *Chanos chanos*) (Cobb 1901).

Functionality in Climate Change

Climate change will shift how species interact within an ecosystem while transforming the phenology, morphology, behavior, and range of individual species (Weiskopf et al. 2020), including those ecologically and culturally important to indigenous aquaculture. If a nuanced understanding of these applied processes fundamentally drives indigenous aquaculture, what happens when these ecological truths no longer hold true?

Some anecdotally deduce the knowledge embedded in indigenous aquaculture will break down along with the systems’ ability to enhance the production of seafood. With the detailed projections of climate change still uncertain (IPCC 2018), this remains a hypothesis. The long history of success of these systems leads us to hypothesize, on the other hand, that indigenous aquaculture can adapt to the changing climate. A significant breadth of research is warranted to better understand how.

Clam Gardens

One of the most immediate threats to clam gardens, and the Pacific Northwest in general, is ocean acidification (OA). The ocean is 30 percent more acidic than it has been in the last 200-plus years; a drop of 0.1 pH units from 8.2 to 8.1, and it is expected to drop another 0.4 units to 7.7 by the end of the century (NOAA 2020). Additionally, the Pacific Northwest’s cold, fresh marine waters historically have had low aragonite saturation (Ωaragonite). This is due to frequent upwelling events low in pH and rich in CO_2, nitrate, and phosphorous (Strong et al.

2014). The region also has numerous freshwater inputs (which seasonally enhance acidification), and it is closely exposed to glacier melt (which delivers low alkaline water and reduces Ωaragonite) (Strong et al. 2014). As a result, the Pacific Northwest is experiencing the corrosive effects of OA sooner and more intensely than the rest of the globe (Washington Ocean Acidification Center 2013), making it difficult for larval shellfish to obtain the calcium carbonate ($CaCO_3$) needed to form their shells.

The numerous larval recruits in clam gardens may survive, however. Most OA experiments have focused on lab-cultured bivalves (Carss et al. 2020), not wild-harvested ones like those in clam gardens. OA experiments have also occurred over relatively short time frames and may not take into account species' capacity to acclimate (Strong et al. 2014). Even within the urgent time frames relevant to present day OA, evolutionary changes are plausible (Hoffmann and Sgrò 2011). For example, recent research with manila clams (*Ruditapes philippinarum*) may imply that within one generation, Pacific littlenecks and butters will no longer need the carbon from seawater to make their shells (Zhao et al. 2018). In these studies, manila clams transgenerationally exposed to pH 7.7 showed a significantly faster growth rate, a higher condition index (measurements to determine the overall health of the bivalve), and a lower standard metabolic rate than manilas whose parents were not exposed to the same conditions. The reason for the adaptation is a preferential uptake of metabolic carbon, involving the use of sodium ions (Zhao 2016) rather than the transport of inorganic carbon from external seawater. The results also showed the internal metabolic carbon process was less costly and more energy efficient (Zhao et al. 2018).

New research from scientists in The Clam Garden Network also shows signs of resilience. Surveys and clam transplants on British Columbia's Quadra Island show the reduced beach slopes of clam gardens enhance sediment carbonate, buffering against environmental fluctuations in temperature and carbonate conditions (Salter *in prep*). Clam gardens' coarse sediment may also help (Salter *in prep*). In addition to the shell hash that naturally accumulates from the rock walls, stewarding communities continually returned empty clam shells (made mostly of mineral $CaCO_3$) to the beach, regenerating alkalinity and buffering against corrosive conditions in coastal waters. (Salter *in prep*, Green et al. 2009, Green et al. 2013, Kelly et al. 2011, Waldbusser 2013)

Loko Iʻa

Today, only about 60 loko iʻa remain. Each are in various stages of restoration, but most still support life despite eutrophication and sedimentation from decades of neglect and upstream water diversions for ranching, pineapple and sugar plantations, American military land use, and rapid urban development (Keala et al. 2007). Now, they also face a complex interconnected web of climate change challenges relating to hydrology, geomorphology, and water quality.

In theory, coastal loko iʻa could be particulary vulnerable since they are brackish estuary-like environments, naturally nourished by freshwater inputs and seawater (Keala et al. 2007 and Costa-Pierce 1987). Changes in precipitation rates, groundwater salinites, stream flow, sea surface temperatures, and wind patterns could alter their water quality and, therefore, their ability to produce phytoplankton and support fish life (McCoy et al. 2017). However, it is precisely these dynamic variations, which loko iʻa, and esturaies in general, have experienced for centuries, that arguably make them resilient. More research would be needed to understand specifically how. To date, only McCoy et al 2017 has looked into loko iʻa and climate change with systematic detail. At the time of writing The Nature Conservancy had also just finished a field study, and results were still being analyzed. However early hypotheses suggest shallow waters, ample sunlight radiation, and high circulation rates are expected to persist within loko iʻa, supporting the idea that they can continue to function. (R. Most & C. Wiggins, TNC, Zoom conversation, May 22, 2020). Future changes to hydrology, geomorphology, and water quality, are also anticipated to happen slowly over years, allowing loko iʻa time to adapt. (Most & Wiggins, The Nature Conservancy (TNC), Zoom conversation, May 22, 2020)

Extreme tide events, such as hurricanes, tsunamis, and higher perigean spring tides (King Tides), bring a more rapid threat and are expected to more than double in the tropics by 2050 (Vitousek et al. 2017). Combine that with Hawaiʻi's expected sea level rise (SLR), and the threat is further compounded. Hawaiʻi's currently mild SLR at 1.44 ± 0.21mm/yr (NOAA 2018) may potentially reach 8mm/year during the second half of the century (Anderson et al. 2018). This is due to increasing sea surface temperatures (Hawaiʻi Climate Change Mitigation and Adaptation Commission 2017) and Earth's gravitational redistribution of meltwater in the equatorial Pacific (near Hawaiʻi) (Spada et al. 2013). Changes will vary substantially between islands (and therefore, loko iʻa) due to geologic uplift and subsidence, ocean currents, wind patterns, and gravitational pull (University of Hawaiʻi at Mānoa Sea Grant Program 2014). Flooding, coastal erosion, and saltwater inundation are anticipated as a result of these threats (Anderson et al. 2018; Hawaiʻi Climate Change Mitigation and Adaptation Comission 2017; and Leong et al. 2014).

Loko iʻa can adapt to these through the very nature of their design. Like clam gardens, loko iʻa were "built for prevailing conditions at the time" and "with an impermance mindset" (R. Alegado, telephone conversation, April 6, 2020). In both clam gardens and loko iʻa, rock walls were dry stacked (*uhauhumu pōhaku* in Hawaiian) without the use of a bonding agent like concrete. The lack of permanence created greater flexibility, allowing the systems to be moved or adjusted with natural climatic variations.

Impermance of design also meant the stewarding community must continually move and rebuild rock walls. In doing so, there was a persistence of practice and *ma ka hana ka ʻike* (Hawaiian for learning by doing) (Montgomery & Vaughan 2018) making individuals, and the community as a whole, well-trained and ready to efficiently coordinate and mobilize under pressure. Current restoration efforts prioritize the multigenerational teaching of these skills so the community will once again be ready to move loko iʻa inland or to build higher walls as needed.

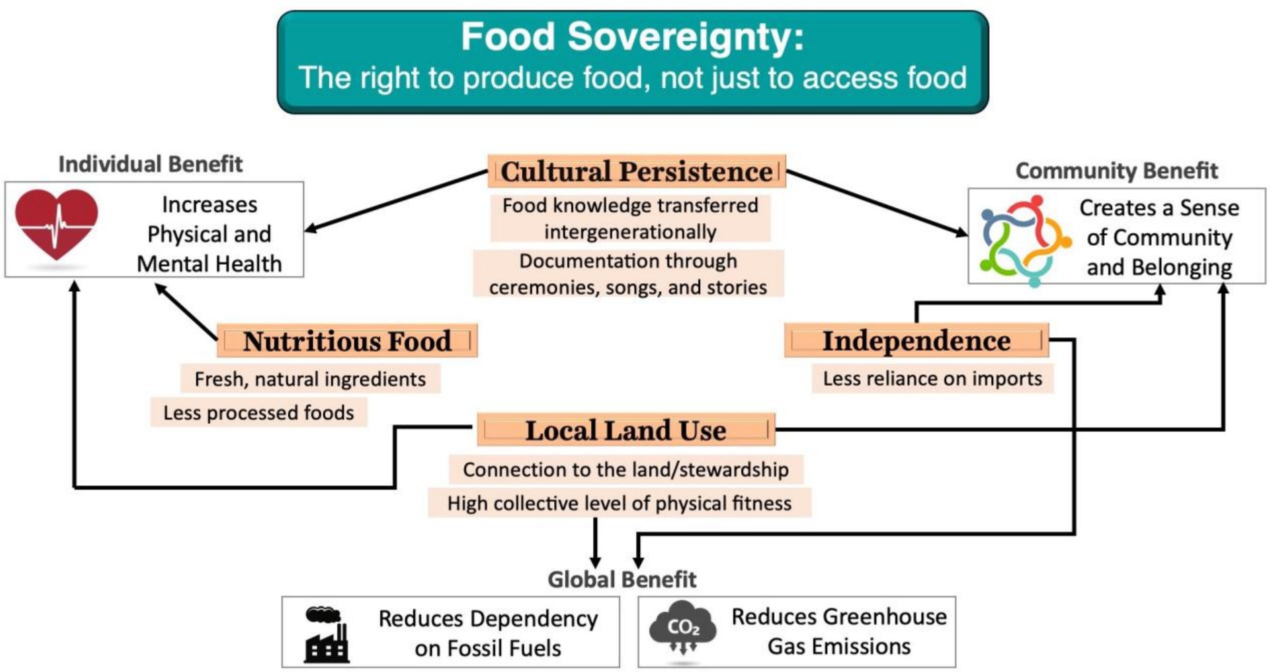
Climate Change Adaptation

Indigenous aquaculture can help coastal communities become more food sovereign, making them better situated to survive climatic events that could threaten food imports. The Food and Agriculture Organization of the United Nations (FAO) discusses food security rather than sovereignty, identifying it as "when all people, at all times, have physical, social and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 2011). This definition does not account for how, where, and by whom the food is produced. Remote food production (Hoover and Mihesuah 2019) continues as a result, increasing the dependence on fossil fuels and oil. There is also a difference of control (Hoover 2019) between the right to access food and the right to produce food (Hoover and

Mihesuah 2019). Restoring indigenous aquaculture systems makes local food production more accessible for vulnerable coastal communities. In doing so, they can keep food dollars within the community (Hoover 2019) and establish better control of their own livelihoods and climate change response.

A greater reliance on small-scale food production also raises up the social perception of local food workers (Segrest 2019), another phenomena we saw during COVID-19. Similarly, having food production rely on local TEK will strengthen civil responsibilities to nature and to the community (Segrest 2019), reconnecting individuals with cultural traditions and to the environment. Overall, this sense of belonging and symbiotic connection to the land increases mental health; what many scientists refer to as cultural ecosystem services (CES) (Pascua et al 2017 and Fisher et al. 2009), while the decreased dependency on processed foods increases physical health (**See Figure 6**).

Figure 6.
Adapted from concepts in *Indigenous Food Sovereignty in the United States: Restoring cultural knowledge protecting environments and regaining health*. Norman, OK.: University of Oklahoma Press, Publishing Division of the University. Images from iStock; heart: 4zevar, community: DESKCUBE, CO2: Muzyka Daria, factory: Shams Suleymanova



Climate Change Mitigation

Knowledge keepers and preliminary studies suggest indigenous aquaculture naturally enhanced food production while generating net positive regulating and supporting (Reid et al. 2005) ecosystem services (Salter *in prep* and Smaal et al. 2019). In theory, these benefits could include disease prevention, water quality enhancement, soil formation, nutrient cycling, increased biodiversity, and overfishing abatement, all of which contribute to climate change mitigation. More research could identify and quantify the specific ecosystem services for each type of indigenous aquaculture system.

Clam Gardens

The role of bivalves as ecosystem engineers that aid in bioturbation, water filtration, sediment erodibility, and alkalinity regeneration are well documented (Carss et al. 2020, Gutiérrez et al. 2003, and Waldbusser et al. 2013). And tertiary documentation of clam gardens' ecosystem services has been published (**See Figure 7**). But the scientific community does not currently understand how the above processes and taphonomic feedbacks function within a clam garden.

We do know that humans used clam gardens to intentionally modify beach substrate both with the rock wall and through continual stewardship. The Kwakwaka'wakw people *gwalis peten* (dug clams) with *kellakw* (a special yew-wood stick), the act of which minimized silt accumulation and aerated the beach, preventing anoxia and encouraging the growth of clams (Deur et al. 2015). Regular maintenance also meant keeping invasive species like sea lettuce (*Ulva lactuca*) in check while selectively harvesting larger clams, which thinned the population, created more space, and decreased competition so young clams could grow (Deur et al. 2015).

New research also suggests clam gardens essentially created healthy and productive rocky reef habitats that increased the biodiversity of numerous species, including octopus, sea cucumber, whelks, chiton, and red turban snails. The abundance improved overall ecosystem biodiversity. Raccoons, river otters, sea ducks, and geese all thrived off hunting in clam gardens, which also turned the sediment. (Augustine *in prep* and Deur et al. 2015).

Loko Iʻa

To date, little research has been conducted identifying the positive ecosystem services of loko iʻa, although they often are alluded to. A 2013 Programmatic Environmental Assessment (PES), for example, mentions the "ecosystem services" of loko iʻa 20 times with minimal concrete details of what those services are. Vague explanations include that they "may benefit water quality by restoring circulation to stagnating pond areas." The report also briefly alludes to "lower concentrations of algal growth" and the "removal of invasive species" (Kēhaulani Watson 2013)

TEK accounts speak to much more. Knowledge keepers anecdotally say the systematic use of loko iʻa throughout the watershed resulted in unpolluted and healthy runoff into the sea. Naturally abundant phytoplankton in the loko iʻa was also reported to spillover to nearshore fisheries, acting similarly to a marine protected area (MPA) and directly increasing biodiversity and population densities of reef fishes and benthic organisms. TNC believes its current research might preliminarily support such claims (R. Most & C. Wiggins, TNC, Zoom conversation, May 22, 2020).

Discussion—What Humanity Stands to Lose

Containing centuries of local, natural knowledge, TEK serves as the metaphoric canary in the coal mine, allowing us to detect environmental changes in the field before Western scientists can document them and develop responses (Grossman 2008: 8). Indigenous aquaculture, in particular, is collectively spread across different cultures, habitats, ecosystems, and marine and freshwater organisms. Indigenous aquaculture also dates to various periods throughout human history. Together, these systems provide an unparalleled way to understand climate impacts on coastal ecological processes across a wide variety of spatial and temporal scales. If left unrestored and unstudied, Western science will lose data in key areas of climate change assessment (Berkes 2008: 164):

- Local-scale expertise
- Climate history and baseline data
- Research questions and hypotheses developed from the frontlines of climate change
- Insight into the impacts of climate disasters and community adaptation methods
- Long-term community-based monitoring
- Governance and enforcement strategies for sustainable land-management principles
- Lessons about adaptable and eco-based design for modern applications

On a smaller scale, thousands of the globe's most vulnerable coastal communities lose a way to produce food locally.

In doing so, they also lose time-tested conservation methods; a direct connection to centuries of traditions, language, ceremonies, and songs; and an opportunity for an active lifestyle that supports the physical demands of specialized food practices (Pascua et al. 2017 especially table 2). This lifestyle includes hands-on skills that have been passed down generationally, such as masonry, paddling, small-boat handling, and net making and repair. Many native peoples directly connect these skills to physical fitness, increased health, self-sufficiency, and overall resilience. (Lindholm 2019 and Mihesuah 2019) The Hawaiians refer to the connection as *ola mau* (Pascua et al. 2017). Without it, coastal communities are more vulnerable to stronger storms, SLR, declining fisheries, and other climate change disasters.

Conclusion

Indigenous aquaculture is not an answer for feeding the planet. Their integrated-ecosystem designs, which sustainably function without external feeds or inputs, inherently can not be scaled up without losing the integrity of the system. But this does not limit them to exist as historical relics or protected cultural heritage sites. Nor does humanity need to revert to traditionalism to incorporate these systems' biomimicry and holistic resource management into small-scale food production and environmental conservation.

Duarte et. al 2020 recently echoed the current prevailing idea that climate solutions need to be "deployed at scale." COVID-19, hit the developed world merely weeks later, perhaps reminding us of something our communities once valued: eating and managing resources locally. Even Duarte et al. admits "locally designed approaches may be most effective" and solutions "should remain flexible to cultural settings." Indigenous aquaculture and its foundation of hyper-local knowledge is one locally designed and culturally appropriate approach that can be invested in as part of a larger, diverse portfolio of food security and marine conservation implementations. Here's how:

Short-term

- Restore to productivity the indigenous aquaculture systems that currently remain. This means continually funding the two clam gardens in British Columbia that have begun restoration and the approximately 60 remaining loko iʻa.

Mid-term

- Indigenous aquaculture can be prescribed compensatory government mitigation sites for American military and development projects. This would facilitate a sustainable revenue stream for the aquaculture systems while providing a continual source of watershed restoration and management. This has recently started with the American Navy and Mālama Puʻuola, a loko iʻa restoration effort in Pearl Harbor.

- The indigenous aquaculture community and the Collaborative Hub should continue to identify and document other indigenous aquaculture systems around the globe.

- More detailed conversations with state and federal governments are required to develop the locally based governance and co-management strategies needed to maintain these systems and fairly distribute the food they produce to the community.

Long-term

- Reports should be written deducing how indigenous aquaculture's foundational TEK and best available Western science can influence large-scale food production.
- Once existing indigenous aquaculture systems are back up and running, and the necessary frameworks are in place for governance and food distribution, new indigenous aquaculture systems can be built in their culturally and ecologically appropriate locations. Although small in scale, their collective resurgence can have large global implications.

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