Net Gains: Customary Fishing Structures

and the

Evolution of Marine Resource Management in Remote Oceania

by

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DISSERTATION ABSTRACT

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Doctor of Philosophy in Anthropology

Title: Net Gains*:* Customary Fishing Structures and the Evolution of Marine Resource Management in Remote Oceania

Oceania's vast expanse of islands offers a natural laboratory for studying human adaptation amid ecological uncertainty. Across Remote Oceania, Indigenous communities developed ingenious coastal subsistence systems, including customary fishing structures such as fishponds, tidal weirs, fish traps, and aggregation devices. This dissertation examines these features to clarify their role in the evolution of marine resource management and to better understand how Pacific Island societies engineered coastal environments over the long term. Although such structures represent a near-universal adaptation among coastal peoples, they remain underrepresented in archaeological scholarship. By examining the spatial distribution of simple stone weirs in Fiji (*moka*) and analyzing the form, labor demands, and governance implications of ancient Hawaiian fishponds (*loko i'a*), this study uses comparative case studies to explore how socioecological pressures shaped adaptive marine infrastructure in the Pacific Islands. A multi-scalar approach integrating archaeological survey, remote sensing, spatial analysis, experimental reconstruction, and agent-based modeling identifies patterns in development, persistence, and failure. It also shows how these systems were shaped by environmental opportunity, labor coordination, and long-term strategies of collective management under variable island conditions. The findings show that customary fishing structures were not peripheral technologies but engineered socioecological systems through

which Pacific communities intensified production, organized labor, and governed access to marine resources, while also creating durable and place-based strategies for resilience in dynamic coastal settings.

Keywords: *Oceania; aquaculture; marine resource management; marine infrastructure.*

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This dissertation bears my name, but it does not belong to me alone.

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1. INTRODUCTION

1.1 Research Problem

Customary aquatic resource management has long been neglected in Oceanic archaeology, reflecting a broader disciplinary bias that favors terrestrial agriculture over marine innovations. Ancient fish traps, stone weirs, shoreline fishponds, and other aquacultural structures are known from historical accounts and Indigenous knowledge throughout the Pacific, yet archaeologists have only begun systematically studying this maritime adaptation (Erlandson 2001; Erlandson and Fitzpatrick 2006; Malindine 2019; Fitzpatrick 2020; Costa-Pierce 2022). The use of such fishing structures is nearly universal among coastal societies globally, attesting to convergent solutions for mass harvesting of marine resources. While their basic function, to catch or raise aquatic food, is simple in concept, these systems' designs and ecological integrations vary significantly by region and environment (Farber and Halapua 2002; Connaway 2007). This high variability and challenges in archaeological visibility due to the perishable nature of some materials used in construction and/or coastal dynamism mean that much about these structures remains poorly understood in archaeological literature (Erlandson and Fitzpatrick 2006; Erlandson 2012).

Recent research in anthropological aquaculture underscores that these practices were not marginal quirks, but fundamental food production strategies that deserve inclusion in narratives of prehistoric agriculture and social complexity. For example, Malindine (2019) surveys case studies from Asia, Oceania, and the Americas to argue that early forms of aquaculture constituted actual farming of aquatic species, effectively an analog to agriculture, and thus should be recognized as a key component of human subsistence evolution. In the Pacific,

ethnohistoric and archaeological evidence reveals sophisticated marine management systems (Kikuchi 1976; Erlandson and Rick 2010; Malindine 2019; Fitzpatrick 2020). Hawaiians, for instance, constructed hundreds of coastal fishponds (*loko i'a*) by the late first millennium CE, an aquacultural feat that yielded reliable harvests and even influenced the development of social stratification (Stokes 1909; Summers 1964; Kikiloi 2003; Costa-Pierce 2022). Across Oceania, many coastal communities employed reef pass weirs, tidal traps, and other installations to catch fish and steward and enhance local marine stocks. However, until recently, such customary aquaculture has been under-recognized in archaeological theory, often dismissed as opportunistic foraging rather than deliberate resource management (Moir 1993; Costa-Pierce 2022).

This dissertation directly addresses that oversight. It investigates how Pacific Island societies engineered and adapted fishing structures over time, contributing to a more balanced understanding of past human subsistence intensification beyond the agrarian bias. In doing so, it confronts a key disciplinary problem: the tendency to overlook marine resource innovation in constructions of cultural evolution (Erlandson 2001; Erlandson and Fitzpatrick 2006; Braje et al. 2017). By bringing together archaeology, historical ecology, and Indigenous perspectives, the study reframes Pacific Islanders as fishers on the margins and pioneers of early aquaculture whose practices were integral to their survival, social organization, and environmental knowledge (Kikiloi 2003; Rogers 2024).

This dissertation argues that customary fishing structures in Remote Oceania were not peripheral or opportunistic features of island subsistence, but durable forms of adaptive marine infrastructure through which Pacific Island communities engineered coastal environments, intensified production, organized labor, and negotiated social power (Erlandson and Rick 2010; Fitzpatrick 2020; Fitzpatrick and Giovas 2021). Rather than treating fishponds, tidal weirs, and

related features as isolated technologies or local curiosities, this study interprets them as material expressions of niche construction, collective action, and long-term marine resource governance.

Recent scholarship demonstrates that aquaculture has deep global antiquity, with documented traditions extending back at least 8,000 years (Rogers 2024). A structural pattern emerges worldwide: societies independently developed aquacultural solutions whenever human demand for seafood outstripped what wild ecosystems could sustainably provide (Costa-Pierce 2022). Viewed in this light, the prevalence of fish weirs and ponds across Remote Oceania is not anomalous, but part of a broader human tendency to innovate food production in challenging settings. What remains unclear, and forms the core research problem, is how these Oceanic systems varied across islands and what factors governed their success or failure over the long term. By tackling these questions, my research fills an important gap and highlights the intellectual merit of studying customary fishing structures: I expand archaeological theory to encompass maritime adaptations and improve upon what has been done previously, and I test ideas of ecological pragmatism, innovation, and resilience in island societies (Erlandson 2001; Fitzpatrick 2020; Braje et al. 2017).

1.2 General Research Objective

This research investigates customary fishing structures in two Pacific Island regions, Fiji and Hawai‘i, to understand the socioecological pressures that contributed to the development and diversification of Indigenous aquaculture. Specifically, this comparative study examines how and why Pacific Island communities invested in marine husbandry and what this reveals about human-environment interactions in island ecosystems. Fiji offers a case of widespread simple tidal weirs (known locally as *moka*) scattered across an archipelago, while Hawai‘i provides an example of elaborate walled fishponds (*loko i‘a*) intensively engineered for stock cultivation. By

examining both cases, along with references to analogous practices in proximal regions such as traditional fish traps in Australia and the Pacific Northwest, this dissertation identifies common drivers and divergent pathways in the evolution of Pacific aquacultural systems (Oliver 2002; Lepofsky et al. 2015; Costa-Pierce 2022). More importantly, it argues that these systems are best understood not as isolated technological responses, but as forms of adaptive marine infrastructure shaped by ecology, labor, and governance.

This objective is pursued through a multi-scalar methodological framework in which archaeological field and remote-sensing surveys locate and document fishing structures across varied landscapes and seascapes. These empirical data provide the basis for spatial analysis of the structures' environmental context, construction patterns, and regional distribution. In parallel, insights from experimental archaeology, including a partial reconstruction of a Hawaiian fishpond wall, help evaluate the material and labor investments required, shedding light on the engineering knowledge and socio-political organization behind these features (Kikuchi 1976; Farber and Halapua 2002). Rather than treating these lines of evidence as separate exercises, this study brings them together to show how customary fishing structures materialized distinct forms of marine intensification and collective action.

Additionally, agent-based simulations employ computational modeling to explore the long-term dynamics of fishpond use under varying social and ecological scenarios. By integrating these approaches, my research tests hypotheses about how Pacific communities responded to resource stress, population pressure, and environmental change through innovation in marine resource management (Morrison and Addison 2008; Romanowska et al. 2019). An underlying premise of this work is that studying the archaeology of aquaculture illuminates broader principles of human adaptation. Pacific Islanders faced highly variable conditions, from

Fiji's rich estuaries to Hawai‘i's isolated shores, yet in each case they developed strategies to enhance food security from the sea. The question is not simply whether these strategies emerged as convergent responses to everyday pressures, such as reef depletion or climate fluctuations, or from culturally distinct priorities and opportunities, but how those pressures and priorities were translated into durable socioecological systems (Fitzhugh et al. 2019). By addressing this question, the dissertation advances our understanding of cultural and biological evolution in island settings. Crucially, this approach blends local ecological knowledge with scientific analysis and responds to calls to bridge traditional knowledge and Western science in resource management studies (Berkes 2008).

In sum, the research objective is both descriptive and analytical. It documents where and how these structures were used, but it also explains why customary aquaculture emerged, persisted in specific contexts, and failed or was abandoned in others. In doing so, the dissertation contributes fresh data and perspectives to broader debates in archaeology and historical ecology concerning intensification, sustainability, and human ecodynamics in coastal environments (Fitzpatrick and Intoh 2009; Fitzhugh et al. 2019). The knowledge gained carries implications beyond Pacific archaeology, offering insight into the conditions under which humans innovate food production strategies in what might be considered to be marginal environments. This remains a pressing issue in the current era of environmental uncertainty (Erlandson and Braje 2013; Rick et al. 2013; Braje et al. 2017).

1.3 Specific Research Questions

To implement these objectives, the dissertation is organized around three key research questions:

1) Where are customary fishing structures found in Remote Oceania, and what does their distribution reveal about adaptive marine infrastructure?

Focus – Fiji Spatial Analysis (Chapter 4): What is the geographic distribution of traditional fishing weirs (*moka*) in the Fijian archipelago, and what spatial or environmental patterns emerge from their locations? This question addresses the extent of aquatic resource infrastructure in Fiji, using GIS mapping and environmental data to determine whether factors such as rainfall, coastal geomorphology, and access to productive marine settings influenced where communities built permanent fishing structures. In doing so, it evaluates how environmental opportunity and constraint shaped the placement of these features within a broader socioecological landscape. An example of the traditional fishing weirs (*moka*) discussed in this chapter can be seen in Figure 1.



Figure 1. Photo of Fijian customary fishing structure (tidal weir) known as *moka* on the island of Nananu-i-Ra. (Sailors 2013).

2) What are the formal and functional characteristics of customary fishing structures in Remote Oceania, and what do they reveal about labor, engineering, and social organization?

Focus – Experimental Fishpond Reconstruction (Chapter 5): What are the material, energetic, and labor requirements of constructing and maintaining customary Hawaiian fishponds (*loko iʻa*), and how do these architectural features reflect their roles in subsistence and social organization? This question explores how form and function co-evolved by investigating the design principles of fishpond construction, including wall architecture and sluice gate technology, as well as the practical demands of maintenance and repair. It also examines how fishponds operated within Hawaiian socio-political systems, where they were often managed by chiefly elites and integrated into the *ahupuaʻa* land division system. More broadly, this question asks how durable marine infrastructure materialized relationships among engineering knowledge,

labor coordination, and political authority. An example of a Hawaiian fishpond can be seen in Figure 2.



Figure 2. Photo of Hawaiian customary fishing structure (fishpond) known as *loko iʻa* on the island of Molokaʻi. (Kanda 2019).

3) What socioenvironmental parameters influenced the adaptive trajectories of customary aquaculture systems in these Pacific Island contexts?

Focus – Agent-Based Modeling (Chapter 6): How do variables such as community cooperation, resource ownership norms, ecological feedback loops, and enforcement of use-rights affect the resilience or decline of customary fishpond systems in an island context? This question uses simulation modeling to test which conditions, such as equitable management versus over-exploitation or relative climatic stability versus increased storm frequency, best explain the trajectories observed in the archaeological and historical records. It seeks to identify tipping points or thresholds beyond which these aquacultural systems thrived for centuries or fell into disuse. In this way, the model evaluates how governance, environmental variability, and collective action shaped the long-term sustainability of customary marine management.

Through these questions, the study links evidence across different scales, from individual sites and architectural features to regional patterns and theoretical models. Each question corresponds to a set of methods and a dissertation chapter, but together they address a shared argument: that customary fishing structures were not simply practical subsistence features, but adaptive marine infrastructure shaped by ecology, labor investment, and systems of governance. Taken together, these questions allow the dissertation to evaluate how Pacific Island communities engineered coastal environments, intensified production, and negotiated social power through long-term marine resource management.

1.4 Projected Outcomes

This research yields outcomes with both significant scholarly impact and tangible benefits for Pacific communities. Intellectually, the project enriches archaeological understanding of how humans manage marine resources over the long term. Systematically analyzing customary fishing structures provides data that helps bridge a gap in Pacific archaeology and paleoecology, integrating the marine realm into broader discussions of subsistence intensification and environmental adaptation (Rick et al. 2013; Kirch 2017). The results challenge and refine existing models of Pacific Island economies, which have traditionally emphasized horticulture and terrestrial foraging while treating aquaculture as peripheral. By demonstrating the complexity and ubiquity of Indigenous aquaculture in Oceania, this dissertation shifts perspective and encourages archaeologists to include maritime food production in comparative studies of cultural development (Costa-Pierce 2022; Malindine 2019). In doing so, it aligns with and contributes to the growing field of historical ecology, which recognizes islands and coastal zones as key contexts for understanding human-environment

interactions over millennia (Athens 1997; Kirch and Hunt 1997; Erlandson and Fitzpatrick 2006; Braje et al. 2017).

On a methodological level, the project's combination of field archaeology, experimental reconstruction, and computational modeling serves as a case study in interdisciplinary research. The findings, whether patterns of fish weir placement in Fiji or modeled outcomes of fishpond use in Hawai‘i, provide a foundation for further comparative analyses in other regions. Broader impacts are also central to this work. Locally, the research process and outcomes are intended to be shared with Pacific Island communities and organizations dedicated to cultural and environmental stewardship. For instance, Fiji's fish weir survey findings may assist heritage managers and community leaders in recognizing and preserving these traditional sites as part of their coastal heritage. In Hawai‘i, this project has been developed in consultation with practitioners involved in fishpond restoration initiatives, especially with Paepae o He‘eia (O‘ahu), a non-profit with which I have volunteered for many years, ensuring that the experimental insights on construction and maintenance remain grounded in contemporary practice (Paepae o He‘eia 2025). Community workshops and educational outreach, including contributions to curricula on Pacific Island studies at the University of Oregon, the University of Hawai‘i at Mānoa, and the University of the South Pacific, provide pathways for disseminating this knowledge in accessible forms. By engaging local stakeholders, the research honors the living heritage of customary fishing practices and supports ongoing efforts to revitalize these systems for food security and cultural identity (Lepofsky et al. 2015). On a regional scale, this dissertation strengthens collaborative networks among scholars and Indigenous experts across Oceania. Through joint field training and shared dialogue, it builds on relationships with researchers and educators in Fiji, Vanuatu, the Solomon Islands, Tuvalu, and Kiribati. These

connections help ensure that the research addresses Pacific priorities, including adaptation of climate change and sustainable resource management, alongside academic questions.

One of the broader goals of this dissertation is to contribute lessons from the past to present-day challenges. Pacific Island societies are on the front lines of climate change, facing threats such as sea-level rise, coral reef degradation, and declining wild fisheries (Nunn 2003; Adger et al. 2005). At the same time, Pacific history shows that Islanders have dealt with environmental instability for centuries, adapting creatively to sea-level fluctuations and marine productivity (Allen 2006). Many traditional practices, for example alternating the use of multiple fishponds to avoid overtaxing a single stock or coordinating communal labor to maintain extensive trap systems, illustrate principles of adaptive management that remain highly relevant (Johannes 2002). By empirically investigating these practices, archaeology can recover valuable knowledge about sustainability. The local ecological knowledge encoded in customary fishing structures, through their placement, construction, seasonal use, and maintenance, represents accumulated knowledge about living within island constraints (Berkes 2008). This dissertation highlights how specific strategies, such as careful stewardship of pond broodstock or cooperative enforcement of taboo periods on fishing, contributed to long-term resilience, while other systems may have faltered under social or environmental stress. Such insights can inform modern resource management and conservation efforts, effectively bringing past and present approaches into dialogue (Erlandson and Braje 2013). Indeed, there is growing recognition within the scientific community that traditional practices and narratives hold important lessons for future sustainability (Erickson and Gowdy 2000). In the context of aquaculture revival across Oceania, from Hawaiian fishpond restoration to renewed interest in Indigenous shellfish and fisheries management elsewhere in the Pacific, this research provides a deep-time perspective that can

help guide and inspire contemporary initiatives. By communicating findings through reports, community presentations, and open-access publications, the project seeks to ensure that these broader impacts extend beyond the dissertation itself.

In summary, the outcomes of this work are both intellectually and practically significant. They advance scholarly debates on human adaptation and resource management, contribute to decolonizing and diversifying archaeological narratives, and support Pacific Island communities in reaffirming sustainable practices rooted in their heritage. This project has also been recognized for its intellectual merit and broader impacts through support from the National Science Foundation's Graduate Research Fellowship Program.

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1.5 Dissertation Structure

Following this introduction, the dissertation is organized into eight main chapters, each of which builds on the last to develop a comprehensive analysis of customary fishing structures in Remote Oceania. This dissertation includes previously published co-authored material. Portions of Chapter 3, especially the discussion in Section 3.2 on remote sensing in coastal archaeology, are adapted from previously published work co-authored with Scott S. Honda (Sailors and Honda 2013). Honda contributed to the acquisition and processing of remote-sensing data and to the technical interpretation of the imagery. I developed the archaeological framing of the study, conducted the field documentation and GIS analysis, interpreted the results, and revised the material for inclusion in this dissertation.

- **Chapter 2 – Literature Review:**

  This chapter situates the research within the broader scholarly context. It reviews relevant literature on Pacific Island environmental history, Indigenous subsistence practices, and archaeological studies of coastal adaptations. Key theoretical and conceptual frameworks are introduced here, including historical ecology, niche construction, and models of agricultural and aquacultural intensification. The chapter highlights previous findings on the importance of islands as "model systems" for studying human-environment dynamics, while also addressing the historiography of aquaculture in archaeology and examining why fishponds, weirs, and other customary marine features have been underrepresented in past research. It further underscores recent calls for greater integration of aquaculture into narratives of Pacific prehistory. In doing so, Chapter 2 establishes the scholarly gap this study addresses and provides the comparative and conceptual foundation for interpreting customary fishing structures as adaptive marine infrastructure rather than peripheral subsistence features.

- **Chapter 3 – Methods and Theory:**

  This chapter outlines the research design, analytical methods, and theoretical framework used to answer the questions posed in this dissertation. It describes the field methodologies for data collection in Fiji and Hawai‘i, including remote sensing surveys utilizing satellite and aerial imagery to locate possible fishing structure sites, on-the-ground archaeological mapping, and experimental methods. The experimental archaeology component, including the reconstruction of elements of a Hawaiian fishpond, is detailed to show how construction metrics and observations were recorded and how labor, materials, and engineering knowledge can be evaluated archaeologically.

Chapter 3 also explains the agent-based modeling approach developed to simulate fishpond management scenarios, including key parameters and assumptions such as community size, fish growth rates, access rules, and ecological variability. The theoretical underpinnings of the study are discussed through concepts drawn from evolutionary anthropology and historical ecology, especially niche construction, resilience, and collective management. Together, these methods and frameworks establish the credibility of the research and provide the basis for evaluating customary fishing structures as socioecological systems shaped by ecology, labor, and governance.

- **Chapters 4, 5, and 6 – Data and Analysis:**

  As the dissertation's analytical core, the following three chapters are three case-study-driven sections corresponding to the specific research questions. Chapter 4 presents the results of the Fiji spatial analysis, cataloguing *moka* fishing structures and mapping their distribution across islands and environmental zones. Spatial statistics are used to identify patterns or clustering in relation to environmental variables, allowing interpretation of how Fijian communities selected locations for communal fish traps and how local conditions constrained or favored forms of infrastructure. Chapter 5 focuses on the Hawaiian fishpond study, providing a detailed account of select *loko i'a*, including measurements of rock wall dimensions, sluice gate remnants, and pond area, alongside the outcomes of experimental reconstruction such as estimated labor hours, material sourcing requirements, and construction challenges. Quantitative and qualitative evidence are combined to evaluate the efficiency, engineering knowledge, and social organization implied by fishpond technology. Chapter 6 presents the agent-based model simulations, using a parameter sweep of management and ecological scenarios to evaluate how

different forms of cooperation, enforcement, ownership norms, and environmental stress shaped system resilience or decline. Graphs and tables illustrate outputs such as long-term fish yield trends, population stability, and conditions associated with persistence or collapse. For each of these chapters, the results are linked directly to the research questions, and interim summaries synthesize how each line of evidence contributes to the larger argument. Comparative discussion between Fiji and Hawai‘i highlights contrasts such as the more decentralized and distributed character of Fijian weirs versus the larger-scale, labor-intensive, and more politically embedded Hawaiian fishponds. These comparisons help clarify that customary fishing structures followed different trajectories, but in both cases functioned as adaptive marine infrastructure.

- **Chapter 7 – Discussion:**

  This brief chapter weaves together the analytical threads of the dissertation to address its broader implications. It interprets the significance of the findings within Pacific archaeology and beyond, asking what these cases reveal about marine intensification, human-environment interaction, and the conditions under which customary aquaculture emerged and persisted. Rather than treating Fiji and Hawai‘i as points along a single evolutionary sequence, Chapter 7 argues that they represent different but comparable pathways of socioecological adaptation. The discussion places the findings within the context of historical ecology and niche construction, showing how Pacific Island communities engineered coastal environments in ways that reshaped both marine habitats and social relations. It also examines the relationship between infrastructure, labor investment, and governance, including the extent to which more intensive systems required greater coordination, political authority, or maintenance. At the same time, the

chapter considers sustainability, resilience, and implications of these findings for present-day restoration ecology and community-based fishery management. Any unexpected findings or anomalies are addressed here as well. By the end of Chapter 7, the reader is presented with a synthesis of customary fishing structures as enduring adaptive strategies that illuminate broader questions of resilience, intensification, and social power.

- **Chapter 8 – Conclusion:**

  In the final chapter, I summarize the dissertation's principal contributions and suggests avenues for future inquiry. It reflects on the main takeaway that ancient aquaculture and customary fishing structures provide critical insight into human innovation, long-term environmental engineering, and the sophistication of Pacific Island resource management systems. The conclusion revisits the central argument that these features were not marginal subsistence technologies, but durable forms of adaptive marine infrastructure through which communities intensified production, organized labor, and negotiated access to coastal resources. It also addresses the study's limitations, including gaps in the archaeological record and uncertainties inherent in modeling, to clarify the scope of the conclusions. From there, the chapter outlines future research directions, including expanded archaeological survey in other island groups, paleoenvironmental work on ancient aquaculture ecologies, and ethnoarchaeological collaboration with Pacific communities who continue to maintain or revitalize these traditions. The dissertation closes by returning to the broader significance of the project: that the study of customary fishing structures offers not only an archaeological contribution, but also a long-term perspective on sustainability, adaptation, and the human capacity to respond creatively to environmental uncertainty.

2. LITERATURE REVIEW

2.1 Islands of Opportunity: Settlement and Adaptation in Hawai‘i and Fiji

2.1.1 Introduction

The Pacific Islands provide a powerful comparative setting for examining human migration, adaptation, and environmental interaction. Hawai‘i and Fiji are especially useful case studies because they differ sharply in geological history, climate, and ecological isolation, yet both were settled by Austronesian-speaking peoples who had to establish viable subsistence systems in island environments (Blust 2013, 2019). Comparing them helps clarify how environmental opportunity and constraint shaped early settlement, resource use, and later trajectories of sociopolitical development (Kirch 1980, 1985; Nunn 1998).

The timing and context of settlement differed substantially. Fiji was colonized during the Lapita expansion around 1100–900 BCE, whereas Hawai‘i, one of the most isolated archipelagos on Earth, was reached much later, roughly between 1000 and 1200 CE (Groube 1975; Best 1984; Wilmshurst et al. 2011). That disparity matters because it placed the two archipelagos in very different regional and ecological worlds. Fiji was settled early, within a relatively interconnected southwestern Pacific sphere, while Hawai‘i was occupied late and under conditions of extreme isolation. Those differences shaped not only subsistence opportunities but also the degree to which people needed to intensify production, modify landscapes, and reorganize social life around limited resources (Ladefoged 2009; Cochrane 2018).

This section examines the geology, climate, ecological setting, and archaeological evidence of adaptation in Hawai‘i and Fiji to show how island environments conditioned human responses in distinct ways. The goal is not simply to catalog environmental contrasts, but to

identify why those contrasts matter for the larger dissertation. Hawai‘i and Fiji represent two different pathways of island adaptation: one marked by extreme isolation, constrained biota, and heavy later intensification; the other by greater ecological diversity, broader subsistence options, and more regionally connected forms of development. That comparison provides the environmental and historical context for later discussions of marine intensification, labor investment, and customary fishing structures.

2.1.2 Geological and Geographical Context

Hawai‘i and Fiji were both formed through volcanic processes, but their tectonic settings and resulting geographies differ in ways that had major consequences for human adaptation. Hawai‘i is a hotspot archipelago formed as the Pacific Plate moved over a fixed mantle plume, producing a chain of high volcanic islands that increase in age from southeast to northwest (Neall and Trewick 2008; Sinton and Sherrod 2021). The youngest island, Hawai‘i Island, remains volcanically active, while older islands such as O‘ahu and Kaua‘i are more deeply eroded. This age progression created steep shield volcanoes, narrow valleys, and relatively limited coastal plains. Freshwater was unevenly distributed, concentrated mainly on windward sides where perennial streams were sustained by orographic rainfall. Soil fertility also varied with age and weathering, with some older landscapes showing nutrient depletion due to prolonged leaching (Kirch 1984, 2010). The broader geographic settings of Hawai‘i and Fiji are shown in Figures 3 and 4.

The biological setting of Hawai‘i was equally consequential. Because the archipelago lies roughly 3,800 km from the nearest continent, it evolved with an extremely limited native biota. Before human arrival, there were no terrestrial mammals other than bats, few edible native plants, and a marine fauna that, while important, was less diverse than that of the western Pacific

(Carlquist 1998; Burney 2002). In practical terms, Hawai‘i offered impressive topographic variety but a highly constrained resource base. Productive land was fragmented, freshwater was patchy, and the native flora and fauna could not support dense human populations without major ecological modification (Ladefoged 2009).

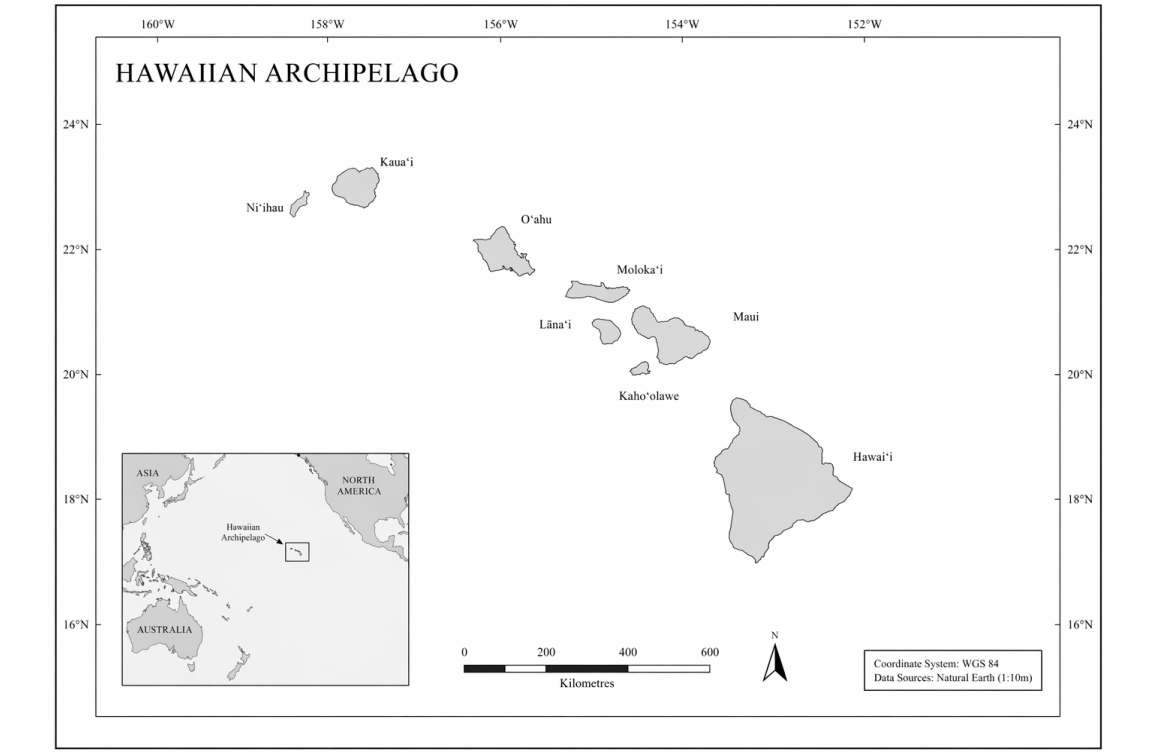

Figure 3. Map of the Hawaiian Archipelago.

Fiji presents a very different geographic setting. Located near the boundary of the Indo-Australian and Pacific plates, Fiji includes volcanic high islands, uplifted limestone islands, reef platforms, and coral atolls, creating a more geologically diverse archipelago than Hawai‘i (Nunn 1998). The two largest islands, Viti Levu and Vanua Levu, contain mountain interiors, broad river valleys, and substantial coastal plains. Uplifted reef limestones and karst landscapes occur in some areas, while eastern island groups include lower coralline and limestone landforms. This geodiversity produced a much wider range of habitats: volcanic uplands, alluvial deltas,

estuaries, mangrove margins, lagoon systems, and extensive fringing and barrier reefs (Clark and Anderson 2001).

Fiji was also less isolated biologically. Its proximity to Melanesia meant that a broader range of plants and animals colonized the islands before human arrival, including fruit bats (Family Pteropodidae), reptiles, and a richer terrestrial flora. Its marine habitats were especially productive, with extensive reef systems supporting abundant fish and shellfish (Nunn 1998; Cochrane 2018). The archipelago's larger river systems also created fertile alluvial zones well suited to cultivation. Compared with Hawai‘i, Fiji offered early settlers a more forgiving and varied environmental mosaic, one in which horticulture, fishing, foraging, and inter-island interaction could be combined rather than forced into a narrow set of options (Coulter et al. 1983; Parry 1994).

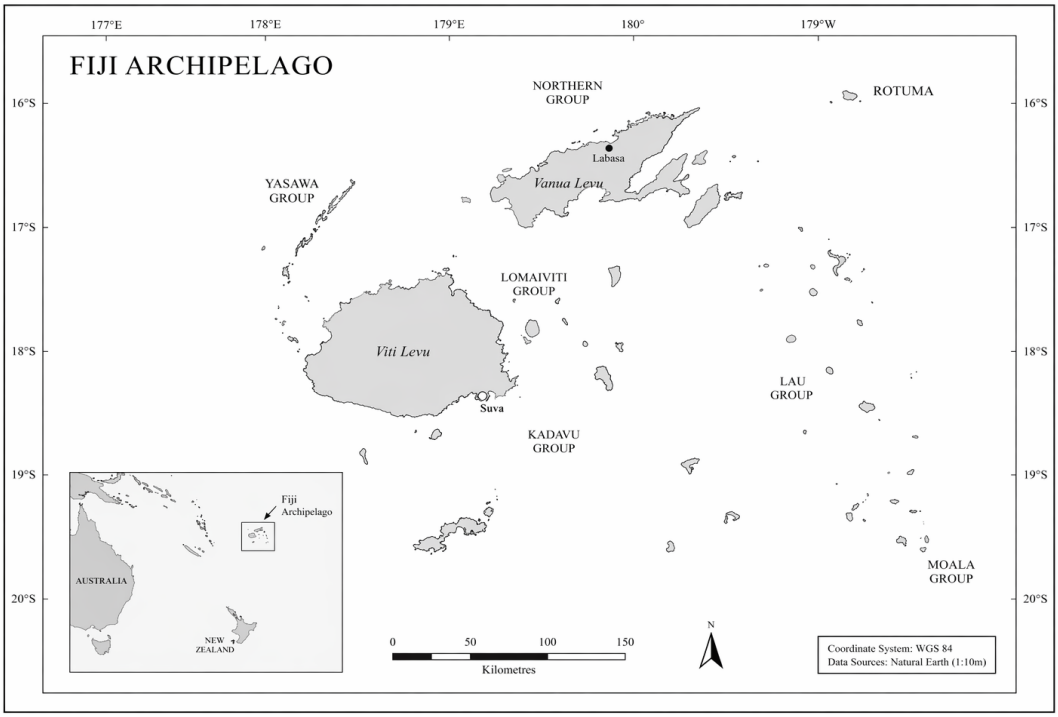

Figure 4. Map of Fiji Islands.

These differences in geological and geographical setting mattered directly for settlement and subsistence. In Hawai‘i, arable land was concentrated in select valleys, slopes, and coastal zones, which likely encouraged later competition and intensification (Kirch 2010). The limited native biota also meant that settlers had to depend heavily on introduced crops and animals. In Fiji, by contrast, wide river valleys, older soils, wetlands, and nearby reefs supported a broader and more flexible subsistence base from the outset (Best 1984; Field 2004). That contrast is important for the larger argument of this dissertation. It helps explain why Hawai‘i became a setting for especially intensive agricultural and aquacultural engineering, while Fiji supported a more distributed pattern of adaptation drawing on agriculture, marine harvesting, and exchange across varied island environments.

2.1.3 Climate and Environmental Influences on Settlement Patterns

Climate added another major layer of contrast between the two archipelagos. Hawai‘i’s climate is dominated by the northeast trade winds and strong orographic effects. Moist air rises over the high islands, producing abundant rainfall on windward slopes while leaving leeward zones in rain shadow (Carlquist 1998). As a result, rainfall varies sharply across short distances. Windward valleys and coastal plains could support irrigated taro and perennial freshwater supplies, while many leeward districts were semi-arid and initially much less attractive for dense settlement. This strong environmental zonation shaped early habitation patterns and later agricultural development.

Hawaiians initially concentrated in areas where rainfall, cultivable soils, and freshwater were most reliable, especially in windward valleys and coastal lowlands (Kirch and Hunt 1997; Kirch 2012). Over time, however, they also developed strategies to exploit drier landscapes. On wet sides of the islands, irrigation systems supported *lo‘i kalo* and intensive taro production. On

leeward slopes, dryland systems used rock alignments, mulching, and careful management of rainfall gradients to support crops such as sweet potato or breadfruit (Yen 1974, 1980; Ladefoged and Graves 2000; Ladefoged et al. 2011). Hawai‘i’s climate was thus not simply restrictive; it created a series of sharply differentiated ecological zones that rewarded spatial specialization and local engineering.

Although Hawai‘i lacks the cyclone regimes characteristic of the southwest Pacific, it was hardly climatically stable in every respect. Interannual variation, especially during El Niño events, can lead to severe droughts in otherwise productive areas (Goodwin et al. 2014; Frazier et al. 2022). Those episodes would have posed serious challenges for communities dependent on rain-fed or marginal agricultural zones, especially on leeward coasts (Ladefoged et al. 2011). The likelihood of periodic drought likely reinforced the value of intensification, food storage, and systems that buffer short-term climatic stress.

Fiji’s climate operated differently. Located within the South Pacific Convergence Zone, Fiji experiences a more pronounced seasonal tropical regime, with a pronounced wet season, a drier season, and frequent cyclone risk (Lal 2008). Annual rainfall is generally high but unevenly distributed, with wet windward zones and somewhat drier leeward zones. Even so, Fiji’s larger river systems and more extensive alluvial lowlands made water far more broadly available than in Hawai‘i. River deltas such as those of the Rewa and Dreketi created fertile, often water-rich environments well suited to taro and other crops (Parry 1994; Mataki et al. 2006).

This climatic regime encouraged a different style of adaptation. In Fiji, agricultural timing had to be synchronized with seasonal rainfall, and communities also had to cope with cyclones, flooding, and occasional storm-driven shortages (Kumar 2013; Cochrane 2018). Cyclones could destroy gardens, breadfruit stands, and coastal infrastructure, creating strong

incentives for food storage, diversification, and mutual aid (Nunn 1998). Settlement location was also affected: communities often balanced access to fertile lowlands with the need to avoid coastal inundation and storm damage (Nunn 1998; Kuhlken and Crosby 1999). In later prehistory, the increased use of fortified hilltop sites may have reflected not only conflict but also the need to secure food and territory during periods of instability (Field 2004a).

The contrast between the two archipelagos is instructive. Hawai‘i’s climate promoted sharp spatial contrasts, encouraging specialized exploitation of wet and dry zones through intensive landscape engineering. Fiji’s climate promoted seasonal flexibility, mixed strategies, and broader use of riverine and coastal environments. In both cases, climate influenced more than agriculture. It helped structure where people settled, how they managed risk, and how later systems of labor and resource control developed. For this dissertation, those differences matter because they help explain why later forms of marine and terrestrial intensification were embedded in distinct ecological and social settings rather than emerging as universal responses to island life.

2.1.4 Human Adaptation and the Role of Transported Landscapes

The settlement of both archipelagos depended on more than simply finding habitable land. It required the transfer and reorganization of subsistence systems. The concept of transported landscapes captures this process: settlers carried domesticated plants, animals, and management practices into unfamiliar island environments, then reshaped those environments to make them productive (Anderson and O’Connor 2008; Anderson 2009; Whistler 2009). Hawai‘i and Fiji both illustrate this process, but in different ways because their environmental baselines were so different.

In Hawai‘i, the importance of transported landscapes was absolute. The first settlers entered an extremely isolated environment with few species useful to humans (Ziegler 2002). Archaeobotanical and ethnohistoric evidence indicates that they introduced staple crops such as taro (*Colocasia esculenta*), breadfruit (*Artocarpus altilis*), banana (*Musa* spp.), sweet potato (*Ipomoea batatas*), coconut (*Cocos nucifera*), sugarcane (*Saccharum officinarum*), and ‘*awa* (*Piper methysticum*), along with pigs (*Sus scrofa*), dogs (*Canis lupus familiaris*), and chickens (*Gallus gallus domesticus*) (Hather and Kirch 1991; Athens 1997; Atkins 2013). Without these introductions, Hawai‘i could not have supported sustained human settlement at scale. The settlers effectively constructed a new food web, supplementing sparse native resources with an imported agricultural and domestic package. At the same time, introduced species such as the Polynesian rat (*Rattus exulans*) altered local ecologies and contributed to the decline of native birds, demonstrating that transported landscapes were never neutral transfers but engines of ecological change (Steadman 2006; Hunt and Lipo 2025).

Over time, Hawaiian communities transformed this imported package into a highly managed landscape. In windward valleys, irrigation systems created extensive *lo‘i kalo* complexes that converted wetlands and stream margins into productive taro fields (Kirch and McCoy 2023). In drier regions, Hawaiians engineered dryland field systems such as the Kohala complex, where large areas were structured through low stone alignments and careful management in face of marginal, environmental conditions (Ladefoged and Graves 2009; Ladefoged et al. 2011). On coasts, they developed fishponds that extended this same logic into the marine realm. By enclosing embayments and estuaries and managing the growth of juvenile fish, Hawaiians transformed portions of the shoreline into productive, semi-controlled food production systems (Kikuchi 1976; Costa-Pierce 1987; Kikiloi 2003). Taken together, these

strategies produced an increasingly anthropogenic environment in which agriculture, aquaculture, and agroforestry were integrated into long-term systems of intensification.

Fiji followed a different trajectory. Like the settlers of Hawai‘i, Lapita populations arriving around 1100–1000 BCE brought a transported suite of crops and domestic animals, including pigs, dogs, chickens, taro, yams (*Dioscorea* spp.), coconuts, and other cultigens (Spriggs 1984, 1995; Clark and Anderson 2001; Clark 2007). Hawai‘i also offered important marine resources and a range of productive local habitats, but Fiji differed in the breadth and density of its preexisting terrestrial and aquatic resource base. Its proximity to Melanesia and greater ecological diversity meant that fruit bats, birds, reef fish, shellfish, turtles, freshwater species, wetlands, and fertile alluvial lowlands were available in especially varied and accessible combinations. As a result, early Fijian settlements appear to have depended somewhat less exclusively on imported domesticates and instead combined introduced horticulture with broad-spectrum exploitation of abundant local resources (Nunn 1998, 2009; Jones and Quinn 2009).

This broader ecological base encouraged more flexible forms of adaptation. Many Fijian communities practiced shifting cultivation and agroforestry rather than immediately committing to the fixed, large-scale field systems later seen in Hawai‘i. Over time, however, intensification also emerged in Fiji. Archaeological evidence from some valleys suggests the expansion of irrigated taro cultivation and more formalized agricultural works, including terraced fields and canals (Kuhlken and Crosby 1999; Field 2005; Nunn 2009). Marine resource management also became more structured. As we the case in Hawai‘i, stone tidal traps and weirs on reef flats and channels used tidal movements to increase capture efficiency and required coordinated labor to build and maintain (Best 1984; Jennings and Polunin 1996). In some cases, wetland or pond-field

systems may have supported limited forms of integrated aquaculture, with fish or prawns raised alongside crops (Parry 1994).

What distinguishes Fiji is that these practices were layered onto a more heterogeneous environment. Rather than one dominant pathway of intensification, Fijian communities appear to have combined shifting cultivation, permanent wetland fields, agroforestry, marine harvesting, and inter-island exchange. Mangrove zones, estuaries, and more extensive reef systems also added resilience by providing shellfish, crabs, and other resources during periods of agricultural stress (Kuhlken et al. 1999; Jones and Quinn 2009). Over time, many Fijian landscapes became hybrid systems in which introduced crops, managed forests, cultivated wetlands, and controlled marine spaces were linked within broader village economies (Parry 1994).

In both archipelagos, then, transported landscapes were not merely imported biological packages. They were ongoing environmental engineering processes. Hawaiians, facing sharper ecological limits, built increasingly intensive and specialized agricultural and aquacultural systems (Kirch 2010). Fijians, working in a richer and more varied setting, developed more mixed and regionally flexible forms of adaptation (Nunn 2009). That contrast matters for this dissertation because it shows that later marine infrastructure did not emerge in a vacuum. Fishponds, traps, and other management systems were part of wider island strategies through which communities reorganized land, water, labor, and ecological knowledge to sustain life under different conditions of opportunity and constraint.

2.1.5 Archaeological Evidence of Social Complexity

The archaeological record in Hawai‘i and Fiji shows that intensification was accompanied by changes in sociopolitical organization, but the forms of complexity that emerged differed significantly. In Hawai‘i, increased control over productive land and aquatic

resources contributed to the rise of highly centralized, stratified chiefdoms. By the fifteenth and sixteenth centuries, the islands were organized into competing chiefly polities headed by *ali'i nui*, and the management of irrigated fields, dryland agricultural systems, and fishponds likely played a major role in that consolidation (Christaller 1966; Kirch 2010). Monumental architecture, especially large *heiau* and *luakini* temples, provides material evidence of the ability of elites to mobilize labor and surplus on a substantial scale (Kolb 1994; Kolb 1997). The same economic base that sustained temple construction also supported elite control over food production.

This process is visible archaeologically in the relationship between landscape modification and hierarchy. Large irrigation systems, extensive dryland field complexes, and major fishponds were not household-scale undertakings. They required coordination, labor management, and systems of authority capable of organizing and maintaining large productive landscapes. By the late prehistoric period, access to highly productive land and marine resources was increasingly mediated through chiefly institutions rather than remaining fully communal (Kirch 1990a, 2017). In this sense, Hawaiian social complexity was closely tied to environmental circumscription. Limited productive land and the need for intensive engineering helped drive the concentration of authority and the development of highly hierarchical political systems (Kelly 2025).

In Fiji, archaeological evidence also points to increasing social complexity, but in a more regionalized and heterarchical form. Fortified hilltop settlements are among the clearest indicators. Sites in the Sigatoka Valley and elsewhere on Viti Levu and Vanua Levu show that by the second millennium CE, communities were investing heavily in defense through ditches, embankments, terraces, and walls (Parry 1987; Field 2004b; Cochrane 2018). These features

suggest competition over land, labor, and productive environments, but they do not indicate the same degree of island-wide political integration seen in Hawai‘i.

Instead, Fijian complexity appears to have been distributed across multiple centers. Irrigated valley systems, fortified ridges, canoe-building traditions, and regional exchange networks indicate organized labor and chiefly authority, but geography limited the emergence of the kind of unified polities seen in Hawai‘i (Best 1984; Kuhlken et al. 1999). Numerous valleys, islands, and local ecological zones could each sustain influential chiefly groups. Thus, while Fiji clearly developed hierarchy, warfare, and specialized production, its political landscape remained more segmented (Field 2005). Rather than converging on single-island monarchies, Fiji sustained a network of competing and shifting chiefly centers (Field 2003).

The contrast is analytically important. In both archipelagos, richer, more productive zones became centers of power and social differentiation. In Hawai‘i, that process favored centralization because arable land and major productive systems were strongly circumscribed. In Fiji, similar pressures fostered hierarchy and conflict, but within a more distributed archipelagic setting. The comparison helps clarify that intensification did not automatically produce the same political outcome everywhere. Environmental structure shaped whether increased production and resource control encouraged tighter political integration or a more fragmented field of competing authorities.

2.1.6 Implications for Pacific Archaeology

The comparison between Hawai‘i and Fiji has broader implications for Pacific archaeology because it highlights how ecological isolation, climatic variability, and resource structure shaped divergent pathways of island adaptation (Kirch 2008). Hawai‘i demonstrates how extreme isolation and a constrained native biota could push societies toward heavy reliance

on transported species, large-scale landscape engineering, and increasingly centralized control over production (Kirch 2007; Gon et al. 2018). Fiji, by contrast, shows how broader ecological diversity and continued regional connectivity supported more mixed and flexible subsistence systems, even as agriculture and political hierarchy intensified (Jones and Quinn 2009; Field and Lape 2010).

This comparison is especially useful for the argument of this dissertation because it helps explain why marine intensification cannot be treated as a uniform Pacific phenomenon. The same broad Austronesian heritage produced different forms of adaptation under different island conditions. Hawai‘i and Fiji, therefore, serve not simply as contrasting case studies but as evidence that local ecology, isolation, and landscape structure conditioned how communities organized labor, controlled resources, and ultimately invested in durable food-production infrastructure.

2.1.7 Synthesis: Environmental Contrasts and Divergent Pathways of Island Adaptation

Taken together, the geological, climatic, and archaeological evidence from Hawai‘i and Fiji shows that island societies in Oceania did not uniformly respond to environmental conditions. Hawai‘i represents a case of extreme isolation, limited native biota, and later intensive niche construction through irrigated fields, dryland systems, fishponds, and increasingly centralized political control (Quintus and Cochrane 2018). Fiji represents a more ecologically varied and regionally connected setting in which adaptation drew on a broader combination of horticulture, fishing, agroforestry, and localized intensification. Both cases demonstrate strong human agency, but they also show that the range of viable strategies was conditioned by island size, ecological diversity, freshwater availability, and climatic risk (Kirch 2007; Ladefoged et al. 2009; Nunn 2009).

In the larger dissertation, this comparison establishes why Hawai‘i and Fiji are productive cases for studying marine resource management. Their differences illuminate the environmental and historical conditions under which customary fishing structures emerged, persisted, and took distinct forms. The Hawaiian–Fijian contrast, therefore, does more than frame early settlement; it helps explain why adaptive marine infrastructure developed differently across Oceania and why those differences must be understood in relation to broader island histories of ecology, labor, and social organization.

2.2 The Peopling of Oceania: Migration Models and Lines of Evidence

2.2.1 Introduction

The peopling of Oceania remains one of the most consequential episodes in human migration, not only because it involved the settlement of some of the most isolated islands on Earth, but because it created the ecological and social conditions from which later Pacific Island lifeways emerged. The spread of Austronesian-speaking peoples into Island Southeast Asia, Near Oceania, and Remote Oceania established the transported landscapes, subsistence strategies, and settlement ecologies that later shaped customary fishing structures, marine tenure, and forms of adaptive infrastructure (Reith and Cochrane 2018). Any effort to understand fishponds, tidal weirs, and related systems in Fiji and Hawai‘i must therefore begin with the broader history of how Pacific Islanders reached, occupied, and transformed island environments (Kirch and Ellison 1994; Hung et al. 2011; Blust 2019; Pugach et al. 2021; Bedford et al. 2023).

This section reviews the principal lines of evidence used to reconstruct that history: archaeology, genetics, and linguistics. Archaeology provides the primary record of settlement chronology, material culture, subsistence, and environmental modification on these islands (Bedford et al. 2023). Genetics offers evidence for ancestry, admixture, and population

movement, particularly through ancient DNA (aDNA) and genome-wide studies (Skoglund et al. 2016; Lipson et al. 2018; Pugach et al. 2021). Linguistics traces the dispersal and divergence of languages, helping clarify how Austronesian-speaking communities expanded and differentiated across the Pacific (Blust 2013, 2019). Taken together, these lines of evidence broadly support an Austronesian expansion from Taiwan through Island Southeast Asia, but they also show that the settlement of Oceania was not a single, simple eastward wave. Rather, it involved multiple regional trajectories, pauses, interactions, and local innovations.

A key distinction is necessary at the outset. Taiwan is central to most linguistic models of Austronesian origins, but Lapita culture did not originate there. Lapita emerged later in the Bismarck Archipelago as a distinct archaeological complex with its own ceramic tradition, exchange networks, and settlement practices, built upon centuries of maritime movements, innovation, and tradition (Green 1989; Spriggs 1995; Sheppard 2011). Keeping those trajectories separate avoids collapsing language history, biological ancestry, and archaeological culture into a single narrative. That distinction is especially important here because the goal is not simply to summarize Pacific settlement, but to identify which migration histories and island conditions later mattered for the development of marine intensification, ecological engineering, and localized systems of resource management (Bellwood 1987, 2005).

Because Fiji and Hawai‘i anchor the comparative framework of this dissertation, they remain the primary points of reference in this section. At the same time, a broader Oceanic perspective requires brief attention to other Pacific regions where settlement histories followed different chronological and ecological trajectories. Including these comparisons helps clarify that the peopling of Oceania did not unfold along a single uniform path, but through varied movements, interactions, and adaptations shaped by island geography, connectivity, and

environmental constraints (Spriggs and Anderson 2013). Framed in this way, the settlement record becomes more than a background chronology; it provides the wider context for understanding how Pacific Island communities established the transported landscapes, subsistence systems, and ecological knowledge that later enabled localized forms of marine intensification that contributed to the long-term resilience and sustainability of these Indigenous island communities. As shown in Figure 5, the Austronesian language family spread across a vast island world extending from Taiwan into Remote Oceania.

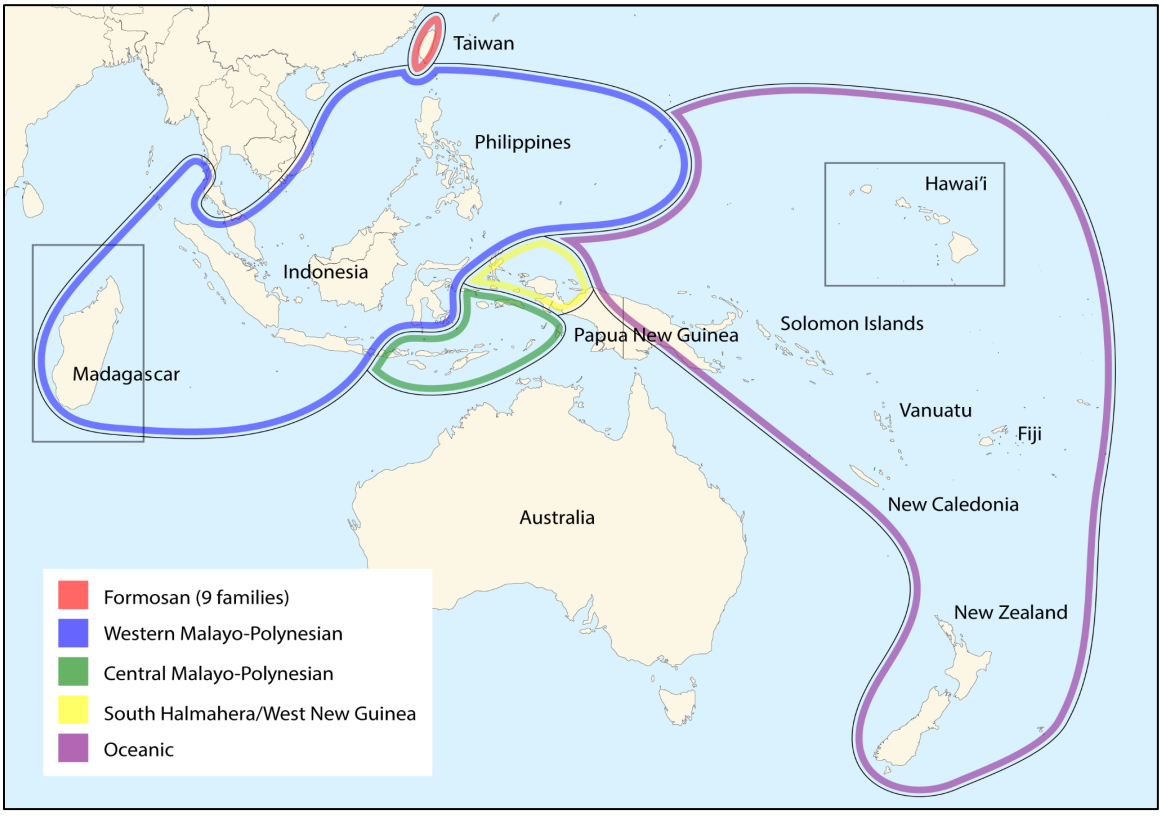

Figure 5. Map of Austronesian Language Dispersal. Blust (2013).

2.2.2 Austronesian Migration Models for Remote Oceania Settlement

The most widely accepted model for the spread of Austronesian-speaking peoples is some version of the "Out of Taiwan" hypothesis. In its broadest form, this model proposes that Austronesian languages, of which there are approximately 1200 worldwide, began diversifying in Taiwan and then spread southward through the northern Philippines and Island Southeast Asia

before contributing to later expansions into Oceania (Blust 2013; Bellwood 2017). This framework remains influential because it aligns linguistic subgrouping with broad archaeological and genetic patterns. At the same time, the archaeology of the Pacific makes clear that the emergence of Lapita was not simply the appearance of a ready-made "Taiwan package" in the remote islands. Lapita first appears in identifiable archaeological form in the Bismarck Archipelago around 3300 BP, where a distinct ceramic complex, maritime network, and colonizing tradition took shape before moving eastward into Remote Oceania (Bellwood 2005; Sand 2016; Kirch 2017).

This distinction between Austronesian origins and Lapita emergence matters because it sharpens how we think about migration. Taiwan is most important for explaining the early history of Austronesian language dispersal. The Bismarcks are most important for explaining the archaeological formation of Lapita and the threshold crossing into Remote Oceania. From there, Lapita communities expanded rapidly into Vanuatu, New Caledonia, Fiji, Tonga, and Samoa between roughly 1100 and 900 BCE, creating the earliest widely accepted archaeological horizon of Remote Oceania (Green 1989; Spriggs 1995; Sand 2016; Hunt and Lipo 2017). The speed of that dispersal gave rise to the "Express Train" metaphor, although the phrase can overstate uniformity and understate later interaction (Diamond 1988).

The "Pulse-Pause" model refines this narrative by arguing that Austronesian expansion into Oceania occurred in major episodes rather than as a continuous, steady wave. The first pulse corresponds to the Lapita movement into western Remote Oceania. This was followed by a long pause during which populations in Fiji, Tonga, and Samoa grew, interacted, and differentiated locally before a second major pulse carried Polynesian voyagers into central East Polynesia and eventually to Hawai‘i, Rapa Nui, and Aotearoa New Zealand nearly 2000 years later (Davidson

1979; Van Tilburg 1994; Gray et al. 2009; Wilmshurst et al. 2011). This model remains useful because it accounts for both linguistic divergence and the archaeological gap between the initial settlement in western Remote Oceania and the much later colonization of East Polynesia. It also aligns with seafaring simulations that suggest route choice, wind structure, island visibility, and energetic constraints affected when and how long-distance voyages became viable at different moments in the Pacific's deep history (Finney 1994; Irwin 208; Montenegro et al. 2008, 2014, 2016; 2023). Such work does not replace archaeology, but it helps explain why some island groups were reached rapidly while others remained outside sustained voyaging networks for centuries.

Alternative models, especially the "Entangled Bank" and "Slow Boat" perspectives, emphasize that this process was not purely one-directional or biologically uniform (Terrell 1997, 2009; Oppenheimer and Richards 2001). These critiques argue, correctly, that interaction with Indigenous Near Oceanian populations was significant and that later Pacific populations were shaped by both admixture and migration. In that sense, the sharpest contrast is not between "Taiwan" and "Melanesia," but between explanations that treat the expansion as linear and those that foreground cumulative interaction. The strongest current position is a synthesis: Austronesian language dispersal and early movement out of Taiwan remain foundational, Lapita emerged archaeologically in the Bismarcks, and the populations who later settled Remote Oceania were shaped by both expansion and interaction (Kayser et al. 2000; Bellwood 2005).

The "Triple-I" model offers a useful refinement to this discussion by arguing that Lapita developed through a combination of intrusion, innovation, and integration rather than through simple replacement or the transfer of a fully formed cultural package (Addison and Smith 2010). In this view, incoming Austronesian-speaking populations entered Near Oceania, interacted with

established communities, and developed new archaeological expressions through local innovation and sustained social integration. The model is especially useful because it helps explain why Lapita material culture appears both connected to wider Austronesian dispersal and locally transformed within the Bismarck Archipelago before its movement into Remote Oceania (Green 2000; Davidson 2012).

A related refinement emphasizes voyaging corridors and seascapes rather than treating colonization as a simple point-to-point migration. This perspective stresses canoe performance, island visibility, return voyaging, and the structure of ocean routes shaped where settlement could proceed reliably and where it stalled. Rather than imagining Pacific colonization as a single directional push, this model highlights staged expansion through navigable maritime corridors in which some islands functioned as stepping-stones or hubs within wider seafaring networks (Irwin 2010, 2018; Irwin and Flay 2015).

Micronesia complicates any overly simple west-to-east narrative. Archaeological and genetic work in the Marianas suggests that western Micronesia was also settled early, perhaps by 1500-1200 BCE in the case of Palau and the Marianas, by voyagers with strong ties to the Philippines and/or the Moluccas, rather than by Lapita groups moving eastward through the Bismarcks (Hung et al. 2011; Pugach et al. 2021). Palau also preserves evidence of early settlement, with secure mortuary and radiocarbon records by around 1050 BCE (Clark 2005; Clark et al. 2006; Fitzpatrick and Jew 2018; Matisoo-Smith 2019). These data suggest that parts of Micronesia may represent a separate or parallel stream of Austronesian expansion, one that was broadly related to the larger Austronesian dispersal but not simply a derivative of Lapita. For the purposes of this dissertation, that distinction is useful because it demonstrates that island colonization in Oceania followed multiple trajectories and that local ecology and route structure

mattered from the beginning (Anderson and O'Connor 2008; Goodwin et al. 2014). Figure 6 summarizes the broad chronological dispersal pattern discussed in this section.

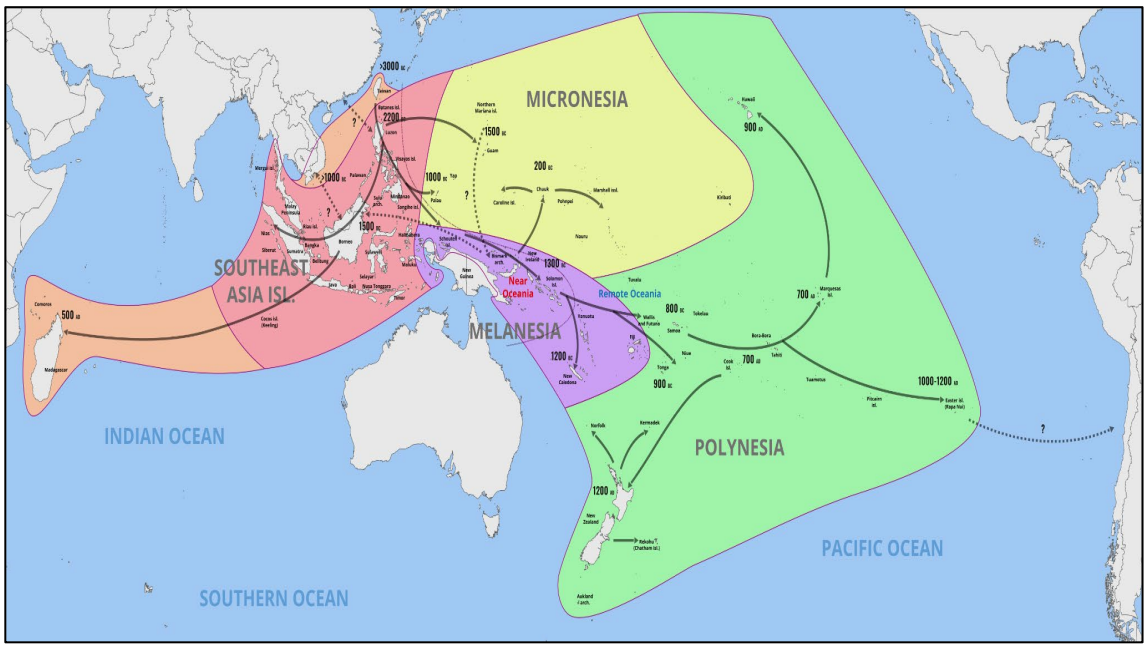

Figure 6. Chronological dispersal of Austronesians from Taiwan. (Wikipedia Commons).

2.2.3 Archaeological Evidence for the Settlement of Oceania

Archaeology remains the strongest line of evidence for reconstructing the settlement of Oceania because it anchors chronology in material traces: pottery, stone tools, burials, paleoenvironmental change, transported animals and plants, and the physical imprint of settlement on coastal and inland landscapes. The best-supported early horizon in Remote Oceania is Lapita. Sites in the Reef/Santa Cruz Islands, Vanuatu, New Caledonia, Fiji, Tonga, and Samoa show that by the late second millennium BCE voyaging communities using dentate-stamped ceramics, shell ornaments, adzes, and domesticated plants and animals had crossed the Near/Remote Oceania boundary and established villages on islands that had not previously been occupied by humans (Green 1989; Bedford et al. 2006; Sand 2016).

Fiji is central to this story because it sits at the junction of Near Oceania and Polynesia and preserves both early Lapita evidence and later trajectories of social transformation. Early

sites such as Lakeba, Natunuku, and the Sigatoka Sand Dunes show a mixed economy of horticulture, animal husbandry, and intensive marine exploitation (Best 1984; Kirch 2017). Fiji is therefore more than a waypoint. It was one of the first major archipelagoes in Remote Oceania where transported landscapes, village settlements, and long-term adaptation took hold. In later centuries, fortified sites, irrigation features, and more permanent agricultural investment suggest that the initial colonizing economy gave way to greater local intensification and territoriality (Nunn 1998; Field 2003; Field and Lape 2010; Sheppard 2011). This matters for the larger dissertation because it shows that marine and terrestrial adaptation in Oceania were never separate domains. The same settlement histories that produced village agriculture and landscape modification also set the conditions for the emergence of later customary fishing structures (Allen 1991).

Archaeology also shows that the Lapita expansion was not uniform across the region. Some parts of the western Pacific were bypassed or incorporated unevenly, and recent work on the southern coast of Papua New Guinea, especially around Caution Bay, has demonstrated that Lapita materials and related communities were not confined to a simple eastward arc from the Bismarcks into Fiji and beyond. Rather, the record suggests a more flexible maritime world of branching routes, exchanges, and localized settlement decisions (Sommer 2001; Sheppard 2011; Sand 2016). Obsidian movement from Talasea and other sources also indicates that long-distance interaction remained important even after initial colonization (Summerhayes 2007). In other words, the archaeological record supports mobility, but not a simplistic model of one-time migration followed by isolation.

Micronesia must be included in this narrative rather than excluded from it. In the Marianas, pottery, settlement evidence, and radiocarbon chronologies support very early long-

distance voyaging from the Philippines into western Micronesia, potentially coeval with or even slightly earlier than the earliest Lapita horizon farther south and east (Hung et al. 2011). In Palau, early mortuary behaviors and settlement evidence confirms human occupation by around 1050 BCE, making it one of the earliest documented parts of Remote Oceania outside the narrowly defined Lapita heartland (Fitzpatrick 2003; Fitzpatrick and Jew 2018). Central and eastern Micronesia followed later and more uneven settlement trajectories, with atoll sequences indicating that some of these islands were colonized around 50 BCE rather than during the initial Lapita pulse (Poteate et al. 2016). This chronology for Micronesian settlement histories underscore the importance of small islands, coral atolls, and highly marine-oriented lifeways in Pacific prehistory (Alkire 1978). They also remind us that maritime adaptation was never just a Polynesian story. In several Micronesian settings, communities were organizing subsistence around reefs, lagoons, and interisland voyaging under conditions very different from those of high volcanic islands such as Fiji or Hawai‘i. The value of this Micronesian evidence is therefore not simply additive. It demonstrates that Pacific colonization involved multiple island worlds, not a single ladder leading from Taiwan to Fiji to Hawai‘i (Rainbird 2004; Fitzpatrick and Kataoka 2005).

The later settlement of central East Polynesia and its outliers forms the second major archaeological pulse. After the long post-Lapita pause in western Polynesia, the Society Islands, southern Cooks, and Marquesas were colonized during the late first millennium CE, followed by the settlement of Hawai‘i, Rapa Nui, and Aotearoa New Zealand over the next few centuries (Wilmshurst et al. 2011). Much of the earliest evidence in eastern Polynesia comes from pollen cores, charcoal records, faunal decline, and a relatively small number of early habitation sites,

but the broad pattern is now more firmly established than it once was. The result is a shorter, more compressed chronology of East Polynesian settlement than older literature often assumed. Hawai‘i occupies an especially important place in this sequence because it represents both the late reach of East Polynesian voyaging and one of the clearest cases of subsequent local and relatively rapid intensification. Archaeological and paleoenvironmental evidence places initial settlement around 1000–1200 CE, followed by the expansion of irrigated taro systems, dryland field systems, monumental architecture, and fishponds over the next several centuries (Ladefoged et al. 2009; Kirch 2012). For this dissertation, the significance is straightforward: settlement history is not only a matter of arrival dates. It explains how certain islands became settings for later marine engineering. Hawai‘i’s relative isolation, demographic growth, and ecologically constrained landscapes helped produce precisely the conditions under which large, durable marine infrastructure became meaningful and necessary.

2.2.4 Genetic Perspectives on Pacific Settlement

Genetic research has substantially reshaped the study of Pacific settlement by clarifying ancestry, admixture, and the timing of interaction among populations moving through Oceania. Early mitochondrial DNA work supported a strong Southeast Asian component in Polynesian ancestry, especially through the so-called “Polynesian motif,” while Y-chromosome studies revealed a more mixed picture in which paternal lineages often showed stronger Papuan affinities than maternal ones (Merriwether et al. 1999; Kayser et al. 2000, 2006). This asymmetry was important because it undermined simplistic either-or models. The Pacific record was clearly not one of total isolation from Near Oceania, but neither was it one in which Austronesian expansion disappeared into a generalized Melanesian background (Friedlaender 2008).

Genome-wide and aDNA studies have sharpened that picture. Ancient individuals from early Lapita contexts in Vanuatu and Tonga show overwhelmingly Asian-related ancestry, with little or no Papuan admixture at the time of the first expansion into Remote Oceania (Skoglund et al. 2016). Later individuals from the same broad region show substantially greater Papuan ancestry, implying that significant admixture occurred well after the initial Lapita dispersal (Lipson et al. 2018). This sequence is one of the clearest pieces of evidence supporting a two-stage model: an early colonizing pulse with strong Austronesian ancestry, followed by later interaction and population turnover in parts of western Remote Oceania. For this section, the importance of that result is not merely biological. It helps explain why archaeology, genetics, and linguistics sometimes seem to tell slightly different stories. They often capture different moments in a longer historical process (Pugach et al. 2021).

More recent genomic syntheses have further reinforced that Pacific settlement involved branching routes rather than a single demographic stream. One of the most important examples for Micronesia is aDNA from Guam, which indicates ancestry closely linked to the Philippines and no detectable Papuan-related ancestry in the sampled individuals. That finding supports the argument that the Marianas were settled by a northern route distinct from Lapita expansion through the Bismarcks and Near Oceania (Pugach et al. 2021). Although Micronesian genetics remain less densely sampled than Polynesian datasets, the available evidence is enough to show that western Micronesia cannot simply be folded into a Lapita-centered demographic history (Liu et al. 2026). Recent work has strengthened this interpretation by emphasizing regionally distinct pathways of dispersal, later local interaction, and the cumulative reshaping of Pacific populations through time rather than a single demographic wave (Nägele et al. 2025; Stoneking 2026).

Genome-wide studies of later Polynesian populations confirm that eastern Polynesians inherited already mixed ancestries, with most admixture occurring before the major eastward pulse into central East Polynesia. Founder effects then reduced diversity as smaller populations moved outward to Hawai‘i, Rapa Nui, and Aotearoa New Zealand (Lipson et al. 2018; Ioannidis et al. 2021). In broad terms, then, the genetic evidence supports a model in which Austronesian-speaking populations carried the initial dispersal into Oceania, while subsequent interaction with Near Oceanian populations helped shape the biological ancestry of many later Pacific Islanders. The exact proportions and timings vary by region, but the larger pattern is no longer in doubt (Matisoo-Smith 2019).

Some genetic findings also speak to later voyaging rather than initial settlement. Evidence of pre-Columbian contact between Polynesians and Indigenous peoples of the Americas does not change the basic chronology of Oceania’s initial peopling, but it does reinforce the scale and capabilities of Polynesian voyaging networks after eastern Polynesia was colonized (Matisoo-Smith and Robins 2004; Ioannidis et al. 2021; Berenguer et al. 2024). That point is best treated cautiously here. Its value lies less in revising the first settlement than in reminding us that Pacific mobility did not cease once the islands were occupied.

2.2.5 Linguistic Contributions to Understanding Voyaging and Settlement

Linguistics remains indispensable because it provides the clearest evidence that the deeper origin of the Austronesian language family lies in Taiwan. The earliest branching diversity of Austronesian occurs there, and all Austronesian languages outside Taiwan belong to the Malayo-Polynesian branch, indicating an expansion southward into the Philippines and beyond (Blust 2013, 2019). This does not mean that every later archaeological complex can be read directly from language dispersal, but it does provide the broadest available framework for

understanding how Austronesian-speaking populations moved into the Pacific (Pawley and Green 1973; Bellwood 2017).

Within Oceania, the Oceanic branch is generally associated with the populations that expanded through the Bismarcks and into Remote Oceania, and Proto-Oceanic is commonly linked to the broader cultural world from which Lapita emerged (Pawley and Green 1973; Greenhill and Gray 2005). Later differentiation produced Proto-Polynesian in western Polynesia, followed by the language groups associated with central East Polynesia and its outliers (Marck 2000; Wilson 2012). Linguistic subgrouping, therefore, aligns reasonably well with the archaeological sequence from western Remote Oceania to eastern Polynesia. This is one reason the "Pulse-Pause" model has been so persuasive: language divergence suggests an early west-to-east expansion, a period of relative consolidation in western Polynesia, and then a later burst of diversification associated with East Polynesian settlement (Gray et al. 2009; Greenhill and Gray 2005).

At the same time, Micronesia again resists oversimplification. Some Micronesian languages belong to the Oceanic world, usually associated with eastern Austronesian dispersals, while western Micronesia also preserves linguistic histories that do not fit cleanly within a Lapita-to-Polynesia sequence (Pawley and Green 1973; Zobel 2002). Yap is especially important here. Although Yapese is Austronesian, it does not fit neatly within the Nuclear Micronesian pattern and has long been treated as a highly distinctive western Micronesian outlier, shaped by deep histories of contact that complicate any simple Lapita-to-Polynesia linguistic sequence. That heterogeneity is analytically important (Ross 1996; Napolitano et al. 2019). It reminds us that Austronesian expansion was real, but that it did not produce a single uniform linguistic

geography across the Pacific. Different island regions were drawn into Austronesian dispersal through different pathways and at different times.

Linguistic evidence also captures interaction and dispersal. Austronesian languages in parts of Near Oceania include substrate effects and borrowings that indicate sustained contact with Papuan-speaking populations (Ross 2001; Donohue and Denham 2010). Such evidence complements the genetic record of admixture and reinforces the point that early Pacific history involved both entanglement and expansion. Within Polynesia, close linguistic ties among Hawaiian, Tahitian, Cook Islands, and Marquesan traditions continue to inform debates over later voyaging routes and the role of central East Polynesia as the final launching point for the colonization of Hawai‘i and other outliers (Marck 2000; Wilson 2012; Blust 2019).

For this dissertation, the linguistic contribution is especially important because it helps separate scales of explanation. Linguistics is strongest at clarifying broad ancestry and dispersal relationships; archaeology is stronger at documenting specific settlement histories and material adaptations; genetics helps reconstruct biological ancestry and later interaction (Posth et al. 2018). Read together, they make it possible to situate Fiji, Micronesia, and Hawai‘i within a single historical frame without collapsing their differences. They also help prevent a common mistake in Pacific scholarship: assuming that linguistic similarity necessarily implies identical ecological histories or similar pathways of social development. That wider frame is essential if later customary fishing structures are to be understood as regionally specific responses emerging from a shared but differentiated history of Austronesian expansion, island adaptation, and ecological transformation.

2.2.6 Synthesis: Migration, Adaptation, and the Making of Oceania

The peopling of Oceania was not a single event, route, or population movement. It was a long historical process in which Austronesian-speaking peoples expanded from Taiwan into Island Southeast Asia, contributed to the emergence of Lapita in the Bismarck Archipelago, settled western Remote Oceania, interacted with Near Oceanian populations, and later expanded into central East Polynesia and its farthest island frontiers (Kirch 2017). Micronesia forms an essential part of this story rather than a peripheral aside (Rainbird 2004). The Marianas, Palau, and later central and eastern Micronesia show that there were multiple pathways into the Pacific and that not all early island colonization can be reduced to a Fiji–Tonga–Samoa sequence or a unilinear trajectory (Hung et al. 2011).

The strongest interpretation, then, is neither a simple "express train" nor a wholly diffuse entanglement model. Austronesian language origins in Taiwan remain fundamental, Lapita remains the key archaeological horizon for initial settlement in much of Remote Oceania, and genetic evidence confirms substantial later admixture and regional divergence. The convergence of archaeology, genetics, and linguistics is strongest when these are treated as related but non-identical records. Each captures a different dimension of the peopling process.

That conclusion matters directly for the argument of this dissertation. Settlement history structured later possibilities for marine intensification. The movement of people, crops, animals, technologies, and ecological knowledge into island environments created the transported landscapes from which later systems of labor coordination, territoriality, and marine infrastructure emerged. Fiji and Hawai‘i were both settled within the wider history of Austronesian dispersal, but they developed under different chronologies, ecologies, and scales of isolation. Those differences help explain why customary fishing structures took different forms

across Oceania and why some island societies invested heavily in durable marine infrastructure while others did not. In that sense, the peopling of Oceania is not background material alone. It is the first stage in the longer history of adaptation, environmental engineering, and marine resource management that this dissertation seeks to explain.

2.3 Customary Fishing Structures in Oceania

This section presents a typological survey of customary fishing structures across the Pacific Islands. By highlighting examples from Hawai‘i, Fiji, Micronesia, the Marshall Islands, Takū’u, Australia, and the Pacific Northwest, it showcases the diversity of Indigenous strategies for managing coastal and lagoon environments. These examples show how communities adapted their technologies to local ecological conditions, social structures, and cultural values (Williams and Calvert 1860; Tinker 1950; Kikuchi 1976; Best 1984; Moir 1993; Farber and Halapua 2002; Rainbird 2004). The survey also grounds the classification system in real-world cases before moving into the more focused analyses of this dissertation.

To organize this diversity, a paradigmatic classification system is introduced. Rather than forcing fishing structures into rigid categories, this approach describes each through a combination of independent attributes: type, shape, habitat, hydrology, material, permanence, and purpose. This method allows more flexible comparison across regions and cultural contexts. It also accommodates hybrid and multifunctional designs that fall between labels like "trap" or "pond." Using this framework, we can better analyze patterns in fishing infrastructure and explore broader questions of resource management, labor investment, and environmental adaptation throughout Oceania.

2.3.1 Definitions Used for Pacific Island Fishing Structures

Fish Aggregation Devices: These are semi-permanent to permanent structures built to attract marine organisms for easier foraging. Typically simple in design, such as a stone alignment mimicking a reef, they often attract species beyond fish, including crustaceans, gastropods, echinoids, and cephalopods, which were used for food and tool manufacture.

Fish Traps: Capture devices made of natural fibers that often demonstrate some form of mobility and are usually lower in labor investment than fishing weirs and fishponds. Form and function vary widely, but they are universal in opportunistic operation, relying on the movement of marine organisms in their natural environment. These devices may require bait to increase effectiveness.

Fishing Weirs: Semi-permanent to permanent structures constructed with earthen, coralline, or plant materials that take advantage of moving water by channeling fish and other marine organisms into a procurement area or device for easier harvesting. Pacific Island fishing weirs can be further subdivided into three general types:

Tidal Weirs: Arc-shaped structures built in intertidal zones. These are submerged at high tide, trapping fish as the tide recedes.

Longshore Weirs: Feature a leader alignment extending perpendicularly from the shore toward the sea, ending in an enclosure designed to trap fish as they follow the alignment during tidal movement.

Flowing Stream Weirs: Placed in rivers or channels with continuous water flow, these deflect the upstream/downstream movement of marine organisms into enclosures for easier procurement. These are rare in Oceania due to the limited presence of large freshwater rivers.

Fishponds: Permanent structures, typically built from rock, coral, or earthen material, to encourage the gathering, nurturing, and harvesting of select fish and other marine organisms. Fishponds are often larger and more technologically complex than other fishing structures, requiring coordinated labor investment and maintenance.

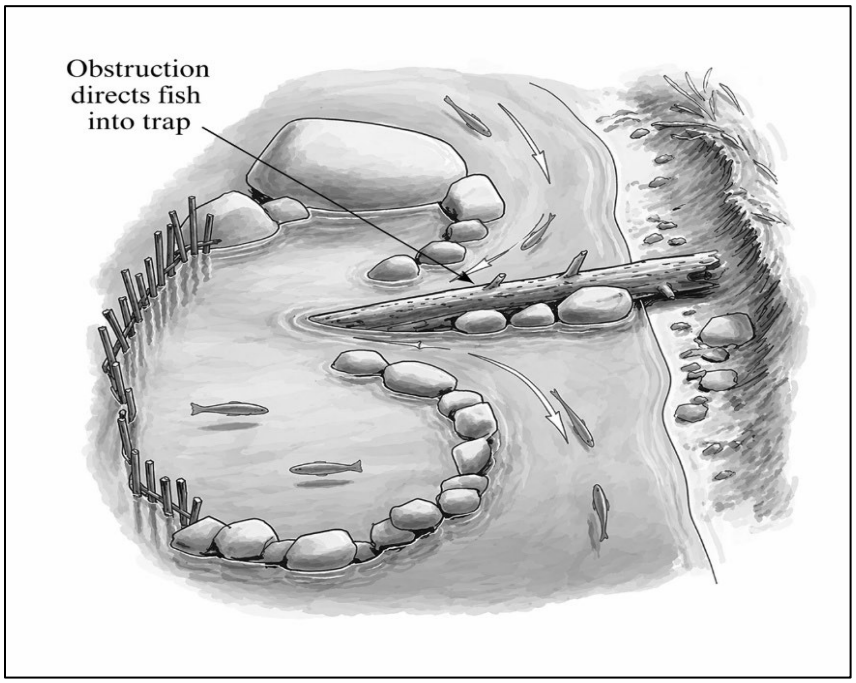

Figure 7. Diagram of a typical longshore weir, a fishing structure widely found in coastal settings among communities that rely on marine subsistence.

2.3.2 Classification Systems in Archaeology and Anthropology

As shown in Figure 7, the longshore weir is not a simple or uniform feature, but a composite structure made up of distinct elements, including a leader alignment, enclosure, and capture area, underscoring the difficulty of forcing such features into overly rigid classificatory categories. The diversity of customary fishing structures across Oceania presents a challenge of

classification. In science, broadly, classification systems reduce complexity by grouping phenomena into categories, thereby making patterns more discernible. This is as true in archaeology as in biology: just as Linnaean taxonomy organizes biodiversity into a manageable hierarchy, archaeologists develop typologies to organize artifacts and features for analysis (Dunnell 1971; Adams and Adams 1991). Classification allows researchers to compare like with like, identify variation, and infer behavioral or cultural patterns from material remains. A well-crafted classification system can thus bring analytical clarity and comparability across regions and time periods (Dunnell 1986; O'Brien et al. 2005). By sorting the "messy" continuum of real-world observations into discrete units, archaeologists can highlight essential similarities and differences that inform past human activities (Adams and Adams 1991).

Strengths of Classification: A primary strength of using explicit classification schemes is the creation of mutually comparable units of analysis. When archaeologists define types or categories consistently, they can quantitatively compare data from different sites or islands. For example, if we classify a stone tidal weir in the Marshall Islands and a similar feature in Fiji under the same type, we can more directly compare their construction, function, and context. Classification also forces researchers to define attributes and criteria, reducing ambiguity (Dunnell 1971). This can illuminate technological and functional patterns: we may discover that certain fishpond types occur only in specific environmental settings or that a specific fish trap form correlates with targeting particular species. In short, classification brings order and allows for generalization; we can discuss "fish traps" or "fishponds" as categories and explore their roles in subsistence or social organization across the Pacific (Kirch 2017). Moreover, formal typologies enable cumulative knowledge; future studies can build on established categories to test new hypotheses (O'Brien et al. 2005).

When done well, classification enhances communication among scholars by providing a common language (Adams and Adams 1991; Lyman and O'Brien 2001). For instance, defining what constitutes a *loko iʻa kuapā* (Hawaiian walled fishpond) versus a *moka* (Fijian tidal fish trap) ensures that when those terms are used, they refer to clearly delineated concepts.

Limitations and Challenges: Classification also has inherent weaknesses, especially in anthropology and archaeology, where cultural phenomena seldom fit into tidy boxes. One issue is oversimplification: by forcing continuous variation into discrete classes, we risk ignoring important subtleties and creating artificial distinctions (Pargeter and Shea 2023). Many fishing structures blur the boundaries between "trap" and "pond," or between "permanent" and "temporary." For example, an enclosure might initially be built to trap fish but later be maintained and stocked, functioning more like a pond; should it be classified as a trap or a pond, or both? Rigid classification could obscure such hybrid usage. Archaeologists have noted that overlapping terminology and criteria lead to "ill-formed inferences": if our categories do not match past reality, our analyses may be misleading (O'Brien et al. 2005).

Another challenge is that different cultures have their own classifications, which may cut across our analytical categories. Indigenous terminology for fishing structures often reflects nuanced distinctions of purpose or form that one-size categories fail to capture (Moore 2022). For instance, Indigenous Hawaiian fishery experts traditionally distinguished at least six types of fishponds (*loko iʻa*) by environment and construction (*loko kuapā, loko puʻuone, loko wai, loko iʻa kalo, loko ʻumeʻiki,* and *kāheka*) (Handy et al. 1972; Kikuchi 1976). A simple category such as "fishpond" might flatten these differences. Conversely, different cultures might use one term for structures that archaeologists would classify separately. This cultural richness can be lost or misrepresented in archaeological typologies.

Because of such issues, classification can create artificial boundaries. The gradient from small, expedient fish traps to massive, permanent fishponds gets chopped into bins like "trap" vs. "pond" when intermediate cases exist. These artificial dichotomies may lead researchers to overlook instances that do not fit well (Dunnell 1986; Lyman and O'Brien 2001). For example, consider a low-investment stone tide pool modified to hold fish briefly; is it a naturally occurring pool, a modified weir, or a proto-fishpond? If our typology has no room for it, it may be ignored in analyses, skewing our understanding. Thus, while classification reduces complexity, it can also excessively reduce diversity. Archaeologists must be vigilant that typological convenience does not impose a false uniformity on a varied record (Dunnell 1971).

2.3.3 Approaches to Classifying Fishing Structures

Researchers have approached the classification of customary fishing structures using different guiding criteria. Three common approaches in anthropological literature are functional, morphological, and cultural/linguistic classifications:

Functional Classification: This approach categorizes structures by their intended use or role in subsistence. A basic functional dichotomy is often drawn between structures for capturing wild fish and those for cultivating or holding fish (i.e., aquaculture) (Costa-Pierce 1987; Rogers 2024). For example, builders designed stone tidal weirs to funnel fish for immediate harvest, classifying them as traps or capture devices, whereas they constructed enclosed ponds to nurture fish over time, placing them in the category of grow-out or aquacultural systems. Functional classifications can directly relate form to subsistence strategy (Birkeland 1997). They highlight, for instance, whether a community's focus was on maximizing immediate catch or longer-term husbandry. In practice, however, function can be fluid. Many structures served multiple

functions. In Micronesia, *me* fish weirs in the Marshall Islands were primarily catch devices. Still, oral accounts say that rituals were used to hold fish in place for later harvest at specific chief sites, effectively turning a short-term trap into a temporary holding pond via cultural practice (Tinker 1950; Ahlgren 2016). Functional labels can therefore oversimplify when a single structure is used in multiple ways. Still, scholars like Johannes (1978) found functional classification helpful as a cross-cultural shorthand: nearly every island group had some variant of a fish trap, a fish weir, and a fishpond, even if the materials and details differed.

Morphological Classification: Another approach classifies fishing structures by their physical shape and construction, irrespective of use (Connaway 2007). This method includes planform shape (e.g., V-shaped, circular, linear), building materials (stone, wood, coral, etc.), and structural layout (enclosures, channels, gates). For instance, researchers in Polynesia have distinguished V-shaped tidal weirs from circular stone enclosures and from straight embankments, noting that these forms often reflect adaptations to local geomorphology. An example of morphological classification is found in the Society Islands (French Polynesia), where traditional fish traps called *ʻauaiʻa* included elaborate arrangements of stone walls with circular catchment basins at the V-apex (Davidson et al. 1999). Likewise, on atolls like those in the Marshall Islands, the prevailing form is a long, arrowhead- or V-shaped weir extending from the shoreline into the lagoon (Tinker 1950). Morphological typologies are valuable for technological and environmental analysis; a heart-shaped trap with a circular pool, as seen in Huahine, Society Islands, indicates a solution for holding fish as the tide recedes (Davidson et al. 1999).

The downside is that similar shapes can be used for different purposes in different places. A stone semi-circle in Fiji might be a short-term fish drive trap, whereas a similar semi-circular

enclosure in Hawai‘i is a permanently managed fishpond (Stokes 1909; Scheffler and Lockwood 2014). Purely shape-based categories might lump these together, missing functional distinctions. Additionally, convergent evolution is an issue: different cultures may independently arrive at similar weir shapes, so morphological similarity does not always indicate a shared origin or mode of use (Moss 2013). Despite this, morphology-focused studies help archaeologists recognize features in the field and infer how they worked mechanically to impound fish.

Cultural/Linguistic Classification: A third approach uses indigenous terminology and folk taxonomy to classify fishing structures. Anthropologists and linguists have documented a rich vocabulary for fishing features across Pacific societies (Moir 1993; Farber and Halapua 2002). These terms often embed cultural knowledge about function, form, and status. For example, the Hawaiian language differentiates fishpond types: *loko i‘a kuapā* (walled coastal pond), *loko pu‘uone* (sand dune pond), *loko wai* (freshwater inland pond), *loko i‘a kalo* (taro field-integrated pond), etc., each term specifying construction and environment (Kikuchi 1976; Handy et al. 1972). In Fiji, *moka* refers to tidal stone fish traps, while *ba ni ika* refers to wooden weirs or fences for fish (Hocart 1929; Thompson 1940). On Takū’u (a Polynesian outlier off Papua New Guinea), no indigenous term might exist for the giant clam "gardens" practiced there, as it was an esoteric tradition. Still, the activity is described in oral history (Moir 1993). Cultural classifications are invaluable for understanding Indigenous perspectives and social significance.

They can reveal which structures were considered high-status, as in Hawai‘i, where large fishponds were royal constructions, or how local people distinguished subtle environmental types (Farber and Halapua 2002; Kikuchi 1976). However, these classifications are not uniform across regions; one culture's categories may not translate neatly to another's. They may also include cosmological or legal dimensions beyond purely functional or morphological concerns. In

comparative archaeological analysis, relying solely on cultural labels can be problematic; one must first interpret them within each culture's context (Quinn 2023). Nevertheless, integrating linguistic data often enriches archaeological classification. For example, understanding that the Marshallese call fish weirs me and have no traditional concept of a long-term "fish farm" helps clarify why the weirs there were for short-term catch, whereas other societies developed true aquaculture (Tinker 1950; Farber and Halapua 2002).

Each of these approaches offers insights, and researchers often use a combination in practice. Early surveys often describe morphology, infer function, and consult local knowledge for indigenous terms and uses (e.g., Kikuchi 1976 did this for Hawaiian fishponds). A key point from reviewing these approaches is the tension between comparability and fidelity to cultural context. Functional and morphological classifications strive for comparability across the Pacific, allowing one to tally "how many fish traps vs. fishponds" in different archipelagos. Meanwhile, cultural classification strives to remain faithful to how Indigenous peoples categorize and use these structures. The ideal typology for Pacific Island fishing structures should seek a balance: robust enough to compare across regions yet flexible enough to honor local distinctions and hybrid forms that do not fit neatly into simple labels.

2.3.4 Toward a Paradigmatic Typology of Customary Fishing Structures

Given the strengths and limitations discussed above, this section proposes a paradigmatic classification to systematically yet flexibly categorize customary fishing structures. A paradigmatic classification is one in which a set of defined dimensions (attributes) is established, and each structure can be characterized by a combination of modes (values) along each dimension. The benefit of this approach is that it does not force a single hierarchy (e.g., "trap" vs.

"pond") but instead allows classification across multiple independent dimensions (Dunnell 1986). In other words, instead of pigeonholing a feature into one category, we describe it by several attributes, for example: mobility, permanence, shape, habitat, hydrology, material, etc., and then compare structures by their profiles.

Archaeologist Robert Dunnell (1971, 1986) argued that paradigmatic classifications maximize clarity by using consistent, orthogonal criteria that yield mutually exclusive and exhaustive combinations. This means that every observed case can fit into the multidimensional matrix, and no two types overlap if their defining attributes differ. For Pacific fishing structures, a paradigmatic typology can incorporate the diverse criteria that earlier approaches emphasized separately. Rather than debate whether a given enclosure is a “trap” or a “pond,” we can classify it, for example, as: Type: enclosure; Primary function: capture (short-term) vs. culture (long-term); Morphology: V-shaped vs. circular vs. linear; Habitat: reef flat vs. estuary vs. inland; Construction: stone vs. wood vs. composite; Hydrological context: tidal vs. non-tidal, etc. Each of these is a dimension with a set of modes. By recording a structure’s attributes in this way, we preserve a great deal of information: one structure might turn out to be a “stone enclosure on reef flat, tidal, used for short-term holding,” essentially a tidal weir, while another is “earthen enclosure inland, fed by stream, used for long-term cultivation,” essentially a pond. If a structure is hybrid, it can be coded as such on the relevant dimension. An example of this type of paradigmatic classification can be seen in Table 1.

Table 1. A paradigmatic classification of customary fishing structures.

Dimension I: Type				
Mode A: Fish Trap	Mode B: Fish Aggregation Device	Mode C: Fish Weir	Mode D: Fishpond	Mode E: Mixed Fishpond
1: Mobile 2: Permanent	1: Mobile 2: Permanent	1: Flowing Stream 2: Tidal 3: Longshore	1: LBM 1 (Protection from Predators) 2: LBM 2 (Control of Reproduction) 3: LBM 3 (Regulation of Growth) 4: LBM 4 (Control of Harvest)	1. LBM 1 & 2 2. LBM 1,2, & 3 3. LBM 1,2, 3, & 4 4. LBM 2 & 3 5. LBM 2, 3, & 4 6. LBM 3 & 4

Dimension II: Shape			
Mode A: Point	Mode B: Line	Mode C: Polygon	Mode D: Complex Shape
1: Discrete Object 2: Rock Cluster 3: Other	1: Alignment 2: Arc 3: Arc with Lip	1: Triangular 2: Rectangular 3: Pentagonal 4: Annular 5: Amorphous	1: V-Shaped 2: V-Shaped with Leader 3: V-Shaped with Enclosure at Apex 4: Arc with Leader 5: Spiral 6: Labyrinth

Dimension III: Habitat		
Mode A: Inland	Mode B: Coastal	Mode C: Ocean
1: Lake 2: River 3: Natural Pond	1: Shoreline 2: Reef Flat 3: Reef Edge 4: Lagoon	1: Benthic 2: Pelagic

Dimension IV: Form		
Mode A: Independent	Mode B: Linked	Mode C: Adventitious
1: Small 2: Medium 3: Large	1: Small 2: Medium 3: Large	1: Small 2: Medium 3: Large

Dimension V: Hydrology		
Mode A: Inland	Mode B: Coastal	Mode C: Ocean
1: Fresh 2: Salt 3: Brackish	1: Fresh 2: Salt 3: Brackish	1: Fresh 2: Salt 3: Brackish

Dimension VI: Composition			
Mode A: Earthen Material	Mode B: Calcareous Material	Mode C: Organic Material	Mode D: Composite Material
1: Igneous 2: Sedimentary 3: Metamorphic	1: Coral 2: Limestone 3: Lithified Sand 4: Shell	1: Faunal 2: Floral 3: Mixed	1: A/B 2: A/C 3: B/C 4: A/B/C

Dimension VII: Shoreline Location (if Coastal)		
Mode A: Facing Windward	Mode B: Facing Leeward	Mode C: Facing Crosswind
1: Bay 2: Promontory 3: Straight	1: Bay 2: Promontory 3: Straight	1: Bay 2: Promontory 3: Straight

- *Size* = Area in square meters reported as hectares. Small, Medium, and Large attributes are arbitrarily defined by the quartiles of the size distribution observed. The smaller outer quartile is considered “small”, while the larger outer quartile is “large”. “Medium” is the center batch of values.

- *LBM* = Levels of Biological Mutualism, originally described as “levels of domestication” by Kikiloi, are necessary for inter-species relations to “intensify” in a biologically mutualistic manner (Kikiloi 2003).

Such a multi-dimensional approach addresses the hybrid and multifunctional nature of many Indigenous fishing systems. Consider the eel traps of Australia's *Budj Bim* cultural landscape: an intricate network of channels, weirs, and ponds used by the Gunditjmara to both trap eels and keep them alive for later harvest. A *Budj Bim* feature can be coded as a trap and holding pond rather than forced into a single category within a paradigmatic classification. This region-specific system, which involved damming wetlands to create controlled pools, underscores the need for flexibility, as it is both aquaculture and active trapping (Wettenhall 2010; Rogers 2024). Similarly, in the Marshall Islands, if magic was used at a natural tidal pool to hold fish, turning it into a kind of informal pond, we can reflect that by coding the cultural practice or management strategy as an additional attribute separate from the physical form (Tinker 1950; Ahlgren 2016). In essence, paradigmatic classification creates a matrix that can accommodate regional diversity without losing the ability to compare structures across the Oceanic region.

We facilitate both within-region analysis and cross-cultural comparison by coding each structure in this multi-attribute way. Within a given region, say Hawai‘i, we can examine the distribution of types: e.g., most Hawaiian fishponds are coastal (*loko kuapā* and *loko pu‘uone*), with relatively few purely freshwater *loko wai*, a pattern that might relate to environmental availability of suitable sites (Summers 1964; Kikuchi 1976). Across regions, we can query how many cultures practiced true pond aquaculture by combining attributes such as permanent,

enclosed, and long-term holding. Preliminary review shows that, aside from Hawaiians, examples include certain Micronesian cases, such as Nauru's inland lagoons for milkfish cultivation, perhaps the Yapese mud crab enclosures, and Palau's eel ponds (Spennemann 1989; Rainbird 2004; Fitzpatrick and Kataoka 2005). In contrast, nearly all cultures had simple tidal weirs or temporary capture structures (Johannes 1978; Tinker 1950). A paradigmatic database enables the systematic extraction of such patterns. In other words, a paradigmatic classification records its attributes (e.g., stone weir, V-shape with basin, tidal estuary habitat) rather than assigning a single label, allowing comparison with superficially similar traps elsewhere in Polynesia and Micronesia. As shown in Figure 8, the Maeva weir combines a V-shaped alignment with a circular catch basin, illustrating how multiple structural elements could be integrated within a single fishing feature.



Figure 8. Photo of stone fishing weir in Maeva, Huahine (Society Islands) showing a V-shaped dry-stone wall enclosure with a circular catch basin. (Sailors 2015).

In addition to the core dimensions of structure, shape, habitat, and hydrology, a set of auxiliary attributes can help contextualize fishing features within their broader cultural and economic systems. These include purpose (e.g., cultivation vs. capture), socio-political role (such as elite control), management strategies (e.g., engineered sluice gates), target taxa, and labor investment. While these dimensions add interpretive depth, especially when reconstructing systems of political authority or economic intensification, they are often more difficult to detect archaeologically (Wolverton and Lyman 2000; Lyman and O'Brien 2001; Quinn 2023). Unlike physical attributes such as shape or material, which leave durable traces, these social and functional aspects often rely on ethnographic analogy, oral tradition, or historical documentation (Ascher 1961b; Wylie 1985; Lyman and O'Brien 2001). As such, they are valuable but less consistent variables and may not always be as analytically sound as the more immediate and materially expressed dimensions captured in the paradigmatic matrix. Nonetheless, when available, these auxiliary dimensions offer important insights into the lived realities of how fishing structures were built, used, and embedded within Pacific Island societies.

2.3.5 Regional Examples of Customary Fishing Structures

Using the typology above, we can better appreciate the diversity of customary fishing structures across Oceania through specific examples. Here, we present a detailed typological survey of several cases, highlighting how each fits into, or challenges, our classification framework:

Hawai'i: Royal Fishponds and Integrated Systems: Hawai'i is renowned for its extensive use of fishponds (locally known as *loko i'a*). These were typically large, engineered structures that reflected significant social investment and control by the chiefly elite (Stokes 1909; Kikuchi

1976; Costa-Pierce 1987; Wyban 1992). There were multiple types: the *loko kuapā* (seawall pond) is perhaps best known; an example is He‘eia Fishpond on O‘ahu, an 88-acre enclosure bounded by a long stone wall with sluice gates (*mākāhā*) to regulate water and fish movement (Apple and Kikuchi 1976; Wyban 2020; Graydon, Hollyer, and Castro 2007). In our classification, *loko kuapā* scored high on permanence, scale, and management intensity. Another type, *loko pu‘uone*, utilized natural brackish lagoons separated by sandbars; Hawaiians would cut channels and add sluice gates to manage these ponds (Summers 1964; Kikuchi 1976). *Loko wai* were freshwater ponds inland, often much smaller, sometimes modified sections of streams. Unique to Hawai‘i and a few other Polynesian cultures was the *loko i‘a kalo*, where fish, usually young herbivores, were introduced into flooded taro fields *(lo‘i*), a form of integrated aquaculture and agriculture (Handy et al. 1972; Costa-Pierce 1987).

Regarding typology, *loko i‘a kalo* are hybrid structures: part irrigated field, part fishpond. They exemplify multifunctionality, yielding taro and fish and thus defying a single-category label (Costa-Pierce 1987). Figure 9 illustrates the principal types of Hawaiian customary fishing structures, highlighting the internal diversity contained within the broader category of *loko i‘a.* All Hawaiian fishpond types share specific attributes: they were stationary, permanent ponds constructed with stone or earthen walls, and their primary purpose was to fatten juvenile fish, often herbivores like mullet (*‘ama‘ama;* Mugilidae) or milkfish *(awa; Chanos chanos*), for later consumption. Functionally, they are true aquaculture (Kikiloi 2003).

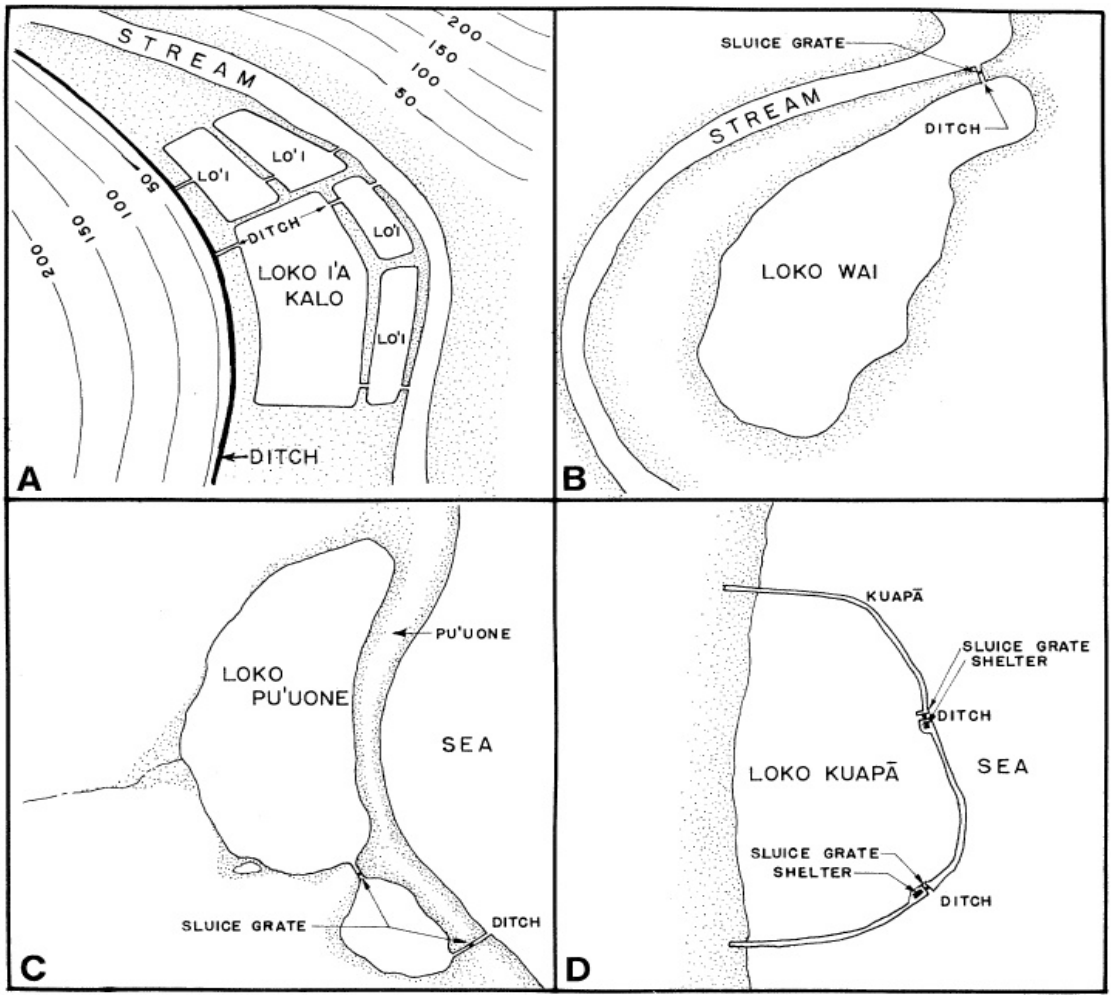

Figure 9. Illustration of four main types of Hawaiian customary fishing structures (*loko i‘a kalo*, *loko wai*, *loko pu‘uone*, & *loko kuapā*. (Kikuchi 1976).

The Hawaiian examples underscore how classification must handle scale and sociopolitical context: these ponds were typically large and required chiefly authority and coordinated labor to build and maintain (Kikuchi 1976; Ladefoged et al. 2009; Kirch 2010). Indeed, control of fishponds was a source of political power; an *ali‘i,* or social elite, who held many productive ponds could feed communities and host feasts, reinforcing status (Costa-Pierce 1987; Kirch 2010; Wyban 2020). When categorizing these, one might add a dimension for "socio-political role," since fishponds in Hawai‘i were closely associated with chiefs, unlike the more common traps anyone might use. In sum, Hawai‘i illustrates the apex of fishery intensification in the Pacific: a proliferation of large, engineered fishponds that complement

other subsistence activities and indicate a high degree of resource management (Kirch and McCoy 2023). The paradigmatic typology easily captures Hawaiian fishponds' distinctive traits, allowing them to be compared to smaller household-level ponds elsewhere. Figure 10 highlights the multi-species character of precontact Hawaiian integrated farming systems, reinforcing the argument that these were complex, managed production systems rather than simple or narrowly focused subsistence features.

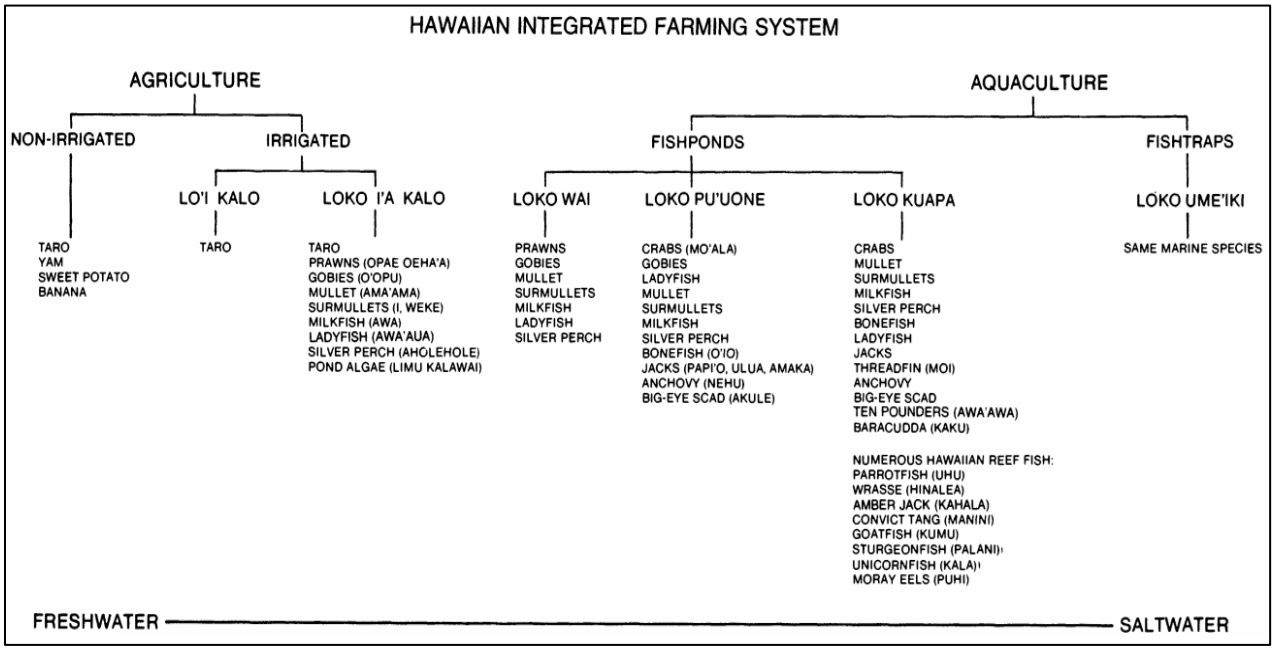

Figure 10. Species produced in integrated farming systems of precontact Hawai‘i. Adapted from Kikuchi (1976).

Fiji: Communal Weirs and Inland Pond Alignments: Fiji's fishing structures were historically less formalized than Hawai‘i's ponds, but diverse. Along the coasts of Fiji's high islands, stone tidal fish fences called *moka* were widespread (Hocart 1929; Thompson 1940; Parry 1994). A typical Fijian *moka* consists of a circular or C-shaped stone wall on a reef flat or tidal zone; at high tide, water flows in, and fish swim over the wall; as the tide falls, they become trapped inside the enclosure, which may be partially emptied of water. Fishermen seal the enclosure's opening ("mouth") with stones or nets during low tide harvests (Thompson 1940;

Veitayaki 2000). *Moka* are relatively simple in design, but their communal construction and use are noteworthy: oral accounts describe entire village lineages cooperating to build *moka* and drive fish into them during sanctioned communal harvests. In our typology, *moka* are semi-permanent tidal weirs, typically medium-sized and stone-built, used for opportunistic capture of whatever marine life wanders in. Interestingly, some Fijian communities gave special names to different fish-drive techniques; one account describes the *tuva moka*, a festive fish-drive event in which villagers herd fish toward the trap. This hints at a cultural dimension: the *moka* is not just a trap but a focal point of community ritual and cooperation. (Hocart 1929; Veitayaki 2000). Finally, Fijians also used fish drives with nets and temporary brush weirs in rivers for freshwater fish and prawns, showing that not all customary fishing involved building substantial structures (Jennings 1979; Watling 1985; Jennings and Polunin 1996). The typology can include a "no structure" or ephemeral structure category to remind us of these other strategies and to avoid overemphasizing visible archaeology. In Fiji's case, the paradigmatic typology highlights a spectrum: from large, communal, fixed stone traps on the reef to small, ephemeral traps inland, with variation influenced by habitat and target species (Ash and Ash 1985). Figure 11 grounds the broader typological discussion in a specific island case, showing how multiple *moka* on the island of Nananu-i-Ra can be compared spatially within a shared environmental setting.

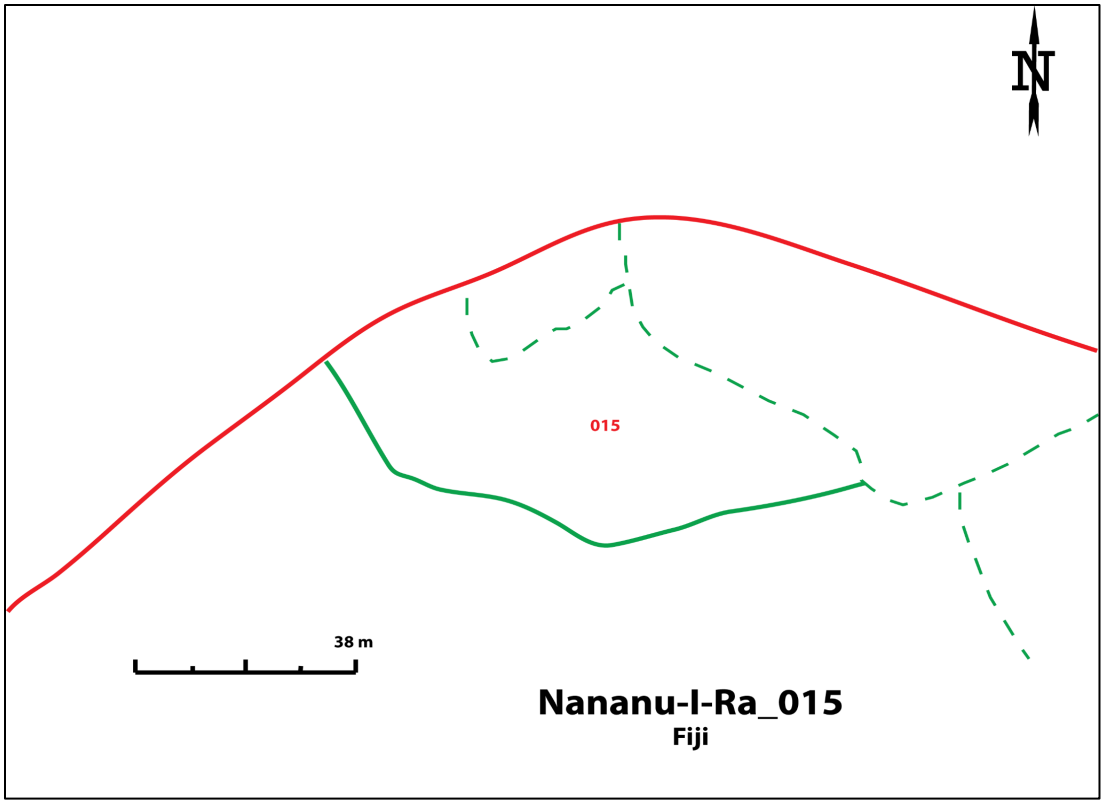

Figure 11. Map of Fijian customary fishing structures known as *moka* found on Nananu-i-Ra.

Marshall Islands: Atoll Weirs and Ritual Fish Calling: The low coral atolls of the Marshall Islands lacked large-scale fishponds but made up for it with ingenious tidal traps and a rich cultural context. Dozens of stone-and-coral fish weirs (*me*) have been documented across the Marshall Islands. These were typically V- or semicircular walls built on reef flats or at reef passages, designed to catch fish on the ebbing tide (Tinker 1950; Farber and Halapua 2002). Because atolls have expansive shallow lagoons, Marshallese weirs could be long and complex; one noted example is between the islets of Ruōt and Nimur on Kwajalein Atoll, where natural channels were modified to create a huge trapping pond. Such a structure effectively formed a lagoonal pond where fish and even sea turtles could be kept for some time until needed (Guinea 1993; Rudrud et al. 2007). However, Marshallese weirs generally did not constitute a proper aquacultural "system" on the scale of Hawai‘i. They were widespread but used primarily for short-term holding (Tinker 1950; Rainbird 2004). What distinguishes the Marshallese case is the

integration of magic and oral tradition in the use of these fishing structures. According to anthropologist Ingrid Ahlgren (2016), specific, chiefly-owned reef locales had rituals or divination practices to "call in" schools of fish and keep them in a particular area until a community harvest could take place. This activity effectively turns a naturally favorable reef, perhaps a chokepoint where fish gather, into a virtual fishpond through cultural means. From a classification standpoint, how does one classify this? Physically, the structure might be minimal or non-existent, yet culturally it is defined and managed. We might introduce a "cultural modification" attribute, e.g., ritual management present vs. absent. Marshallese also sometimes dug small pools or enhanced tidepools near their homes to temporarily hold fish, as one story from Mili Atoll recounts (Tinker 1950; Ahlgren 2016). These ad hoc “homemade” ponds blur the line between natural features and intended structure. In paradigmatic terms, they are small, improvised, short-term holding ponds, which might be archaeologically invisible but are important ethnographically.

Additionally, Marshallese practices of temporarily holding marine animals in managed spaces suggest that customary “aquaculture” was not limited to fish alone. More broadly across Oceania, mariculture could include other taxa, such as clams and turtles, reminding us that a useful typology must be broad enough to encompass intent, management, and tradition rather than only built form (Moir 1993; Ahlgren 2016).

Takū’u and Manus: Mariculture and Specialized Practices in Melanesia: In parts of Melanesia, especially Polynesian outliers like Takū’u (Mortlock Islands) and certain communities in Manus (Admiralty Islands, Papua New Guinea), we find interesting twists on customary fishing structures. Takū’u, as mentioned, practiced a unique form of giant clam mariculture. Barbara Moir’s study (1993) documents how Takū’u islanders transplanted juvenile

Tridacna gigas clams from the reef to shallow, protected lagoon flats near their village, effectively creating clam beds that they tended over the years (Moir 1993). These clam "gardens" might not look like built structures; a Western observer might see only a cluster of large clams half-buried in sand, but they were a deliberate food production system. They highlight that not all aquaculture requires a pen or enclosure. The Takū'u clam beds were essentially open systems relying on knowledge of clam growth and predation avoidance (Rogers 2024).

Similarly, on Manus Island, traditional fishers employed reef enclosures known locally as *alei* for nurturing parrotfish and other reef species. Manus communities also constructed elaborate fish fences in mangrove channels to trap swarms of migratory fish. These structures often incorporated sago-palm leaf fences guiding fish into holding pens. Such structures combine organic and inorganic materials and may be erected seasonally. Variation in Melanesia can be high even over short distances. For example, neighboring atolls in the Caroline Islands, geographically part of Micronesia but exhibiting cultural practices that align in some ways with Melanesia, demonstrate ecological specialization: one atoll might focus on trapping flying fish with large nets, while another relies on stone weirs to catch reef fish, depending on local environmental conditions (Alkire 1978; Johannes 1978; Rainbird 2004).

The paradigmatic approach posited in this section allows each case to be recorded without forcing them into a uniform mold, then later allows filtering to find whether any other locale shares that combination of traits. It turns out that giant clam cultivation like Takū'u's was also recorded in Palau, where specific communities maintained clam gardens for shells that served as a tool resource (Moir 1993). Likewise, milkfish were raised in a defined inland lagoon on Nauru Island, divided among families (Spennemann 1989). Such cases are aquacultural but

outside the classic "fishpond" narrative centered on Hawai‘i. They demonstrate the convergent evolution of aquaculture in the Pacific: distant societies independently developed the cultivation of different species, including fish, clams, turtles, and other organisms, across diverse environments (Rogers 2024; Malindine 2019; Fitzpatrick 2020). A comprehensive typology must be broad enough to include these, and our multidimensional matrix does, by design, absorb "all cases" (Dunnell 1986; Adams and Adams 1991).

Australia and the Pacific Northwest: Comparative Perspectives: Although outside Remote Oceania proper, it is instructive to compare the fishing structures of Indigenous Australia and the Pacific Northwest, as they have often been cited alongside Oceanic examples. In Australia, the Gunditjmara people of western Victoria engineered the extensive *Budj Bim* eel-trapping system: a network of basalt rock weirs, canals, and ponds along streams flowing from Lake Condah. These date back at least 6,600 years and represent one of the world’s oldest aquaculture systems (Wettenhall 2010; McNiven et al. 2012). The *Budj Bim* case is interesting because it combines mass capture during seasonal eel migrations with storage to keep eels alive in pond segments for later consumption or trade. It underscores that the capture/culture dichotomy is artificial; robust management systems often do both (Fitzpatrick 2020; Rogers 2024). Like Hawaiian fishponds, the *Budj Bim* traps supported surplus production and possibly social complexity, as evidenced by semi-sedentary villages and food storage, challenging outdated stereotypes of all Aboriginal Australians as nomadic foragers (Wettenhall 2010).

Meanwhile, on the Pacific Northwest coast of North America, Indigenous peoples built thousands of wooden stake weirs and stone tide traps to harvest salmon and other fish (Moss and Erlandson 1998; Byram 2002; Johnsen 2009; Moss 2021). These features are remarkably similar in principle to Oceanic tidal traps, though adapted to different tides and species. For example, a

wooden post weir serves the same function as a flowing stream weir in Oceania, though the latter were rare. Northwest stone tidal traps on beaches resemble small Polynesian or Micronesian traps in morphology, often crescent-shaped rocks that snag fish as the waters recede (Moss 2013). The cultural context differs, but environmental constraints led to analogous solutions (Moss and Erlandson 1998).

Outside Oceania proper, the clam gardens of the Pacific Northwest provide a powerful comparative example of Indigenous marine engineering. Built as rock-walled intertidal terraces, these features expanded and stabilized productive clam habitat, concentrating shellfish resources in places that were accessible, repeatedly tended, and embedded within local systems of stewardship and territorial management (Deur et al. 2015; Smith et al. 2019). Archaeological and ecological work has shown that clam gardens were not simply opportunistic harvest locations, but maricultural features capable of increasing clam abundance, growth, and survival by altering beach slope and improving intertidal habitat conditions (Groesbeck et al. 2014). They also formed part of broader Indigenous management portfolios that linked food production, social organization, and resilience within coupled human–ocean systems (Jackley et al. 2016). As a comparative case, Pacific Northwest clam gardens strengthen the broader argument advanced here: coastal peoples in very different regions independently engineered durable marine landscapes to intensify food production without abandoning locally grounded systems of ecological knowledge and governance.

Table 2. Comparative examples of customary fishing structures in Oceania and adjacent regions.

Region / Example	Type	Form / Shape	Habitat	Hydrology	Material / Construction	Permanence / Scale	Primary Purpose	Target Taxa
Hawai'i– *Loko i'a kuapā*	Fishpond[1]	Semicircular walled enclosure	Coastal anchialine	Brackish (spring + tide)	Basalt and coral with sluice gates	Permanent-large	Cultivation	Milkfish, mullet, other herbivorous fish
Fiji– *Moka*	Weir/trap[2]	C- or U-shaped enclosure with mouth	Coastal reef flat	Tidal	Coral and stone rubble	Semi-permanent-medium	Communal fish capture	General reef fish
Marshall Islands– *Me*	Stone reef weir[3]	Elongated V or chevron	Atoll lagoon shoreline reef passage	Tidal	Coral heads and rubble	Permanent-medium to large	Capture with short-term holding	Fish and sea turtles
Takū'u– *Giant clam gardens*	Mariculture plot[4]	Clustered patches, no formal walls	Lagoon shallows	Marine, low-energy lagoon	Live clams placed on substrate	Ongoing - small	Cultivation	*Tridacna gigas*
Australia– *Budj Bim*	Eel-trapping/ Possible aquaculture complex[5]	Network of weirs, canals, and ponds	Wetland stream margins	Freshwater	Basalt rock engineering	Permanent-extensive	Capture and storage delayed harvest	Eels
Pacific Northwest- *Various*	Stake weirs/stone tide traps/clam gardens[6]	Linear weirs, crescents, enclosures	Rivers, estuaries, beaches	Riverine or tidal	Wooden stakes or stone	Seasonal to permanent-variable	Capture	Salmon and other fish

Social / Management Notes

[1]High labor investment; elite-controlled; highly engineered

[2]Village-based, communal use; maintained and aligned with tidal cycles

[3]Sometimes ritually managed; could involve chiefly or sacred associations

[4]Family or clan-managed; long-term tending rather than formal construction

[5]Highly managed, integrated system combining trapping and holding

[6]Regionally diverse; structurally analogous to Oceanic traps but adapted to local ecologies

These comparative cases broaden our perspective on what constitutes a "fishing structure" and validate our paradigmatic dimensions: environment, tidal range, and materials all vary, yet the constructs still fit the model. By including these in a global typology, we can explore independent innovation versus diffusion of ideas, a topic beyond our immediate scope

but facilitated by having a common descriptive framework (Connaway 2007). For the present focus, the takeaway is that Pacific Island communities were part of a larger human story of developing fishing structures, and their solutions were, in many cases, at the pinnacle of complexity. Table 2 consolidates representative regional examples of customary fishing structures, illustrating variation in morphology, habitat, hydrology, target taxa, and management regime across Oceania and comparative cases beyond it.

2.3.6 Synthesis: Justification for a Paradigmatic Typology

Considering the above exploration, we return to the question of how best to classify the myriad forms of customary fishing structures in the Pacific. The theoretical discussion showed that while classification is indispensable for reducing complexity, it must be handled carefully to avoid oversimplification and misrepresentation (Dunnell 1971; Adams and Adams 1991). Earlier approaches that included functional, morphological, and cultural classifications each contributed insights but also left ambiguities when confronted with cases that did not fit neatly into these categories. A paradigmatic typology, as proposed, offers a robust solution by using multiple dimensions to classify each structure, thereby respecting hybrid forms, multifunctional systems, and regional diversity in a way no single-axis classification could (Dunnell 1986; Lyman and O'Brien 2001).

One of the most compelling reasons to adopt this paradigmatic approach is its capacity to "absorb all cases". In practical terms, that means researchers examining any Pacific Island, or even areas beyond, should be able to describe the fishing structures they find in terms of the established dimensions without feeling that the existing types are inadequate (Adams and Adams 1991; Connaway 2007). If a new form is encountered, say a previously undocumented fish trap

style on a Polynesian outlier island, we can slot it into the framework by noting the attributes that make it mutually exclusive. The typology is flexible enough to accommodate such a discovery rather than forcing it into an ill-fitting category or ignoring it. This is critical given that the Pacific is vast, and not all traditional practices have been documented; our classificatory net must be wide-meshed enough to catch unexpected variants (Dunnell 1986).

Another justification lies in honoring cultural and environmental variation. The paradigmatic system explicitly includes dimensions for environmental setting and material, thereby inherently highlighting how regional ecology shaped the form of structures. For instance, the absence of large freshwater weirs in most of Oceania is immediately apparent in a data table, as almost all cases show "Hydrology: tidal" rather than "riverine". At the same time, outliers like Nauru's inland lagoon or Palau's taro-pit ponds stand out, prompting explanation rather than being glossed over (Spennemann 2002; Koshiba et al. 2013). Culturally, by not collapsing Indigenous categories, we can incorporate multiple native terms as needed under a single umbrella type. Rather than treating Hawaiian *loko i'a* and Marshallese *me* as fundamentally different because the cultures viewed them differently, we can describe them in commensurate terms while still noting the cultural distinctions in usage and meaning. This approach thus balances universals and particulars, a key goal in anthropology (Berlin 1992).

Finally, adopting this paradigmatic typology is justified because it aligns with an ethic of fairly representing Indigenous innovations. Instead of imposing an external notion of what counts as aquaculture or an advanced fishing technique, we catalog the diverse ways Pacific peoples managed marine resources (Johannes 1978; Johnson et al. 2016; Kawelu 2014). This helps dispel any lingering notions from older literature that, for example, only Hawaiians practiced aquaculture. We see that many Pacific Islanders developed sophisticated methods

suited to their locales, whether dry-stone traps on atolls, brackish fish propagation in Micronesian lagoons, or the capture-and-grow strategy for eels in streams (Moir 1993; Spennemann 1989; Wettenhall 2010). By using a multidimensional classification, we do not privilege one type as "the fishpond" and relegate others to lesser status; instead, we appreciate a spectrum from low-investment opportunistic traps to high-investment aquaculture, all part of a continuum of human adaptation. This inclusive outlook resonates with current perspectives in archaeology and anthropology that emphasize diversity, agency, and the avoidance of teleological judgments of Indigenous technologies (Rogers 2024; Malindine 2019; Quinn 2023).

The paradigmatic typology presented here provides a comprehensive and flexible framework for understanding types of customary fishing structures in the Pacific Islands. It reduces complexity without losing the richness of the data and facilitates meaningful comparisons across different cultures and environments. Subsequent chapters will apply this typology to archaeological case studies in Fiji and Hawai‘i, testing its utility with real datasets. By examining patterns through this classification lens, the aim is to gain deeper insight into how and why these remarkable fishing structures developed, how they reflect human-environment interactions, and what role they played in the evolution of Pacific Island societies. The paradigmatic approach ultimately enables a more nuanced appreciation that, in the Pacific as elsewhere, people responded to ecological challenges with creativity and ingenuity, building structures that were not just traps or ponds, but manifestations of cultural knowledge, social organization, and traditional ecological knowledge. While these customary structures have been documented archaeologically and ethnographically, their evolution and persistence require an interpretive lens that accounts for environmental feedback, social cooperation, and long-term investment. These theoretical frameworks are explored in detail in the following chapter.

3. METHODS AND THEORY

In this chapter, I review the methodologies and evolutionary theories that incorporate remote sensing, spatial analysis, and experimental modeling to investigate Pacific Island aquaculture, human-environment interactions, and settlement systems. Each section discusses either the methods or the theory utilized, complemented by case studies summarizing their application. To further illustrate these regional examples and to demonstrate my proficiency with these techniques, a field case study from Windward Oʻahu, focused on a submerged alignment at Kualoa, is used throughout the remote sensing section. This example supplements broader literature with firsthand application of the methods described and underscores the practical and interpretive value of remote sensing in dynamic coastal environments (Carson and Athens 2007).

Portions of this chapter, especially parts of Section 3.2 on remote sensing in coastal archaeology, are adapted from previously published co-authored work with Scott Honda (Sailors and Honda 2013). Honda contributed to the acquisition and processing of remote-sensing data and to technical interpretation of the imagery. I developed the archaeological framing of the study, conducted the field documentation and GIS analysis, interpreted the results, and revised the material for inclusion in this dissertation.

3.1 Theoretical Frameworks

In this section, I employ complementary theoretical perspectives to interpret the evolution and use of customary marine fishing structures in Oceania. Human behavioral ecology (HBE) offers insights into how environmental and social factors influence subsistence decision-making, illuminating why Pacific Island societies invested in fishponds, weirs, and traps (Winterhalder

and Smith 2000). Evolutionary theory and related models of strategic interaction help explore how communities cooperated or came into conflict in managing these marine resources over time (Renfrew 2016; Cochrane 2020). Finally, Niche construction and domestication theory provide a lens for understanding how people actively engineered their environments and coevolved with other species through practices like aquaculture (Laland and O'Brien 2010; Costa-Pierce 2022; Lepofsky and Salomon 2023; Thompson 2024). Together, these frameworks help explain how and why Oceanic peoples built elaborate marine structures, as well as the broader evolutionary logic and ecological dynamics underlying those practices. Each subsection below elaborates on one of these theoretical perspectives, drawing on Pacific Island studies and selective comparisons to other regions, such as the Pacific Northwest, to build an interpretive model for customary marine resource management.

3.1.1 Human Behavioral Ecology

HBE provides a valuable framework for analyzing the development and maintenance of customary fishing structures in Remote Oceania. As an evolutionary approach to human adaptation, HBE examines how environmental constraints and social conditions shape resource procurement strategies. HBE asks how people make subsistence decisions that maximize their fitness, which is often proxied by efficiency or caloric returns under given ecological circumstances (Winterhalder and Smith 2000; Weitzel 2026). These concepts align closely with the archaeological and ethnographic evidence of fish traps, weirs, and pond fields used by Pacific Island societies (Johannes 1978; Malindine 2019). By focusing on optimization and adaptation, HBE helps illuminate why Indigenous communities invested labor in building and maintaining these structures rather than relying solely on wild foraging or fishing (Fitzpatrick 2020).

One fundamental HBE model is optimal foraging theory (OFT), which predicts that foragers will pursue resources and use methods that yield the highest net energy gain per unit time (Smith 1983; Rogers and Weisler 2021). In marine structures, OFT would suggest that features such as fishponds or tidal weirs should be constructed and maintained only if they improve long-term foraging returns relative to other methods (e.g., line fishing or open-sea netting) (Aswani 1998). The placement and design of these structures often bear out OFT predictions. In Fiji, for instance, the location of stone tidal weirs corresponds to optimal foraging expectations: fishers minimized travel distance and energy expenditure by building weirs at productive reef edges and tidal inlets where fish are naturally funneled by currents. By leveraging tidal movements and fish behavior, these weirs enabled a high capture rate with relatively low ongoing effort, letting nature do much of the work of concentrating prey. Ethnographic observations and oral histories from Fiji confirm that such weirs were positioned in locations known for abundant fish runs and were used when conditions specific to tides and seasons maximized efficiency (Johannes 1978; Jennings and Polunin 1996; Johannes 2002).

Similarly, in Hawai‘i, the large-scale *loko i‘a* (fishponds) like those at He‘eia and Mōli‘i on O‘ahu, reflect an advanced understanding of ecological productivity and long-term optimization. These ponds are walled enclosures built in estuaries or coastal flats that allow fish to be bred, reared, and harvested in a semi-controlled setting (Kikuchi 1976; Costa-Pierce 1987). By investing labor upfront to construct walls, sluice gates, and channels, Hawaiian communities created a self-replenishing fishery that reduced search and pursuit costs at each harvest. Over time, the steady yields from fishponds could offset the initial energy costs of construction: one estimate puts the average production of Hawaiian fishponds at around 3,000 kg of fish annually, providing a substantial caloric return that justified their maintenance (Wyban 2020). The success

of these ponds in producing regular surpluses illustrates the HBE principle of delayed returns, where short-term costs are tolerated in exchange for long-term gains when environmental knowledge and planning indicate an overall improvement in foraging efficiency (DiNapoli and Morrison 2017).

HBE also emphasizes patch-choice and habitat-selection models relevant to how Indigenous communities decide where to concentrate their efforts. A "patch" in foraging is any discrete area that yields a specific return rate (Charnov 1976). Fish aggregation sites, reef flats, estuaries, and lagoon passages can be viewed as patches with varying productivity. Pacific Island fishers appear to have been keenly aware of patch productivity and diminishing returns characteristics, choosing to build fixed structures in locations that consistently outperform others (Weitzel and Munro 2026; Thomas 2019). In many cases, the presence of a fishpond or weir effectively "fixed" a high-yield patch in place, ensuring that people could repeatedly exploit a known rich location rather than expending energy searching widely for schools of fish. For example, archaeological surveys in Micronesia show that precontact communities often settled near productive marine patches and even modified them to enhance them, consistent with central place foraging expectations (Tinker 1950; Bird and O'Connell 2006).

Central place models predict that foraging locations will be optimized relative to residential sites, balancing travel costs against resource returns (Drennan et al. 2015). The dense clustering of fishponds around key chiefly centers in Hawai‘i and of communal weirs adjacent to village sites in Fiji supports the idea that settlement location and food production were co-optimized: people built villages near good resources and invested in structures to make those resources even more dependable (Winterhalder and Kennett 2006). In essence, Pacific Island

societies actively shaped their resource landscape to create high-yield "patches" where needed, exemplifying rational habitat selection tuned to local ecology (Innes-Gold et al. 2024).

Another critical aspect of HBE is risk management in subsistence. Islands are inherently variable environments that experience catastrophic events such as storms, tsunamis, seasonal shortages, and resource crashes (e.g., coral bleaching events that reduce wild fish stocks), which can threaten food security. Human behavioral ecologists recognize that foragers are not solely maximizers of mean returns but often minimizers of variance when the shortfall risk carries a high penalty (Winterhalder et al. 1999; Erickson 2000). In Oceania, risk-buffering strategies are evident in both terrestrial and marine domains (O'Connor et al. 2019). One can interpret the construction of fishponds and weirs as a risk-reduction measure: they provide a more predictable and controllable food supply to hedge against the unpredictability of open-ocean fishing. The predictability of fish stocks in an enclosed system, such as a pond or behind a weir, would have been a significant advantage during seasons of rough seas or when pelagic fish were scarce.

Ethnohistoric accounts from Hawai‘i note that fishponds were often tapped during famine or bad weather when other fishing was impossible, underscoring their role as a reliable safety net (Kikuchi 1976; Kirch 2010). Likewise, in remote atolls of Micronesia, where communities faced periodic droughts and lean periods, archaeological evidence suggests they intensified lagoon-fishing structures and food-preservation techniques to buffer against risk (Rainbird 2004). HBE models of risk-sensitive foraging predict that in high-variability contexts, foragers may prefer a lower-return but more reliable strategy over a "higher-return" but "boom-and-bust" one (Winterhalder et al. 1999). The prevalence of fixed-gear fishing (i.e., weirs, traps) in Oceania's most drought-prone or El Niño–La Niña-affected regions supports this idea: communities invested in methods that consistently guaranteed a modest catch rather than gambling each day

on open-water catches that could vary wildly (Nunn 2003; Matali et al. 2006). In a real sense, fishponds and weirs may have been insurance devices as much as food producers. This perspective aligns with patterns in terrestrial resource management as well (Ladefoged and Graves 2000). For example, the introduction and intensive cultivation of the sweet potato (*Ipomoea batatas*) in Polynesia during late prehistory can be seen as a risk-spreading adaptation, as the sweet potato provided a reliable crop in marginal areas when other staples failed (Iese et al. 2018). In the same vein, diversified subsistence economies that combined arboriculture, agriculture, fishing, and aquaculture, as in Hawai‘i and parts of Micronesia, reflect HBE-predicted strategies for minimizing the probability of total failure in any one subsystem (Winterhalder and Smith 2000).

Importantly, HBE approaches do not view indigenous Pacific peoples as passive recipients of environmental dictates. Instead, communities are active managers and decision-makers, continually adapting to feedback. The archaeological record increasingly affirms this agency. Rather than randomly exploiting whatever resources were at hand, Pacific Islanders strategically implemented systems such as fish traps to enhance yields, in line with rational cost-benefit calculations (Wyban 1992 and 2020). Their subsistence strategies exhibit characteristics of formal models, like diet breadth expansion by adding lower-ranked resources like small fish or shellfish to the diet when higher-ranked ones become scarce and patch switching or by moving effort to more productive zones when returns drop in a given patch. For instance, analyses of midden remains in Polynesia show shifts to new resource types or to intensified use of inshore fish and shellfish as large game fish and birds declined, consistent with optimal foraging predictions of resource depression and the subsequent broadening of the diet (Nagaoka 2006).

In many islands, once high-return reef fishes became over-harvested, people may have responded by investing in traps and ponds targeting herbivorous or juvenile fish that were previously less taken, thereby broadening the resource base in an efficient, structured way (Smith and Wishnie 2000). Rather than evidence of mismanagement, these shifts underscore adaptive decision-making. By applying HBE principles to such archaeological and ethnographic patterns, researchers can better reconstruct how past societies in Remote Oceania optimized their economies, balanced labor and return, and navigated environmental change (Kennett and Winterhalder 2006, 2008). In summary, HBE offers a powerful lens showing that features like fishponds, weirs, and traps were not anomalies or simply cultural curiosities; they were logical outcomes of adaptive choices made by people finely attuned to the costs and opportunities of their island environments.

3.1.2 Game Theory and Strategic Interaction

While HBE often focuses on individual decision-making or household-level optimization, many resource management problems are inherently social in nature. Customary marine structures like fishponds and communal weirs required collective effort to build and maintain, and their benefits were shared or contested among community members. Here, Game theory and related concepts of strategic interaction provide a framework for understanding cooperation and conflict in these contexts. In anthropology, game theory explores how individuals or groups make decisions when outcomes depend on others' choices (Maynard Smith 1976; Smith 1983). In common-pool resources, such as a village's lagoon or reef, game-theoretic models can illuminate how communities navigate potential dilemmas, including overfishing, labor investment, and benefit distribution (Ostrom 1990; Tu et al. 2024). In Oceania, where kin-based societies managed marine commons for centuries, one finds ample evidence of institutions and

behaviors corresponding to equilibrium solutions of iterative "games" from informal reciprocity pacts to formal chiefly regulations. By examining fishponds and weirs through the lens of public goods games or evolutionary game dynamics, insight is gained on how cooperative strategies emerged and were stabilized in Pacific Island communities (Axelrod 1984; Ashleigh and Weisler 2021).

One classic challenge in communal resource use is the "Tragedy of the Commons" (Hardin 1968), the idea that without coordination, individuals acting in self-interest will over-exploit shared resources, leading to collective ruin. However, archaic island and coastal societies long managed to sustainably harvest reef fisheries, suggesting they averted tragic outcomes through social mechanisms (Fitzpatrick and Giova 2021; Fitzpatrick et al. 2024). Traditional fishing structures themselves often enforced a form of management (LeFebvre et al. 2022). For example, a fixed tidal weir in a Fijian bay, constructed by a group of families, inherently limits catch to those who contribute labor or are part of the user group entitled to the weir's harvest. The existence of the weir thus creates a *de facto* property regime and a context for repeated games among those families, as everyone has a stake in not depleting the fish stock because they expect to keep benefiting over time. Historical accounts from Fiji and Polynesia describe how those who violated communal fishing rules, for instance, by poaching from someone else's weir or taking more than their share, faced social sanctions that ranged from shaming to exclusion from future benefits (Thompson 1940; Thomas 1991; Veitayaki 2000; Dacks et al. 2018). In game-theoretic terms, these societies evolved strategies analogous to “tit-for-tat” in repeated prisoner's dilemma games: cooperation was the norm, but defection or selfish behavior was met with punishment or reciprocity, thereby encouraging a return to cooperative equilibrium (Axelrod 1984; Field 2003).

Oral traditions sometimes recount how a lineage monopolizing a specific fish trap would reciprocate by sharing a portion of the catch during hard times with neighboring communities, expecting that generosity to be repaid later (Johannes 1978). Such reciprocal altruism can be stable if communities anticipate long-term interaction, a condition ideally suited to small island settings where people interact with the same partners over a lifetime. Strong reciprocity, where individuals willingly cooperate and punish defectors even at personal cost, has been observed in many small-scale societies and is thought to underpin the success of communal resource management (Gintis 2000). The "tit-for-tat" dynamic noted in Fijian fishing cooperative behavior exemplifies this: villagers who contributed labor to communal weirs were rewarded with shares of fish; those who shirked were noted and potentially left out or obliged to make amends before being reintegrated into the next cooperative venture (Dacks et al. 2018).

In many parts of Remote Oceania, cooperation in building and using fishing structures resembles a public goods game. In this scenario, individuals must decide whether to contribute to a common project that benefits all. Construction of a large stone fish trap or an extensive pond often requires dozens of people moving rocks, dredging mud, or assembling wood barriers. This labor investment is costly, and, individually, one might prefer to “free-ride” by letting others do the work and still enjoy some fish later (Gürdal and Farmer 2024). However, ethnographic records indicate surprisingly high levels of participation and low incidence of free-riding in such projects (White 2007). This observation suggests that cultural norms and reputation effects kept free-riding in check (Quan et al. 2024). Contributing to a communal fishpond could enhance one's standing in the community, whereas nonparticipation might lead to social disapproval or a reputation for laziness (Oliver 2002).

In game terms, island societies converted what could be a one-shot public goods dilemma into a repeated, reputation-based game where cooperative behavior was the rational long-term strategy. Anthropologist Elinor Ostrom (1990) identified several principles from global case studies that foster cooperation in commons management, such as clearly defined group membership, transparent decision-making, and monitoring. Many Pacific Island systems met these criteria: for instance, only members of a clan or village could use a particular fish trap indicating clear group boundaries, the community collectively decided on seasonal closures or harvest limits, which involves participatory rule-making, and appointed watchers that were sometimes a designated elder or the trap owner who monitored compliance at the weir (Ostrom 1990; Hviding 1996). Through such measures, what could have been an open-access "free-for-all" became a governed commons, with outcomes closer to a cooperative equilibrium than a tragedy.

Not all interactions were purely egalitarian, however. Hierarchy and centralized control also played a role in strategic resource management, particularly in larger or more stratified societies. In Hawai‘i, for example, the extensive pond fields and fishponds were often under the purview of chiefs (*ali‘i*), who coordinated labor and dictated access to these resources (Summers 1964; Kikuchi 1976; Kurashima and Kirch 2011; Costa-Pierce 2022). From a game-theoretic perspective, this resembles an asymmetric game or an ideal despotic distribution model (Winterhalder et al. 1999). The social elites acted as central organizers who served as effective "enforcers" of cooperative outcomes, while commoners complied, accepting the arrangement because it provided stability and fairness under the chiefs' oversight. Chiefs could demand labor to build a massive fishpond, but they were also expected to redistribute a generous share of the catch during feasts or times of need, thus maintaining loyalty (Sahlins 1972). This patron-client

dynamic solves collective action problems: the chief internalizes the cost of organizing and the benefit of larger harvests, and followers get reliable access under the chief's rules. Hawaiian fishpond management, with royal fishponds reserved for chiefly use and common ponds for the community, reflects a structured game in which players had different roles but a shared interest in not overexploiting the resource (Hardin 1968). If a commoner overharvested or broke a taboo (*kapu*) by taking fish out of turn, swift chiefly punishment followed, likely a form of centralized sanction that paralleled the community-enforced sanctions in less stratified societies. Both systems, egalitarian and hierarchical, solved the commitment problem in cooperation: people needed assurance that if they restrained themselves, others would too. Chiefs provided that assurance through command-and-control in stratified contexts, whereas mutual monitoring and social pressure did so in egalitarian contexts (Kirch 2010).

Another layer where game theory applies is with competition and conflict between groups. Resources like particularly productive fishing grounds or large fishponds could become points of rivalry (Kurashima and Kirch 2011). There are oral accounts, for instance, of inter-village disputes in Polynesia over productive reef sections, occasionally leading to sabotage of each other's fish traps or to poaching from ponds during raids (Kennet and Winterhalder 2008). Such scenarios are modeled as “hawk-dove” games (also known as “chicken” games), in which groups choose either an aggressive strategy (hawk) to take over a resource or a sharing/withdrawal strategy (dove) to avoid costly conflict (Dubois 2024; Bigoni et al. 2026). The outcomes in the archaeological record are long-term coexistence among adjacent communities, each with its own managed marine space, suggesting that outright "hawk" strategies or violent competition were relatively rare compared to negotiated arrangements (Cochrane 2020).

In many cases, territoriality was well-defined: traditional marine tenure in the Pacific often marked clear boundaries and violating them could provoke conflict (Johannes 1978; Johannes 2002). The game-theoretic analysis would say that when the cost of conflict was high and future interactions were assured, separate groups had incentives to establish conventions (e.g., reef boundaries, alternating use of a lagoon) rather than constantly fight (Maynard Smith 1976; Lam 1998). One could view these as an analog of the Bourgeois strategy in game theory, where contestants respect prior ownership to avoid costly fights. Indeed, ethnographers in Micronesia noted that if a reef area had an existing weir owned by one village, neighboring villages typically avoided fishing there without permission, not purely out of fear but because norms recognized the investment of labor as conferring a kind of right. In evolutionary terms, groups that established stable sharing arrangements likely outlasted those that fell into destructive feuds, suggesting a form of group selection favoring cooperative norms (Soltis et al. 1995). The fact that communal fishing structures persisted and were maintained over generations is indirect evidence that Pacific communities achieved a balance between cooperation and conflict in resource use, validating models in which communication, reputation, and trust mitigate the prisoner's dilemma in common-resource settings (Nowak 2006; Cinner and Aswani 2007).

Game theory also intersects with HBE in its treatment of optimality under social constraints. For example, earlier, I noted that optimal foraging might dictate investing in a fishpond if it yields high returns. Game theory adds that this investment will occur only if enough community members agree to cooperate, because no single person can build a large fishpond. Thus, the decision itself is strategic. Everyone benefits when everyone contributes: there is a high payoff if cooperation succeeds, but if too few contribute, the effort fails, and those

who try are worse off. Assurance games have two equilibria: one "all-cooperate" and one "all-defect." The key is to assure individuals that others will cooperate, so that it is worth doing so themselves (Skyrms 2004; Bripi and Greico 2025). Culturally, Pacific Islanders had various ways of providing such assurance. Group rituals and ceremonies often preceded large labor projects, such as the ceremonial ground-breaking of a pond or a community invocation before constructing a weir, serving to publicly commit everyone to the task (Kikiloi and Graves 2010).

In some cases, a respected elder or chief would allocate tasks and solemnly pledge communal feasting or reward upon completion, thereby giving each person confidence that others would not back out (Oliver 2002). Behavior such as this is analogous to a public signal that locks in the cooperative equilibrium of the assurance game. The success of these practices can be inferred from the scale of projects accomplished. Some Hawaiian fishponds have walls stretching hundreds of meters, embodying thousands of person-hours of collective labor (Summers 1964; Kikuchi 1976; Wyban 2020). They could not have been built without a strong system of trust and assurance in place. Comparative evidence from the Pacific Northwest Coast of North America offers an interesting parallel: some Indigenous communities built wooden fish weirs across entire rivers to trap salmon, undertakings that required dozens of people to coordinate during installation and operation (Byrams 2002; Johnsen 2009; Moss 2013; Bowden 2021). As in Oceania, Northwest Coast groups employed social coordination, often under a clan leader's direction, to ensure everyone worked together, and they developed elaborate ownership rules to manage the harvest fairly and avoid conflict (Moss and Wellman 2021). This cross-cultural similarity underscores that wherever humans engaged in large-scale cooperative harvesting, they innovated social contracts, whether implicit or explicit, to align individual incentives with group goals.

Applying game theory and strategic interaction models to the case of Oceanic fishponds, weirs, and traps reveals that these were not just food-getting devices but also social institutions. They were focal points around which rules, norms, and strategies evolved to address issues of contribution, allocation, and sustainability. The archaeological and ethnographic records show that Pacific communities effectively addressed collective action challenges highlighted by modern theory: they achieved high levels of cooperation and enforced sustainable use by avoiding “tragedy of the commons” dilemmas and, when necessary, leveraged hierarchy or norms to prevent conflict. Rather than selfishly overexploiting their fisheries, as the simplistic "tragedy" scenario suggests, island societies demonstrated a nuanced understanding of shared interests and long-term payoffs (LeFebvre et al. 2022). Game-theoretic perspectives thus complement HBE by adding the crucial dimension of social interaction. It helps explain how organized, lasting marine resource management systems could arise without central governments or written laws. Indeed, examples of Pacific Island customary practices have become classic case studies in the literature precisely because they show how local communities can avoid overexploitation through evolved cooperative behaviors (Johannes 2002; Cinner and Aswani 2007). The strategic perspective reinforces the view that fishponds and similar structures were sustainable because of their ecological design and the social strategies that underpinned their use.



Figure 12. Photo of local Fijian family constructing reed traps called *bai ni ika*. (Sailors 2013).

3.1.3 Niche Construction, Domestication, and Coevolution

Human behavioral ecology and game theory treat the environment as a backdrop for human adaptation and strategy. The third perspective, niche construction theory (NCT), and related ideas of domestication and coevolution flip this view by emphasizing humans as active agents who modify their environments, thereby altering the selective pressures and ecological conditions for themselves and other species (Odling-Smee et al. 2003; Zohary et al. 2012). NCT posits that organisms, including humans, do not just adapt to environments; they also adapt environments to themselves, creating feedback loops between organisms and ecosystems (Laland and O'Brien 2010). In anthropology and archaeology, this has led to a rethinking of domestication not as a sudden "invention" or as one-way human control over nature, but as a gradual coevolutionary process in which human practices and target species evolve in tandem (Zeder 2016). Customary marine structures in Oceania offer clear examples of cultural niche

construction: by building fishponds, weirs, and other modifications, Pacific Islanders physically reshaped coastal ecosystems, creating new habitats, changing species' population dynamics, and in some cases, initiating quasi-domestication of wild resources (Wyban 1992; Kikiloi 2003).

This section explores how niche construction and domestication theory help explain the ecological logic of these practices, from the manipulation of trophic networks to the mutualistic relationships that developed between humans and marine organisms. Terrestrial and maritime examples from the Pacific Islands, with occasional comparisons to the Pacific Northwest, illustrate a continuum of niche-construction activities that significantly altered environments long before industrialized aquaculture or agriculture, highlighting an often-undervalued aspect of human ecological impact: intentional ecosystem engineering for long-term productivity, food security, and sustainability (Lepofsky et al. 2015; Malindine 2019; Lepofsky et al. 2021).

NCT broadens our understanding by arguing that humans have not been passive recipients of environmental pressures but have been active ecosystem engineers for millennia (Jones et al. 1994). In Oceania, this is dramatically evident. When Polynesian voyagers settled previously uninhabited islands, they brought with them a suite of plants and animals to establish familiar subsistence systems (Anderson and O'Connor 2008). The transportation of these organisms, referred to by some scholars as "transported landscapes", was an initial form of niche construction, effectively transplanting and reassembling ecosystems in new locales to better suit human needs. Hawai'i is a prime example: as noted earlier, the first Hawaiians introduced root crops like taro (*kalo*; *Colocasia esculenta*) and sweet potato (*u'ala; Ipomoea batatas*), tree crops like breadfruit (*Artocarpus altilis*) and coconut (*Cocos nucifera*), and domesticated pigs (*Sus scrofa*) and chickens (*Gallus gallus domesticus*), turning an ecosystem with few edible native species into a Polynesian-style food web that could sustain a growing

population (Bevacqua 1994; Athens 1997). They adapted to the islands and actively created a new niche; a hybrid landscape of Polynesian domesticates and native resources. Over generations, these practices led to significant environmental changes: forests were cleared for gardens, new species, including invasive ones such as rats, altered ecological balances, and eventually highly managed systems like irrigated taro terraces and fishponds emerged (Steadman 2006; Kirch 2017; Hunt and Lipo 2025). Each of these steps is part of cumulative niche construction, where earlier modifications (e.g., stream diversions for irrigation) set the stage for later ones (e.g., integration of taro ponds with fish cultivation in the same watershed).

Focusing on marine niche construction, one of the most striking examples is the Hawaiian fishpond (*loko i'a*) system. Here, people built massive stone or earthen walls in estuaries and shallow bays, enclosing ocean areas to create semi-controlled brackish ponds for fish rearing (Summers 1964; Kikuchi 1976; Costa-Pierce 2022). By modifying tidal flow through sluice gates that regulated water exchange, altering predator-prey relationships with walls that kept out large predators like sharks and barracuda, and even introducing or encouraging particular cultivated species such as herbivorous fish like mullet (*'ama'ama;* Mugilidae) that were preferred for consumption, Hawaiian fishers fundamentally changed the selective nearshore environment for marine life (Kikiloi 2003). Fish experienced a very different habitat within a fishpond than in the wild. Plentiful food was in the form of algae proliferating in the nutrient-rich pond; they had shelter from predators, and eventually, human-controlled harvesting exerted selective pressure. Over time, this could lead to faster-growing fish populations that perhaps bred more in tune with pond conditions. Some researchers have suggested that fishponds initiated a domestication process for some species, not to the extent of full genetic domestication as with

cattle or dogs, but rather a shift in traits such as behavior and size structure due to human selection (Kikiloi 2003; Zeder 2015).

Historical records mention the deliberate stocking of ponds with juvenile fish caught from the wild and, occasionally, the translocation of species between ponds, indicating an early form of aquaculture breeding management. Hawaiian fishponds thus exemplify niche construction: humans created a novel niche (the pond), and both humans and fish populations adapted to it (Rogers 2024). In doing so, Hawaiians were redirecting natural selection pressures. For example, large, bold fish that might be easily caught were removed, potentially favoring those that matured quickly or reproduced at smaller sizes within the pond environment if allowed to spawn there. Indeed, archaeological sampling of fish bones from pond contexts shows a preponderance of size classes and species consistent with such selective pressures (Farber and Halapua 2002). These dynamics support the idea that the Hawaiians were not just harvesting fish but subtly shaping the evolution of their marine resources by engineering the environment (Smith 2016).

Similar processes occurred elsewhere in Oceania. In Fiji and other parts of Melanesia, communities constructed stone tidal weirs on reef flats. These were often simple rows of rocks or logs that trapped fish behind them as the tide fell (Connaway 2007). Although simpler than Hawaiian ponds, these weirs still created a persistent change in the environment: they formed small pools on the reef where fish would predictably gather when the tide receded (Gillett 2014). Particular fish species became the regular targets of these traps, and their populations would have experienced repeated "harvest events" at specific locations and times. Over generations, this "ecological trap" could exert selective pressure on fish behavior (Boivin et al. 2016). For instance, fish habitually returning to specific reef passages might be preferentially removed,

whereas those with more erratic movement patterns occasionally escape, potentially influencing migration behavior over time.

The placement of the weirs also reflected deep traditional ecological knowledge. Builders knew which species would move with the tide and how water flows over the reef, tuning their niche construction to existing ecological rhythms (Bond and Gmirkin 2003). It is an iterative coevolutionary process in which fishers adjusted the designs and locations of weirs based on how fish responded, then learned and refined their techniques. The outcome was a human-reshaped coastal niche where stone alignments, tidal ecology, and the life cycles of fish and people became intertwined. Evidence of long-term use of the same weir in archaeological layers, like sediment buildup and repair events, suggests these features were sustainable, not one-off exploitations (Athens 1997; Walter and Weisler 2002). Sustainability in this sense implies that fish populations were not driven to extinction by the traps, likely because customary practices regulated their use and because the traps themselves perhaps had a size-selectivity that let juveniles or certain species escape, unintentionally conserving them as seen in other areas of the Pacific, such as the Solomon Islands (Aswani 1997; Aswani and Hamilton 2004; Leach and Davidson 2008). In other words, the niche created by various customary fishing structures was one that humans managed, but in a way that maintained enough ecological balance for the relationship between humans, fish, and reef to continue over centuries, a hallmark of a stable and sustainable, coevolved system (Boivin et al. 2016; Lefebvre et al. 2022).

When discussing domestication, we often think of genetic change under human control, as described in the domestication of pigs or taro (Zohary et al. 2012). However, scholars have proposed a broader concept of domestication as mutualism. Rather than a one-sided imposition of human will, many domestication processes can be seen as a form of biological mutualism

where both humans and target species derive benefits, and each influences the other's success. Conceptualizing like this is a helpful way to understand fishpond systems in the context of Pacific aquaculture (Kikiloi 2003; Smith 2007). Humans provided protected, food-rich habitats for fish to their benefit, and in return, the fish provided a reliable food source for humans (Leigh 2010). Unlike terrestrial farm animals, the fish in Hawaiian ponds were not penned or bred into markedly different forms, but they did become habituated to the pond environment, perhaps even accumulating across generations if ponds were managed such that some stock always remained.

Historical anecdotes in Hawai‘i describe certain revered ponds known for particularly tasty or large fish, suggesting that informal selective breeding or at least preferential culling was taking place (Farber and Halapua 2002). Mutualistic framing helps shift our view: rather than humans dominating the environment, we see an interdependent system where the fish thrive because human intervention ensures no predators and ample food, and humans thrive because of the surplus fish. The longevity of some fishponds maintained for hundreds of years until the 19th century indicates that this mutualism was robust (Kikuchi 1976; Wyban 2020). In some Pacific Island languages, terminology for tended fish or tended plots draws on kinship or caring metaphors, reinforcing the idea that people saw themselves as stewards of these living systems, not just exploiters (Hiatt 1962; Poepoe et al. 2007). This resonates strongly with niche construction theory's emphasis on ecological inheritance: each generation inherits genes and a modified environment from the previous generation, affecting their survival and practices (Odling-Smee et al. 2003). A Hawaiian child born into a community with a functioning fishpond inherited a very different set of opportunities and obligations to maintain that pond than one born in a community without ponds. Thus, cultural knowledge, social organization, and the local fish gene pool in the pond all coevolved as an integrated system.

Niche construction in Oceania was not limited to food production; it often had broader landscape impacts. Hawaiian irrigated taro farming is one terrestrial parallel exemplified by terracing valley bottoms and diverting streams where early Hawaiians created expansive wetland ecosystems (*loʻi*) where none existed before, supporting not just taro but a host of other organisms like mollusks, prawns, and even waterfowl that were drawn to these artificial ponds (Kikiloi 2003; Kirch 2017). These *loʻi* could be seen as domesticated landscapes as much as fields. Similarly, the creation of large dryland field systems with stone alignments, as on Hawaiʻi Island's leeward plains, altered wind patterns, soil moisture retention, and plant communities, which was effectively a large-scale niche construction effort to favor crops like sweet potato (Ladefoged and Graves 2000). The coevolutionary aspect here is that Hawaiian society changed in response to these engineered niches: increased food yields supported population growth and political centralization, which led to further production intensification (Kirch 1994). The feedback loops are evident; more fish from ponds and taro from *loʻi* meant chiefs could feed more retainers and warriors, strengthening their power.

This consolidation and projection of power allowed them to mobilize more labor to expand or build new systems. Over time, a tight coupling emerged between social complexity and niche construction. Archaeologists have noted that the apogee of large-scale stonework construction in Hawaiʻi corresponds to the later centuries of the precontact era, when chiefly societies were highly stratified (Kolb 1997). This fluorescence could be interpreted as the coevolution of sociopolitical structures and food production systems: as society stratified, elites sought methods to secure food surpluses, such as fishponds, and the success of those methods, in turn, reinforced the social hierarchy that initiated them. A similar pattern appears in some parts of Micronesia; for instance, the elaborate irrigation systems and possibly fishponds of Pohnpei

went hand in hand with the rise of paramount chiefs who organized their construction (Ayres 1992).

Kekuewa Kikiloi (2003) outlined a hierarchy of domestication behaviors for Hawaiian fishponds and similar systems to systematically understand the domestication aspect of Pacific aquaculture. In increasing order of human intervention, these include: (a) protection from predators (e.g., building enclosures that keep out sharks and large predatory fish); (b) control over reproduction (e.g., timing water exchanges or adding spawning stock to encourage breeding in ponds); (c) regulation of growth conditions (e.g., improving nutrient flow, removing competitor species, perhaps feeding the fish with additional algae or cooked taro leaves as reported in some Hawaiian traditions); and (d) management of harvesting (selectively culling fish at specific sizes or seasons). Each level represents a deeper form of engagement in the resource's life cycle, edging closer to full domestication. By these criteria, Hawaiian fishponds consistently achieved at least the first and last steps of predator exclusion and managed harvest. There is evidence suggestive of the second and third steps as well: some accounts claim that in certain ponds, fish known to be near spawning were allowed to escape to the sea to reproduce, and then their offspring would recruit back into the pond, which is an indirect form of breeding management (Kikuchi 1976; Wyban 2020). Also, pond caretakers sometimes transplanted edible seaweed (*limu*) or introduced brackish-tolerant taro around pond edges, which fertilized the water and fed the fish in a modest form of supplementary feeding and habitat enhancement (Malo 1903; Costa-Pierce 1987). In sum, while Pacific Islanders did not "genetically" domesticate marine species in the way carp or tilapia were later domesticated elsewhere, they did meet many functional criteria of domestication by shaping the phenotypes and abundances of target species through environmental modification and selective harvest (Teletchea 2018; Zeder

2012, 2015). The result was a suite of semi-domesticated systems: fishponds, clam gardens, and managed estuaries that blurred the line between wild and cultivated.

Beyond fishponds and weirs, other Pacific examples highlight the breadth of niche construction and proto-domestication in aquatic contexts. On some Polynesian atolls and islands, people practiced clam mariculture where the conditions favored this adaptation. For instance, the people of Takū'u (a Polynesian outlier in Melanesia) maintained giant clams (*Tridacna gigas*) in designated lagoon groves, effectively farming them for later consumption (Moir 1993). They cleared reef areas to create an ideal clam habitat and periodically "seeded" them with juvenile clams, as one might tend a garden. In the Marshall Islands, historical reports describe turtle *kraals* where sea turtles were kept in lagoon pens for fattening until needed for feasts, indicating a form of animal husbandry in the marine realm (Fosberg 1955). Various Pacific Island groups also cultivated edible seaweed by encouraging growth on nearshore rocks or by transferring starter fragments to new areas, a practice tied to both diet and medicine, akin to tending wild algae gardens (Abbott 1978). Moreover, in the Cook Islands and Society Islands, there is evidence of pearl shell management: not fully farmed as in modern pearl culture, but villages claimed and systematically harvested patches of pearl oyster beds in ways that suggest they understood how to sustain yields, adding substrate for larval oysters to cling to, and rotating harvests (Moir 1993). Each of these practices can be seen as part of a continuum of domestication. They did not always result in true genetic domestication, where humans exert direct selective breeding. However, they all involved environmental engineering and lifecycle manipulation that increased resource predictability for humans while often also expanding the niche or population of the target species (Boivin et al. 2016). In other words, humans expanded

the ecological opportunities for these organisms, providing space and removing competitors and predators, and in return reaped a larger, more reliable, and more sustainable harvest.

Comparative cases from the West Coast of North America further reinforce these principles. Indigenous peoples from Alaska to British Columbia constructed clam gardens, rock-walled terraces in the intertidal zone that enhance shellfish production. They created broader level beach terraces with an optimal sand-to-mud mix for clam habitat by building low walls at the low-tide line. Studies show that these ancient mariculture features, some over 2000 years old, significantly boosted clam growth rates and densities, effectively increasing the environment's carrying capacity for clams (Groesbeck et al. 2014; Lepofsky et al. 2015, 2021). This is a textbook example of niche construction: natural limiting factors for clam populations, such as intertidal slope and substrate stability, were altered by human agency, leading to greater abundance of favored food. Over generations, the practice would have shaped cultural habits through clam feasts, seasonal scheduling of digs, inheritance of clam plots, and possibly clam biology through selection of faster-growing individuals in the garden environment (Lepofsky et al. 2015). Significantly, the clam garden tradition, like Pacific Island fishponds, was sustainable over millennia, indicating careful management. Another Northwest Coast practice used fish weirs and selective harvesting technologies for salmon, culturally analogous to the Oceanic fish traps. Heiltsuk and other First Nations in British Columbia placed elaborate wood-stake weirs in streams but refrained from catching the entire salmon run; they often released a portion of the salmon or operated weirs intermittently, ensuring enough spawners escaped upriver (Byram 2002; Deur and Turner 2005). Such stewardship reflects an implicit understanding of coevolutionary needs: humans "farmed" the salmon runs by culling some and sparing others, a balance that sustained both the salmon population and the people. If too many salmon were

taken, future runs would collapse, and the feedback would be quickly apparent to indigenous managers (Trosper 2003). The same likely held in Oceania: fishponds and weirs were managed with an eye toward not exterminating the very resource they cultivated. Hawaiian *kapu* systems, for example, imposed seasonal restrictions, such as months when fishing a pond was prohibited to allow spawning or protect certain species, operating much like adaptive management rules (Poepoe et al. 2007). All these examples underscore that niche construction was not haphazard. Instead, it was guided by observation, learning, and evolving cultural protocols, a process some describe as the coevolution of institutions and resources (Smith and Wishnie 2000).

From an energetic perspective, this trophic-level manipulation is a key benefit of niche construction in aquaculture. Wild fisheries often target high-trophic-level predators (e.g., tuna, reef carnivores), which are less energy-efficient yields because so much energy is lost in each step up the food chain (Pauly 1998). By contrast, traditional fishponds in Oceania typically raised algae-eating or detritus-eating fish (low trophic levels) such as mullet or milkfish (*awa*; *Chanos chanos*), capitalizing on the abundant primary productivity of shallow waters (Kikuchi 1976; Kikiloi 2003). Essentially, people were farming solar energy via algae and filtering it through fish they could eat rather than "fishing down" the food chain. The result was impressively productive systems. As noted, a single Hawaiian pond of a few hectares could yield thousands of kilograms (kg) of fish annually (Kikuchi 1976; Wyban 2020). This output is analogous to agricultural yield on land, and indeed, missionaries in the 19th century, familiar with European carp ponds, marveled at the scale of Hawaiian *loko i‘a* and their integration with taro fields, calling them a form of "sea gardening" (Ellis 2004). In these integrated Hawaiian systems, the by-products of agriculture, like taro leaves or waste, could feed fish, and fish waste, in turn, fertilized the taro waters. It is an early example of nutrient cycling that modern

agroecology lauds (Costa-Pierce 1987). Such synergy indicates a sophisticated understanding of ecosystem processes, in which Pacific Islanders effectively managed aquatic food webs to enhance energy flow into forms they could use.

This strategy is a form of ecosystem domestication seen in many maritime cultures globally, orchestrating not just a single species but interactions among species for productive ends (Erlandson and Rick 2010). It also has coevolutionary implications: species that thrived in these human-created niches, whether a type of algae that grows on pond walls or a strain of taro that does well in fish-fertilized water, would spread and become more common, often reliant on continued human management to persist. Thus, humans and certain domesticates entered a long-term coevolutionary pact: taro tubers got propagated and spread to new islands by people, and people became increasingly dependent on taro; fish in ponds multiplied under human protection, and humans, in turn, invested ever more effort in maintaining ponds. Evolution favors genetic traits in plants and fish that make them easier to cultivate through human practices. Likewise, human cultural habits and even genetic traits may evolve in response to these changes (Smith 2016; Zeder 2016).

Finally, niche construction and domestication frameworks allow us to reconsider these systems' long-term trajectories and resilience. A standard narrative for many Pacific Islands, especially small ones, has been ecological fragility and human impact leading to resource crashes (e.g., deforestation and fauna extinctions on Rapa Nui or Henderson Island) (Diamond 2005). Niche construction theory provides a more nuanced narrative and asks, "Under what conditions did human-environment modifications lead to sustainable mutualisms versus destructive outcomes?" The evidence for the marine structures in question suggested resilience and sustainability when traditional management was in place. Hawaiian fishponds, for example,

remained largely productive until the 19th and 20th centuries, when they were abandoned or damaged due to population collapse and new property regimes following European contact (Wyban 1992). Under indigenous stewardship, they were stable and sustainable for centuries. Similarly, ethnographic records from places like Roviana Lagoon (Solomon Islands) show that communal management of fish traps maintained high catches into living memory, deteriorating only with the breakdown of customary tenure in recent decades (Aswani 1997; Cinner and Aswani 2007).

This implies that the coevolved norms and practices were integral to the niche. Once those were disrupted by colonial law and missionization, which was nearly universal across the Pacific Basin, the niche construction could turn maladaptive (e.g., outsider commercial fishing overharvesting the previously managed lagoon). Thus, coevolution occurred between humans and target species, and between culture and environment. Customary law, spiritual beliefs with many fishing practices tied to religious observances or taboos, and social institutions were part of the coevolved complex that kept these systems functional (Johannes 2002; Poepoe et al. 2007; Berkes 2008). In the Pacific Northwest, elders have similarly noted that clam gardens and other sea gardens require the "culture" around them to function. Simply having the rock wall is insufficient; people must tend, monitor, and restrain themselves accordingly (Deur and Turner 2005). Without the cultural component, the mutualistic relationship can decay (e.g., clams get over-harvested, or gardens silt up or erode away).

This highlights a critical insight from niche construction and coevolutionary theory: evolutionary success is measured in the persistence of the system, not just short-term yields. The interplay of human behavior, social rules, and environmental feedback determines persistence. In Oceania, the longevity of fishponds and weirs as effective institutions suggests a successful

coupling of culture and nature, an adaptive fit that has evolved. These were not static systems; they were dynamic and capable of adjustment. For instance, if a pond's fish began to decline, Hawaiians might respond by declaring a *kapu,* or temporary no-fishing period, to let stocks rebound, or by repairing walls to prevent escapes, actions indicating feedback management. In evolutionary parlance, they engaged in ecological niche management, fine-tuning their constructed niches to enhance stability.

The niche construction and domestication perspective allows us to see fishponds, weirs, and traps in Oceania as far more than clever fishing techniques. They embodied a coevolutionary relationship between Pacific Island societies and their nearshore marine ecosystems. By intentionally modifying environments, humans in Oceania expanded the production potential of their islands, creating novel ecological niches that increased food yields and reliability. In doing so, they set in motion reciprocal changes in species abundance and behavior, human social organization and knowledge systems, and the flow of energy through island ecosystems. These changes often led to mutualistic outcomes where both humans and target species benefited and became interdependent. By examining customary marine structures through NCT, I highlight the agency of Indigenous peoples in shaping their world, countering older narratives that cast them only as responders to environmental whims. Instead, Oceania's ancient aquaculturists were knowledgeable and proactive experimenters and stewards, engaging in what might be called proto-domestication of the sea.

This theoretical lens also emphasizes that culture and environment evolved together: practices like fishpond aquaculture cannot be separated from the cultural context that enabled them, nor can island environments be understood without recognizing the long-term imprint of human niche construction. Together with HBE and game theory, NCT and domestication theory

round out our theoretical framework by accounting for how people innovate on and transform ecosystems, becoming a driving force of evolutionary change. This perspective is crucial as I interpret the archaeological evidence of marine resource use in Oceania, enabling the ability to see fish traps and ponds not just as static artifacts but as traces of an ongoing dialogue between humanity and nature, one that, in the best cases, achieved a long-lasting and dynamic equilibrium.

3.2 Remote Sensing in Coastal Archaeology

3.2.1 Introduction

Remote Oceania's coastal and island environments present unique challenges and opportunities for archaeological research. Customary fishing structures, such as fishponds, stone tidal weirs, and other marine resource management features, are often partially submerged, obscured by vegetation, or threatened by dynamic processes like erosion and sea-level rise (Erlandson 2012; Luo et al. 2015, 2017; Nunn et al. 2017). In recent decades, archaeologists have increasingly turned to remote sensing technologies to identify, document, and analyze these features at landscape scales (Ladefoged et al. 2011; McCoy 2018; Traviglia and Bernardoni 2020; Casana et al. 2021). This section reviews the historical development and current applications of key remote sensing tools in archaeology, focusing on airborne and satellite imagery, LiDAR (Light Detection and Ranging), unpiloted aerial vehicles (UAVs or drones), and multispectral analysis.

Here, I emphasize case studies from the Pacific Basin, including the Pacific Islands, Southeast Asia, and the Pacific Northwest, illustrating methodological innovations in coastal and island archaeology. By examining how these technologies are used to locate and interpret submerged or coastal archaeological features, we gain insight into their value for fieldwork in

dynamic coastal environments affected by climate change (Sailors and Honda 2013; Quintus et al. 2015; Trant et al. 2016).

3.2.2 Historical Development of Remote Sensing in Archaeology

Remote sensing in archaeology broadly refers to detecting and recording archaeological information from a distance without direct physical contact. The use of remote sensing has evolved significantly over the past century. Early applications date back to the mid-20th century with conventional aerial photography. For instance, researchers in New Zealand were experimenting with aerial photos for site discovery as early as the 1940s (Palmer 1947). By the 1960s and 70s, aerial surveys had become an established tool in Pacific archaeology (Jones 1996). These early efforts in Oceania primarily identified extensive earthworks, agricultural terraces, and fishpond walls visible from the air. For example, aerial surveys helped map extensive ancient field systems and coastal archaeological complexes in Hawai‘i, providing the first regional views of these features (Ladefoged et al. 2011; McCoy 2018; Kirch and McCoy 2023). Such aerial imaging laid the groundwork for today's more advanced techniques by highlighting the value of a "bird's-eye view" in archaeological reconnaissance.

The satellite era brought new opportunities and challenges. Declassified military satellite images from the CORONA program (1960s–70s) were first applied to archaeology in other regions (Casana et al. 2012). However, coarse resolution and minimal coverage of small islands limited their use in the Pacific. By the 2000s, however, high-resolution commercial satellites (e.g., QuickBird, WorldView) began delivering sub-meter imagery with multiple spectral bands, making them powerful tools for archaeologists (Agapiou 2020). At the same time, the growing integration of GIS and, later, increasingly accessible GPS data, especially after the end of Selective Availability in 2000, allowed archaeologists, Historic Preservation Offices, and other

heritage agencies across the Pacific to georeference sites more accurately, manage spatial and visual datasets at larger scales, and coordinate remote sensing results with survey, monitoring, and preservation work (Menéndez-Marsh and Jiménez Cano 2023).

In Polynesia and Island Southeast Asia (ISEA), satellite imagery has been used to detect subtle landscape modifications not apparent at ground level. On Rapa Nui (Easter Island), for instance, researchers employed satellite data to map the distribution of stone mulch rock gardens used in prehistoric agriculture (Ladefoged et al. 2013). By analyzing spectral differences in vegetation growth, they identified garden features across the island that had eluded earlier ground surveys. Similarly, Hunt and Lipo (2008) used satellite imagery and GIS to trace prehistoric road alignments associated with statue transport on Rapa Nui, demonstrating how remote sensing could reveal patterns of ritual landscape use invisible on the ground (Hunt and Lipo 2008, 2011). These examples mark a significant shift from opportunistic aerial photo interpretation to systematic digital remote sensing analysis in Pacific archaeology.

Perhaps the most transformative development in archaeological remote sensing has been the advent of airborne LiDAR in the early 21st century. LiDAR, which uses laser pulses to generate high-resolution elevation models, was initially developed for surveying vegetation and topography in Mesoamerica (Chase et al. 2011). Its archaeological potential was first hinted at in the 1980s but not fully realized until technological advances in the 2000s made high-resolution data more accessible (Chase et al. 2012). By the late 2000s and early 2010s, archaeologists in the Pacific began experimenting with LiDAR to "see through" dense tropical vegetation and map subtle earthworks. One pioneering project in Hawai‘i demonstrated LiDAR's value: Ladefoged et al. (2011) conducted an airborne LiDAR survey of the leeward Kohala field system on Hawai‘i Island, producing a detailed digital elevation model that revealed agricultural terraces, walls, and

pathways with unprecedented clarity. This study quantified agricultural development in ways not possible with ground survey alone, refining models of how food production supported the island's ancient political economy. Since then, LiDAR has gained prominence in archaeology worldwide, including in Remote Oceania, where vast expanses of rainforest and rugged terrain often conceal sites.

The toolkit for remote sensing in archaeology has expanded from simple aerial photos to sophisticated multi-sensor platforms. The historical trajectory shows increasing resolution, broader coverage, and enhanced analytical techniques, such as digital image processing and machine learning for feature detection. The following sections examine each major technology: satellite imagery, LiDAR, UAV photogrammetry, and multispectral analysis, highlighting their methodological roles in investigating customary fishing structures and coastal sites, particularly under the pressures of environmental change.

3.2.3 Satellite Imagery and Aerial Photography in Coastal Contexts

Satellite imagery provides a synoptic, wide-area perspective that is especially useful in island and coastal archaeology, where sites may be distributed along shorelines or across archipelagos. Modern high-resolution satellites can capture images with pixel sizes of less than 1 meter, allowing the identification of relatively small features, such as stone walls, earth mounds, or vegetation alignments, that indicate past human activity. For coastal and nearshore sites, certain spectral bands (such as visible blue and near-infrared) can aid in detecting features beneath shallow water or within moist soils. A notable example comes from windward Oʻahu, Hawaiʻi, where an offshore stone alignment at Kualoa, interpreted as a probable prehistoric fishing infrastructure or boundary, was investigated using WorldView-2 satellite imagery (alongside other tools). The WorldView-2 satellite carries a coastal blue band optimized to

penetrate clear, shallow water; by analyzing these spectral data, Sailors and Honda (2013) discerned linear stone anomalies on the seafloor.

With its broad coverage, the satellite imagery first pinpointed the feature's location and extent, which could be examined in detail with drones and divers. This case study applied multispectral satellite imagery processed through principal component analysis (PCA) and non-homogeneous feature difference (NHFD), which enhanced spectral differentiation and improved underwater visibility (Jensen 2005, 2007; Sailors and Honda 2013). This technique facilitated the identification of the submerged stone alignment from space, which was later confirmed through UAV and GIS-based analysis, as well as ground-truthing. The findings support the value of satellite imaging as a first-pass tool for identifying submerged cultural landscapes. This case exemplifies how satellite remote sensing can jump-start the survey of submerged cultural structures by identifying targets that warrant closer investigation. For an example of the imagery analyzed for Fijian customary fishing structures, see Figure 13.



Figure 13. Satellite imagery of Fijian fishing structures from Google Earth (2015).

Beyond single-site discovery, satellite imagery has been instrumental in regional studies of coastal land use. In the western Pacific, for instance, analysts have used multi-temporal satellite photos to track coastal erosion and site exposure (McCoy 2018). On low-lying atolls and islands in Micronesia, a comparative analysis of historical aerial photos and recent satellite images reveals shoreline retreat that has exposed cultural layers and features, alerting archaeologists to new finds on eroding beaches (Nunn et al. 2017). In ISEA, medium-resolution satellites, such as Landsat and Sentinel, have been used to detect landscape changes, such as mangrove clearing or construction, that might disturb coastal archaeological sites (Gandhi et al. 2019). While these applications are often more environmentally focused, they demonstrate the integrated use of remote sensing data: multispectral imagery can flag environmental processes, such as sedimentation or vegetation shifts, that indirectly signal where archaeological deposits might be threatened or revealed.

It is worth noting that traditional aerial photography plays a role, often complementing satellite data. Many Pacific Island studies still rely on analysis of aerial photo archives to map features such as ancient fishponds, agricultural grids, or fortifications (Parry 1994; McCoy 2018). Modern researchers can georeference these historic photos in GIS and compare them with current imagery to observe changes over decades. This approach has been used in the Pacific Northwest to study wooden intertidal fish weirs: historical aerial photos taken at low tide in the mid-20th century often show patterns of stakes or rock alignments that have since degraded or been obscured, thus serving as a baseline for current surveys (Byram 2002). In short, satellite and aerial imagery, both old and new, serve as a foundational resource for remote sensing in coastal archaeology, providing a broad perspective, guiding ground-based efforts, and documenting change over time.

3.2.4 UAV-Based Imaging and Photogrammetry

The past decade has seen an explosion in the use of unpiloted aerial vehicles (UAVs, or drones) for archaeological surveying, particularly in coastal areas where access can be challenging, and site footprints are best appreciated from above (Lambert and Skousen 2023; Casella et al. 2020). UAVs equipped with cameras allow archaeologists to collect extremely high-resolution imagery (a few centimeters per pixel) and to generate 3D models via photogrammetry (Structure-from-Motion, SfM) (Lambert and Skousen 2023). For methodological reasons, we de-emphasize the detailed photogrammetric technique here. However, it is important to note that drone-based SfM has become a standard practice for creating orthophotos and elevation models of sites. These UAV-derived products fill a spatial niche between broad satellite coverage, which has a lower resolution, and ground total station mapping, which has high resolution but can only be used in a limited area. In dynamic coastal contexts, drones offer a quick and non-intrusive way to map features that are periodically obscured by tides or prone to erosion (Casella et al. 2020, 2022).

Alongside UAV-based approaches, Kite Aerial Photography (KAP) remains a useful low-altitude remote sensing method for archaeological survey, especially in open coastal settings where steady winds, short tidal windows, and the need for very high spatial resolution make small and flexible imaging platforms advantageous (Verhoeven 2009; Bryson et al. 2013; Duffy and Anderson 2016). Compared with satellite or conventional aircraft imagery, KAP can be deployed quickly and at relatively low cost over site-scale targets, allowing the collection of oblique and near-vertical photographs at centimeter-scale resolution and, where image overlap and control are sufficient, the creation of orthophotos and other photogrammetric products. The method is particularly well suited to intertidal and shoreline archaeology because it can be timed

to low tide, repeated across narrow environmental windows, and used in some windy coastal conditions that may be unfavorable for drone operations. Although kite systems offer less precise positional control than many UAV platforms and depend heavily on wind and operator experience, they remain an effective way to bridge the scale between pedestrian survey and broader satellite or LiDAR datasets. For coastal archaeological features such as fishpond walls, reef alignments, and tidal weirs, that flexibility is often more valuable than full automation, particularly when the goal is to document planform, wall curvature, and feature visibility across shallow and dynamic marine margins.

In my own fieldwork, I used KAP to capture higher-resolution imagery of customary fishing structures at Kualoa and He‘eia on O‘ahu, and at Nananu-i-Ra in Fiji, where the method helped document features that were difficult to appreciate fully from the ground or in lower-resolution satellite imagery. At Kualoa, KAP complemented multispectral and bathymetric datasets by providing close aerial views of the submerged alignment and its relationship to the nearshore reef flat during favorable tide and light conditions. At He‘eia, the same general approach provided a practical means of recording sections of the fishpond wall and adjacent shoreline from low altitude, creating a visual scale more directly comparable to pedestrian observations and restoration work. On Nananu-i-Ra, KAP was especially useful for imaging intertidal *moka* in plan view, clarifying wall curvature, enclosure size, and spatial relationships among individual structures across the reef flat. In each case, the method operated as an intermediate analytical scale between broad synoptic imagery and ground verification, strengthening interpretation by showing how these customary fishing features were situated within the shallow coastal landscapes they modified and depended upon.



Figure 14. Kite aerial photo of sluice gate (*mākāhā*) of Hawaiian fishpond at He‘eia, O‘ahu. (Sailors 2014).

One compelling case study of UAV usage comes from northern Australia’s Gulf of Carpentaria, which, while just outside Remote Oceania, provides a methodological template applicable to Pacific islands. Kreij et al. (2018) used low-altitude drone photogrammetry to document 13 stone-walled intertidal fish traps on Sweers Island, creating a digital elevation model with a resolution of ~2 cm. With this precise topography, they conducted tidal inundation simulations to determine the functional "catch range" of each trap, effectively tying archaeology to tidal science. The results indicated that all recorded fish traps operated most efficiently at the current mean sea level, suggesting they were constructed within the last ~3500 years, as sea level stabilized. This innovative melding of UAV mapping with sea-level modeling exemplifies how drones can facilitate analyses of chronology and function for coastal features, an approach

equally relevant to Polynesian fishponds or Micronesian causeways, where understanding the relationship between feature height and tidal ranges is crucial. Moreover, Kreij et al. (2018) emphasized that quantitative recording techniques and analytical procedures that used GIS-based flow accumulation to study trap placement improved standardization in documenting these significant features. In other words, drone mapping produced pretty pictures and enabled new quantitative insights (e.g., calculating trap volume and wall length, and systematically comparing their designs).

In Hawai‘i, UAVs have been used extensively to support community-led efforts to restore and study ancient fishponds (*loko i‘a*). These coastal fishponds often consist of long rock walls (*kuapā*) enclosing a portion of a shallow bay or estuary (Summers 1964; Kikuchi 1976; Kikiloi 2003). Traditional mapping of *loko i‘a* can be hampered by murky water and the sheer size of the ponds, where some walls are hundreds of meters long. Steward et al. (2024) demonstrated that drones are cost-efficient tools for mapping fishponds at the community level, producing up-to-date, high-resolution DEMs and imagery that far exceed the detail of existing maps. In their project on Moloka‘i and O‘ahu, UAV surveys provided fishpond stewards with precise models of wall contours and pond depths, which were used to plan restoration and run flooding scenarios (Steward et al. 2024).

Notably, by flying drones during seasonal King Tide events, they could directly observe which sections of the fishponds flooded at extreme high water levels and then compare these observations with simple "bathtub" flood models on the drone-derived DEM. This exercise revealed that some low-lying fishponds would significantly coalesce or expand under modest sea-level rise, information vital for resilience planning (Steward et al. 2024). The study concluded that UAVs can rapidly provide data to increase the resilience of Native Hawaiian

coastal cultural heritage sites by guiding adaptation strategies. In methodological terms, it underscores how drones serve a monitoring role: UAV flights can be repeated annually or after major storms to detect changes in site condition (e.g., new breaches in a fishpond wall or scouring of an archaeological mound), thereby establishing an ongoing record of impacts. This kind of monitoring was impractical at scale before, but drones have made it feasible for even community groups or small research teams to undertake.

A caveat in using UAV photogrammetry is the reliance on good environmental conditions: low wind, appropriate sunlight, and clear water for submerged features. Nonetheless, the flexibility of drones to target specific windows, such as that perfect low tide on a calm day, gives them a distinct edge over satellite platforms that operate on fixed schedules. From a methodological standpoint, UAVs democratize high-resolution remote sensing (Sailors and Honda 2013; Gesch et al. 2020; Steward et al. 2024). What once required chartering aircraft or satellites can now be done with a consumer-grade drone and a skilled operator at a fraction of the cost. This democratization is significant in remote Pacific communities, where local archaeologists or cultural practitioners can independently undertake mapping projects in rural areas. The imagery and models produced are immediately useful for interpretation and can be easily shared with local stakeholders, integrating scientific documentation with community heritage priorities (Kawelu 2014). In customary fishing structures, drones thus serve both research and preservation, mapping the past and helping safeguard it for the future.

3.2.5 Airborne LiDAR and Topographic Mapping of Archaeological Landscapes

Airborne LiDAR has significantly expanded archaeological survey capacity, particularly in heavily vegetated or topographically complex landscapes (Ladefoged et al. 2011; Quintus et

al. 2015). Its greatest value lies in generating high-resolution models of ground surface morphology that can reveal subtle archaeological features, including embankments, terraces, ditches, and low-relief stone constructions (Ladefoged et al. 2011; McCoy 2018). In Oceania, this has important implications for identifying large-scale anthropogenic landscapes, including wetland field systems, habitation mounds, and some fishpond or shoreline constructions where vegetation, rugged terrain, or limited visibility hinder conventional survey (Sailors and Honda 2013; Quintus et al. 2015). Used alongside other remote sensing methods, LiDAR offers an effective means of detecting and mapping such features at broader spatial scales (McCoy 2018).

Early Pacific applications of LiDAR underscored these advantages. The study by Ladefoged et al. (2011) in Hawai‘i, mentioned above, was among the first to demonstrate how LiDAR can quantify an archaeological landscape, revealing that dryland field walls were far more extensive than previously mapped, thereby transforming understanding of agricultural scale. Shortly after, Ladefoged and colleagues (2011) used high-resolution LiDAR data covering a broad regional area to more accurately identify agricultural alignments and trails, refine their spatial distribution, and distinguish different modes of agricultural development, including expansion, segmentation, and intensification. Rather than simply showing that field walls were more extensive than previously recognized, the study argued that LiDAR enabled combining fine-grained feature mapping with broad spatial coverage, thereby improving the interpretation of how agricultural development varied across the field system. When integrated with GIS analysis and productivity modeling, LiDAR data showed that different parts of the Kohala landscape were developed at varying intensities and trajectories, helping clarify how environmental variation influenced Hawaiian agricultural practices (Ladefoged et al. 2011). In the Kualoa case previously mentioned, airborne LiDAR data generated high-resolution

bathymetric models. These models were interpolated using inverse distance weighting (IDW) and natural neighbor techniques, which helped delineate subtle topographic variations along the submerged alignment. These refinements proved critical in mapping elevation differences and understanding the potential extent and configuration of the ancient fishpond infrastructure (Sailors and Honda 2013).

Following these successes, LiDAR surveys expanded across Remote Oceanic contexts. A notable example of this is the Kingdom of Tonga in West Polynesia. Freeland et al. (2016) used aerial LiDAR to map about 10,000 earth mounds on Tongatapu Island, many of which were interpreted as residential or burial mounds from the Formative period (ca. first millennium AD). By developing an automated “iMound” algorithm to detect mound-like shapes from the LiDAR-derived elevation model, they achieved an 84–85% identification rate when tested against known mound locations. This automated feature-extraction approach saved significant field time and enabled a comprehensive reconstruction of settlement patterns, suggesting a far denser ancient population than previously assumed (Freeland et al. 2016). In American Samoa, researchers harnessed LiDAR to reveal a "hidden" inland settlement pattern. Quintus et al. (2017) combined extensive ground survey with LiDAR mapping in the Manu'a Group, showing continuous indigenous occupation zones far inland that earlier coastal-focused surveys had missed. The LiDAR data in Samoa identified house platforms, path terraces, and agricultural modifications under the forest canopy, fundamentally altering settlement models by confirming that prehistoric communities had a substantial inland presence (Quintus et al. 2015; Quintus et al. 2017). Subsequent discussion of the project highlighted LiDAR’s value for identifying archaeological landscapes in Samoa that earlier surveys had only partially recognized (Jackmond et al. 2018).

LiDAR has also been effectively used in Melanesia and the islands of Southeast Asia, and on the island of Efate, Vanuatu, a LiDAR survey allowed Bedford et al. (2018) to identify ancient agricultural terraces and irrigation features on a landscape scale, providing evidence for an anthropogenic transformation of the island's interior previously only hypothesized (Bedford et al. 2018). In Micronesia, Jalandoni et al. (2022) analyzed a new high-resolution LiDAR dataset (acquired in 2020) to test its efficacy in identifying known site types, such as latte stone house foundations, earthen fortifications, and historical-era features. They found that LiDAR effectively detected most archaeological sites across various periods on Guam, though some subtle features remained obscured by modern disturbances (Jalandoni et al. 2022). Importantly, these studies across different Pacific locales demonstrate that LiDAR is scalable and versatile: it can map entire islands at high cost, and the derived models can be analyzed manually by archaeologists or processed with algorithms to pinpoint potential sites.

LiDAR's precise elevation data have been used in coastal applications to model past and future sea levels relative to sites. Johnson et al. (2015) applied coastal LiDAR data in Hawai‘i to simulate the impacts of a 2011 tsunami and various sea-level rise scenarios on the famous coastal site of Honaunau (Hawai‘i Island). Using a FEMA-provided LiDAR DEM (digital elevation model) of the shoreline, they could virtually "flood" the landscape to see which areas would be inundated at +1 m or +1.9 m sea-level rise. Their findings indicated that the tsunami's impacts closely matched those of a 1–2 m sea-level rise, thereby validating LiDAR-driven models of site vulnerability (Johnson et al. 2015). This analysis has crucial implications for customary fishing sites, many of which are located at current high-tide lines. High-resolution LiDAR can delineate subtle beach ridges, old shoreline berms, and low-elevation cultural features, providing a

baseline for predicting how much of a fishpond's walls or a coastal village might be underwater with each incremental rise in sea level.

Another advantage of LiDAR in coastal zones is the ability to detect features in the intertidal zone during low tide. While standard topographic LiDAR struggles with water because the infrared laser does not penetrate it, flights timed to extremely low tide have mapped features such as exposed reef structures and fish traps. In some cases, bathymetric LiDAR using green laser pulses has been deployed to map shallow seabeds. Though primarily used for nautical charting, bathymetric LiDAR data can incidentally capture submerged cultural features. For example, in Florida's Gulf Coast, a bathymetric LiDAR survey revealed possible linear arrangements on the seafloor that were later confirmed as prehistoric fish weirs (Hale et al. 2023). In Oceania, such technology could similarly detect drowned walls or tidal flat fish traps if water clarity and depth conditions are favorable. However, most Pacific archaeological LiDAR work has been conducted on land or in intertidal areas rather than in fully underwater environments.

Airborne LiDAR has become a cornerstone of archaeological methodology in remote Pacific regions. It has extended the survey scale from site to landscape, enabled discovery in heavily vegetated zones, and provided data for quantitative analysis (e.g., calculating site extents, construction volumes, or spatial patterns) (Ladefoged et al. 2011; McCoy et al. 2011; Quintus et al. 2017). LiDAR provides an effective way to document the layout of traditional marine resource management features, many of which span hundreds of meters with walls or ditches (Sailors and Honda 2013). The examples from Polynesia and Micronesia demonstrate how LiDAR data underpin new interpretations of demographic and economic systems (Cochrane and Mills 2018; Parton and Clark 2022) and directly inform cultural heritage management under

climate change scenarios (McCoy 2018). As more Pacific governments acquire LiDAR data for whole islands (e.g., for infrastructure or forestry purposes), archaeologists gain a ready-made resource to explore "known unknowns," locations likely to contain sites based on LiDAR anomalies that can then be ground-truthed in the field.

3.2.6 Multispectral and Thermal Analysis for Archaeological Feature Detection

While LiDAR and standard imagery have garnered much attention, archaeologists are also exploring multispectral and hyperspectral remote sensing for coastal and island archaeology. Multispectral analysis involves examining the reflectance of surfaces in multiple wavelength bands (beyond just true-color vision) to detect subtle differences often related to material composition or vegetation health. Coastal archaeological features, such as buried foundations, old earthworks, or middens, often affect soil chemistry and vegetation, leading to spectral anomalies in certain bands (e.g., higher near-infrared reflectance of vegetation over nutrient-rich ancient habitation soils). In dynamic coastal settings, multispectral data can sometimes highlight features obscured in regular photographs: for example, a stone fish trap wall that is underwater may be hard to see in an RGB image, but a coastal blue band or a red-edge band might better penetrate water or pick up algal growth on the stones, respectively (Jensen 2005; 2007).

One of the earliest successes in Pacific multispectral archaeology was the use of ASTER satellite imagery on Rapa Nui to map volcanic stone mulch gardens. These rock mulch gardens retain moisture and alter soil properties; by comparing ASTER's shortwave infrared bands, the patterning of these gardens became distinguishable across large areas (Ladefoged et al. 2013). Another example is the use of WorldView-2's 8-band imagery on O‘ahu, not just for the aforementioned Kualoa underwater alignment but also to distinguish invasive vegetation species that tend to grow on abandoned archaeological terraces versus surrounding native vegetation,

essentially using plant cover as a proxy for site location (Sailors and Honda 2013; Sankey et al. 2014). In Southeast Asia, researchers at Angkor (Cambodia) have integrated LiDAR with multispectral Landsat data to investigate hydrological features. At the same time, LiDAR maps the physical canals, and multispectral indices (such as the normalized difference vegetation index) help identify areas with different soil moisture that could indicate ancient rice fields or reservoirs (Evans et al. 2013). By extension, a similar approach could be applied in Oceania's coastal wetlands: multispectral imagery might detect ancient wet taro beds or aquaculture ponds if their soil moisture or vegetation differs from that of the surrounding areas.

Thermal infrared imaging is another remote sensing avenue, though less commonly used in Oceania. Thermal sensors detect heat differences, revealing sub-surface structures that retain heat differently or freshwater springs with cooler water outflows near sites (Di Napoli et al. 2021). With this technique, it would be feasible in a tropical coastal context to conduct thermal drone flights to locate subterranean stone enclosures or tunnels associated with human activity; according to the inherent thermal properties of lithic material, these stones cool off more slowly than the surrounding sediment at night. Similarly, thermal data might spot active erosion at sites by identifying cool seepage areas along eroding banks, indicating where groundwater exits, often taking archaeological materials with it.

Multispectral drone cameras are emerging, enabling analysis once limited to satellites to be performed at much finer scales. For example, a drone carrying a six-band multispectral camera was used in 2019 in Pohnpei (Federated States of Micronesia) to survey the perimeter of Nan Madol, the famous coastal megalithic site. The aim was to see if specific spectral signatures could differentiate cultural stone alignments in the mangrove shallows from natural coral formations. Early results indicated that combinations of red-edge and near-infrared bands

successfully highlighted linear features consistent with causeways or walls, providing targets for marine geophysical surveys (Jensen 2005, 2007; Comer et al. 2019). This kind of sensor fusion, optical multispectral data guiding geophysical sonar or sub-bottom profiling, represents a forward-looking methodology for submerged site exploration in Remote Oceania, marrying low-cost aerial reconnaissance with targeted high-resolution underwater investigation (Casana 2021).

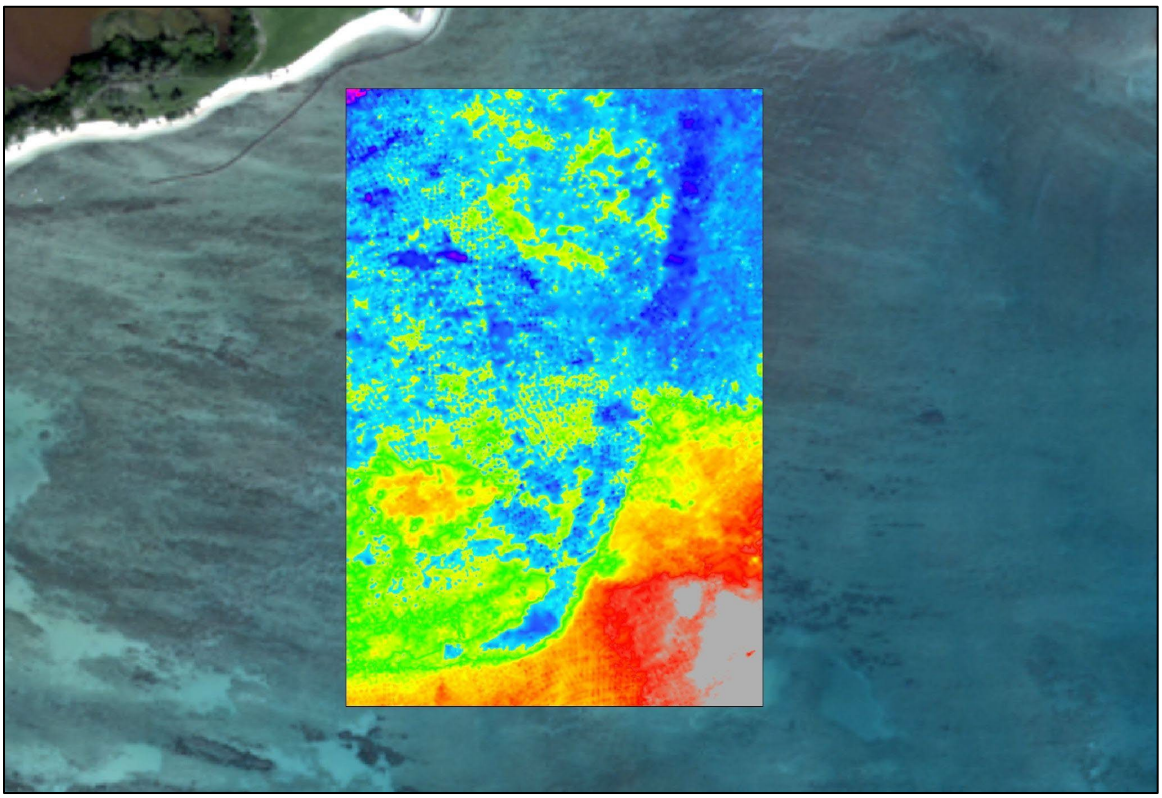

Figure 15. Multispectral imagery of submerged alignment at Kualoa, O‘ahu using principal component analysis (PCA) and non-homogenous feature difference (NHFD) to statistically extract target features. (Sailors and Honda 2013).

It is important to emphasize that multispectral analysis in archaeology often requires substantial processing and, in some cases, ground-truthing. Unlike LiDAR, where a hillshade image can directly show a ruin, multispectral results might be less direct and need interpretation. For example, an anomalous patch of healthy vegetation could indicate a buried feature enriching the soil, but one must confirm on-site conditions before proceeding with the survey (Kadhim and

Abed 2023). Still, as computing tools and image processing techniques, like machine learning classification, become more accessible, archaeologists are better equipped to tease meaningful patterns from these complex datasets. Multispectral techniques are especially valuable for detecting hidden sites in coastal peat swamps or marshes, landscapes familiar in Oceania, where visible-light imagery reveals only uniform grass or mangrove cover. By analyzing those areas in infrared or other spectra, subtle differences might betray an underlying fish trap or an artificial island. For instance, recent work in the Pacific Northwest has used LiDAR combined with multispectral land-cover data to successfully predict the locations of ancient shell middens, which often support distinct plant communities (Trant et al. 2016).

In my study at Kualoa, UAV photogrammetry was supported by the capture of ultra-high-resolution images of the nearshore and intertidal zones. These drone flights, conducted during low tide, helped document surface expressions of the alignment and generated 3D models for visualizing wall height and consistency. When combined with spectral and bathymetric data, UAV-derived imagery improved spatial accuracy and facilitated a more straightforward interpretation of construction morphology (Sailors and Honda 2013).

In the context of climate change, multispectral and repeat imagery can also be used to monitor environmental stress on sites. Repeated satellite passes can reveal coral bleaching, which may indicate increased wave energy over a submerged site or sand encroachment in a lagoon that could bury or expose features. Thus, beyond discovery, these techniques play a role in tracking change. Remote sensing is not just about finding archaeological features but increasingly about monitoring them, a necessary shift as rising seas and extreme weather threaten to alter site contexts dramatically (Johnson et al. 2015; Erlandson et al. 2025).

3.2.7 Addressing Dynamic Coastal Change: Remote Sensing for Climate Challenges

Remote Oceania's coastal sites are on the front lines of climate change (Nunn 2003; Erlandson 2012). Many islands have relatively short human histories, dating back only a few millennia. Thus, archaeological sites dating to the initial settlement often lie near the current shoreline, which has shifted over time (Nunn et al. 2017). Unlike regions where sites have experienced multiple sea-level fluctuations and some were already lost to the sea long ago, in Polynesia and Micronesia, even a modest sea-level rise can inundate sites that have never been submerged. This fact underscores the urgency of documenting coastal and nearshore archaeology in a rapid, comprehensive manner. Geospatial technologies, including remote sensing, are central to this effort (McCoy 2018; Quintus et al. 2017).

Remote sensing contributes to climate change responses in coastal archaeology in several ways. First, it enables scale-based baseline documentation (Lasaponara and Masini 2011). For example, aerial lidar has become especially valuable in Pacific Island archaeology because it allows researchers to examine large, rugged, and densely vegetated landscapes more efficiently than a pedestrian survey alone. In the Manuʻa Group of American Sāmoa, Quintus and colleagues (2015) paired lidar data with ground survey on Ofu and Olosega to test the method's effectiveness for identifying archaeological features and for extending analysis into previously unexamined terrain. Their results showed that lidar was particularly effective for detecting earthen landscape modifications, especially terraces and some ditch features, and allowed the researchers to identify and record 104 terraces in the Sili-i-uta study area. More importantly, by comparing this digitally documented settlement zone with three previously surveyed zones, they demonstrated how remote sensing can contribute to regional analyses of settlement structure, feature distribution, and possible social differentiation. At the same time, they emphasized that

lidar is best understood as complementary to fieldwork rather than a substitute for it, since field surveys of surface remains such as paving, curbing, ovens, and artifacts are often necessary to interpret feature function and intra-site activity patterning (Quintus et al. 2015).

Second, remote sensing data feeds directly into predictive models of site vulnerability. GIS analyses overlaying sea-level rise projections on archaeological site locations are now standard in cultural resource management. In Hawai‘i, high-resolution drone DEMs of fishponds were used to pinpoint the elevation at which overtopping occurs, helping to prioritize which cultural sites need seawalls or other interventions first (Steward et al. 2024). McCoy (2018) emphasizes that archaeologists must employ these technologies proactively to stay ahead of the "rising tide," urging rapid evaluation of new tools and impact studies in the Pacific. Remote sensing offers a non-invasive means to gather data from sites that might be too vulnerable to excavate or even to be visited frequently. For instance, a collapsing seawall temple platform might be too dangerous for complete mapping on foot, but it can be captured via drone imagery from a safe distance. Its rate of collapse is monitored through periodic re-flying and model comparisons (Jensen 2007).

A third aspect is public communication and heritage management. The visual nature of many remote sensing outputs, in the form of detailed maps and 3D models, provides compelling evidence of climate impacts that can be shared with policymakers and local communities. In the Marshall Islands, drone maps of atoll islets showing erosion cuts near historic cemeteries have been presented to local councils to advocate for protective measures (Gesch et al. 2020). Meanwhile, combining remote sensing with traditional knowledge has proven powerful. Many Oceanic cultures have oral histories of past shoreline changes or flooding events; when LiDAR or aerial imagery validates such stories by showing an old paleoshoreline ridge or a drowned

arbor, it reinforces the value of Indigenous memory in long-term environmental monitoring (Nunn 2014). Thus, the technology can complement and corroborate local observations, facilitating a two-way knowledge exchange important for community-based adaptation.

It should be noted that remote sensing is not a panacea for all climate-related challenges. Some threats, like ocean acidification that damages underwater cultural materials or increasing cyclone wave energy that washes structures away, are difficult to counter with documentation alone. However, remote sensing at least ensures that data about sites is preserved even if the site itself is lost. High-density LiDAR scans, photogrammetric models, and multispectral images can be archived as a digital surrogate of a site. Future researchers may interrogate these datasets to glean information.

Finally, the dynamic nature of coastal landscapes means remote sensing should be viewed as an iterative and integrative methodology. A single LiDAR scan or one satellite image is a valuable snapshot, but ideally, the imagery should be part of a time series (Nunn et al. 2017; McCoy 2018). Many researchers advocate for repeat LiDAR acquisitions in threatened zones every 5–10 years to directly measure geomorphic and cultural change (McCoy 2018). In practice, costs and logistics may occur only in select areas, such as some Hawaiian Islands, where state agencies periodically collect new LiDAR. Where repeat LiDAR is not feasible, a combination of annual drone surveys and ongoing satellite monitoring using imagery from platforms like Sentinel-2 can approximate a time-series approach (Rayne et al. 2020). Methodologically, this requires archaeologists to be adept at data capture, data management, and change-detection analysis. The toolkit now includes algorithms that automatically compare successive DEMs or orthophotos and highlight differences. Such analyses have already been used to detect looting in conflict zones; in our context, the "enemy" is environmental change

(Tapete and Cigna 2019). For example, an automated comparison might flag that a segment of a fishpond wall has disappeared between last year's and this year's drone survey, quantifying erosion. The datasets gathered for our case study of the Kualoa alignment were integrated and analyzed within a GIS environment using platforms such as ArcGIS 10.3 and ERDAS Imagine. These tools enabled spatial modeling, classification, and feature extraction from the composite imagery. GIS integration also supported the cross-validation of multispectral, LiDAR, and UAV data layers, providing a robust interpretive framework for reconstructing the alignment's extent and architectural coherence (Sailors and Honda 2013).

In conclusion to this section, remote sensing methods, from satellites in orbit to drones in the sky, are essential allies in confronting the challenges of climate change for coastal archaeology. They expand our ability to document widely and quickly, provide data for modeling future scenarios, and help engage broader audiences in the fate of cultural heritage. The case studies from Polynesia, Micronesia, and beyond collectively show that embracing these technologies has already yielded significant discoveries with inland sites and unseen features while improving our capacity to protect what can be protected. As this dissertation focuses on customary fishing structures, it will build on the methodological insights reviewed here to apply appropriate remote sensing techniques in the study area, ensuring that the research is scientifically rigorous and responsive to the pressing context of environmental change.

3.3 Experimental Archaeology

3.3.1 Introduction

Understanding how Pacific Island societies adapted and managed resources often requires going beyond observation of archaeological remains to actively test how those remains might have been formed or used. Experimental archaeology is a methodological approach that uses

replication and simulation to generate data for interpreting the past (Ascher 1961a; Mathieu 2002). By recreating artifacts, structures, or processes under controlled conditions, archaeologists can observe the outcomes and analogize them to archaeological patterns (Seetah 2008). This section reviews experimental archaeological methods applied to Pacific contexts and comparable cases elsewhere, focusing on three domains: artifact replication (with an emphasis on fishhooks), large-scale cultural reconstruction (such as rebuilding fishponds), and computer-based simulations (including drift-voyaging models and agent-based societal modeling) (Mathieu 2002; Callaghan and Fitzpatrick 2008; Cegielski and Rogers 2016). At the heart of this section is a foundational challenge in archaeology: how we use the present to make sense of the past. Experimental archaeology leans heavily on analogical inference, observing how things work today to model what might have happened long ago (Wylie 1985; Seetah 2008). Here, I explore the theoretical foundations of this approach, especially how it enables us to test adaptive hypotheses about past technologies and behaviors using observable, replicable methods (Wylie 1985; Lake 2014; Lin et al. 2018). These tools not only connect static archaeological materials to dynamic cultural processes but also align with this dissertation's broader evolutionary lens, helping to assess how innovations functioned over time in Pacific Island settings.

3.3.2 The Rationale for Experimental Approaches

Experimental archaeology provides a direct aid in the development of theory by bridging the gap between static archaeological data and the dynamic past behavior that produced it (Ascher 1961a). In Oceania, many aspects of marine resource management, such as how fish traps were built and used or how long Oceanic voyages were undertaken, involve processes that are no longer directly observable (Finney 1979, 1994; Graydon et al. 2007). Actualistic experiments offer one way to investigate those processes. The rationale is rooted in

uniformitarian assumptions: if we can show that under similar conditions, a specific action produces a particular material pattern in the present, we gain confidence in interpreting similar patterns in the archaeological record (Ascher 1961b; Binford 1981). For example, experimentally reproducing a Polynesian shell fishhook and using it to catch fish on a reef can reveal insights into its performance characteristics, such as strength, hook rate, and breakage pattern. If those characteristics match what we see on archaeological hooks (e.g., wear patterns or standard breakpoints), we strengthen the inference that ancient fishers used the hooks similarly (Kirch and Dye 1979). Alison Wylie has argued that analogical reasoning is inevitable in archaeology; we always link present observations to past phenomena through analogy, so the key is to do so critically and transparently (Wylie 1985). Middle-range theory, as popularized by Lewis Binford, seeks to bridge the gap between static, observable phenomena in the present, such as artifacts, features, and experimental results, and the dynamic behaviors and cultural processes of the past, using carefully constructed analogies. (Binford 1981). Experimental archaeology is one pillar of middle-range research, alongside ethnoarchaeology and taphonomy.

In the Pacific, experimental methods have particular resonance because many traditional practices persisted into the ethnographic period or are being revived by indigenous and local communities. This offers opportunities for collaborative experiments. For instance, in Micronesia, master navigators have worked with researchers to sail traditional canoes without modern instruments, experimentally validating how Polynesian navigation can successfully cross vast distances (Finney 1991, 1994). Such experiments test hypotheses (e.g., "Could intentional two-way voyaging connect distant archipelagos regularly?") and enrich our understanding of the skill and knowledge involved. Similarly, Hawaiian communities involved in fish pond restoration effectively conduct large-scale experiments in ancient aquacultural techniques as they

rebuild pond walls and observe fish recruitment and growth. Archaeologists can learn alongside practitioners about construction sequence, labor investment, and yield of these structures, data that inform interpretations of ancient usage (Graydon et al. 2007; Kikiloi and Graves 2010; Möhlenkamp et al. 2019). Therefore, the ethos of experimental archaeology in Oceania often integrates scientific inquiry with indigenous knowledge and practice, providing a more holistic picture of how customary marine resource management functioned.



Figure 16. Photo of students from University of Hawai‘i rebuilding a section of fishpond wall at He‘eia, O‘ahu. (Sailors 2014).

3.3.3 Analogical Inference and Theoretical Foundations

Because experimental archaeology relies on drawing analogies between experimental results and archaeological cases, a solid theoretical understanding of analogy is crucial. Wylie (1985) emphasized that analogies in archaeology are not wild guesses but structured comparisons guided by theory. There are two classic types: *general analogies*, which are broad similarities

drawn from cross-cultural or experimental observations, and *formal analogies*, which are specific one-to-one resemblances. For example, a general analogy might be "shell hooks of similar shape tend to break in similar ways when used," derived from many observations. In contrast, a formal analogy would be, "this prehistoric hook, which broke in X manner, was likely subject to force Y because in my experiment a hook broke that same way under force Y." Wolverton and Lyman (2000) enhanced our understanding of analogical reasoning by distinguishing between "immanence" and "configuration." Immanent analogies rely on inherent, universal properties, such as the predictable way a shell breaks due to its tensile strength, a quality rooted in material physics. In contrast, configurational analogies depend on culturally specific practices; for example, the way a Hawaiian fisher ties a line to a hook may reflect local tradition and influence how that tool breaks or functions.

In experimental archaeology, immanent properties often guide our expectations. We can assume, for instance, that any human, ancient or modern, flaking a glassy rock will produce specific fracture patterns due to material physics. By documenting those patterns in experiments, we gain imminent analogies for stone tool production (Wolverton and Lyman 2000; Lyman and O'Brien 2001). Outram (2008) discusses the logical structure of archaeological inference, arguing that strong arguments often involve multiple independent analogies that point to the same conclusion. In practice, we should not hang an interpretation on a single experiment; we should combine evidence from replication experiments, ethnographic parallels, and other lines of evidence to build a robust case (Mathieu 2002; Outram 2008).

Robert Ascher (1961b), one of the early advocates of experimental archaeology, cautioned that while experiments can demonstrate the possibility, they do not automatically prove that is what happened in the past. Instead, they provide plausible scenarios. Ascher's view,

which still holds, is that experiments must be designed to answer specific questions, and their results must be evaluated in context. Experiments must be coupled with contextual archaeological evidence to narrow the possibilities when multiple scenarios could yield the same archaeological pattern. Wylie (1985) later expanded on this by advocating a conjunctive approach to analogy, combining analogical reasoning with statistical and theoretical reasoning. For example, a computer simulation might show that voyaging can occur frequently between two islands under specific parameters. However, whether ancient people voyaged intentionally often depends on cultural factors such as intent or other social drivers that the simulation might not capture. Thus, before we accept the inference, analogical insights from simulation must be integrated with cultural evidence, like shared artifacts or genealogical histories between the islands. Experimental archaeology draws on a mix of approaches: it uses real-world observations, looks for patterns in them, and tests ideas about the past through experiments (Mathieu 2002; Outram 2008).

Anthropologists have also noted the "paradox of analogies," which suggests that archaeology needs them to interpret the past, yet every past context is unique to some degree (Wylie 1985; Lin et al. 2018). The solution is to identify relevant conditions in which similarity is likely to occur. For instance, a fishhook experiment conducted on the West Coast of North America might be similarly useful in Polynesia if the shell material and fish targets are similar, but less so if the cultural method of manufacture differs greatly. Therefore, experimental studies strive to match critical variables: they use similar raw materials, replicate ancient techniques faithfully, and operate under environmental conditions like those in the archaeological case. Doing so increases the "relevance" of the analogy (Wylie 1982). Experiments should be hypothesis-driven, and results should be treated as pieces of a larger inferential puzzle. With this

cautionary framework in mind, we can now survey specific applications of experimental archaeology relevant to Pacific marine resource adaptation (Ascher 1961a, 1961b; Wylie 1985; Wolverton and Lyman 2000; Lyman and O'Brien 2001; Smith 2016).

3.3.4 Replicating Artifacts: Fishhooks and Fishing Gear

One of the most common forms of experimental archaeology is artifact replication, which is the making and using of copies of ancient tools to understand how they were produced and functioned. In Pacific Island archaeology, fishhooks are a particularly illuminating artifact type for replication experiments. Fishhooks made of shell, bone, or wood are abundant in Oceanic sites and were crucial to subsistence (Sinoto 1962; Paulin and Fenwick 2015; O'Connor et al. 2017). However, understanding these hooks' manufacturing sequences and performance characteristics often requires replication. For example, Smith and colleagues (2015 and 2018) experimentally reconstructed the multistep process that Nicoleño people (Native inhabitants of California's San Nicolas Island) used to craft one-piece abalone-shell hooks (*Haliotis spp.*). They identified the tools and techniques likely involved by analyzing unfinished hook blanks from an island site and attempting to replicate the manufacturing steps, such as cutting, filing, grinding, and polishing shell pieces. The experimental hooks bore distinctive marks and breakage patterns that matched those of archaeological specimens, strengthening the interpretation of how prehistoric artisans worked. Efforts in the Southern Cook Islands have also addressed the manufacture of one-piece pearl-shell hooks. Research by Allen on Aitutaki indicates that pearl-shell hook production involved labor-intensive abrasive techniques and the use of tools such as coral abraders, underscoring the investment required to produce these objects (Allen 1992a, 1992b). Later discussion of Allen's work likewise notes use-wear evidence linking coral tools to the manufacture of fishhooks.

Beyond manufacture, experiments with one-piece vs. two-piece hooks in controlled fishing trials in Aotearoa/New Zealand waters have highlighted why different forms might have been preferred: one-piece hooks had higher catch rates for reef fish. However, they were more prone to breaking on larger fish, whereas composite two-piece hooks, whose points were lashed to a separate shank, were sturdier for larger game (Paulin and Fenwick 2015). These functional experiments allow archaeologists to read use-wear on artifacts as meaningful signals (Schiffer 1987). Suppose many hooks at a site show breakage at the barb, and experiments indicate that barb breakage often happens when fighting hefty fish. In that case, fishermen at that site regularly encountered large fish, perhaps due to reef ecology or targeting strategy. Thus, replication experiments feed into behavioral reconstructions: how people fished, how often hooks were replaced, and whether specific designs were favored for practical reasons (Bradfield 2019).

In sum, artifact replication in Pacific archaeology has proven invaluable for interpreting the archaeological record. It yields analogical insights, underpinned by material science in the immanent properties of shell and bone, and by observed human behavior, including how people today, or in controlled settings, perform tasks. Of course, one must be cautious: modern experiments are often limited in duration and scope. An archaeologist might fish for a few days with a replicated hook, whereas ancient fishermen used theirs for years under varying conditions. However, even limited trials can suggest trends and provide quantitative ranges (e.g., how many fish can a shell hook catch before it snaps?). These figures enrich models of the past economy; they allow us to estimate more accurately how often people needed to manufacture new hooks and how many might be in use at any given time in a community. This, in turn, ties into understanding labor organization and resource scheduling in those societies.

3.3.5 Reconstructing Structures: Fishponds and Aquaculture Systems

Beyond portable artifacts, experimental archaeology extends to built structures and facilities, essentially early forms of engineering. In Oceania, indigenous aquaculture features like fishponds and tidal weirs stand out as large-scale modifications of nearshore marine environments (Summers 1964; Kurashima and Kirch 2011). Fishponds, such as Hawaiian *loko i‘a* and Fijian *moka*, are semi-enclosed coastal pools with stone or earthen walls used to rear fish. Hundreds of these existed historically in places like Hawai‘i, but by the 20th century, many had fallen into disrepair (Wyban 1992, 2020). In recent decades, efforts to restore fishponds have provided an experimental context to learn about their construction and efficacy. Community-led restorations, such as at He‘eia Fishpond on O‘ahu by the non-profit Paepae o' He‘eia, involve repairing rock walls (*kuapā*) and clearing invasive mangroves (Graydon et al. 2007; Paepae o He‘eia 2025). Observing these projects has provided insights into construction techniques that likely parallel ancient methods: how basalt rocks are interlocked without mortar to create a permeable barrier, how sluice gates (*mākāhā*) are crafted and positioned to allow small fish in and prevent large fish from escaping (Bond and Gmirkin 2003). It turns out that traditional knowledge, often preserved in oral histories, aligns with what experimental rebuilding confirms: for example, oral tradition says pond walls should be built with a sloping profile and layered with smaller stones on the interior to buffer wave action, and indeed, experimental trials found that currents more quickly undermine vertical walls, whereas sloped, rubble-core walls are more stable. Practitioners effectively rediscover ancient engineering principles by applying a trial-and-error approach during restoration (Möhlenkamp et al. 2019).

The functional performance of restored fishponds can also be monitored scientifically, effectively making it a controlled experiment in ancient aquaculture (Malindine 2019; Rogers

2024). A recent study (Wyban 2020) measured fish production in a functioning traditional pond over several years and found that properly maintained ponds significantly increase the biomass of certain fish (e.g., mullet, milkfish) within the pond and adjacent reef areas due to spillover. This research experimentally validates historical accounts that fishponds were crucial food reservoirs, acting as a buffer against seasonal shortages or reef overfishing (Wyban 2020). Such data helps archaeologists quantify the potential contribution of aquaculture to Hawaiian subsistence and model how its adoption would have affected settlement (e.g., supporting larger, more permanent communities near ponds). It also sheds light on maintenance requirements: experiments to rebuild show that pond walls require regular labor to clear sediments and repair storm damage (Innes-Gold et al. 2025). Thus, we infer that ancient communities likely organized workdays or had specialists, such as pond caretakers, responsible for upkeep, indicating a complex level of social organization (Kikiloi 2003). Reconstructive archaeology, in this sense, connects to the dissertation's theme by illuminating the socioecological system around these structures, including cooperation, labor investment, and the scheduling of resource harvesting, all of which leave only indirect traces archaeologically but can be fleshed out via analogy to experimental restoration (Mathieu 2002).

A recent master’s thesis by Endress (2024) extends this experimental and reconstructive approach to Palau by documenting traditional marine fishery practices through the rebuilding of an Indigenous fish trap Endress (2024) documented 93 traditional fish traps and participated in the restoration of one as part of a community-led revitalization effort. Using drone mapping, field observations, and interviews with elder fishers, the study found that Palauan traps were commonly built of limestone and living coral heads and operated as tidal features that corral fish as the water recedes, allowing harvest until the next high tide. The restored trap reportedly

functioned as intended and served as an educational tool. These results support the interpretation that such structures were practical components of customary marine subsistence and resource management, not merely symbolic or incidental remains (Endress 2024).

One novel experimental archaeology endeavor focused on iconic Pacific Island structures was the attempt to understand how the colossal stone statues (*moai*) of Rapa Nui were transported across the island. Though not directly about marine resources, it illustrates experimental archaeology in a Pacific context. A team led by Hunt and Lipo (2011) created a replica statue and experimentally "walked" it upright with ropes, hypothesizing this was how ancient Rapa Nui people moved the *moai* (Hunt and Lipo 2011; Lipo et al. 2013). This process can be seen in Figure 17. The experiment's success was that a small team moved the heavy statue several hundred meters, providing a tangible analogy to solve a long-standing archaeological question. Similarly, one might imagine applying this to marine structures: for instance, how were massive basalt boulders moved to build fishpond walls? Experiments using local materials and replica canoe sleds could test transport methods on land or water. Although such specific experiments have yet to be systematically reported, the principle stands that reconstructing and using infrastructure can yield insights not attainable by simply measuring ruins.



Figure 17. Photo of research team led by Hunt and Lipo (2011) “walking” a *moai* statue in an experiment on O‘ahu modeled after similar archaeological features found on Rapa Nui.

Reconstructive experiments of Pacific structures, such as fishponds and fish traps, serve a dual purpose: they demonstrate the functional effectiveness of these systems and provide cultural insight into the social organization and traditional knowledge required for their construction and maintenance. Analogical inferences, such as using a restored pond's fish yield to estimate ancient production or a reconstructed trap's labor demands to infer past labor organization, must be interpreted with careful attention to context. Combined with archaeological evidence, such as pond sediment cores indicating prolonged use or the distribution of ponds relative to settlements, which suggest centralized planning, they greatly enhance our understanding of how Pacific Islanders engineered their landscapes for resource management. These experiments underscore the theme of adaptation: they show, in real time, how working with environmental processes (tides, fish behavior, hydrology) enabled people to create productive niches, reinforcing the idea of niche construction within an evolutionary framework.

3.3.6 Computer Simulations: Voyaging and Societal Models

A more recent and rapidly growing branch of experimental archaeology uses computer simulations to model past processes that cannot be directly replicated in the physical world. While one might not consider computer modeling "experimental archaeology" in the traditional sense, it shares the core approach: creating a simplified version of past conditions and running scenarios to observe outcomes, which are then compared to archaeological or historical data (Lake 2014). In Pacific research, two prominent types of simulations are voyaging (drift) models and agent-based models (ABM) of human-environment interactions. These digital experiments complement physical experiments by exploring large-scale or long-duration phenomena. Seafaring simulations have been particularly influential in studying the colonization of Remote Oceania, a process critical to the development of settlement patterns (Levinson 1973). Efforts to simulate canoe voyages across the Pacific using computer models that incorporate winds, currents, vessel capabilities, and navigational strategies are demonstrated in one landmark study by Montenegro and Fitzpatrick (2014), which modeled thousands of voyages between islands in Remote Oceania under different conditions to assess likely pathways and travel times. By programming virtual canoes to either drift with winds or make purposeful "short-hop" journeys and using real Pacific wind/current data, they could experimentally evaluate competing hypotheses: for example, was the Polynesian expansion eastward facilitated by El Niño westerly wind bursts? The simulation results showed that voyaging from West Polynesia into East Polynesia (e.g., from Tonga/Samoa toward the Society Islands) was feasible even without extraordinary weather events, provided navigators took indirect routes and stopped at intermediate islands (Lewis 1994; Montenegro and Fitzpatrick 2014; Montenegro et al. 2016).

This experiment supports an incremental "island-hopping" colonization model rather than requiring long one-shot voyages. The models also indicated that certain islands, such as

Rarotonga in the Cook Islands, are natural "choke points" or hubs under prevailing conditions. This prediction aligns with archaeological evidence indicating that those islands were settled relatively early and served as dispersal nodes. Another earlier study by Callaghan and Fitzpatrick (2008) specifically simulated drift voyaging to Palau in Micronesia, finding that canoes launched from the Philippines rarely reach Palau by chance, suggesting that deliberate exploration was more likely (Callaghan and Fitzpatrick 2008). These computer experiments function as analogical tools: the virtual canoes stand in for ancient canoes, and their success rates can be analogized to what ancient navigators might have experienced. The strength of simulation is in testing "what if" scenarios. For instance, one can alter parameters and ask, "What if Polynesians could sail upwind efficiently?" Montenegro et al. (2023) tweaked their models to distinguish between purely drifting and navigated voyages. They found that even modest upwind sailing ability dramatically shortens specific travel routes, suggesting that colonization could accelerate once people developed better sailing rigs (Montenegro et al. 2023).

Simulations have also tackled the puzzling case of the sweet potato's presence in Polynesia. Recent drift models (Montenegro et al. 2008; Temmen et al. 2022) simulated the dispersal of botanical proxies (virtual "drift items") from South America and found it plausible that sweet potato could drift to Polynesia on rare occasions, but the timing and genetic evidence still lean toward human transport, whether deliberate or accidental (Montenegro et al. 2008; Temmen et al. 2022). Thus, modeling helps quantify the likelihood of scenarios. The analogical inference here is subtle: a drift model showing the low probability of random transport strengthens the argument that Polynesians must have voyaged to South America, or vice versa, to account for the plant's transfer, because the alternative hypothesis of natural drift is statistically improbable (Storey et al. 2007; Roullier et al. 2013).

Agent-based models (ABMs) represent another experimental paradigm that my dissertation employs. ABMs simulate the interactions of autonomous "agents" that represent individuals, households, or even villages, following set behavioral rules within an environment. They are computational experiments in social dynamics (Premo 2010; Lake 2014). In the Pacific context, ABMs have been used to explore issues such as cooperation in common-pool resource management, the emergence of social hierarchies, and settlement pattern formation, offering a valuable framework for examining long-term human-environment interactions, particularly in resource-limited island contexts. Morrison and Addison (2008) used ABM to assess how molluscan life history traits, especially age of reproductive maturity (ARM) and energetic return rate (ERR), affect resilience under sustained foraging. Their NetLogo model showed that high-yield, late-maturing taxa were especially vulnerable to exploitation while early-maturing species maintained stable populations despite ongoing harvests. Additionally, spatial aggregation initially boosted foraging efficiency but led to rapid resource collapse, in contrast to the stability of more dispersed populations (Morrison and Addison 2008).

The ABM developed for this dissertation also examines the conditions under which collective restraint, as represented by limits on each agent's harvest, yields better outcomes than overexploitation (Ostrom 1990). When resource depletion occurs rapidly after intense harvesting, agents that adopt conservative, quota-like behaviors tend to outperform those that harvest aggressively. In other words, without explicit social rules, ecological feedback alone can promote sustainable practices over time. This model aligns with Elinor Ostrom's theories on common-pool resource management. Small communities can avoid a "tragedy of the commons" if certain conditions and norms are in place (Ostrom 2009). The ABM thus lends theoretical weight to the idea that features such as fishponds or communal taboo periods on fishing, as

observed ethnographically in some Polynesian societies, were practical adaptations to prevent resource depletion.

It is important to note that validation of computer simulations is achieved by comparing their outcomes with real-world evidence. They can be powerful if they yield patterns that match archaeological observations and can isolate key mechanisms. However, they can also produce realistic-looking outputs for the wrong reasons, a phenomenon known as equifinality (Premo 2010). For example, one could model Rapa Nui's societal collapse using combinations of warfare, disease, and ecological disaster and obtain similar population decline curves. We can only judge which simulation scenario is more plausible by integrating archaeological evidence, such as pollen data or skeletal trauma. Alex Morrison's multi-scalar analysis of Rapa Nui settlement structure, for instance, combined spatial modeling (a form of simulation) with empirical survey data, finding that the dispersed "clan" model of settlement best fits the pattern of housing and ceremonial platform (*ahu*) locations (Hunt 2007; Morrison 2012). That simulation supported the hypothesis that competition and monument-building were tied to dispersed communities rather than to a centralized polity.

In experimental archaeology, computer models function as virtual experiments in which controlled manipulation of variables such as sailing ability, cooperation rate, and crop growth tests their importance. They are particularly valuable for exploring time or spatial scales we cannot reproduce physically, such as centuries of population growth on an island or thousands of voyages crisscrossing the Pacific. The analogical argument is that the simulation is a simplified but valid parallel to the real past system: if, under most plausible conditions, the simulation yields outcome X and we observe outcome X archaeologically, then the processes in the simulation were likely at play in the real past. Of course, caution is warranted to avoid overfitting

models or ignoring alternative explanations. However, when used judiciously, these models have significantly advanced Pacific archaeology. Experimental archaeologists have, for example, shifted the long-standing debate about accidental vs. intentional voyaging into a more quantitative realm, demonstrating that deliberate two-way voyaging was not only possible but also likely necessary to account for the known settlement pattern of Remote Oceania (Di Piazza et al. 2007; Montenegro et al. 2016, 2023). Likewise, ABMs of resource management help explain how Pacific communities could achieve sustainable yields from fragile ecosystems by cooperating, moving, or innovating, enabling our models to replicate and test hypotheses.



Figure 18. Photo of "Hōkūleʻa", a replication of a traditional voyaging canoe who recently celebrated its 50th year testing voyaging scenarios in the Pacific Island and around the world. (Sailors 2011).

Experimental archaeology, whether replicating a single tool or simulating an entire society, is a vital component of the methodological toolkit in this dissertation's exploration of the evolution of marine resource management. It allows us to test hypotheses about how and why specific adaptations, like fishhooks, fishponds, and long-distance voyaging, were developed, maintained, and transmitted. When supported by robust theory and multiple lines of evidence, the analogies drawn lend credibility to reconstructions of Pacific lifeways. By demonstrating the feasibility, performance, and constraints of ancient techniques and strategies, experimental approaches ground our evolutionary interpretations in empirical reality. They underscore that the impressive adaptations of Pacific Islanders, navigating by stars, engineering coastlines for aquaculture, and crafting marine toolkits from limited materials were not happenstance but the result of iterative trial-and-error and knowledge transmission that we can partially recapitulate today. In the next chapter, we will apply these methods and theoretical insights to specific archaeological case studies, further illuminating the interplay between environment, innovation, and social organization in Oceania's past.

4. MAPPING ISLAND *MOKA*

4.1 Introduction: Customary Fishing Structures in the Fiji Island Group

Customary Fijian fishing weirs, known locally as *moka*, are an archaeological feature type readily identified by their large size, uniform shape, stone construction, and conspicuous locations on the tidal flats and shorelines of both high and low islands. Although *moka* do not play a major part in the local economy today, they likely served a significant role in early Fijian subsistence, and knowledge of this customary practice remains valuable to current socioenvironmental and anthropological studies. In 1994, J. T. Parry conducted an aerial survey of Fijian fishing weirs to document and explore the social phenomenon of what he called "fish cropping," or the intensification of aquatic subsistence using intertidal fishing weirs. Parry's survey recorded 273 structures, mainly on the large southern island of Viti Levu, and included numerous smaller islands in proximity to this main island. From his aerial photographs, Parry collected data on the formal and spatial characteristics of intertidal fishing weirs and then argued that their apparent aggregation on the northern shores of Viti Levu, in the province of Ra, was a result of locally low rainfall in this region where fewer crops could be grown (Parry 1994).

Viti Levu is a Pacific high island 10,400 km² in area and with summits rising to 1000 meters. This topography creates an orographic effect, resulting in a wet environment on the southeast side of Viti Levu, where southeasterly trade winds prevail, and a dry, leeward environment on the northwest side of the island (Colter et al. 1983; Metaki et al. 2006). Parry assessed rainfall gradients on Viti Levu using the coefficient of variation of daily rainfall amounts and posited that there were three distinct ecozones on Viti Levu, each with unique food production systems dependent on this environmental variable. He suggested that "fish cropping"

is restricted to the coastal lowlands of north and northwest Viti Levu, or Zone 1, a marginal area receiving less than 125 days of rain per year and with an especially severe dry season (Parry 1994:157). Parry observed that Zone 1 is not conducive to growing an abundance of terrestrial crops and argued that the aggregation of fishing weirs in this area can therefore be explained as an alternate means of subsistence for people living in these arid locations. The three ecozones described by Parry can be seen in Table 3.

Parry (1994:162) also claimed that the *moka* he surveyed are made of a universal construction material and occur only in areas where volcanic rock, either Vatia Andesite or Rokavukavu Basalt, is locally available and abundant on the foreshore. He also provided a brief analysis of *moka* shape and size, concluding that most Fijian fishing weirs are simple in shape, vary considerably in size, and are typically built out from shore rather than isolated on the reef flats. He also described these features as often linked to larger fishing complexes, with most fishing weirs facing the windward direction. Finally, Parry stated that the fishing weirs he observed were predominantly concentrated on straight shorelines, as opposed to the bays or promontories one typically finds on a normal coastline (Parry 1994:162–166).

Archaeological research on Fijian fishing weirs is rare, and while Parry's (1994) report is anthropologically valuable, his study was limited to the single island of Viti Levu and was not representative of the larger Fiji island group. Considering the wide range of environmental variation across the island group, an expanded survey of this subject is warranted, as much more could be learned about the maritime subsistence practices of this region (Keegan et al. 2008; Maladine 2019; Fitzpatrick 2020). Advances in remote sensing technology have also enabled improved surveying of Fijian fishing weirs, giving archaeologists greater ability to identify, map, and analyze large spatial datasets (Gillings and Wheatley 2001; Kantner 2008).

Table 3. The three ecozones of Viti Levu, Fiji are based on rainfall amounts, rainfall variability, and their primary means of food production (Parry 1994).

Zone	Location on Viti Levu	Number of days of rain per annum	Percent of rain in dry season	Primary subsistence
Zone 1	coastal lowlands north/northwest Viti Levu	<125 days of rain per annum	<25% of rain occurring in "dry season	"fish cropping"
Zone 2	the west central interior	>150 days of rain per annum	25-33% rain occurring in "dry season"	irrigated crops
Zone 3	inland and coastal areas of southeast Viti Levu	>200 days of rain per annum	33% of rain in "dry season"	pond field/raised bed

This report, therefore, analyzes data recovered from both local and regional surveys using traditional mapping techniques and remote sensing methods at inter- and intra-island scales beyond Parry's original investigation to test his conclusions and explore spatial patterns of *moka* beyond the main island of Viti Levu. Specifically, this archaeological investigation used remote sensing and pedestrian survey to map 683 customary fishing weirs across 34 Fijian islands. The spatial configurations and physical characteristics of these fishing weirs were investigated at the inter- and intra-island scales to open a discussion of adaptive responses to ecological uncertainty and to determine whether the aggregation of Fijian fishing weirs along the shoreline might be explained by environmental parameters, specifically rainfall, as Parry suggested in 1994.

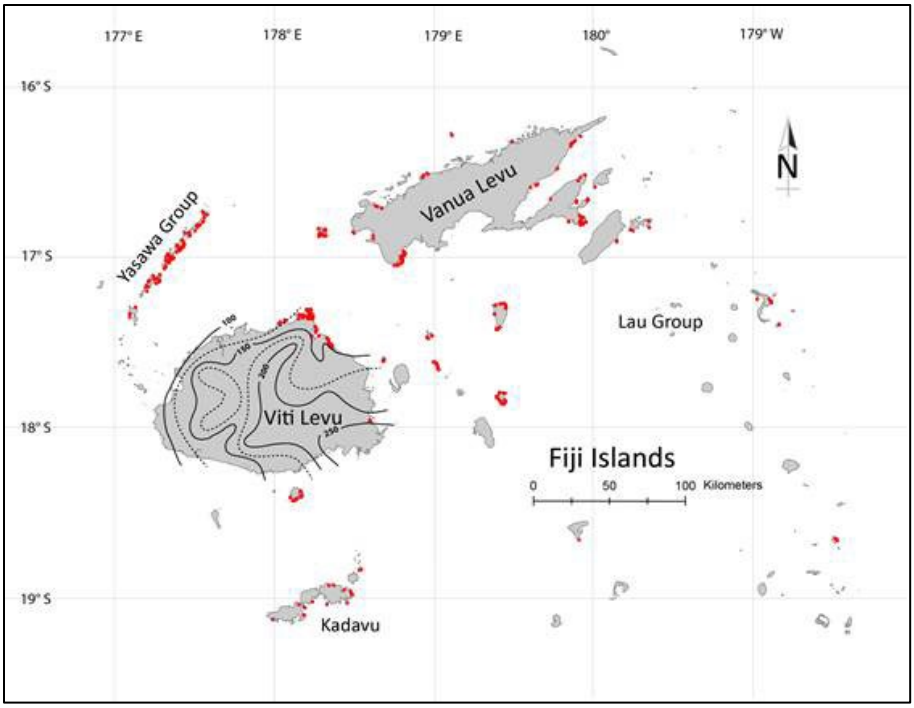

Figure 19. Map of Fiji Islands showing the point location (red dots) of 683 intertidal fishing weirs located with Google Earth Pro satellite imagery and plotted in ArcGIS (10.5).

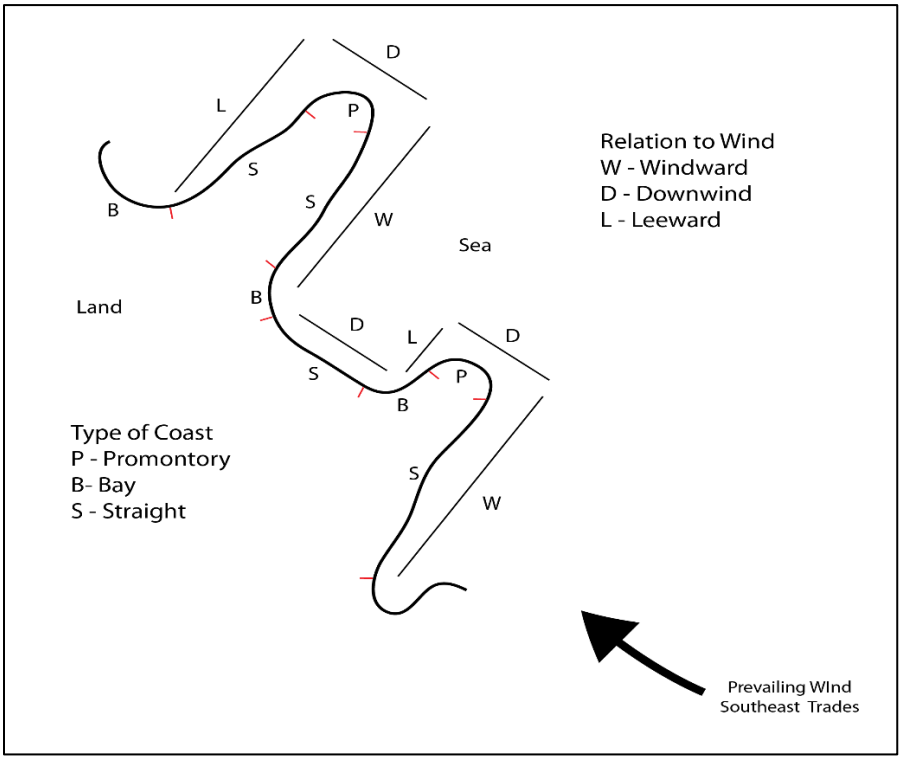

Figure 20. Diagram showing coastline categories where *moka* are found and their relation to prevailing trade winds (Parry 1994).

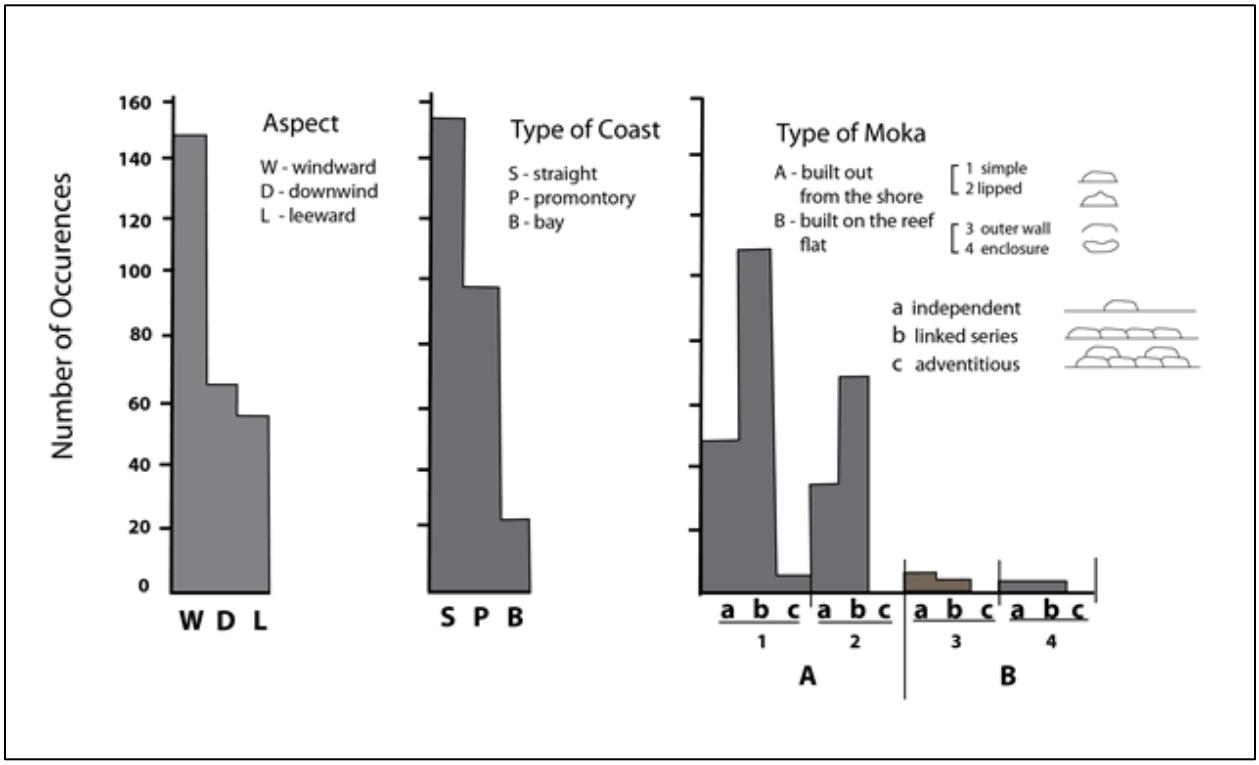

Figure 21. A series of graphs summarizing the findings of Parry's survey in Viti Levu, Fiji (Parry 1994). According to Parry, a majority of *moka* face a windward direction, are located on straight coasts, are simple shaped, linked, and built out from the shore.

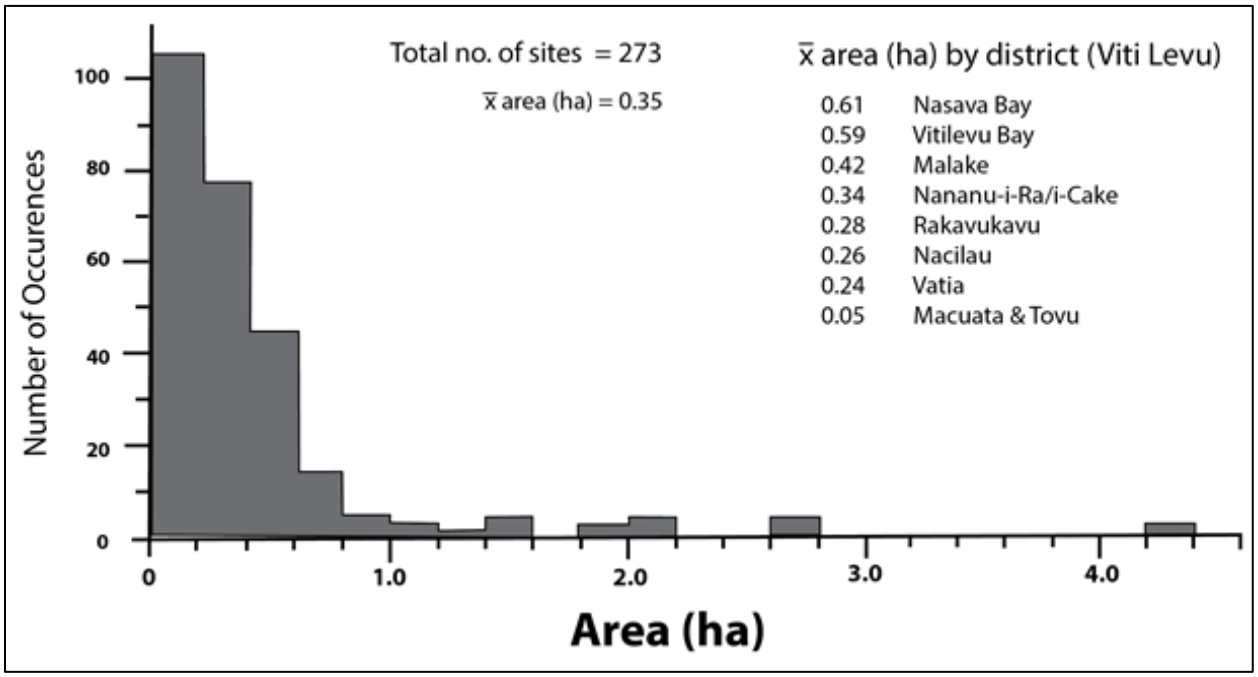

Figure 22. A graph showing the size distribution of *moka* on Viti Levu. The average size of *moka* on Viti Levu is .35 hectares and range from .05 ha to .61 hectares in area (Parry 1994).

4.2 Cultural and Ecological Context of *Moka*

Ecological knowledge regarding Fijian fishing weirs is limited, but it is locally known that *moka* are used to catch a variety of reef fish, such as mullet (Mugilidae), parrot fish (Scaridae), eels (Muraenidae), and numerous other marine organisms, such as crabs, clams, and crustaceans caught within the weir during a receding tide. *Moka* are opportunistic in that they do not rely upon bait, poison, or physical encouragement (i.e., corralling) to catch fish, rather, they are dependent upon the tidal pulse where at high tide, fish swim into the weir as they explore the reef flats and when the tide recedes, some are caught in the deepest part of the weir making them easier to catch (Reinman 1967). Based on similar examples from other parts of the world, it is thought that this type of weir is more productive during spring tides, when water movement is more extreme, and that its location within the littoral fringe is dependent on this hydraulic phenomenon (Connaway 2007).

It is not known with any certainty how old these structures are in Fiji, as this is an understudied subject hampered by methodological challenges in building chronologies, as is the case for most archaeological features in coastal areas exposed to the sea. Because standard radiometric dating methods are typically untenable in the littoral environment, it is difficult to establish the chronology of this feature type, not only in Fiji but throughout the world where these features occur (Burney 2003; Athens et al. 2014; Neudorf et al. 2017). It is likely this technology arrived with the Austronesian speaking settlers who arrived at the Fiji islands ca.3200 BP and it is possible that this fishing technology became more common on the landscape when Fiji saw an intensification of fortress building possibly as much as 600 years ago as a likely result of contested resource allocation (Field 1998; Clark and Anderson 2001; Field and Lape 2010; Smith and Cochrane 2011; Luo et al 2015). On Nananu-i-Ra, where my pedestrian survey

was conducted for this study, it is notable that archaeological features described by locals as fortifications were observed at the tops of each hill on this island, and all these archaeological enclosures had a commanding view of the fishing weir complexes on the reef flats. However, this observation is anecdotal, though the relationship between these features would be an interesting pursuit for further research

The management of *moka* is thought to have been the responsibility of social elites who would have claimed rights to the coastlines where they are found. Some Pacific Island scholars have suggested that large fishing complexes needed conscripted laborers to build, maintain, and defend these important sources of protein (Preston 1993; Kirch 1990b). This may be true, especially in more complex Pacific Island societies that utilize this technology at a larger scale, such as in Hawai‘i, and is an idea briefly suggested by Parry (1994). However, these claims rely on scant ethnographic and archaeological data and lack documented support in Fiji (Apple and Kikuchi 1976; Kurashima and Kirch 2011). Regarding modern usage of this type of customary fishery, it should be noted that while I was conducting research on Nananu-i-Ra, there were a few occasions where local fishermen were observed using motorboats to check these weirs while fishing along the Raki Raki coast. So, it could be argued that they are still being employed to some degree today.

Considering that *moka* are simple in design and likely easy to construct, they could have allowed individuals and families who were not elites to engage in a delayed-return economy, and this may still be true even in a modern economic system (Parry 1991; Jones and Quinn 2009). However, it is thought that the Fijian fishing weirs were abandoned by local fishermen in favor of a fishing method conducted by small kin-groups known as *bai ni ika,* which utilize mobile, reed traps placed in patch locations that shift along the reef flats through various times of the

year (Dacks et al. 2018). Of course, there are numerous and diverse examples of fishing techniques found throughout the Pacific, and *moka* technology accounts for only a small part of the maritime toolkit Fijians had in deep time and maintain today (Kirch and Dye 1979; Dye 1978).



Figure 23. Photograph of a fishing weir complex on the northeast section of the island of Nananu-i-Ra. (Sailors 2013).

During my pedestrian survey on the island of Nananu-i-Ra, it was determined that the formal attributes of *moka* from this location conformed with the measurements provided by Parry (1994) in his preliminary study. Parry noted that *moka* on the island of Viti Levu had an average size of 0.35 hectares, with a range of 50 m^2 to 610 m^2, and were composed entirely of basalt stones averaging about 30 cm in diameter, constructed using the dry-stacking method. While the sea level in Fiji was ca. 1.5 meters higher at the time of colonization than it is today, the tidal range is thought to have been about the same throughout prehistory as it is today, at

approximately 1.1 meters (Ash and Ash 1985; Nunn 2009). Consequently, the average wall height of *moka is* just over one meter, with wall widths ranging from one to two meters.



Figure 24. Close-up of *moka* alignment showing size and type of stone used in dry-stacking construction (Sailors 2013).

4.3 Regional Survey and Spatial Analytical Methods

Site Area, Data Acquisition, & Analyses

Fiji is a large, diverse island group where various environmental conditions, such as rainfall and island geomorphology, strongly influence the nature of the resource management systems people participate in (Parry 1994; Nunn 2003; Fields 2004). Because of the ecological variability of the Fiji Island group, it is important to conduct research of subsistence technologies at both the inter- and intra-island scales to better understand the adaptive use of fish weirs by Fijian people in a culturally holistic manner.

At the regional or island-wide scale, the open-source platform Google Earth Pro was used to survey the shorelines of 79 Fijian islands at ~300-meter elevation to map the distribution of intertidal fishing weirs common to the area (Google Earth 2016). Using this method, a total of 683 fishing weirs were identified on 34 islands. It is important to note, however, that additional structures may yet be identified using higher-quality imagery from other orbital platforms, such as WorldView-3 or Landsat. Higher-resolution data would likely reveal smaller features not visible in Google Earth's open-source imagery, which was derived from DigitalGlobe QuickBird at roughly 65 cm panchromatic resolution at nadir and predates the satellite's 2015 decommissioning shortly after this survey was conducted (Jensen 2005, 2007; Maxar Technologies 2021).

To "ground truth" the point data acquired from Google Earth (2015), and to conduct a more exhaustive pedestrian survey of Fijian fishing weirs, I traveled to the island of Nananu-i-Ra, located off the northeast coast of Viti Levu in the province of Ra, and spent four weeks field mapping the island's numerous fishing weirs. Nananu-i-Ra is a small island about 1.5 km from the northeast coast of Viti Levu with an area of 3.7 km², an elevation of 181 meters, and is home to numerous *moka* that are easily accessible from shore for study. Remote sensing of the shoreline of Nananu-i-Ra revealed 47 *moka* of various sizes, and ground-truthing documented a total of 51 fishing weirs, with an accuracy rate of approximately 93%. While traveling within this subregion of Viti Levu known as Raki Raki, it should be noted that numerous other *moka* on other small islands were observed in the vicinity. A map of Nananu-i-Ra showing a topographic relief of the island and the point location of these 51 documented fishing weirs and their relative size and aspect can be seen in Figure 25.

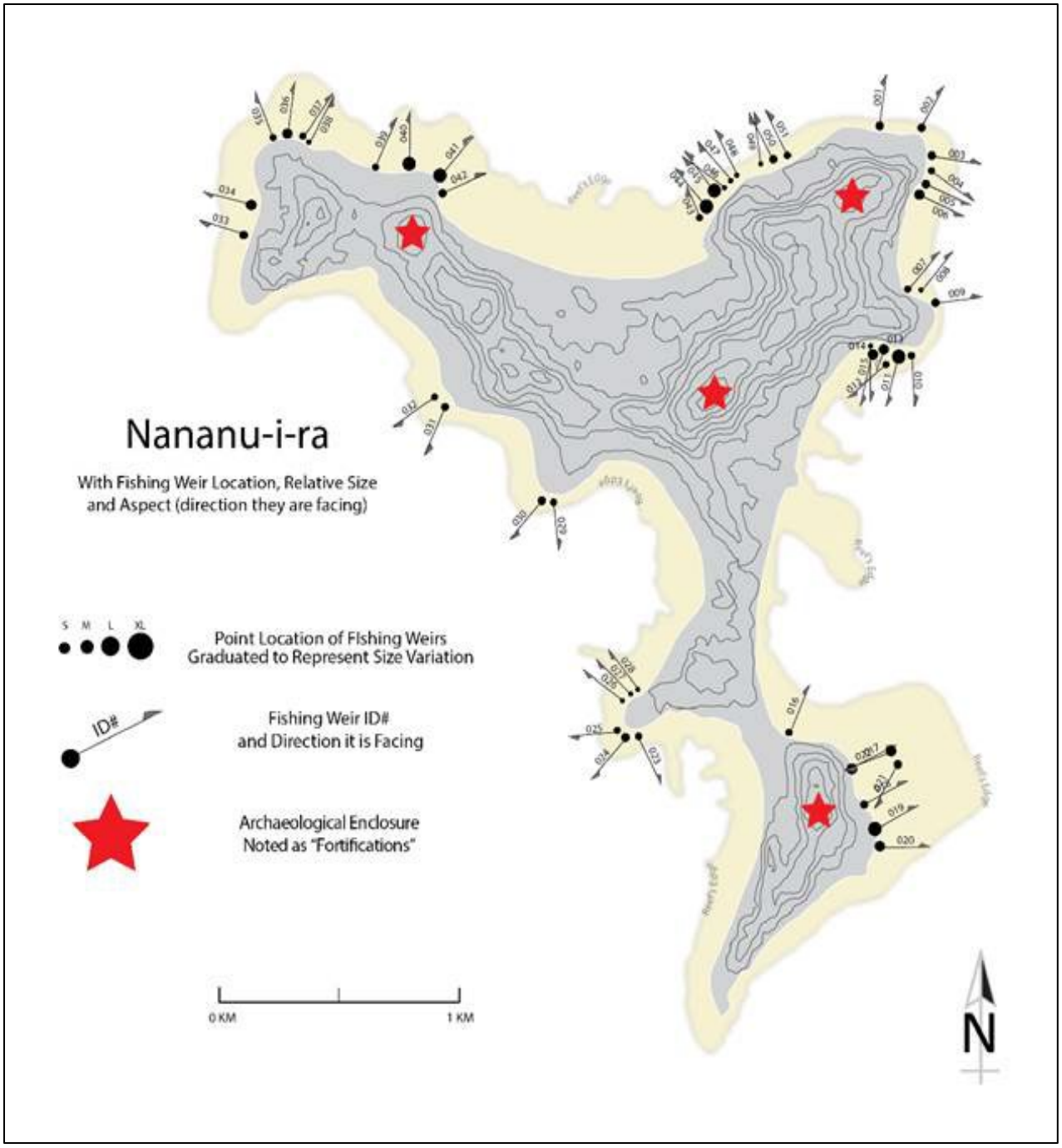

Figure 25. Map of Nananu-i-Ra showing a topographic relief of the island and the point location of 51 documented fishing weirs. These points have been graduated in relative size and display an arrow pointing in the compass direction in which the weir is facing. Also noted by red stars are the locations of the stone enclosures referred to as "fortifications" by local informants.

The overall effort of this fieldwork demonstrated that the error associated with using the Google Earth satellite survey method was minimal, resulting in only a 7% underrepresentation, which allowed for additional documentation of individual fishing weir form and function (O'Brien et al. 2005; Jensen 2007). The formal variables documented in this survey were location, size (area), wall length, aspect (compass direction the weir is facing), and a ratio called 'maximization index' that was calculated from area/wall length and whose value represents how well a wall's perimeter encapsulates the amount of reef area being used. This value has the potential to inform "optimal" behavior, expressed in the uniform use of space, which often results when common-pool resources managed by people are spatially constrained (Ladefoged and Graves 2000b; Davies et al. 2012). The formal variables of size, wall length, aspect, and maximization index gathered during the pedestrian survey of Nananu-i-Ra were added to the GIS dataset as attributes and the standard descriptive statistics for these variables are seen in Table 4.

Table 4. A display of standard descriptive statistics related to the formal variables of Fijian fish weirs measured on the island of Nananu-i-Ra.

	Wall Length (m)	**Area (m²)**	**Maximization Index**	**Aspect (radians)**
Minimum	34.2	166	0.04	0.02
Maximum	181.6	4284	0.61	6.14
Median	104.6	1402	0.07	3.37
Mean	103.55	1600.9	0.11	3.1
Skew	0.12	0.64	3.51	-0.02
Kurtosis	-0.69	-0.29	13.16	-1.48
Variance	1406.32	1172626.99	0.013	4.05
Standard Deviation	37.5	1082.88	0.11	2.01

The geographic locations of *moka* I recorded in the Fiji island group were downloaded into a GIS, and a regional map was created for visualization and statistical testing of the distribution of fishing weirs at both local and global scales. Spatial autocorrelation of fishing weir location was tested at the 95% confidence level using a Moran's *I* statistic, while potential clusters were mapped using an optimized hot spot analysis or general Getis-Ord Gi* statistic with the 'null hypothesis' being that the fishing weir locations are randomly distributed along Fijian shorelines (Koeing 1999). Because this type of point data is consistent and not stochastic, the matrix used in this method was weighted using the Inverse Distance Weighted formulation. After testing for spatial autocorrelation, size, wall length, maximization index, and aspect were subjected to a Mantel t-test, a versatile statistic capable of assessing the correlation of a wide variety of binomial variables; especially those that are ecological in nature (Ord and Getis 1995; Koening 1999) The reason for documenting these attributes was to parameterize the sensitivity of each variable in relation to its geography or distance from each other and to use these inferential statistics to explore possible environmental factors related to their spatial pattern.

To investigate Parry's (1994) claim that *moka* are predominantly found in arid regions, a broader-scale analysis beyond Viti Levu was conducted using a clinal map derived from rainfall data provided by Kumar et al. (2013). This paper examines climate trends in Fiji rainfall using records of rainfall amounts from 14 stations across the island group spanning more than 90 years. This study used a data set longer than any other previous study in this region and confirmed what models from the past had suggested: that Fiji experiences high interannual rainfall variability that is mainly affected by the El Niño-Southern Oscillation event and that there is little long-term variability in climate change (Coulter et al 1983; Lal et al 2008; Kumar et al 2013). Parry (1994) established three rainfall zones based solely on the total number of rainfall days, whereas the

more recent and comprehensive data set from Kumar et al. (2013) provides rainfall amounts at point locations averaged over an extended period. Using these more accurate estimates, a rainfall gradient map was interpolated in ArcGIS from the average rainfall at each rain gauge location in Fiji, and rainfall clines were classified arbitrarily into 12 equal intervals. The number of fishing weirs in each cline was then calculated, and the proportions of *moka* for each cline were determined.

4.4 Spatial Patterns and Environmental Correlates of *Moka*

Inter-Island Distribution of Moka

Based on the final count of weirs and their distribution among Fiji's provinces, a density measure was used based on land area which demonstrated that the densest aggregation of fishing weirs is in the province of Lomaiviti (n=120) while those of the north shore of Viti Levu are as Parry (1994) stated, in the province of Ra, followed by the province of Bua. A matrix of density values related to Fiji's provinces can be seen in Table 5. Also evident from this method of survey is that there are provinces in Fiji (Maitarsiri, Namosi, Serua, and Navosa) that do not appear to have any fishing weirs, and that out of the entire assemblage of 683 weirs, three of these were of the weir type known as a "longshore weir" located on the islands of Makongai and Rabi. The longshore type of weir is a universal form found in many cultures worldwide (Connaway 2007), and the fact that its representation is so limited in the Fiji Islands is an interesting spatial anomaly. The limitation to assessing patterns with this type of density measure is that *moka* are only found on the shoreline, and the actual size of each province varies greatly. As such, the relation to its number of weirs may not be that useful when considered on its own. Also, these provinces have modern political boundaries that may not have been the same in the deep past. However, we can compare this density measure to a simple cluster analysis of all weirs in the

island group which was performed using a general Getis-Ord Gi* statistic in ArcGIS and shows with statistical certainty that two meaningful clusters exist, one in the provincial area of Ra, as Parry (1994) stated, and another to the northwest amidst the island chain known as the Yasawa Group. These clusters can be seen in Figure 26, and the provincial densities can be seen in Figure 27.

Table 5. Matrix of values showing the quantity of weirs in each province of Fiji, the total area of land in each province (square kilometers), and an associated density value for each province.

Fiji Province	Total Weirs	Area (km^2)	Density
Lomaiviti	120	429.8	.295
Ra	170	1298.5	.130
Bua	78	1460	.053
Rewa	22	425.3	.052
Ba	147	2865	.051
Kadavau	25	492.8	.050
Lau Group	14	544.9	.025
Cakaudrove	69	2763.1	.025
Rotuma	1	47.2	.021
Tailevu	15	958.2	.015
Macuata	16	2245.6	.007

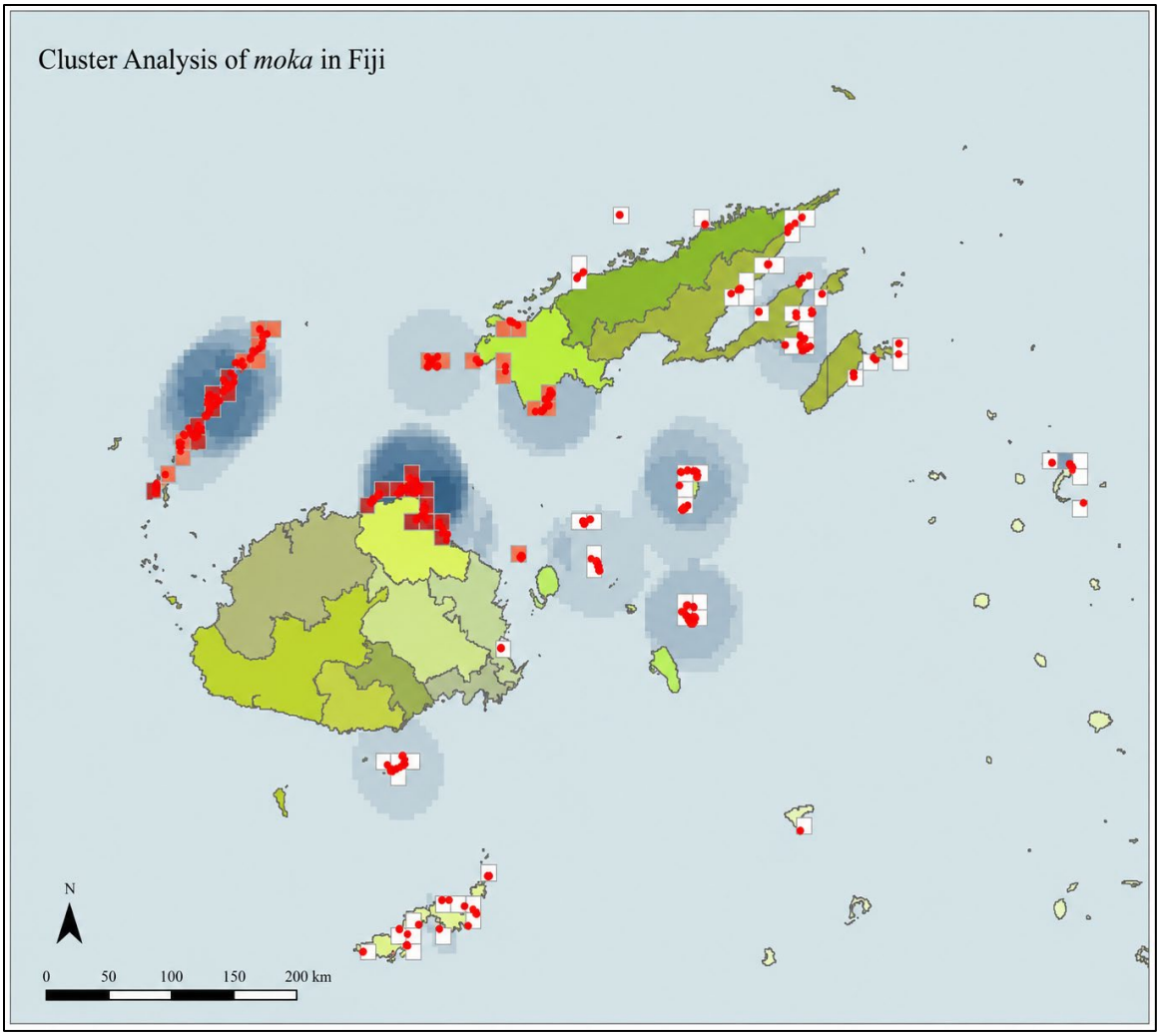

Figure 26. Cluster analysis in ArcGIS (Getis Ord Gi*) showing the highest aggregation of weirs in the Ra province in northeast Viti Levu and the Yasawa Group, the northwest of Viti Levu.

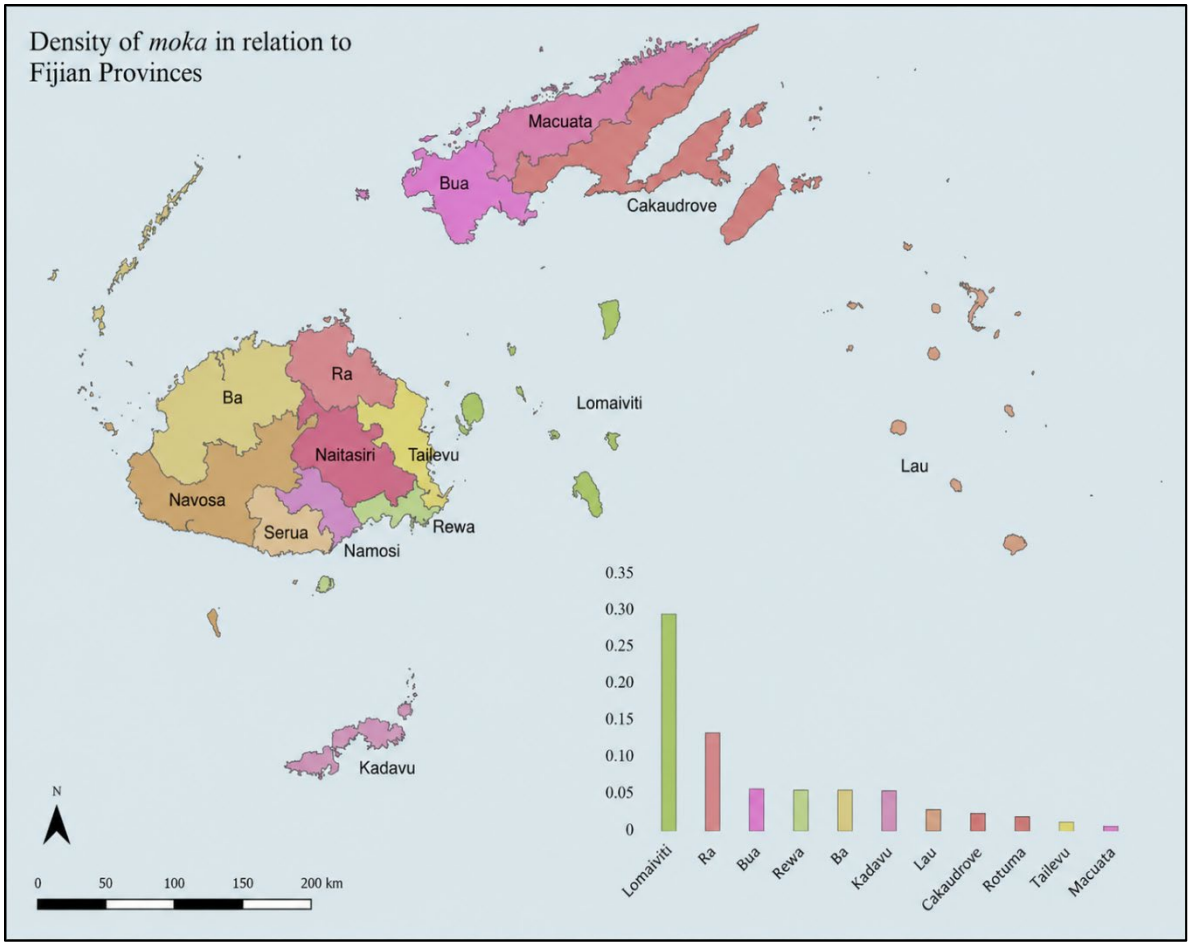

Figure 27. Map of Fiji showing respective provinces in a categorical color scheme with a histogram showing the levels of fishing weir density based on weir count and total area of province.

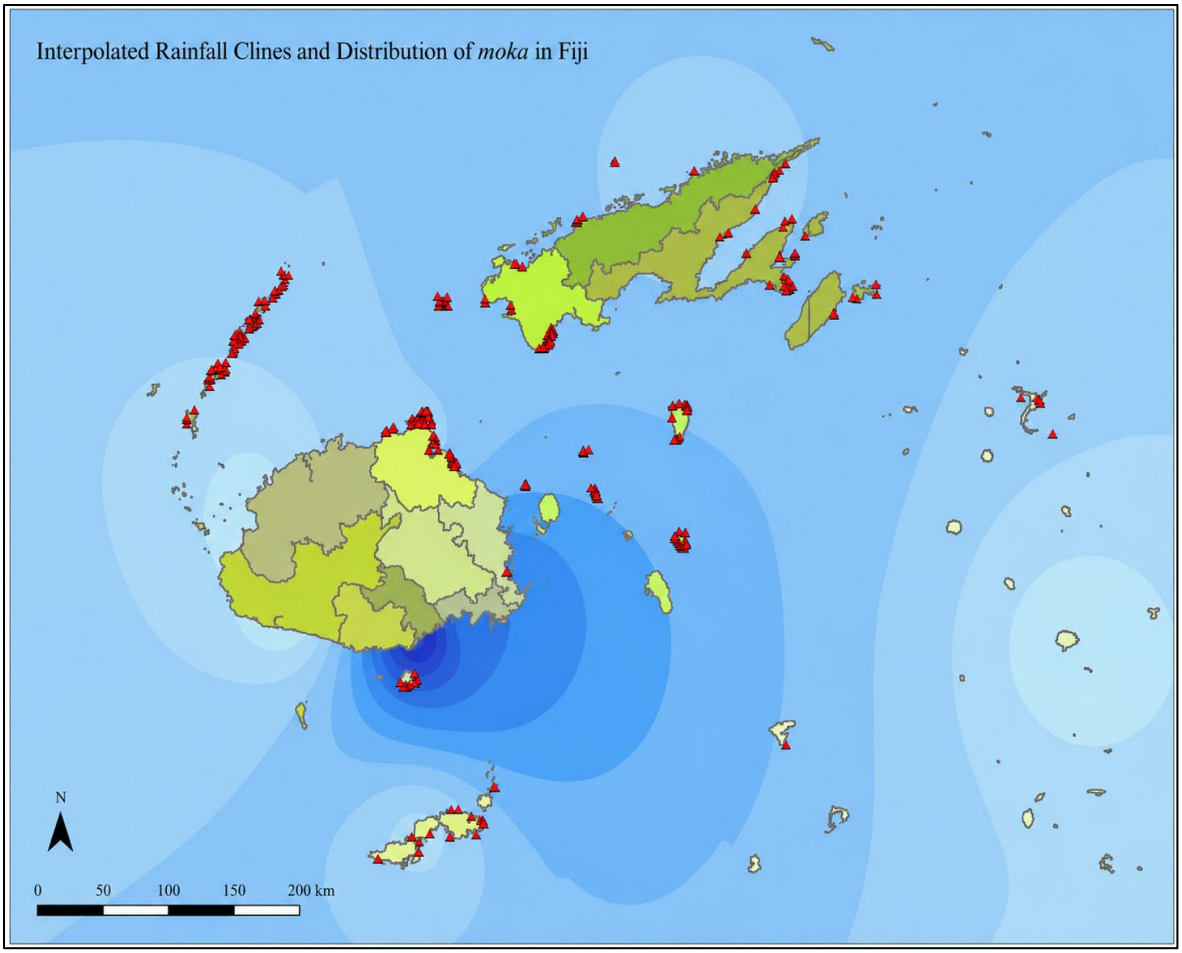

Figure 28. Map showing interpolated rainfall clines (12 classes-even interval) with weir distribution at inter-island scale. Darkest blue is the wettest cline while the lighter blue represents the drier clines. Testing for spatial autocorrelation at this scale, the Moran's Index = .682, z-score = 22.55, and p-value < .001 indicating that there is less than a 1% chance that this clustered pattern could be the result of chance or the vagaries of sampling.

When the distribution of fishing weirs is plotted against the rain clines derived from Kumar et al (2013), Parry's claim that *moka* are aggregated in drier regions seems to hold up. The spatial patterns of Fijian fishing weirs are overwhelmingly located in the more arid areas of rainfall in the Fiji island group, as seen in Figure 28 and listed in Table 6. Notably, 95% of the *moka* assemblage is in the five driest rain clines that receive less than the average rainfall per annum (2623.79 mm/year). However, the driest rainfall cline (1676 mm/year – 2055 mm/year), observed in the far west of Viti Levu, does not have any *moka* observed. A small number of weirs fall within the wetter interpolated clines to the southeast of Viti Levu (n=30), but this

likely reflects a scaling issue in the rainfall surface rather than a true contradiction of the broader pattern. Because the interpolation is strongly influenced by precipitation values from high-relief mainland areas, some lower offshore islands may be pulled into wetter clines even though their reduced elevation likely limits orographic rainfall and makes their local conditions effectively drier than the model suggests.

Table 6. Equal Interval Bands of Average Fiji Rainfall with the proportion of fishing weirs in each cline. Note that 24 Islands were discarded from this proportional analysis because they lay outside the rainfall interpolation (Taveuni, Qamea, Lauthala, Vanua Balavyu, Mothe, and Munia).

Intervals	Value (mm/year)	Number of Weirs	Proportion of Weirs
1 (driest)	1,676 - 1,833.97	0	0
2	1,833.96 - 1,991.94	0	0
3	1,991.93 - 2,149.9	38	.06
4	2,149.89 - 2,307.87	286	.43
5	2,307.86- 2,465.83	203	.31
6	2,465.82 - 2,623.8	101	.15
7	2,623.79- 2,781.76	0	0
8	2,781.75 - 2,939.73	7	.01
9	2,939.72 - 3,097.69	13	.02
10	3,097.68 - 3,255.66	10	.02
11	3,255.65 - 3,413.62	0	0
12 (wettest)	3,413.61 - 3,571.58	1 (Rotuma)	0
	Total Weirs =	659	1

Intra-Island Distribution of Moka

Following the field mapping of 51 *moka* on the island of Nananu-i-Ra, the Moran's *I* statistic was calculated to test for global spatial autocorrelation of fishing weirs regarding the four variables of length, area, maximization, and aspect for the island of Nananu-i-Ra. The index matrix was weighted using Inverse Distance Weighting, and significance was determined at the .05 level. A Mantel statistic was then determined by a Monte Carlo test at 9999 permutations. Using Moran's *I,* the results demonstrate that for wall length, there appears to be some degree of

positive spatial autocorrelation (Moran's *I* = .197), and with the low p-value (.001) and a 95% confidence level, we can reject the 'null hypothesis' that wall length is randomly distributed on the shoreline of this island. The same goes for the variable of aspect, but in this case, positive autocorrelation is even stronger (Moran's *I* = .428) and more significant (< .001), suggesting its potential importance. The other two variables, area and maximization, show a trend towards randomness, and we fail to reject the 'null hypothesis'. The Mantel correlation coefficient in this study demonstrates that for wall length, area, and maximization index, there is no correlation, and because of their high p-values, we cannot reject the 'null hypothesis' that there is no patterning to fishing weir direction. However, the variable of aspect, even though it has a weak association, has a low enough p-value (.05) that we can reject the 'null hypothesis' with 95% confidence, which makes this variable enticing for further analysis.

Table 7. List of descriptive statistics and elements produced from Moran's *I* analysis. The Mantel statistics, derived from a Monte Carlo test with 9999 permutations and significance determined at the .05 level.

Moran's *I*				
Variable	**Wall Length**	**Area m²**	**Max Index**	**Aspect**
Moran's *I* Statistic	.197	.0603	-.0173	.429
Expected *I*	-.02	-.02	-.02	-.02
Variance	.0046	.005	.003	.005
z-score	3.195	1.187	.046	6.556
p-value	.001	.236	.963	< .001
Mantel Test				
Variable	**Wall Length**	**Area m²**	**Max Index**	**Aspect**
Observation	0.014	-0.055	-0.077	.060
p-value	0.355	0.872	0.878	.05

4.5 Environmental Affordances and Social Implications of *Moka* Construction

Material Affordances and Construction Logic

All *moka* observed on Nananu-i-Ra and most documented elsewhere were constructed from rounded basalt boulders measuring approximately 25–35 cm in diameter. These boulders were locally available on the windward shorelines and promontories, where wave action dislodges and smooths volcanic rock. This supports Parry's (1994:162) observation that *moka* are often constructed in areas where basalt is abundant, particularly Vatia Andesite and Rokavukavu Basalt, thereby reducing the time and effort required to construct these features. This relationship between weir location and building material availability may explain why aspect (weir direction) is the most strongly patterned variable. Shorelines facing southeast trade winds tend to experience more erosion, exposing loose stone. Thus, rather than *moka* being preferentially constructed to *catch more fish* in a certain direction, it may be that they were built where the material and reef conditions allowed for construction at all. This aligns with archaeological models of "least-effort construction," in which infrastructure is typically built where raw materials are already available (O'Brien et al. 2005). The consistency in shape and method (dry-stacked basalt, outward-facing hook shape, reef-facing alignment) suggests a high degree of cultural transmission regarding *moka* construction norms. This aligns with archaeological models of "least-effort construction," where infrastructure is typically built where raw materials are already in place (O'Brien et al. 2005). The consistency in shape and method (dry-stacked basalt, outward-facing hook shape, reef-facing alignment) suggests a high degree of cultural transmission regarding *moka* construction norms.

Fortifications and Social Organization

One of the more provocative findings from the pedestrian survey is the proximity of *moka* to elevated stone enclosures, often described by locals as fortifications (*bure kalou* or hilltop platforms). On Nananu-i-Ra, at least four such fortified sites have direct views over large *moka* complexes on the reef flat below. While no direct material link has yet been established between the two feature types, the visual connection supports a hypothesis of social control and active monitoring. These fortifications may have served as lookout points or territorial markers tied to reef access rights. In many Pacific Island societies, coastal tenure and fishing rights are highly regulated by kin-based lineage or chieftainship systems (Kurashima and Kirch 2011; Kirch 1990a). If *moka* represented long-term infrastructural investments with predictable returns, they would have required some degree of defense, especially in times of scarcity or intergroup tension. This supports the broader model proposed by Field and Lape (2010), in which the emergence of built infrastructure and hilltop fortresses reflects intensifying conflict and competitive resource management.

Social Accessibility vs. Elite Control

A persistent question in the literature is whether *moka* were controlled by elites or accessible to non-elites. Some scholars (e.g., Kirch 1990b; Preston 1993) argue that large-scale infrastructure in Oceania often required conscripted labor and elite oversight. However, in the case of *moka*, there is little direct evidence for such hierarchical control. *Overall, moka* construction is relatively straightforward. Unlike Hawaiian *loko i‘a* (fishponds), which require coordinated hydraulic systems and labor-intensive sluice gates, *moka* involve dry-stacking stone in a single enclosure or serpentine shape. This opens the possibility that they were constructed and used by kin groups or individual households, particularly during dry seasons when reef

protein harvesting was critical (Jones and Quinn 2009; Dacks et al. 2018). Still, the aggregation of many *moka* in the same bay or coastline, and the repeated architectural patterns, suggest some degree of social coordination or regulation. Further ethnographic work is needed to clarify ownership regimes and inheritance patterns related to *moka.*

4.6 Interpretations

This section summarizes the spatial patterning, design characteristics, and ecological correlates of 683 intertidal fishing weirs (*moka*) in the Fiji Islands group, using a combination of remote sensing, pedestrian surveys, GIS analysis, and spatial statistics. Building on Parry's (1994) foundational study, this expanded analysis reveals that *moka* are far more widespread than previously reported and that their distribution follows non-random, ecologically informed patterns. The strongest evidence for this comes from the correlation between *moka* density and low-rainfall zones, supporting the idea that these structures were constructed as part of a risk-buffering strategy in ecologically marginal regions. Spatial clustering analyses confirmed statistically significant hotspots in Ra Province and the Yasawa Islands, both of which align with known areas of lower annual rainfall and limited agricultural potential.

At the intra-island level, the analysis of Nananu-i-Ra *moka* suggests some consistency in design (especially in orientation and wall length), while also showing flexibility and adaptation to local reef conditions and building material availability. The proximity of *moka* to fortified hilltops on Nananu-i-Ra raises intriguing possibilities about the social control and territoriality associated with reef access, although more fieldwork is needed to test this hypothesis.

In summary, this chapter provides a robust dataset and analytical foundation for interpreting *moka* not just as fishing tools, but as adaptive infrastructure embedded in dynamic social and ecological landscapes. In Chapter 7, these findings will be interpreted through the

lenses of human behavioral ecology, political economy, and Pacific Island ethnography to explore the implications of *moka* construction and abandonment, as well as their relevance to broader discussions of environmental adaptation and sustainability in the region.

5. BUILDING *KUAPĀ*: FISHPOND WALL CONSTRUCTION

5.1 Introduction: Material, Labor, and Energetics of Fishpond Construction

I ka ʻike i ka hana, or "in the work, is the learning," captures the essence of experimental archaeology, where reconstructing the past through *doing* yields insight that static observation alone cannot (Pukui 1983). In Section 3.3, we reviewed how artifact replication experiments bridge present processes and ancient behaviors. Here, I extend that approach from portable objects to an architectural feature: the *kuapā* (fishpond wall) of Heʻeia, Oʻahu. In 2014, as part of a University of Hawaiʻi graduate course (HWST 323: *Mālama Loko Iʻa*), I participated in rebuilding a section of Heʻeia Fishpond's wall in collaboration with the non-profit group Paepae o Heʻeia. This exercise in feature replication provided first-hand data on construction techniques, labor investment, and material requirements for a large-scale Hawaiian aquaculture system. It also offered an experiential appreciation for the skill and coordination underlying what, on paper, is merely an archaeological feature (Ascher 1961; Mathieu 2002). A map of Oʻahu showing the location of if this fishpond reconstruction can be seen in Figure 29 and Figure 30.

In this section, I analyze the replication results by material type (basalt, coral, sand) and scale them up to infer the effort needed to construct the entire 2.1 km long fishpond wall. I then compare these findings with other major Pacific Island constructions, from extensive dryland field systems to stone temples, to discuss labor organization, elite control, and the idea of costly signaling through infrastructure. Finally, I consider whether fishponds qualify as monumental architecture and examine how their prodigious productive capacity balances against their social and symbolic roles.

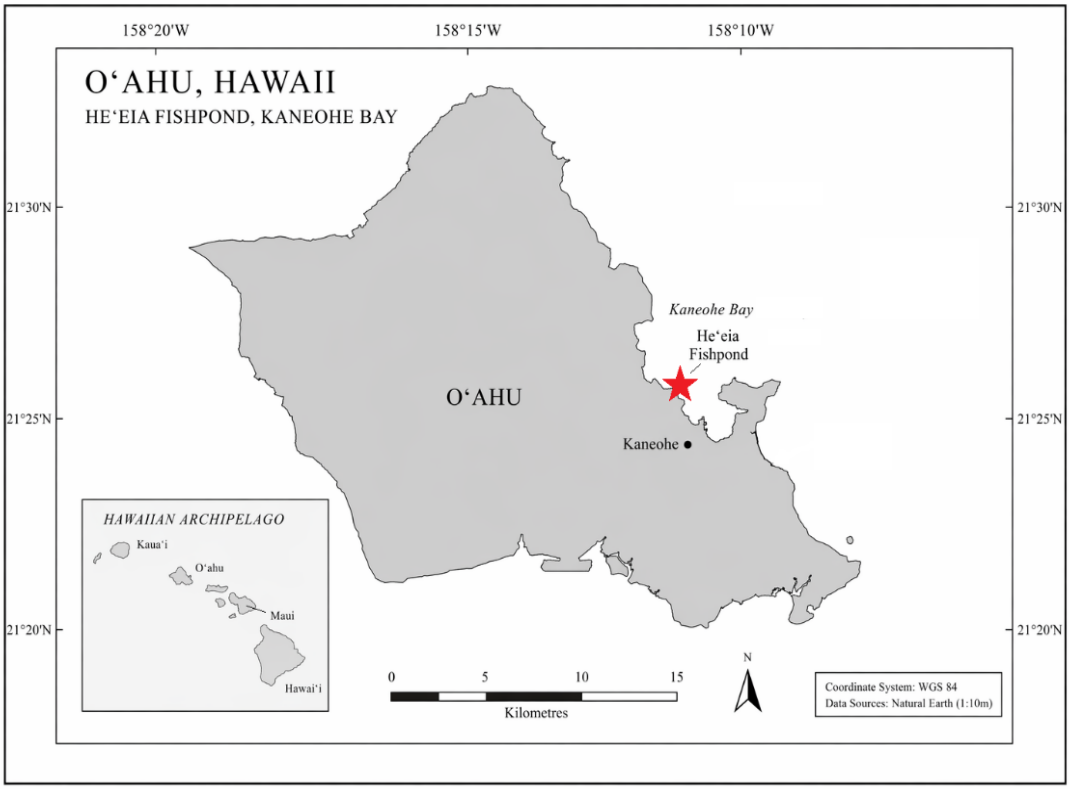

Figure 29. Map of O'ahu showing location of He'eia Fishpond.



Figure 30. Photo overview of He'eia Fishpond. Note red arrow showing location of wall restoration completed by University of Hawai'i students mentioned in this section. View is west.

5.2 Context of He‘eia Fishpond Wall

He‘eia Fishpond (*Loko I‘a o’ He’eia*) is a large walled coastal pond on windward O‘ahu, that covers ~36 ha of shallow water, and its circumferential wall (*kuapā*) stretches ~2.1 km. Unlike typical Hawaiian fishponds whose walls run semi-circularly between points on shore, He‘eia’s *kuapā* is annular and forms a complete ring. The wall was constructed between the 13th and 15th centuries CE and is regarded as one of the engineering feats of ancient Hawaiians (Apple and Kikuchi 1975). This places He‘eia’s construction roughly in the same late precontact interval when large *heiau* and intensive field systems were also being built elsewhere in the archipelago (Kirch 2010). It was built on a fringing reef using the dry-stack masonry method (*uhau humu pōhaku*), i.e., without mortar. The *kuapā’s* design features two parallel, facing walls of basalt cobbles and boulders, spaced ~3.7–4.6 m apart, with the interior filled mainly with coral rubble and sand. Originally, the wall stood roughly 1.5 m high, though centuries of wave action and a devastating 1965 flood have reduced or breached parts of it (Paepae o He‘eia 2014).

Notably, He‘eia’s wall includes at least seven sluice gates (*mākāhā*) built into it, which allowed fish fry to enter and grow inside the pond but limited entry by large predatory fish or the escape of mature fish. Construction of such a structure would have required a sophisticated understanding of tides, hydrodynamics, and materials, as well as the ability to mobilize and organize large labor forces (Kikuchi 1973, Costa-Pierce 1987). Oral traditions do not record a single chiefly name for He‘eia’s construction, but given its scale, it likely involved hundreds, if not thousands, of workers over several years, as the non-profit’s interpretive materials suggest (Paepae o He‘eia 2019). This makes He‘eia an ideal case to explore questions of labor and leadership in Hawaiian engineering. Before turning to those broader questions, however, I detail the empirical results of rebuilding one portion of the wall.

5.3 Rebuilding a Section of *Kuapā*- Materials and Methods

During the Spring 2014 field practicum, our team of 24 students and community members rebuilt approximately a 9–10 m length of the He‘eia fishpond wall. This segment was chosen where the historic *kuapā* had partially collapsed, leaving a gap open to the ocean. Under guidance from Paepae o He‘eia caretakers (*kia‘i*), we recovered and repositioned basalt rocks for the wall’s exterior faces and quarried or collected coral rubble to refill the core. We also cleared invasive mangroves and scooped out accumulated sediment to reach the former base of the wall. Working in knee-deep water at low tide, we passed rocks hand-to-hand, a method likely used by ancient builders. For an image of our work in progress, see Figure 31. We maintained detailed field notes, measuring the dimensions of rebuilt sections and tallying person-hours expended. The effort was essentially a controlled experiment in indigenous construction: we attempted to replicate the traditional style as faithfully as possible, even performing a modern rendition of a stone-working chant (*‘oli hana pōhaku*) before work to focus our coordination. By the end of the project, we had reconstructed the wall segment to roughly one meter in height and sealed the gap.

Below I break down the *materials* we used- basalt, coral, and sand, then present the *volumetric and caloric* figures recorded for this experimental build. Table 8 summarizes the key metrics of the replicated segment and extrapolates them to the entire wall. Figure 32 provides the profile of general *kuapā* construction and Figure 36 provides a plan view of the reconstructed wall’s measurements.



Figure 31. Photo of reconstruction of He‘eia wall section being conducted by students from University of Hawai‘i. (Sailors 2014).

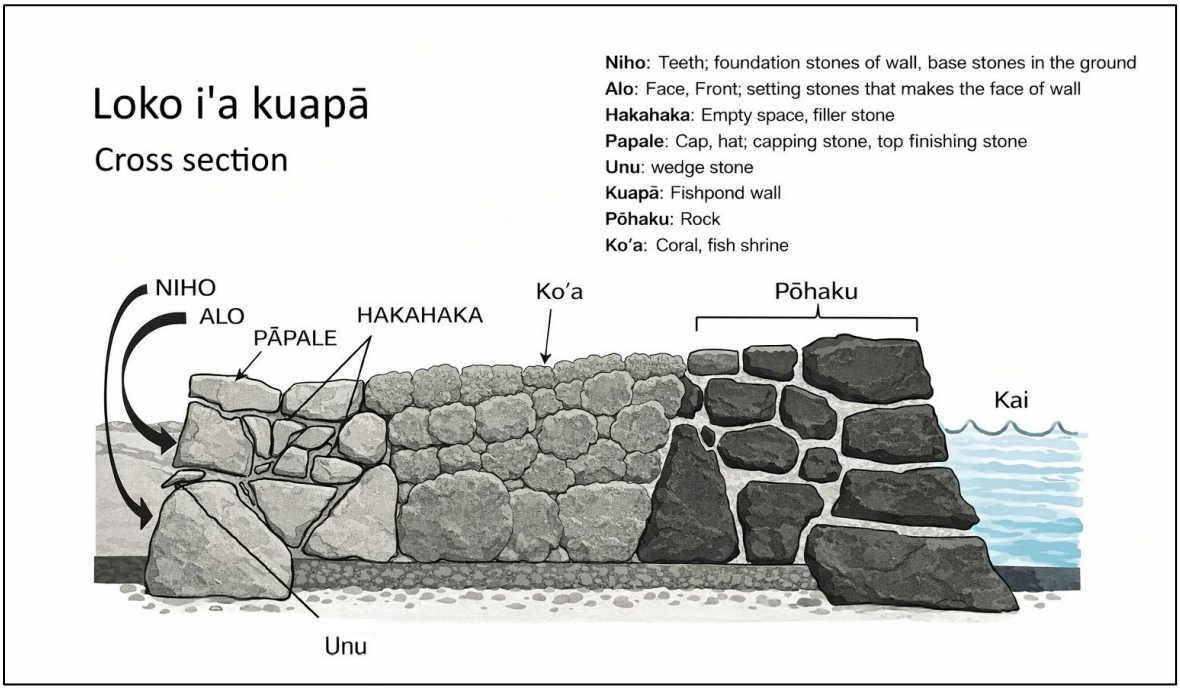

Figure 32. Cross section profile of general *kuapā* construction. (Sailors 2026).

Basalt (*pōhaku*): The wall's facing stones were basalt, locally available in the surrounding geology. At He‘eia, basalt rocks are found in stream beds and the reef flat (eroded outcrops of the Ko‘olau volcanic range), so the original builders did not need to quarry fresh stone far inland. Our team reused basalt boulders found on the beach or in the water, along with stones gathered from a nearby stream mouth. These ranged in weight from ~10–50 kg (large cobbles to small boulders), requiring two or more people to lift the largest. The dry-stacking method of fitting the basalt was like solving a puzzle; each stone was carefully laid to interlock, with its flattest face facing outward. Within this system, the largest foundation rocks or “tooth” stones (*pōhaku niho*) are especially important. *Niho* stones are set first along the original footprint of the wall, keyed tightly into the reef surface so that their mass and interlocking “bite” provide a stable base for all subsequent courses.

In practice, this meant that during our reconstruction we were instructed to locate and reset the *niho* at the bottom of the wall and at key corners before stacking smaller facing stones above them. Once the *niho* were established, we placed the face stones (*alo*) that define the exterior plane of the wall, using wedge stones (*unu*) to tighten gaps and small capping stones (*pāpale*) to finish upper courses and lock the larger blocks in place. The intentional creation and filling of empty spaces (*hakakaha*) behind the *alo* face, later packed with coral (*ko‘a*) and sand (‘*one*) was also part of this sequence. Commonsensically, the heaviest, most stable rocks belong at the bottom and these *niho* stones literally hold the wall in place.

By meticulously setting basalt in a tapered, leaning profile (wider at base), we recreated the wall’s sturdy outer armature. We then recorded the dimensions of two basalt-faced sections (on the seaward and pond sides of the gap), averaging ~9.3 m in length, ~0.6–0.7 m in height, and ~0.6 m in width (each face) after reconstruction. From these, we calculated a basalt volume

of approximately 7.44 m³ used in the segment (Table 8). At an estimated density of ~2.7 g/cc (typical for basalt), that corresponds to roughly 20 metric tons of rock (Basalt - Webmineral 2026). In practical terms, our small crew moved hundreds of basalt stones. I noted that even with 24 people, progress was slow when each rock had to be carefully placed, underscoring how crucial communal labor and perhaps rotating work shifts would have been in ancient times to maintain morale and momentum. It is important to note that basalt is also what gives the wall its strength: the dense volcanic rock absorbs wave energy and locks the structure together, embodying a literal and figurative "backbone" for the pond. The first stage of setting the basalt stones can be seen in Figure 33.



Figure 33. Walls of *kuapā* constructed with basalt stones gathered locally in the He‘eia land division (*ahupua‘a*) of O‘ahu. (Sailors 2014).

Coral (*ko‘a*): The core fill of the He‘eia wall consists of coral rubble and coral sand. In the precontact setting, abundant chunks of dead coral (Porites, etc.) on the reef flat adjacent to the pond could have been gathered, so presumably ancient builders collected coral at low tides

and stockpiled it for construction (Apple and Kikuchi 1975; Paepae o He‘eia 2014). Coral rock is lighter (less dense, ~1.5 g/cc) and more porous than basalt, but, in bulk, it provided a convenient way to fill the 4–5 m-thick interior of the wall. In our replication, however, most of the *ko‘a* we used did not come directly from the adjacent reef. Instead, most of the coral rubble and coarse fragments were trucked in from various beaches on the leeward side of O‘ahu and deposited near our work area, reflecting modern conservation constraints on harvesting live or *in situ* reef material. Five-gallon buckets of the delivered coral and calcareous accretions can be seen in Figure 34. Only in rare situations did we pry loose small, already-detached coral pieces from the reef or reuse coral that had slumped from earlier wall collapses. Once the basalt facings reached a certain height, we began placing these *ko‘a* pieces into the gap between them. The coral ranged from pebbles and cobbles to small boulders about 30–40 cm across. Coral proved easier to handle than basalt; one person could carry a moderately large chunk, or many small pieces in a 5-gallon bucket. We also observed how angular coral rubble, when dumped and compacted, tends to “lock” together, almost like a coarse gravel fill, helping to occupy the void spaces (*hakakaha)* behind the *alo* faces. The team rebuilt the interior coral section behind each basalt face, with an average cross-sectional width of ~2 m and height ~0.6 m (matching the basalt height). The coral volume used in the segment was about 11.98 m³ (Table 8), nearly 60% of the total material volume for that section. This equates to perhaps 15–18 metric tons of coral debris moved.

An interesting observation was the role of coral sand: as we shoveled coral chunks, lots of coarse sand and small chips filled the interstices. This fine material likely helped the wall consolidate, serving as a binding matrix once weight was applied (Li et al. 2022). Although we did not separately measure sand volume, the presence of sand (which we screened out from

reused rubble to an extent) was noted as important for packing gaps. In some historic fishpond walls, sections were even filled with dirt rather than coral, suggesting flexibility in using available fill (Apple and Kikuchi). For He‘eia, *ko‘a* fill was logical given the broader reef setting and modern availability of quarried or beach-derived coral rubble. Our experience reinforced that coral fill is expedient but requires containment by the basalt frames; if the basalt walls were not well-built, coral would slosh out or erode. Thus, coral’s efficacy depends on the basalt structure, highlighting the complementary use of these materials.



Figure 34. Buckets of reef-derived carbonate stone collected mainly from the leeward side of O‘ahu and brought to the site of reconstruction for the He‘eia fishpond wall. (Sailors 2014).

Sand (*‘one*) and Sediment: While not a primary construction material, sand played a subtle role in the replication. We encountered a layer of sand and mud at the base of the old wall, which had accumulated over the years of its disrepair. This had to be cleared up to reach a solid foundation. In doing so, we noticed that a bedding of coarse coral sand naturally remained under

the rebuilt section. It is plausible that ancient builders intentionally leveled the reef with *ʻone* or small rubble as a foundation pad beneath the *niho* and lower courses. Sand also filled voids among larger coral pieces during our rebuild. Though we did not quantify the sand volume, its presence improved stability, much as mortar (or, in this case, fine aggregate) would in modern masonry. In one corner, we dumped buckets of coarse sand gleaned from nearby deposits to ensure smaller basalt rocks sat snugly. Cumulatively, perhaps a cubic meter of sand ended up in our 9 m segment. This suggests that for the entire wall, many tens of cubic meters of sand might naturally be incorporated. The use of ʻ*one* underscores the multicomponent nature of the wall: it was not just boulders piled haphazardly, but a carefully engineered structure with a gradation of materials from large basalt to medium *koʻa* to fine sand, achieving a compact, interlocked mass. In Hawaiian, the chant phrase *pae pōhaku paʻa*—"because the groups of rocks congeal (solidify)" poetically captures the idea that with proper technique, even a wall without mortar becomes a unified, solid entity. The first two stages of basalt and coral construction can be seen in Figure 35. With wall measurements exemplified in a plan view map of the wall section in Figure 36 and wall section construction measurements extrapolated in Table 8.



Figure 35. Finishing stages of wall construction at He‘eia Fishpond, O‘ahu. (Sailors 2014).

Table 8. Experimental wall segment vs. entire He‘eia wall (volumes, labor, and energy).

Metric	Rebuilt Segment (9.3 m length)	Entire Wall (2092 m length)
Basalt volume (m^3)	7.44 m^3	~1,700 m^3 (extrapolated)
Coral volume (m^3)	11.98 m^3	~2,730 m^3 (extrapolated)
Total volume (m^3)	19.4 m^3	~4,430 m^3
Person-hours (recorded)	384 hours	~87,600 hours (est.)
Person-days (8 hrs/day)	48 workdays	~10,950 workdays
Estimated energy expended	~1.46×10^6 kcal (at high exertion)	~4.16×10^7 kcal (est.)
Person-days of food (2200 kcal)	~665 days of adult food energy	~18,900 days of adult food energy

Note: Extrapolations assume the replicated segment’s material density and labor efficiency are representative of the entire wall’s average. Variations in wall height, terrain, and organization could cause some deviation.

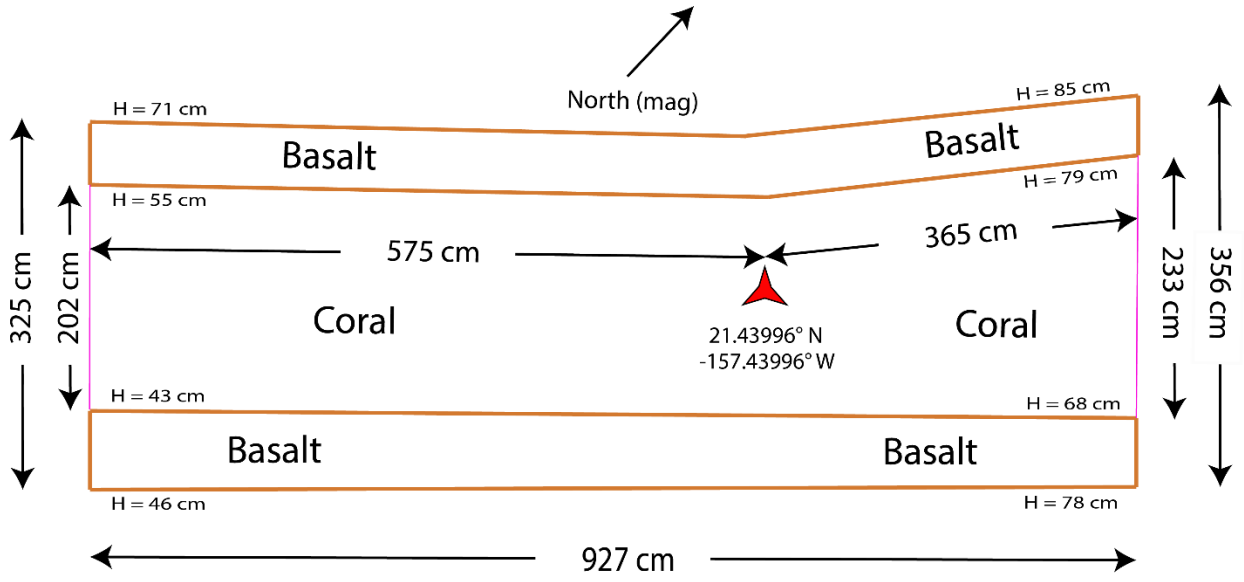

Figure 36. Plan view map with measurements of wall section completed by University of Hawai‘i students at He‘eia Fishpond in 2014.

Nevertheless, these figures offer an approximate sense of scale. Our ~10 m segment took 24 people two full days (16 hours each) to rebuild, which we can generalize to ~10,950 person-days for the whole 2092 m wall. If 500 people worked together, this implies on the order of 22 days of concerted work; if 50 people at a time, about 219 days, spread over multiple periods, quite plausibly “2–3 years to complete” as local lore suggests (Kamakau et. al 1976). The total energy investment (~4.16×10^7 kcal) is enormous, roughly equivalent to the caloric intake of one adult for 50 years, or, tellingly, about half the caloric yield of a single season’s taro crop in He‘eia’s `200 acres of taro fields (*lo‘i kalo*). In other words, building He‘eia’s wall demanded a substantial but not untenable fraction of the community’s energy budget, and the payoff would be a reliable fish supply for generations (Kirch 1994; Paepae o He‘eia 2019; Wyban 2020; Wyban 2022).

5.4 Scaling Up and Comparative Analysis

This experiment highlights that even a small segment of a fishpond wall is a formidable undertaking. When multiplied by the full 2.1 km length, the material volumes and labor estimates underscore the truly monumental scale of this infrastructure. Moving on the order of 4,400 m^3 of stone (perhaps ~7,000–8,000 tons) into a wall that must withstand ocean forces is comparable to the effort invested in other large construction feats of Hawaiian antiquity. For instance, some of the largest temples (*heiau*), such as Pi‘ilanihale *heiau* on Maui, involved moving tens of thousands of cubic meters of rock into terraced platforms (Kolb’s excavations indicate that Pi‘ilanihale’s main terrace alone covers roughly 9,400 m^2 and, with its stepped retaining faces, contains fill on the order of 10^5 m^3 in volume which can be seen in Figure 37) (Kolb 1999: 71–73). While He‘eia’s *kuapā* is somewhat less in total volume, it was built in a far more dynamic setting (intertidal zone) and spread over a much greater linear distance. In many ways, constructing a long continuous wall poses different organizational challenges than building an equivalent volume in one place. The former might be tackled in sections by distributed work groups, whereas temples required concentrated crews at a single location.

That said, both clearly exceed the scale of household labor and enter the realm of chiefly coordinated projects. Kolb’s (1997) analysis of Hawaiian labor mobilization defines a three-tier continuum: (1) household-level tasks, (2) local community works, and (3) supra-community or elite-sponsored works. Fishponds, especially large royal ponds like He‘eia, fall squarely in the third tier. No single family (*‘ohana*) could build a 2-km wall on its own; it required pooling labor from multiple kin groups or entire districts under some central directive. Ethnohistoric accounts support this: high chiefs (*ali‘i nui*) in late pre-contact Hawai‘i claimed ownership of fishponds and could command commoners to maintain them (e.g., through a labor tax or *kūleana* obligations). Thus, Hawaiian fishponds are often described as elite-driven infrastructure, a form

of staple finance that chiefly elites used to augment and secure food surplus ((Graydon et al. 2007; Kirch 2010). Kurashima and Kirch (2011) emphasizes that on Molokaʻi, fishponds rivaled irrigated taro in providing dependable surplus to the ruling class. Our replication quantifies how such surplus came at a steep initial cost in labor and coordination, a cost likely undertaken only when the political economy could support delayed returns (Kurashima and Kirch 2011).

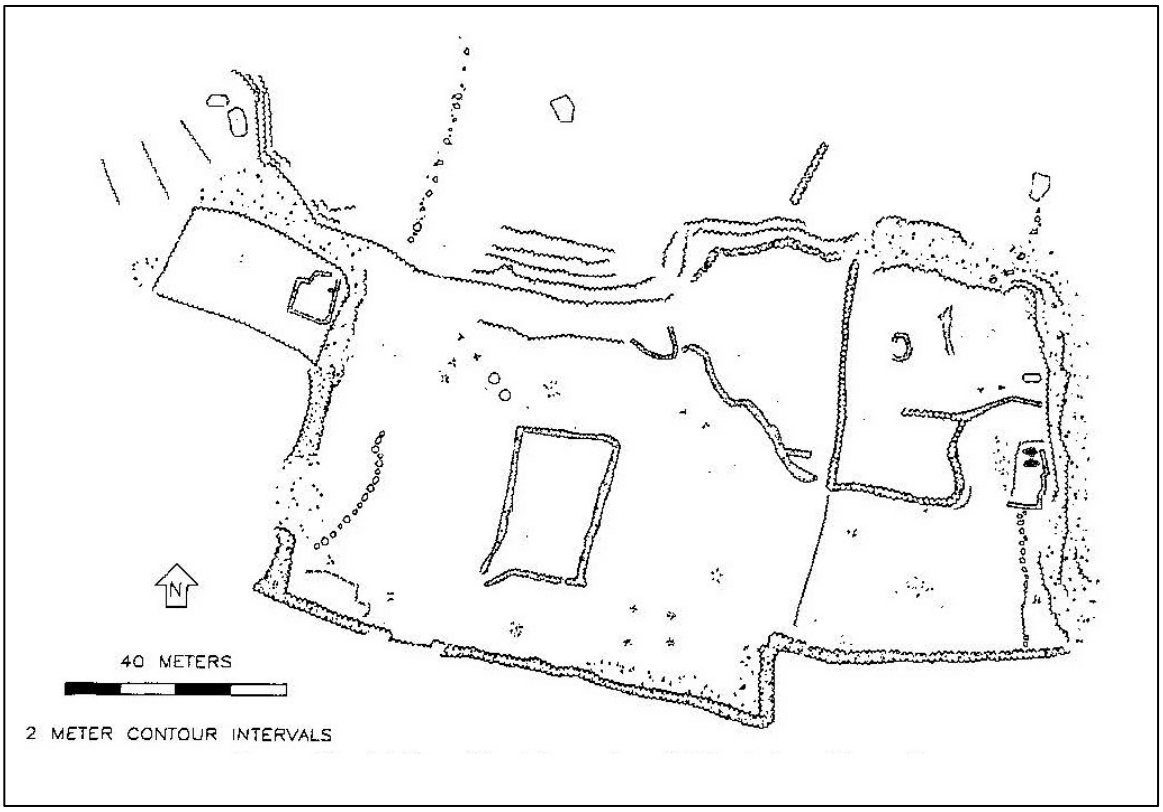

Figure 37. Chiefly residential complex of Piʻilanihale at Hana, Maui used here for comparative scale (Kolb 1994).

It is instructive to compare fishpond construction with other major productive features in the Hawaiian Islands. Consider the vast *dryland field systems* like the Leeward Kohala field on Hawaiʻi Island: thousands of hectares demarcated by low stone terraces and trails but not one continuous build. These field systems appear to have been expanded incrementally over centuries, with families adding new plots bit by bit, an accretive labor investment that fits a context of population growth and local, bottom-up decision-making (Ladefoged and Graves

2000; Ladefoged et. al 2009). By contrast, a fishpond wall must be closed in a shorter timeframe to function as you can't leave a pond half-built for decades and expect it to work or not to deteriorate. The temporal compression of labor for fishponds is more akin to ritual monument projects, which often had to be completed for a dedication or to mark a chief's reign (Kirch 2010). Indeed, Kolb (1994) notes that the largest *heiau* were likely built rapidly during periods of sociopolitical consolidation, serving as theatrical displays of chiefly power and religious authority.

In a similar fashion, building a gigantic fishpond could have been a statement of a chief's organizational might, a demonstration that he could muster the workforce to "farm the sea" on a grand scale (Kolb 1994). Some researchers have explicitly framed large fishponds as costly signaling by elites. By expending tremendous effort on a highly visible, permanent project, chiefs broadcast their ability to absorb costs for long-term benefits, which could enhance their prestige and perhaps intimidate rivals much as monumental temples or statues do in other cultures (Earle 1997; Kurashima and Kirch 2011). Scheffler and Lockwood's (2014) analysis of the royal fishpond of Kiholo, built by King Kamehameha I in the early 19th century, argues that it "lacked an efficient short-term subsistence function" and thus can be seen as chiefly display or wealth in infrastructure, in contrast to incremental agricultural works. Kiholo was so ambitiously scaled that it was partially destroyed by natural forces (lava flows) within decades, yet its conception speaks to the peak of elite resource mobilization; an engineered pond so large it bordered on impractical (Scheffler and Lockwood 2014:39).

Our He'eia case, several centuries earlier, may not have been as inefficient as He'eia undoubtedly was a productive pond, but the choice to completely encircle 88 acres with a wall, when a simpler barrier might have sufficed to impound part of the bay, suggests that symbolism

and overt monumentality were at play. In Hawaiian classification, fishponds (*loko i‘a*) were integrated into the socioeconomic landscape, but archaeologically, one can argue that features like He‘eia approach the status of monumental architecture. They are “sizeable, durable, and non-domestic structures… requiring mobilization of labor beyond the household”, meeting Kolb’s (1999) criteria for monumentality in Polynesia. The fact that He‘eia’s wall remains a prominent landscape feature centuries later and had spiritual/taboo aspects (certain fishponds were sacred to fish gods like Kū‘ula) further blurs the line between a pure subsistence facility and a monument (Kikuchi 1973).

5.5 Interpretations

Beyond Hawai‘i, we find few parallels to the scale of fishpond construction, underscoring how unique this phenomenon is to Hawaiian chiefly economies. Elsewhere in Polynesia, marine constructions tended to be fish weirs or small ponds (Kikuchi 1973). For example, in Fiji (see Chapter 4.1), intertidal stone fish traps (*moka*) were numerous but much smaller and simpler, often just C-shaped walls a few tens of meters long (Parry 1994). Ethnographic studies suggest that Fijian weirs were built and maintained gradually by extended families or village groups, with minimal demands on any central authority (Jones and Quinn 2009). Parry (1994) argued that their distribution correlates with local environmental needs rather than political centers. In Fiji’s case, fish structures did not become a conspicuous elite project; indeed, Parry noted “construction and maintenance are not labor-intensive” for *moka.*

The contrast with Hawai‘i could not be starker: by late pre-contact times, Hawaiian chiefs were building seawalls hundreds of meters long, whereas Fijian communities stuck to modest traps. This aligns with broader patterns. For example, Fijian society, while stratified, was more heterarchical and did not unify at an island-wide scale, and we do not see large-scale “public

works" for subsistence there though they did build impressive fortifications in times of war (Field 2009; Cochrane 2018). In other archipelagos, we see alternative manifestations of labor investment: dryland agricultural terraces in the Society Islands and the New Guinea highlands, or ceremonial centers such as the marae complexes of Tahiti and the megalithic tombs of Tonga (Ladefoged et. al 2009; Clark 2016; Maric 2016; Denham 2011, 2018). Each reflects local priorities. Tellingly, only Hawai'i and certain parts of Micronesia developed extensive walled aquaculture. Micronesia's example is the city of Nan Madol in Pohnpei, where basalt walls and islets were constructed in a lagoon for chiefly ritual residence, a huge labor endeavor, but directed toward ceremony, not directly to food production. Hawaiian fishponds occupy a fascinating middle ground: they were economically productive *and* politically significant (Costa-Pierce 2022).

Labor Coordination and Social Organization: What did it take socially to build a fishpond like He'eia? Our replication. a mere 9.3m section, required continuous teamwork, clear task leadership, and mutual trust in a potentially hazardous work environment. Scaled up to 2 km of wall, this implies a need for a high degree of organization. We can envision a chief or overseer (*konohiki*) coordinating rotating work groups drawn from different kin-groups, perhaps using incentives such as community feasts to encourage participation. Ethnohistoric and oral accounts describe large communal projects ending with celebratory feasts, and, in the case of fishponds, the sharing of the first harvest of fish as a way to reinforce social ties and obligations (Kamakau 1976; Kikiloi 2003). In some cases, ritual specialists likely oversaw proper alignment and spiritually sanctioned the work (fishponds often had associated ceremonies to dedicate them to the gods of the sea/fertility (Costa-Pierce 2022).

From an evolutionary perspective, this coordinated labor can be seen as a form of cooperation that yields collective benefits, essentially a public good in the form of a stocked fishpond that no one household could produce alone, but many can benefit from once built. The risk with public goods is "free riding", where people benefit without contributing, but in ancient Hawai‘i, the sociopolitical system mitigated this: the chiefly authority and *kapu* system could compel contribution and exclude shirkers or at least ensure that those who contributed, through labor or tribute, had access to the pond's fish. In this light, fishponds reinforce the view of Hawai‘i as a society in which elite management solved large-scale coordination problems to the benefit of both chiefs and commoners, though not necessarily equally (Bowles and Gintis 2011). Hommon's (2013) analysis of the ancient Hawaiian state notes that infrastructure such as fishponds and extensive irrigated taro fields (*lo‘i*), were critical to the transformation from chiefdom to archaic state, as they increased surplus and tied the populace's well-being to elite-controlled resources (Hommon 2013).

By controlling the ponds, chiefs could both provision gatherings by feeding people fish at *heiau* ceremonies or during annual harvest festivals (*makahiki*) and exert leverage during hard times. Ethnohistoric records from the 19th century indeed show that fishponds were tapped by social elites as emergency larders during famine or when ocean fishing was too dangerous, a factor that surely enhanced their perceived value and strategic importance. One account noted that in a drought year, chiefs opened pond sluice gates to feed the people, an act that both alleviated hunger and heightened the people's reliance on chiefly beneficence, and by extension, the chief's legitimacy (Malo 1903).

However, scholars debate the degree to which such intensification was top-down or bottom-up. Dye (2010), for example, offers a "bottom-up" perspective, suggesting that many

landscape modifications in Hawai‘i, such as field expansions or small-scale fish traps, began as commoner innovations that were later co-opted or formalized by elites. Fishponds might have similarly evolved: perhaps early, smaller ponds were family or community-driven for subsistence buffering, and only later did paramount chiefs invest in truly monumental ponds as they recognized both the economic payback and the political capital to be gained. There is some evidence that not all fishponds were chiefly built; smaller ponds (*loko i‘a*) could be constructed by lesser chiefs or prosperous commoner groups and then commissioned, or appropriated, by higher chiefs in the expansion of royal estates. For instance, the chiefly Mahele of 1848 codified many ponds as crown or chiefs' lands, indicating elite control in late times (Kikuchi 1973; Hommon 2013; Osorio 2014).

What our labor estimates contribute to this debate is a sense of threshold: a pond like He‘eia was likely beyond the capability of a local kin group alone, implying orchestrated labor by a higher authority. Smaller ponds, enclosing a few acres or less, might not have needed such hierarchical coordination. Thus, Hawaiian aquaculture could have started as a localized practice and scaled up as socio-political capacity grew. Kirch (2010) describes a general pattern in Hawai‘i of intensification accompanying the rise of the chiefly stratum, with major surges in infrastructure around the 15th–17th centuries. The radiocarbon dates of fishpond walls (some ca. 1400s AD) coincide with this trajectory (Burney 2002; Kelley 2025). It seems likely that the *motivation* to build fishponds was both practical (more fish reliably) and social (competition among chiefs, display of piety to gods by providing abundance, etc.). The concept of "costly signaling" in evolutionary anthropology is useful here: chiefs may have built expensive works to signal their prowess and thereby solidify their leadership. Unlike a purely wasteful signal (like burning a pile of yams to show you can), fishponds are "costly signals with benefits" in that they

demonstrate power *and* later produce food. This dual character might explain why Hawaiian chiefs favored them: they were investments that paid dividends in protein and status (Zahavi and Zahavi 1999; Scheffler and Lockwood 2014).

Productivity and Payoff: Were these massive investments worthwhile in subsistence terms? The historical and ethnographic data suggest yes; *loko i'a* were remarkably productive once operational. A well-managed pond could yield 136–272 kgs of fish per acre annually. For He'eia's 88 acres, this implies perhaps 12,000–24,000 kgs of fish each year under optimal pre-contact conditions (Graydon et al. 2007: 4-6). Traditional accounts and early Western observers support these figures: Kamakau wrote of ponds teeming with mullet (*'ama'ama*) and milkfish (*awa*), enough to feed whole communities and for chiefs to send tribute fish to the paramount (Kamakau et. al 1976). One cited estimate is that in the late 18th century, Hawai'i's fishponds (about 360 across the islands) produced nearly 900,000 kgs of fish annually (Costa-Pierce 1987: 320-323). He'eia, being one of the largest, was surely a significant contributor to that total. By comparison, that scale of output is on par with agricultural staples. For example, 24,000 kgs of fish contains on the order of 20–26 million kcal (assuming ~1,100 kcal per kg of fish), which is comparable to the caloric yield of 20–30 acres of taro in a year as taro yields ~8–12 million kcal per acre per year in wet cultivation, as seen in other pre-contact Polynesian islands (Hamilton and Kahn 2007; Khan and Kirch 2013).

In essence, once built, a fishpond was like an extra swath of highly productive "farmland" except that its crop (fish) was protein-rich and could complement the carbohydrate-heavy taro and sweet potato diet (Parry 1994). This helps explain why Hawaiian elites would invest in ponds: it diversified the food base and added resilience. Fishponds provided a steady supply even when pelagic fishing was risky (during high surf or storms) or when agricultural

yields fluctuated. They functioned as a risk-buffering mechanism in the subsistence economy otherwise seen as a principle of "resource diversification" in Human Behavioral Ecology (Smith 2017). In evolutionary terms, communities that built ponds could better withstand bad seasons or years, giving them an adaptive advantage. By extension, chiefs who sponsored ponds could maintain power by preventing famine and expanding the number of people over whom they ruled. It is notable that the greatest concentrations of fishponds in Hawai‘i were on Moloka‘i and O‘ahu, islands with extensive reef flats and dense late-period populations. Moloka‘i was famed as a "land of abundance" (*‘āina momona*) partly due to its many ponds (Kamakau et. al 1976). In those contexts, ponds likely reached a point of diminishing returns because not all could be fully always stocked, but even a few high-yield ponds would dramatically increase local protein availability and food security.

My energy accounting, admittedly rough, indicated ~4.16×10^7 kcal expended to build He‘eia. If the pond produced say 2.0×10^7 kcal of fish per year (≈18,000 kgs at ~1,100 kcal/kg), it would "repay" the caloric investment in about 2 years of operation. Maintenance costs would reduce net returns as walls need upkeep and sluice gates repair, etc., which require periodic labor inputs. But even if net payback were, say, 5–10 years, that is a short time relative to the centuries many ponds were used for. This aligns with an HBE delayed return strategy in which people tolerate high upfront costs for long-term yields (Olszewski 2007; Smith 2017). Hawaiian ponds exemplify delayed returns par excellence, and their success illustrates why chiefs who sponsored them ultimately benefited. By the 19th century, some Hawaiian royalty even commercialized pond harvests for sale, showing the surplus value these systems generated (Costa-Pierce 1987). Productivity also had a sustainability angle: unlike wild fisheries, which can be over-harvested or "collapse", ponds are semi-closed systems that are carefully managed. Ancient caretakers

practiced methods akin to aquaculture science, such as rotating sections of the pond, removing invasive seaweed, and perhaps fertilizing ponds with taro detritus to boost algae growth (Kikuchi 1973; Kikiloi 2003). Such management ensured yields could be maintained over time, making the pond not just a one-time benefit but a renewable asset.

All that said, it is important to temper the view that fishponds were purely utilitarian triumphs. They also carried social and ceremonial significance. Certain fish like the revered *awa* from ponds might be reserved for chiefly tables or religious offerings (Malo 1903). The pond walls themselves, though not temples, were lasting testaments to a community's labor which were arguably a monument to cooperative work. In debates on monumentality, scholars often emphasize that monuments are imbued with meaning beyond their practical function (Kolb 1994; Earle 1997). Do fishponds meet that criterion? Some argue they do: Scheffler et al. (2014) explicitly conclude that large fishponds "should be considered in terms sometimes reserved for monumental architecture," (abstract) serving as symbols in elite status competition as much as subsistence ventures. On the other hand, one could argue that fishponds differ from classic monuments, like pyramids or statues, because they directly provisioned the populace. Their glory was in feeding people, which ties them closer to economic infrastructure.

This perhaps makes them a category of "productive monuments" or "utility monuments." Kurashima and Kirch (2011) noted that fishponds were political instruments as much as food producers, implying that Hawaiians understood their dual role. In functional terms, a fishpond embodies ecological niche construction: people altered an ecosystem (reef/estuary) to create a new niche that favored algae and herbivorous fish, thereby reliably boosting the biomass available to humans (Odling et. al 2003). This niche construction had feedback: it domesticated certain fish behaviors making them dependent on pond conditions and domesticated humans to

the pond requiring permanent stewardship roles (Kikiloi 2003). The pond guardians (*kia‘i loko i‘a*) became a specialized class of workers under the chief, reflecting how monumentality and labor specialization go hand in hand in a complex society (Kirch 2010; Hommon 2013).

In summary, the feature replication of He‘eia Fishpond’s wall reveals the immense material and energetic demands of such construction, confirming that only a well-organized society with surplus labor, and food to feed that labor, could accomplish it. Extrapolating from our data, we see that He‘eia’s *kuapā* likely required on the order of 10^4 person-days of work and careful resource marshaling. The comparative context shows this is in the league of many other monumental constructions in Oceania, though Hawaiian fishponds are unusual in being directly subsistence-oriented monuments. The exercise supports the view that Hawaiian fishponds were projects of political economy, instrumental in both boosting food production and broadcasting the power of chiefs who controlled that production. These ponds embodied an interplay of function and symbol; they were engines of marine food output and, simultaneously, statements of dominion over land, water, and people. As we move forward, this case study will inform the Discussion (Chapter 7) on how customary infrastructure can be re-evaluated not just as static “features” on a map, but as dynamic focal points of social relations, cultural values, and evolutionary strategy. First, however, I discuss fishpond governance and resilience through the lens of agent-based modeling.

6. AGENT-BASED MODELING OF A HAWAIIAN FISHPOND

6.1 Introduction: Fishpond Governance and Resilience

Customary Hawaiian fishponds, or *loko i‘a*, were not simply passive enclosures for storing fish. They were engineered socioecological systems that required recurring labor, ecological knowledge, and governance to remain productive through time. In the case of He‘eia Fishpond on O‘ahu, these dynamics are especially clear. The pond’s annular wall (*kuapā)*, multiple gates (*mākāhā)*, and long history of maintenance and restoration demonstrate that such systems were not one-time constructions, but infrastructures of ongoing stewardship (Paepae o He‘eia 2025). As the previous section argued, the construction and repair of *kuapā* required substantial labor and coordination. Yet labor investment alone does not explain long-term viability. The more difficult question is how such systems persisted as functioning commons under variable ecological conditions, competing human strategies, and the constant risk of overuse.

This section uses agent-based modeling (ABM) to explore those dynamics. Rather than attempting a literal reconstruction of ancient He‘eia, the model treats the fishpond as a simplified but theoretically grounded socioecological system in which human decisions, ecological productivity, and institutional constraints interact over time. The central aim is to evaluate how variation in reproduction, enforcement, storm disturbance, and seasonal access influences whether a fishpond system collapses, persists under exploitative pressure, or stabilizes as a governed commons (Premo 2010; Romanowska et al. 2019). In this sense, the model serves as an experimental extension of the archaeological argument developed elsewhere in my dissertation. Archaeological, ethnohistoric, and ecological data identify the structural components of fishpond

systems, but ABM allows those components to be placed into motion and tested as interacting processes (Poepoe et al. 2007; Cegielski and Rogers 2016).

The model is framed primarily through principles of HBE and Ostrom's work on common-pool resource management (Winterhalder and Smith 2000; Ostrom 1990). HBE is useful here because it treats human strategies as adaptive responses to constraints, incentives, and risk. In a fishpond setting, cooperative maintenance, moderate harvesting, defection, and costly enforcement can all be interpreted as strategic responses to the distribution of costs and benefits in a managed aquatic landscape (Winterhalder and Smith 2000). Ostrom's framework is equally important because fishponds are classic examples of governed commons: they require monitoring, graduated sanctions, territoriality, rule-bound access, and ecological feedback to remain productive over the long term (Ostrom 1990). Niche Construction Theory serves as the environmental engineering framework that links human strategies to ecological consequences (Odling-Smee et al. 2003; Laland and O'Brien 2010). Fishponds altered tidal flow, substrate conditions, and aquatic habitat, thereby increasing the productivity of *limu* (seaweeds) and herbivorous fish, thereby restructuring the local marine niche to favor sustained human use (Odling-Smee et al. 2003; Zeder 2016).

Accordingly, this section asks a narrower, more analytical question than earlier discussions of fishpond construction or distribution: under what socioecological conditions does a He‘eia-inspired fishpond system remain resilient, and under what conditions does it fail? To answer this, I will first explain why ABM is an appropriate method for aquatic systems and customary marine infrastructure. I then describe the model's design and parameterization, including the treatment of human agents, fish biomass, algae (*limu*) productivity, territoriality, seasonal closure, and environmental disturbance. Finally, I present the results of a two-stage

simulation program in NetLogo: an initial pilot sweep (Wave 1) used to identify sensitive parameters and validate model behavior, followed by a larger factorial experiment (Wave 2) used as the primary dataset. A screenshot of this software's interface can be seen in Figure 38. Together, these simulations suggest that demographic pacing, enforcement capacity, and seasonal governance are more important to long-term persistence than environmental productivity alone. The results also indicate that fishpond resilience is not simply a byproduct of resource abundance, but emerges from contingent interactions among labor, institutional strength, and ecological engineering.

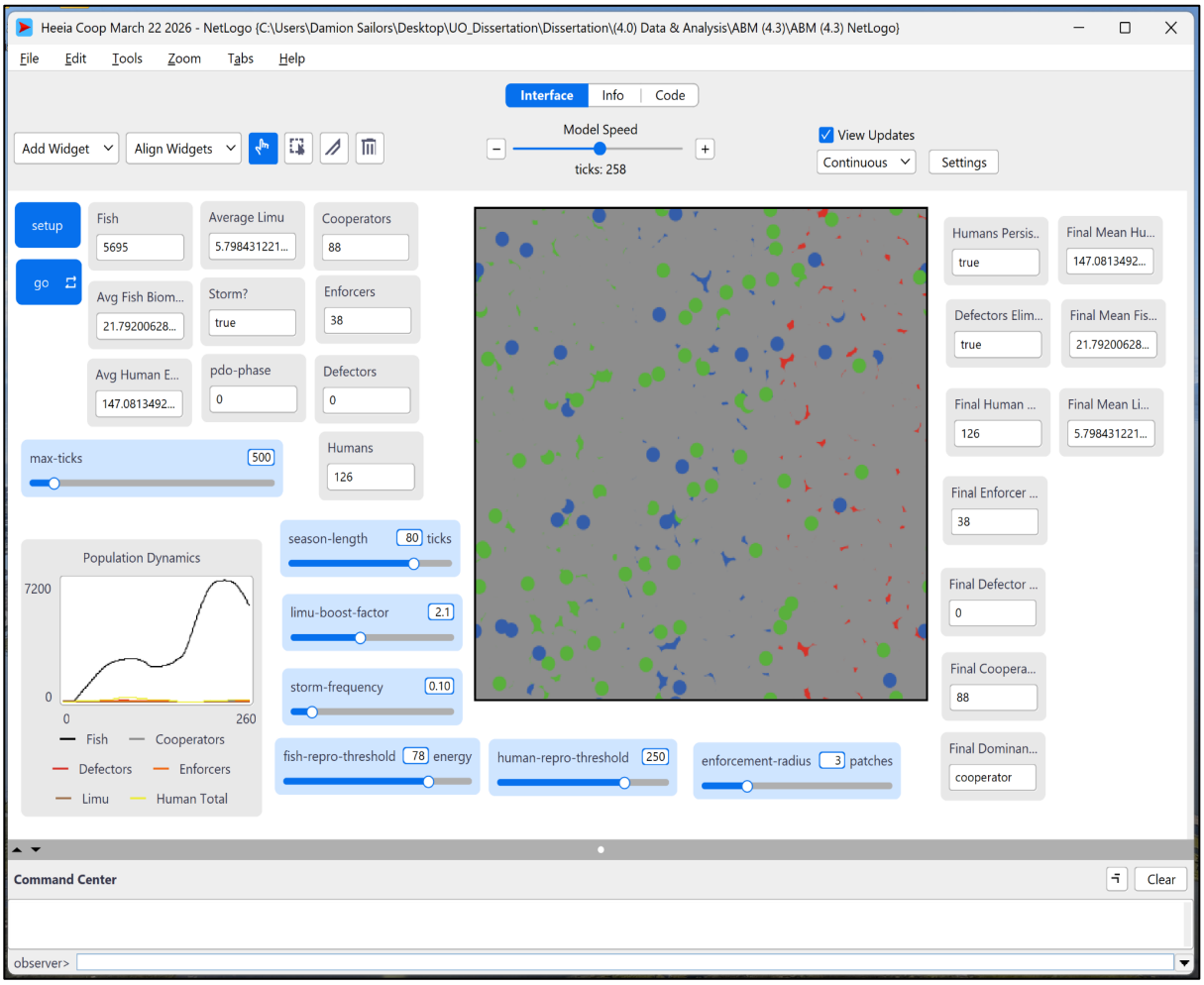

Figure 38. Screenshot of NetLogo cooperation model created for this dissertation section.

6.2 Why Use Agent-Based Models for Aquatic Systems?

ABM is especially appropriate for this dissertation because fishponds are neither purely environmental features nor purely social institutions. They are coupled systems in which human decisions affect ecological productivity, which in turn affects the payoffs of different human strategies. Conventional archaeological approaches can identify the material traces of such systems, walls, sluice gates, sediment accumulation, faunal remains, labor investment, and settlement context, but they are less well suited to exploring how everyday decisions accumulate into long-term outcomes. Agent-based modeling is useful precisely because it allows those decisions to be represented as repeated interactions among heterogeneous actors operating within a structured environment (Lake 2014; Cegielski and Rogers 2016; Romanowska et al. 2019).

This is particularly important for aquatic systems. Marine and brackish environments are dynamic, patchy, and vulnerable to stochastic disturbance. Fishponds depend not only on construction, but on maintenance of flows, substrates, and food webs. *Limu* abundance, fish recruitment, and harvest success vary across time. Storms can damage pond walls, reduce productivity, and disrupt otherwise stable cycles. Human users, meanwhile, do not all behave identically. Some may invest in upkeep and take moderate returns. Others may overharvest. Still others may monitor and sanction. These interactions are difficult to reduce to static variables because they are fundamentally processual. ABM enables observation of what happens when these processes interact repeatedly (Romanowska et al. 2019; Cegielski and Rogers 2016).

From an HBE perspective, the value of ABM lies in its ability to operationalize strategy under environmental constraints. Fishpond management is not simply a cultural ideal; it involves tradeoffs. Cooperative agents incur short-term maintenance costs but may improve long-term returns. Defectors can gain immediate benefits from aggressive harvest, but at the risk of

reducing future productivity. Enforcers incur monitoring costs yet may stabilize the system if sanctions deter unmanaged exploitation. These are precisely the kinds of adaptive choices that HBE predicts will vary according to local return rates, risk, and time horizons (Winterhalder and Smith 2000). A model allows these tradeoffs to be examined experimentally rather than inferred only in principle.

Ostrom's work on common-pool resources provides a second reason ABM is useful here. Fishponds fit the logic of common-pool systems because exclusion matters, overuse is possible, and maintenance of the resource depends on rules and monitoring. Ostrom emphasized that durable commons are not sustained by goodwill alone, but by institutional arrangements that define access, monitor compliance, and sanction free-riding (Ostrom 1990). Those principles are especially relevant to fishponds, where access to *mākāhā*, harvesting times, wall maintenance, and village-level claims would have shaped whether the system remained productive. An agent-based model is particularly effective for testing this because it allows enforcement and noncompliance to be represented as recurrent behaviors rather than abstract institutional labels (Ostrom 1990; Castillo and Saysel 2005; Schlüter and Pahl-Wostl 2007).

Niche Construction Theory adds the ecological side of the equation. The *loko i'a* was an environmental modification designed to change the local conditions under which fish and *limu* grew. By altering tidal exchange, retaining young fish, and enhancing shallow-water productivity, pond builders changed the resource landscape itself. In that sense, fishpond management was not merely extraction from a naturally given environment, but engineering of a productive niche. ABM is useful because it can explicitly represent this feedback: maintenance can improve *limu*, *limu* can improve fish biomass, and fish biomass can alter the returns to human labor (Odling-Smee et al. 2003; Laland and O'Brien 2010; Klein et al. 2017). These are

precisely the recursive ecological relationships that niche construction highlights (Odling-Smee et al. 2003).

Finally, ABM is valuable because it allows archaeological interpretation to move from description toward mechanism. The question is not whether Hawaiian communities were capable of cooperation; they clearly were, but what kinds of conditions made cooperative governance more or less stable. Likewise, the issue is not whether environmental disturbance mattered; it certainly did, but whether storms and productivity shifts by themselves explain collapse or whether institutional strength mediates those effects. By treating the fishpond as a dynamic commons rather than a static feature, ABM enables testing those questions in a structured, replicable way (Premo 2010; Romanowska et al. 2019; Schlüter and Pahl-Wostl 2007).

6.3 Parameterization and Design of the Fishpond Model

The model was built in NetLogo and designed as a He‘eia-inspired representation of a walled Hawaiian fishpond governed as a village-based marine commons (NetLogo 1999). The model does not attempt to reproduce the exact hydrodynamics, population history, or daily practices of He‘eia. Instead, it formalizes the socioecological relationships most relevant to this dissertation: labor investment, harvest strategy, sanctioning, habitat maintenance, environmental disturbance, and persistence through time. Its purpose is heuristic and experimental rather than predictive (Premo 2010; Cegielski and Rogers 2016).

The spatial environment is organized as a patch-based pond divided into village territories. Each patch carries values for *limu* and fish biomass, and each also belongs to a village zone. This territorial structure is important because it permits the model to represent localized claims and differential access within the fishpond system (Ostrom 1990). Human agents are assigned a home village and operate within a setting where territorial mismatch can impose

costs. This territoriality echoes the dissertation's broader argument that fishponds were not merely undifferentiated food pools, but managed landscapes structured by local rights, obligations, and social boundaries.

The model includes three types of human agents: cooperators, defectors, and enforcers. Cooperators harvest moderately and invest in maintenance. Defectors harvest more aggressively and do not contribute to upkeep. Enforcers harvest moderately while also patrolling for defectors and imposing sanctions at a cost to themselves. These agent types are not intended to map directly onto named historical offices or rigid social categories (Castillo and Saysel 2005; Janssen and Rollins 2012). Rather, they operationalize different strategic roles within a common-pool resource system. In HBE terms, they represent alternative behavioral responses to incentive structures (Winterhalder and Smith 2000; Janssen and Rollins 2012). In Ostromian terms, they represent the difference between contributors, free-riders, and monitors in a governed commons (Ostrom 1990; Castillo and Saysel 2005).

Ecological productivity is represented through two linked variables: *limu* and fish biomass. *Limu* is treated as the foundational productive layer because it supports fish biomass and can be enhanced through maintenance. This was a deliberate modeling decision (Klein et al. 2017). The dissertation has emphasized that Hawaiian fishponds were not simply fish storage facilities, but managed ecologies that relied on productive relationships among algae, shallow substrates, tidal exchange, and herbivorous fish (Kikiloi 2003). *Limu* therefore serves as the ecological base of the pond in the model (Odling-Smee, Laland, and Feldman 2003; Laland and O'Brien 2010). Fish biomass, in turn, represents the harvestable stock available to human agents. Rather than modeling fish as the primary resource entirely through free-moving individuals, the

model uses patch-based biomass to capture harvest dynamics more directly and to keep the focus on the human governance problem.

Environmental variability enters the model through two mechanisms: storm frequency and PDO-linked (Pacific Decadal Oscillation) productivity. Storms reduce *limu* and fish biomass, acting as episodic ecological shocks. The PDO phase alters the productivity regime, affecting *limu* growth over time. These variables were included because fishpond systems in Hawai‘i did not operate in climatological isolation (Klein et al. 2017). Windward O‘ahu environments are highly productive but are also shaped by storm runoff, freshwater inputs, suspended sediments, and broader hydrodynamic variability tied to tides, winds, and stream discharge (De Carlo et al. 2007; Möhlenkamp et al. 2018). The model, therefore, treats ecological productivity not as a fixed background constant but as something that can be dampened or enhanced by broader environmental conditions.

Seasonal governance is represented through a season-length parameter that controls the duration of open access before closures recur. This does not attempt to reconstruct a single historical calendrical regime at He‘eia, but it does formalize the idea that regulated access matters (Ostrom 1990; Schlüter and Pahl-Wostl 2007). A fishpond governed only by constant extraction is expected to behave differently from one in which access is periodically constrained. This aligns closely with Ostrom’s emphasis on clear rules and locally meaningful access controls.

Human reproduction threshold was included as a key parameter because early exploratory runs showed that demographic pacing strongly influenced system outcomes. Agents reproduce only when they accumulate sufficient energy, meaning that population growth is tied to successful use of the pond. This is analytically useful because it allows the model to track

whether a system is merely surviving, overshooting, or supporting sustained human persistence. In practice, the parameter proved to be one of the most important switches in the model (Castillo and Saysel 2005; Janssen and Rollins 2012). For source code of this cooperation model, see Appendix A.

The simulation program proceeded in two stages. Wave 1 served as an exploratory pilot and validation sweep. At that stage, three variables identified during calibration as particularly important were systematically varied: storm frequency, enforcement radius, and human reproduction threshold. Season length was held constant to isolate the strongest controls first. Wave 1 established that the model generated stable and interpretable regime differences rather than arbitrary noise (Premo 2010; Romanowska et al. 2019). Wave 2 then expanded the design into the main factorial experiment by adding season length as a fourth parameter. The full Wave 2 experiment varied storm frequency, enforcement radius, human reproduction threshold, and season length while holding the remaining parameters constant. BehaviorSpace in NetLogo was used to automate the runs, and named reporters were added to capture final human counts, strategy counts, persistence, defector elimination, mean *limu* and mean fish biomass, mean human energy, and the dominant social regime.

The resulting dataset was not the product of casual slider manipulation, but of a structured two-stage experimental design. Wave 1 established sensitivity and internal consistency. Wave 2 generated the main analytical dataset used in the discussion below. The three core visual outputs presented in this section summarize the most important outcomes: persistence rate by human reproduction threshold and season length, defector-elimination rate by enforcement radius and season length and mean final human population by storm frequency and reproduction threshold.

The simulations produced three broad classes of outcomes: collapse regimes, exploitative persistence regimes, and cooperative persistence regimes. These are more useful analytically than any single run, as they capture recurrent patterns across replicated parameter combinations rather than anecdotal cases (Premo 2010; Romanowska et al. 2019).

The first class consists of collapse regimes, in which the human population failed to persist to the end of the run. These outcomes were most strongly associated with low human reproductive thresholds and long season lengths. In practical terms, this means that when agents could expand too easily and when access remained open for extended periods, the pond system became fragile. In some combinations, humans overshot the system's productive capacity and then declined to zero, even though ecological variables did not necessarily disappear immediately. This is important because it suggests that model collapse is not simply a result of environmental scarcity (Schlüter and Pahl-Wostl 2007; Klein et al. 2017). It emerges when demographic pressure and permissive access outrun the ability of governance and maintenance to stabilize the system. Figure 39 makes this threshold especially clear: the lowest reproduction threshold combined with the longest season length consistently pushed the model toward failure.

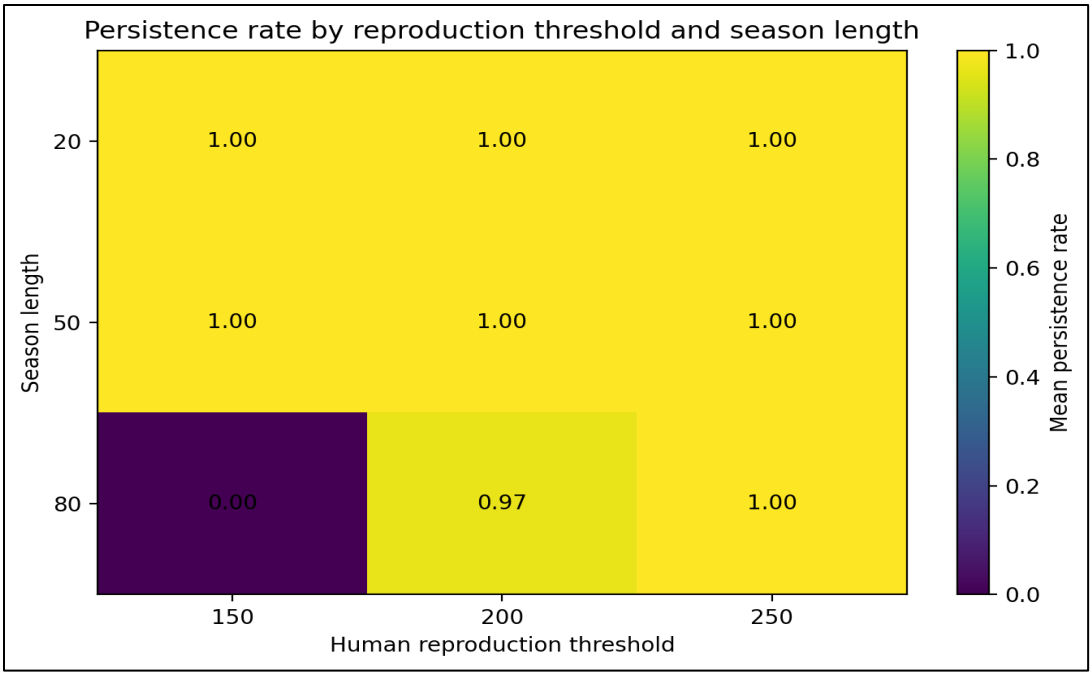

Figure 39. Persistence rate by human reproduction threshold and season length.

The second class consists of exploitative persistence regimes. These are especially visible at low enforcement radii. Under those conditions, human populations often persisted, sometimes at very high final totals, but defectors remained present and frequently dominated the system. From an archaeological perspective, this is a useful result because it separates persistence from resilience. A fishpond may continue to produce and sustain a population in the short to medium term without functioning as a well-governed commons. Low-enforcement conditions in the model create precisely this outcome: the system remains socially viable, but under a regime of aggressive extraction rather than regulated stewardship (Ostrom 1990; Castillo and Saysel 2005; Janssen and Rollins 2012). Figure 40 shows this clearly. Weak enforcement does not necessarily eliminate persistence, but it sharply reduces the elimination of defectors.

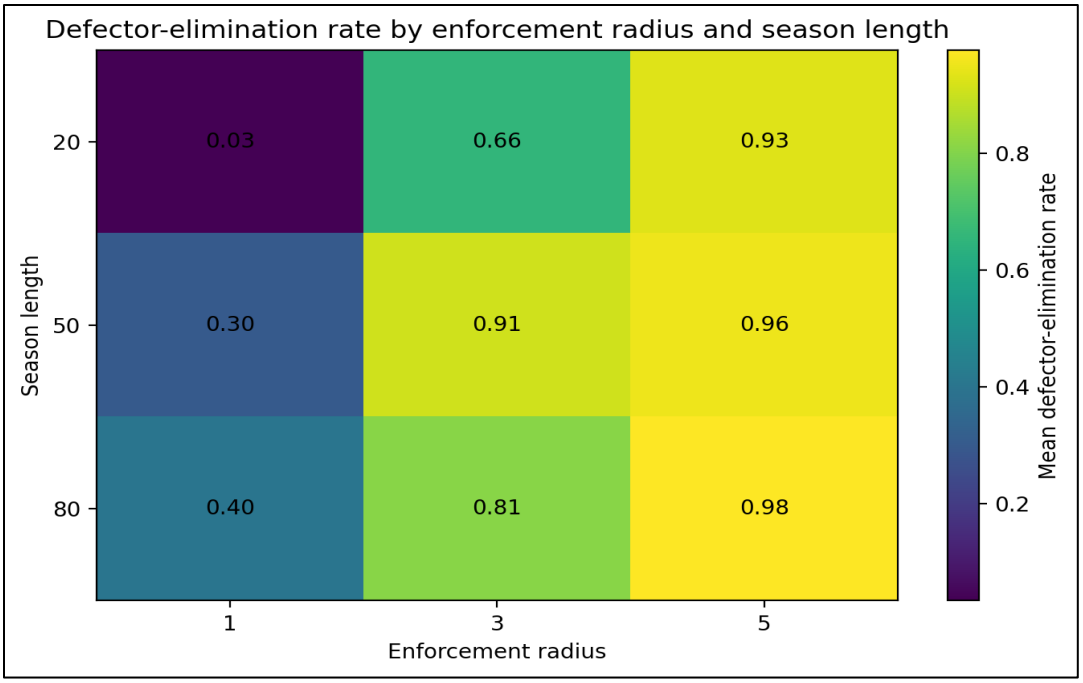

Figure 40. Defector-elimination rate by enforcement radius and season length.

The third class consists of cooperative persistence regimes. These are most strongly associated with higher reproduction thresholds and larger enforcement radii. In these cases, defectors are consistently suppressed, and end states are dominated by cooperators, enforcers, or mixed cooperator–enforcer systems. These regimes are especially important because they suggest that fishpond persistence in the model depends less on maximum extraction than on socially regulated extraction. In other words, the system persists not because agents harvest more aggressively, but because labor, sanctioning, and ecological maintenance sustain productivity over time (Ostrom 1990; Klein et al. 2017).

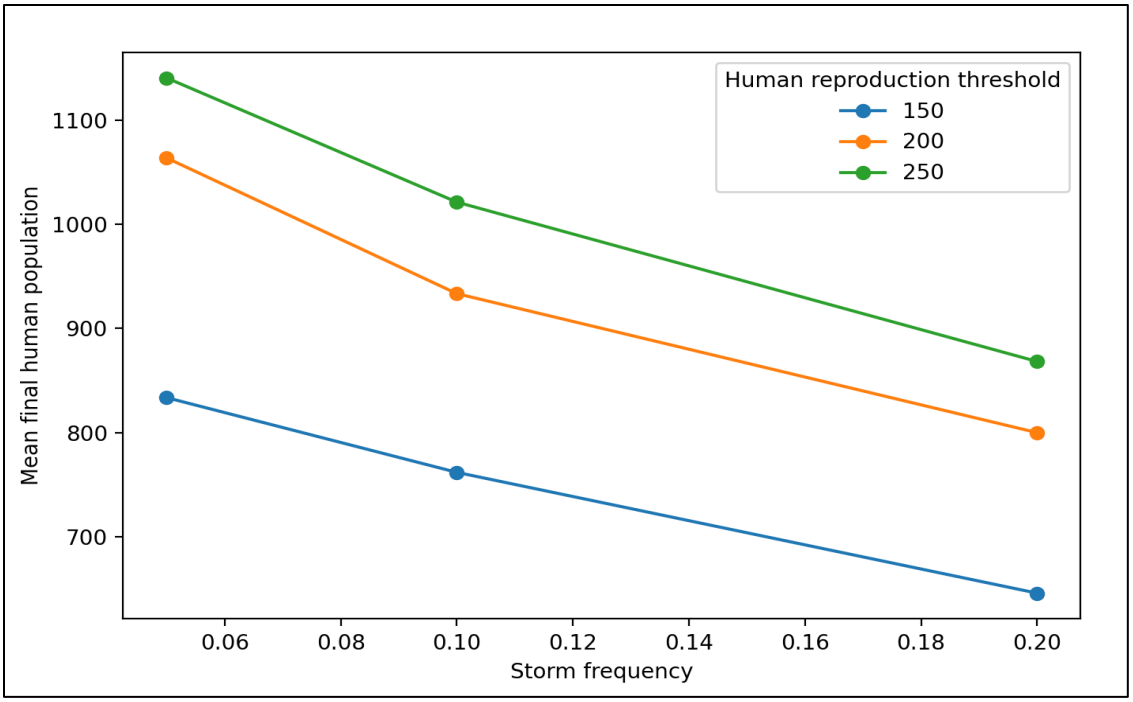

Figure 41. Mean final human population by storm frequency and human reproduction threshold.

6.4 Scenario Outcomes: Resilience, Yield, and System Failure

Storm frequency modifies these outcomes, as seen in Figure 41, but it does so differently from enforcement or the reproduction threshold. In the main Wave 2 dataset, higher storm frequency generally reduced final human population and dampened abundance, but it did not by itself force the system into collapse across all conditions. Figure 41 captures this pattern well. As storms become more frequent, the final human population tends to decline, yet the larger regime structure remains recognizable. This suggests that environmental disturbance primarily acts as a brake on abundance rather than as the sole determinant of success or failure (Klein et al. 2017; Schlüter and Pahl-Wostl 2007). Governance and demographic pacing mediate whether ecological shocks are survivable.

Season length proved more influential than expected. Short and medium season lengths often supported large, persistent populations and strong rates of defector elimination. By contrast, long season lengths produced smaller final populations and, in some parameter

combinations, allowed defectors to persist or return. This is analytically important because it indicates that long access windows are not automatically beneficial (Ostrom 1990; Owusu et al. 2021). In this model, prolonged opportunity to harvest does not produce a more stable commons. Instead, shorter or intermediate seasons seem to create conditions under which sanctioning and maintenance are more effective relative to extraction pressure (To et al. 2025).

These scenario outcomes support a view of fishponds as systems in which resilience emerges from the interaction of governance, ecological engineering, and demographic pacing. Abundance alone is not enough. Low disturbance and high productivity can coexist with defector dominance even when governance is weak. Conversely, the system can remain viable under environmental stress if social regulation is strong and population growth is paced. The principal parameter effects run in this model have been summarized in Table 9.

Inferential tests reinforced the descriptive patterns observed in the Wave 2 simulations. Chi-square tests showed that persistence was most strongly structured by human reproduction threshold and season length, with higher reproduction thresholds and shorter to intermediate season lengths producing substantially higher survival rates to 500 ticks. By contrast, enforcement radius and storm frequency were not significant predictors of persistence itself. A second set of chi-square tests showed that defector elimination was driven above all by enforcement radius, with larger enforcement radii dramatically increasing the frequency with which defectors were removed from the system; season length and human reproduction threshold also affected defector elimination, though the latter appears to do so partly through its relationship to broader system instability.

Table 9. Summary of principal parameter effects in the He‘eia-inspired fishpond model.

Parameter	Low setting outcome	Intermediate setting outcome	High setting outcome	Interpretive takeaway
Human reproduction threshold	Collapse-prone regimes; rapid demographic growth often outpaces governance and maintenance	Moderate persistence with smaller surviving populations	Strong persistence, often with larger oscillating populations	Demographic pacing is one of the strongest controls on resilience; systems become more stable when reproduction is slowed relative to ecological renewal
Enforcement radius	Defector-dominant persistence; exploitative strategies remain viable and often dominate	Transitional regime; some runs eliminate defectors while others retain mixed strategies	Cooperative persistence; defectors are consistently suppressed and cooperator–enforcer systems dominate	Governance strength determines whether the fishpond functions as an exploitative system or a regulated commons
Storm frequency	Larger final human populations and higher average abundance	Moderate final populations with continued persistence	Smaller final populations, but persistence often retained under strong governance	Environmental disturbance acts mainly as a brake on abundance rather than the sole cause of collapse
Season length	Large persistent populations and strong defector suppression	Large oscillating populations with durable governance	Smaller populations, increased fragility, and occasional defector return	Seasonal regulation shapes access pressure and can strongly influence long-term system balance

Finally, a linear model of log-transformed final human population showed that season length was the strongest predictor of final abundance, followed by human reproduction threshold, while enforcement radius and storm frequency were weaker in the main-effects model. Taken together, these results indicate that demographic pacing and seasonal structure largely determine whether the fishpond system persists and how large it becomes, whereas governance strength most strongly determines whether that persistence takes the form of an exploitative or cooperative commons. Summaries of these statistical tests can be found in Table 10.

Table 10. Summary of inferential tests for persistence, defector elimination, and final human population.

Outcome	Predictor	Test	Statistic	p-value
Persistence[1]	Human reproduction threshold	Chi-square	$\chi^2 = 190.45$	4.42×10^{-42}
Persistence[2]	Season length	Chi-square	$\chi^2 = 210.13$	2.35×10^{-46}
Persistence[3]	Enforcement radius	Chi-square	$\chi^2 = 0.22$	0.896
Persistence[3]	Storm frequency	Chi-square	$\chi^2 = 0.22$	0.896

Interpretations:
[1]Strong positive effect on persistence; higher thresholds greatly increased survival to 500 ticks
[2]Strong effect on persistence; long seasons sharply reduced survival
[3]No significant main effect on persistence itself

Outcome	Predictor	Test	Statistic	p-value
Defector elimination[1]	Enforcement radius	Chi-square	$\chi^2 = 336.01$	1.09×10^{-73}
Defector elimination[2]	Season length	Chi-square	$\chi^2 = 27.71$	9.62×10^{-7}
Defector elimination[3]	Human reproduction threshold	Chi-square	$\chi^2 = 60.46$	7.45×10^{-14}
Defector elimination[4]	Storm frequency	Chi-square	$\chi^2 = 0.58$	0.750

Interpretations:
[1] Strongest predictor of defector removal; higher enforcement strongly suppressed exploitative strategies
[2] Significant secondary effect on whether defectors persisted
[3] Significant effect, though partly mediated by broader system instability at low thresholds
[4]No significant effect on defector persistence

Outcome	Predictor	Test	Statistic	p-value
Final human population[1]	Season length	Linear model (log-transformed)	$F = 56.89$	1.51×10^{-15}
Final human population[2]	Human reproduction threshold	Linear model (log-transformed)	$F = 20.06$	1.19×10^{-7}

Final human population[3]	Enforcement radius	Linear model (log-transformed)	F = 0.26	0.771
Final human population[4]	Storm frequency	Linear model (log-transformed)	F = 0.15	0.857

Interpretations:
[1] Strongest predictor of long-term abundance
[2] Significant predictor of final population size
[3] No significant main effect on total final abundance
[4] Weak directional effect, but not significant in the main-effects model

6.5 Lessons on Governance, Resource Pressure, and Adaptability

The results speak most directly to three issues central to this dissertation: the role of governance, the importance of resource pressure, and the adaptive significance of fishpond maintenance as a form of niche construction. First, governance clearly matters. In the model, the enforcement radius is the strongest predictor of defector persistence. At low values, exploitative strategies remain viable and often dominant. At intermediate values, the system becomes contingent, sometimes eliminating defectors and sometimes not. At high values, defectors are consistently removed, and cooperative persistence becomes much more likely. This is one of the clearest Ostromian findings in the entire section. Monitoring and sanctioning do not merely improve an already stable system; they alter which strategies are evolutionarily and economically viable within it (Ostrom 1990; Castillo and Saysel 2005; Janssen and Rollins 2012). In that sense, governance is not an ornamental addition to fishpond productivity. It is constitutive of whether the fishpond functions as a managed commons at all.

Second, the model shows that resource pressure was partly demographic rather than purely environmental. Low reproduction thresholds produced fragile systems, while higher thresholds slowed growth enough for governance and maintenance to keep pace, reframing

fishpond resilience as a problem of paced returns rather than maximum extraction (Bird and O'Connell 2006; Winterhalder and Smith 2000).

Third, the model supports the argument that fishponds were forms of niche construction whose success depended on continual labor. When fish biomass was more tightly linked to limu, cooperative and enforcement-based strategies outperformed defectors, showing that human labor reshaped the conditions of production and fed back into the costs and benefits of different strategies (Odling-Smee et al. 2003; Klein et al. 2017).

The He'eia-inspired structure of the model also helps clarify a broader point about Hawaiian aquaculture. Fishponds were not merely elite symbols or static monuments, though they could certainly operate within the political economies of chiefly control (Kurashima and Kirch 2011). They were also governed working systems that had to absorb ecological variation, demographic pressure, and strategic conflict. The model suggests that durable pond management required more than abundant fish or ample labor. It required institutions capable of coordinating labor, restricting access when necessary, and maintaining ecological conditions that supported future yield (Ostrom 1990; Schlüter and Pahl-Wostl 2007). This result aligns with the dissertation's broader view of fishponds as productive monuments whose social significance was inseparable from their ecological function.

At the same time, the simulations complicate any simple claim that more governance always means less abundance. Under some parameter combinations, strong governance and short or medium season lengths produced very large populations. This suggests that regulated systems can outperform exploitative ones not only morally or normatively, but materially. That is a crucial point. In the model, cooperation is not maintained through altruism alone (Castillo and Saysel 2005; Janssen and Rollins 2012; Klein, Barbier, and Watson 2017). It can become a

higher-return strategy when ecological maintenance and enforcement preserve the pond's productivity.

6.6 Interpretations

The broader implication of this ABM exercise is that long-term sustainability in Hawaiian fishpond systems was likely contingent rather than automatic. The He‘eia-inspired model suggests that resilient aquaculture emerges where demographic growth is paced, maintenance remains continuous, access is regulated, and monitoring is strong enough to suppress exploitative behavior before it becomes system-dominant. Environmental shocks matter, but they do not determine outcomes on their own (Klein et al. 2017; Schlüter and Pahl-Wostl 2007). Their effects are filtered through social organization.

This reinforces a key argument of the dissertation: customary marine infrastructure should be understood not only as a technological adaptation to coastal productivity, but as a socially governed system of ecological engineering. The pond itself altered habitat and resource flow, but the durability of that transformation depended on institutions capable of reproducing labor and restraint over time. Seen in this light, Hawaiian fishponds become especially important examples of how common-pool resources can be intensified without collapsing into simple tragedy-of-the-commons models (Rankin et al. 2007; Ostrom 2008). Under the right conditions, the model shows that sanctioning, territoriality, and maintenance can support long-term persistence even in the face of storms, climatic fluctuations, and variable productivity.

The model is intentionally simplified, and its limits should be kept in view. It does not reconstruct the exact hydrology of He‘eia, represent the full range of species interactions in Hawaiian fishponds, or reproduce the historical complexity of Hawaiian political economy (Kirch 1990a; Kikiloi 2003; Paepae o He‘eia 2025). Its agents are stylized, and its spatial

environment is abstract. Even so, the model makes an important contribution. It clarifies mechanisms. It shows which parameters act as thresholds, which dampen abundance without necessarily causing collapse, and which determine whether cooperative governance is even possible. Most importantly, it bridges the dissertation's archaeological and theoretical arguments by placing labor, ecology, and institutions within a single experimental frame (Premo 2010; Cegielski and Rogers 2016).

In that sense, the ABM does not replace the archaeological record; it sharpens the kinds of claims that can be made from it (Romanowska et al. 2019). For a dissertation concerned with customary fishing structures as adaptive infrastructure, that is precisely its value. The He'eia-inspired fishpond model suggests that the long-term success of marine management systems depended less on static resource abundance than on recurrent social decisions about maintenance, access, and sanctioning. Sustainability, in other words, was not a background condition of these engineered seascapes. It was an achievement.

7. DISCUSSION

7.1 Customary Fishing Structures as Adaptive Marine Infrastructure

This dissertation began with three closely related questions: where are customary fishing structures are found in Remote Oceania, what do formal and functional characteristics reveal about how they operated, and which socioenvironmental conditions shaped their persistence or decline. When the analyses from Chapter 4-6 are read together, the clearest answer to those questions emerges when these features are understood not as isolated archaeological remains, but as forms of adaptive marine infrastructure. In both Fiji and Hawai‘i, customary fishing structures materially reorganized the relationship between people and nearshore coastal environments. They altered tidal flows, structured fish movement, fixed labor in place, and transformed sections of reef, estuary, or shoreline into more predictable zones of production. Yet they did not do so in the same way, at the same scale, or under the same social conditions.

That contrast is one of the dissertation's central findings. The Fijian *moka* documented in Chapter 4 represent a distributed and comparatively low-investment form of marine intensification. Their regional patterning suggests flexible adaptation to local coastal settings, especially in areas where lower rainfall and greater agricultural uncertainty increased the value of supplemental marine capture (Parry 1994; Field 2004; Cochrane 2018). By contrast, the Hawaiian fishpond case explored in Chapter 5 points toward a far more engineered and labor-intensive system, one capable of producing substantial and more predictable returns, but only through sustained construction, maintenance, and coordination of labor (Apple and Kikuchi 1976; Costa-Pierce 1987; Kurashima and Kirch 2011). The heuristic agent-based model in

Chapter 6 adds a third line of evidence by showing that these larger systems did not persist simply because they were productive. Their durability depended on governance, the pacing of demographic pressure, ecological maintenance, and the effective suppression of exploitative behavior (Ostrom 1990; Janssen and Rollins 2012; Schlüter and Pahl-Wostl 2007).

Seen together, these case studies suggest that customary fishing structures in Oceania were neither peripheral technologies nor static vestiges of local tradition. They were long-term investments in environmental predictability, food security, and sustainability. They transformed dynamic coastal settings into more structured and, under the right conditions, more reliable sources of protein. In that sense, the broader argument of this dissertation is that customary fishing structures should be understood as infrastructural solutions to island uncertainty. What varied across time and place was not whether island societies engineered marine space, but how they did so, with what labor demands, and under what political and ecological constraints (Kirch and Hunt 1997; Erlandson and Rick 2010; Laland and O'Brien 2010).

7.2 Fiji and the Logic of Distributed Intensification

My Fiji study provides the clearest regional answer to the first research question. The distribution of *moka* across the Fijian archipelago shows that these structures were far more numerous and widespread than has been assumed and that their occurrence was not random. Their concentration in drier areas, especially along northern and western coasts, supports Parry's (1994) suggestion that fish weirs became particularly important where agricultural productivity was less reliable. In practical terms, this suggests that *moka* were one means by which coastal communities buffered themselves against the unevenness of island production regimes. They were not simply opportunistic fishing devices placed wherever reef flats happened to allow it.

Their distribution implies patterned investment in marine capture where such investment offered clear adaptive value.

This matters because it shifts *moka* from the margins of interpretation into the center of subsistence strategy. Once mapped at a regional scale, they begin to read less like isolated local curiosities and more like a recurring response to environmental variability. In areas where rain-fed cultivation was less predictable, intertidal stone weirs provided a reliable way to capture marine protein with relatively modest daily labor once construction was complete. That does not mean every *moka* was identical in scale, ownership, or social meaning, nor does it justify a universal model for all of Fiji. It does suggest that these structures participated in what can reasonably be described as distributed intensification: a durable but comparatively decentralized investment in coastal productivity that did not require the same scale of engineering or political concentration seen in the Hawaiian case.

The Nananu-i-Ra data strengthen that interpretation. The repeated use of recognizable construction logics, including similar wall forms, orientations, and use of locally available stone, indicates that *moka* were not improvised one-off features. At the same time, local variation in layout and placement suggests flexibility rather than rigid standardization. That balance is important. It points to a shared technological tradition shaped by practical knowledge of tide, shoreline form, and available stone, but one that remained responsive to local coastal conditions rather than being imposed as a fixed template (Parry 1994; Cochrane 2018). In this sense, *moka* show how distributed infrastructure can remain technically coherent without being centrally standardized.

The spatial relationship between some *moka* concentrations and elevated fortified locations adds another layer to this interpretation. The dissertation has already treated this

evidence cautiously, and that caution remains warranted here. The presence of hilltop enclosures overlooking productive coastal zones does not by itself prove centralized ownership or direct elite administration of the weirs below. Chronology remains uncertain, and association is not equivalence. Even so, the repeated visual association between productive reef zones and elevated surveillance points suggests that access, visibility, and territoriality were not irrelevant to the operation of these seascapes (Field 2004). At minimum, the data imply that some *moka* were embedded within social landscapes in which marine productivity could be seen, monitored, controlled, and potentially contested.

That is a more defensible claim than a stronger argument for uniform elite control. One of the more important results of this dissertation is precisely its resistance to flattening all marine infrastructure into the same political model. The Fiji evidence does not support the conclusion that *moka* were simply small versions of Hawaiian fishponds or that they necessarily required chiefly coordination. Their comparatively simple construction suggests that many could have been built and maintained by smaller social units, including households, lineages, or village communities. Here, the analytical value of common-pool resource theory lies less in imposing a formal model than in clarifying the kinds of institutions such systems are likely to require. Durable weirs imply durable rules: who built them, who maintained them, who harvested from them, and under what circumstances those rights could be defended or shared (Ostrom 1990; Lam 1998). The archaeological record does not directly preserve those rules, but the visible persistence of *moka* implies that such institutional arrangements once existed.

The Fiji case, therefore, makes an important comparative point. Considered at the regional scale, *moka* suggest that substantial and enduring marine infrastructure can emerge through decentralized, repeated, and place-specific labor investments without requiring the same

level of political centralization evident in later Hawaiian aquaculture. In that sense, Fijian fishing weirs were not merely passive traps. They were adaptive infrastructure embedded in local tenure, environmental knowledge, and risk management. Their importance lies not in how closely they resemble more elaborate systems elsewhere, but in the distinct pathway they reveal: one in which coastal communities stabilized returns through distributed stone architecture and socially embedded marine access.

7.3 Hawai‘i and the Logic of Engineered Intensification

If Fiji demonstrates distributed intensification, the Hawaiian case demonstrates what intensification looks like when it becomes heavily engineered, materially costly, and deeply entangled with political economy. The He‘eia reconstruction data make this point forcefully. Even a modest section of *kuapā* required substantial labor, coordination, and technical judgment in the movement and placement of stone. Once those figures are scaled to the pond's full circumference, the resulting labor and energy estimates confirm what Hawaiian archaeology and ethnohistory have long suggested: major *loko i‘a* were not casual constructions. They were cumulative undertakings requiring organized work, sustained upkeep, and institutions capable of translating labor into enduring productive returns (Apple and Kikuchi 1976; Kamakau 1976; Costa-Pierce 1987; Graydon et al. 2007).

This case directly answers the second research question concerning the formal and functional characteristics of customary fishing structures. Hawaiian fishponds were not simply enlarged fish traps. Their walls, sluice systems, and enclosed habitats made them ingenious engineered aquatic landscapes. They altered fish behavior, protected growing stock, structured water movement, and converted sections of the nearshore into managed environments capable of

supporting predictable yields over time (Costa-Pierce 1987; Kikiloi 2003; Kurashima and Kirch 2011; Wyban 2020). This is an important distinction. It shifts interpretation away from seeing fishponds primarily as architectural features and toward understanding them as infrastructures of controlled productivity. Their significance lies not only in size but in the creation of managed ecological conditions.

At the same time, the discussion here deliberately pushes back against an overly simple monumental reading of Hawaiian fishponds. There is analytical value in recognizing their scale, visibility, and association with chiefly authority. Fishponds clearly participated in political economy, and their construction implies organization beyond the household level (Kirch 1990; Earle 1997; Kurashima and Kirch 2011; Hommon 2013). Yet to lean too heavily on monumentality risks misdescribing what made these structures distinctive. Their social power did not rest primarily in display, ritualized spectacle, or commemorative function. It rested in utility. Fishponds fed people, supported redistribution, and converted large labor inputs into sustained protein production. If they carried symbolic weight, they did so through their productivity as much as through their visibility.

For that reason, it is more useful to understand Hawaiian fishponds as concentrated productive power rather than monuments in any narrow sense. The *kuapā* was not merely a statement of authority; it was a working boundary that organized water, fish, labor, and rights. This also helps clarify the dissertation's position on top-down versus bottom-up development. The evidence does not support either extreme. Hawaiian fishponds cannot be reduced to purely elite-imposed constructions detached from local practice, but neither can the larger and more elaborate examples be understood as simple household initiatives. A more convincing interpretation is that fishpond systems developed along a continuum in which practical

experimentation, community-level food production, and elite incorporation interacted over time. Smaller and simpler systems may have emerged from local efforts to stabilize marine returns, while larger and more hydraulically elaborate ponds became increasingly tied to chiefly authority, territorial administration, and surplus mobilization (Dye 2010; Kirch 2010: Kelly 2025).

That reading fits the broader dissertation better than any single-origin model. It also aligns with the reconstruction results themselves. The lesson of experimental rebuilding is not merely that large and elaborate fishponds were difficult to construct. They required repeated social coordination to remain effective. A fishpond wall could be built once, but a functioning aquacultural landscape had to be maintained continuously. That distinction matters. It links construction to governance and helps explain why Hawaiian fishponds should be treated not simply as static remains of labor mobilization, but as long-lived working systems whose success depended on the reproduction of ecological knowledge, labor obligations, and managed access through time.

7.4 Governance, Persistence, and Comparative Synthesis

The heuristic ABM model in Chapter 6 was designed to address the dissertation's third research question by examining which socioenvironmental parameters most strongly shaped the resilience or decline of customary aquaculture systems. Its value is explanatory rather than predictive. The model does not reconstruct the full historical complexity of the He‘eia Fishpond, nor was that its purpose. What it does provide is a controlled way to isolate the interacting effects of governance, demographic pressure, ecological maintenance, and disturbance in a system inspired by Hawaiian fishpond management (Premo 2010; Romanowska et al. 2019; Cegielski

and Rogers 2016). In that sense, it sharpens the interpretive claims that can be made from the archaeological and experimental record.

The clearest result is that sustainability was not automatic. Productive infrastructure did not ensure persistence on its own. Systems endured when monitoring was strong enough to constrain exploitative behavior, when demographic growth was paced with the pond's productive capacity, and when maintenance reproduced the ecological conditions that made future harvests possible. This is one of the most important implications of the model because it reframes customary aquaculture as a governed achievement rather than a simple technical success. Fishponds did not persist merely because they were built. They persisted when they proved productive and social institutions kept them functioning as managed commons (Ostrom 1990; Castillo and Saysel 2005; Janssen and Rollins 2012).

Here, Ostrom's work is especially useful, though not sufficient on its own. The model shows with clarity that monitoring and sanctioning alter which strategies remain viable within a common-pool resource system. Weak enforcement allowed defectors to persist, while stronger enforcement made cooperative strategies more sustainable. That result is consistent with long-standing commons scholarship, but it also strengthens the comparative argument of this dissertation by showing why infrastructure and institutions must be discussed together. A wall without rules is not enough. A productive habitat without mechanisms of restraint remains vulnerable to social erosion no less than to storm runoff or sedimentation (Ostrom 1990; Schlüter and Pahl-Wostl 2007; De Carlo et al. 2007).



Figure 42. Photo of sluice gate (*mākāhā*) and guard house at He‘eia fishpond exemplifying the integration of monitoring systems in large-scale fishing management strategies. (Sailors 2014).

The model also reinforces a broader claim already suggested by the Hawaiian reconstruction: fishponds functioned as niche-constructing systems only so long as labor reproduced the conditions of their productivity. *Limu* management, wall upkeep, territorial structuring, and seasonal controls were not secondary details appended to an already finished system. They were the recurrent practices that turned one-time construction into a durable ecological advantage (Kikiloi 2003; Laland and O’Brien 2010; Zeder 2016). This is one of the strongest contributions of the modeling exercise. It makes visible the mechanism by which ecological engineering remains socially dependent. Customary aquaculture was not only a built environment, but it was also a built relationship between labor, regulation, and ecological feedback.

Taken together, the three case studies bring the dissertation's central argument into focus. Fiji and Hawai‘i occupied different positions along a continuum of marine intensification. Fiji's *moka* represent distributed, place-responsive, and comparatively low-investment infrastructure aimed at stabilizing access to marine foods across variable island environments. Hawai‘i's fishponds represent a more fully engineered and labor-intensive form of intensification in which managed aquatic space became increasingly tied to hierarchy, surplus production, and political coordination (Kirch and Sahlins 1992; Kirch and Green 2001). An important distinction, however, is that Fiji and Hawai‘i were colonized at very different times and under very different historical conditions. The more centralized forms of control that developed in Hawai‘i emerged within a relatively compressed timeframe of only a few centuries and should therefore be understood as historically contingent rather than as the inevitable outcome of a shared Oceanic trajectory. These are not two points on a simple ladder of progress, nor should one be treated as the incomplete version of the other. They are different solutions to related problems.

What converges across them is the underlying logic. In both settings, people materially modified coastal environments to regularize productivity and reduce uncertainty. In both settings, fishing structures embodied delayed-return strategies in which labor invested in stone, placement, and maintenance generated benefits over time rather than immediately. In both settings, those benefits were inseparable from questions of access, governance, and the reproduction of ecological conditions. The technologies, scale, and political implications differed, but the infrastructural principle remained comparable: coastal societies reshaped marine space so that it would yield more predictably than it otherwise would (Kirch and Hunt 1997; Erlandson and Rick 2010).

This, in turn, helps answer the dissertation's research questions without merely repeating them. The first question, concerning distribution, is answered by showing that fishing structures in Fiji were widespread, patterned, and linked to ecological variability rather than random placement alone. The second, concerning form and function, is answered by demonstrating that customary fishing structures ranged from distributed tidal weirs to heavily engineered aquacultural systems, each with distinct labor requirements and sociopolitical implications. The third, concerning socioenvironmental parameters, is answered by showing that persistence depended not only on productivity or environmental setting, but on human institutions capable of pacing extraction, organizing maintenance, and constraining short-term exploitation. These answers are not separate. Together, they show that customary fishing structures in Remote Oceania were regionally varied, socially embedded, and fundamentally infrastructural.

More broadly, this dissertation contributes to Pacific archaeology by resisting two recurring distortions. The first is the tendency to marginalize marine infrastructure relative to agriculture, architecture, or exchange when discussing intensification and social complexity. The second is the tendency to assume that durable infrastructure necessarily signals the same kind of political formation everywhere it appears. The comparative evidence here suggests otherwise. Marine intensification took multiple forms in Oceania. Some were decentralized and widely distributed. Others were tightly engineered and politically integrated. What united them was not a single institutional template, but a shared commitment to making coastal productivity more accessible and dependable through built interventions in dynamic seascapes.

In that sense, customary fishing structures should not be treated as peripheral curiosities. They are central evidence for how island societies organized labor, structured access, and invested in future returns. They reveal that marine management in Oceania was not simply

reactive or extractive. It was constructive, cumulative, and at times highly sophisticated. The archaeological record of stone weirs and fishponds is therefore also a record of how Pacific peoples converted uncertainty into infrastructure.

8. CONCLUSION

8.1 Summary of Findings

In this dissertation I have argued that customary fishing structures in Remote Oceania should be understood not as marginal curiosities or merely localized subsistence devices, but as durable forms of engineered socioecological infrastructure. Across Fiji, Hawai‘i, and beyond, such features materially expressed long-term efforts to reorganize coastal space, channel ecological productivity, and stabilize access to marine resources under variable environmental and social conditions. Read at this scale, they reveal that Indigenous Pacific communities did not simply harvest naturally occurring abundance. They built, maintained, modified, and governed productive seascapes through cumulative labor, technical knowledge, and historically situated institutions of cooperation (Kikuchi 1976; Rogers and Weisler 2024).

One of the central findings of this study is that customary fishing structures are best interpreted as socioecological systems rather than as isolated artifacts or site types. Their significance lies not only in their architecture, distribution, or morphology, but in the relationships they materialized among labor, marine ecology, tenure, governance, and local environmental knowledge (Rogers 2024). This point emerges most clearly when the Fijian spatial analysis, the Hawaiian feature replication work, and the agent-based modeling are considered together as complementary parts of the narrative, rather than as separate exercises. Viewed in combination, these components demonstrate that the archaeology of fishing structures is not simply about stone alignments, walls, or traps. Instead, it is about how communities

organized themselves around recurring ecological opportunities and constraints, with those arrangements becoming durable in the landscape and seascape over time (LeFebvre et al. 2022).

A second major finding is that these structures illuminate forms of marine management rooted in cooperation rather than simple extraction. This does not mean all such systems were uniformly egalitarian, harmonious, or insulated from hierarchy. It means that their persistence depended upon patterned forms of coordination, maintenance, timing, access control, and ecological attentiveness (Johannes 1978; Nunn et al. 2024). Whether in the context of Fijian weirs or Hawaiian fishponds, the archaeological record points toward infrastructures whose productivity was inseparable from social rules and collective practice. The dissertation's modeling work reinforces this interpretation by showing that productive aquatic ecosystems- whether natural or constructed by humans- are not shaped solely by environmental factors. Their long-term outcomes depend heavily on active management: enforcement, harvesting norms, demographic pacing, and feedback between ecological abundance and social behavior (Jokiel et al. 2011; Innes-Gold et al. 2025).

This matters because it places customary fishing structures within broader archaeological debates about commons governance, resilience, and niche construction. The evidence assembled here supports the view that marine infrastructure in Oceania was often neither a passive reflection of environmental conditions nor merely a byproduct of elite ambition. Rather, it was one medium through which communities actively reshaped ecological relations and negotiated the terms of use, maintenance, and benefit (LeFebvre et al. 2022). Such systems were productive and sustainable over the long haul precisely because they were social as well as environmental. The walls, sluices, embankments, and tidal barriers at the center of this dissertation should

therefore be read as material traces of recurring decisions about how to distribute effort, manage uncertainty, and convert local knowledge into durable resource strategies (Johnson et al. 2016).

A third broad finding concerns the mutual constitution of labor, ecology, and social organization. The reconstruction work at He‘eia helps clarify that fishing structures were not lightweight or incidental constructions. They demanded repeated work, familiarity with stone and hydrology, knowledge of seasonality and current, and a willingness to sustain collective effort beyond a single moment of construction. At the same time, such labor was not simply “cost” in the abstract. It was a mode of environmental investment that altered habitat, circulation, and species availability in ways that could produce future returns (Kikuchi 1976; Costa-Pierce 1987). This is one reason the dissertation treats these features as infrastructure rather than static monuments. Their significance lies as much in what they enabled over time as in their construction. The engineering of walls and enclosures was simultaneously an ecological intervention, social coordination, and future-oriented planning.

Taken together, these findings contribute to archaeology more broadly by demonstrating that small islands and coastal systems are not peripheral case studies, but analytically powerful contexts for examining long-term human adaptation (LeFebvre et al. 2022; Fitzpatrick et al. 2024). Island settings often make relationships among scarcity, abundance, isolation, mobility, and ecological engineering unusually visible (Vitousek 2002; DiNapoli and Leppard 2018). In that sense, the fisheries and fishponds examined here do more than fill a regional gap. They sharpen wider archaeological conversations about infrastructure, collective action, production, resilience, and sustainability. As island archaeology increasingly engages questions of climate stress, social resilience, and environmental transformation, customary fishing structures offer an

especially valuable record of how people engineered productivity under dynamic coastal conditions (Johnson et al. 2016).

At the same time, the bridge from the past to the present should be made carefully. This dissertation does not claim that premodern Pacific systems offer a simple blueprint for contemporary sustainability. The social, demographic, legal, and climatic conditions of the twenty-first century differ in important ways. What the archaeological record can offer is a broader archive of tested human responses to ecological variability. It shows that sustainability was not an abstract principle imposed from outside, but often a practical outcome of long-term observation, cumulative labor, and institutions calibrated to local conditions. In that respect, the study of customary fishing structures is relevant not only to Pacific archaeology but also to contemporary conversations about resilience, food security, marine stewardship, and the value of historically grounded local ecological knowledge (Johnson et al. 2016; Nunn et al. 2024; Fitzpatrick et al. 2024; Innes-Gold et al. 2024).

8.2 Limitations

Like any comparative archaeological project, this dissertation is constrained by the quality, scale, and unevenness of its evidence. The arguments advanced here are therefore strongest when read as a synthesis of converging lines of evidence rather than as a claim to total explanatory closure. Several limitations deserve explicit attention, not because they overturn the dissertation's core conclusions, but because they define the boundaries within which those conclusions should be understood.

One limitation concerns scale, aggregation, and spatial framing. The spatial patterns discussed in this dissertation are inevitably shaped by the areal units through which data are

grouped, mapped, and compared. This is the classic modifiable areal unit problem, in which results can shift depending on the scale of aggregation and the boundaries imposed on a dataset (Openshaw 1984). In archaeological terms, this means that clusters, absences, and apparent regional patterning may reflect not only past human behavior, but also the structure of the analytical container through which those behaviors are rendered legible. This issue is especially relevant in a project that compares archipelagic units such as Fiji and Hawai‘i while working across site-, island-, and regional scales. Modern political or island-group boundaries are convenient tools for scholarship, but they may be poor proxies for the social and ecological worlds through which past communities moved and interacted (Fotheringham and Wong 1991).

Second, the dissertation’s regional comparison does not erase the fact that Fiji and Hawai‘i are not equivalent cases. They differ geomorphology, hydrology, reef structure, biodiversity, the chronology of human colonization, sociopolitical history, and regional connectivity. Their comparison is analytically productive because both archipelagos preserve strong evidence of coastal engineering and marine management, not because they followed the same historical trajectory (Field 2005; Kirch 2007). Any comparative synthesis across them must therefore resist flattening difference into analogy. Patterns that appear similar at the level of structure form or broad function may have emerged from distinct political economies, local ecologies, and historical sequences. The dissertation has treated comparison as a heuristic rather than a deterministic approach, but this remains a genuine limitation. Similar forms need not imply identical institutions, and convergent infrastructure does not necessarily imply convergent social worlds (Braje et al. 2017).

A third major limitation concerns the use of ethnographic analogy and historical inference. This dissertation, like much Pacific archaeology, necessarily relies in part on

ethnographic and ethnohistoric materials to interpret the operation, meaning, and governance of customary fishing structures. That move is defensible, but it is not without risk. Ethnographic analogy has a long and contested history in archaeology precisely because continuity cannot simply be assumed (Currie 2016). Later observations may preserve important institutional or technical residues from earlier times, but they may also reflect transformed political economies, colonial disruption, shifting symbolic meanings, or local improvisations specific to a later period (Shelley 1999). The direct historical approach is therefore most persuasive when treated as a configurational and context-bound inferential strategy rather than as a straightforward bridge from the ethnographic present to the archaeological past. Ethnography can constrain interpretation and sharpen hypotheses, but it cannot dissolve the problem of historical distance (Cunningham 2018).

This caution is warranted here because some of the dissertation's strongest interpretive claims concern governance, tenure, maintenance, and ecological knowledge. These are precisely the domains where continuity is tempting to assume and difficult to prove. To infer past management regimes from later ethnographic records requires more than cultural resemblance. It requires attention to the conditions under which a given analogy is licensed, the material correlates that strengthen it, and the alternative explanations that remain plausible. In that sense, ethnographic evidence is most useful not when it is asked to provide certainty, but when it is used to narrow a range of possibilities and guide historically grounded interpretation (Shelley 1999; Currie 2016).

A fourth limitation is the problem of shoreline change, sea-level drawdown, and archaeological visibility. Many customary fishing structures exist in intertidal and nearshore settings that are inherently dynamic. Relative sea-level change, tectonics and isostasy,

sedimentation, reef development, erosion, and progradation all affect where such features survive and how they appear today. Research from Pacific islands has shown that coastal plain stratigraphy and changing relative sea levels can significantly reshape shoreline habitability and the preservation context of coastal features (Kane et al. 2017). The implication is straightforward: the present distribution of visible fishing structures is unlikely to represent the full historical distribution of such systems. Some features may now be submerged, buried, displaced, destroyed, or rendered archaeologically ambiguous by later geomorphic change (Easton et al. 2021; Iwabuchi 2022).

This problem is not merely one of site loss. It also affects interpretation. Paleoshoreline change can distort assessments of function, access, species targeting, and settlement association. A wall or trap identified today as marginal, anomalous, or poorly placed may have occupied a very different ecological setting at the time of use (Iwabuchi 2022). Likewise, the apparent absence of structures in a given coastal sector may reflect preservation history rather than a meaningful prehistoric choice. These issues are especially significant in comparative work, where coastal change has not occurred evenly across islands or through time. For a dissertation concerned with adaptive infrastructure, this means that some of the very systems under study may be selectively invisible in the current record (Reeder-Meyers et al. 2015; Kane et al. 2017).

A fifth limitation concerns chronology, which remains one of the most stubborn problems in the study of customary stone fishing structures. Stone walls, coral fill, and intertidal settings often yield few secure samples for direct dating (Burney and Burney 2003). Conventional radiocarbon methods are frequently hampered by the scarcity of short-lived terrestrial organic matter, while shell-based chronologies introduce reservoir effects that can be difficult to resolve cleanly across the Pacific (Reimer et al. 2020). Petchey's work makes clear that marine reservoir

offsets in the South Pacific are variable and historically dynamic, which complicates efforts to convert shell ages into robust archaeological chronologies without careful regional correction (Petchey 2020; Petchey et al. 2023). Burney and Burney's (2003) work on Kaua'i is valuable precisely because it shows how difficult it can be to link broader environmental change and human activity to clean chronological markers even in well-studied island settings. In short, the dating problem is not peripheral. It limits how confidently archaeologists can sequence construction, reuse, abandonment, and regional comparison (Petchey and Schmid 2020).

A sixth limitation lies in the use of modeled systems, particularly agent-based models. The ABM in this dissertation was designed as a heuristic instrument for exploring how governance strength, seasonality, demographic pacing, and ecological feedback might shape the resilience or failure of fishpond-like systems. Its value lies in clarification and experimentation, not in exact historical reconstruction. Like all models, it simplifies. It compresses social heterogeneity, reduces institutional ambiguity to tractable variables, and treats key ecological and behavioral processes as parameterized relationships. This is useful for asking structured questions, but it also means that modeled outcomes are sensitive to assumptions, parameter choices, and simplifications embedded in the design. Different settings, rules, or initial conditions can yield different emergent patterns, and no simulation can fully reproduce the historical thickness of actual communities (Lake 2014; Romanowska 2015).

This limitation does not make the model trivial; it defines its proper use. The strongest contribution of the ABM is not that it "proves" what happened in any single fishpond, but that it demonstrates how certain variables plausibly interact and why governance cannot be treated as analytically secondary to ecology. Still, a skeptical reader would be right to ask whether alternative parameterizations might generate other equally plausible trajectories. That concern is

legitimate. Modeled systems are at their best when they are used to pressure-test arguments and expose conditional dynamics, not when they are mistaken for direct evidence of the past (Brouwer Burg et al.2016; Schill et al. 2016).

Finally, several additional constraints hover over the project as a whole: preservation bias, detection bias, and equifinality. Some features are easier to identify than others. Some coasts have been more heavily surveyed than others. Similar architectural or spatial patterns may arise from different historical processes. Equifinality remains a central problem in archaeology because multiple pathways can lead to similar material outcomes (Rogers 2000; Heilen and Cruz 2023). A given wall may index cooperative management, elite control, ad hoc opportunism, or some mixture that changed through time. The dissertation has argued for the most plausible readings given the evidence available, but that evidence does not eliminate every competing interpretation. That is precisely why limitations matter. They do not nullify the project. They keep it honest, bounded, and open to refinement (Graesch 2009).

8.3 Future Directions

If one unresolved issue rises above the others, it is chronology. Without stronger chronological control, many of the most important questions in the archaeology of Pacific Island customary fishing structures remain only partially answerable: when such systems first emerged, how quickly they expanded, whether they proliferated in pulses or gradually, how long individual features remained in use, and how infrastructural intensification related to demographic, political, and climatic change. For that reason, future work in this field should not treat dating as a technical afterthought. It should treat chronology as the central research frontier

around which the next phase of customary fishing structure studies in the Pacific is organized (Lucas 2008, 2024).

The most promising near-term avenue, in my view, lies in the more systematic archaeological use of *Halimeda spp.* and related calcareous algae for radiocarbon dating in coastal and intertidal contexts. Carson and Peterson (2012) showed that direct radiocarbon dating of *Halimeda* bioclasts from Guam could yield age estimates that were archaeologically meaningful in beach-site contexts, opening the door to a class of materials long present in tropical coastal sediments but underused in archaeological dating strategies (Carson and Peterson 2012). This matters because customary fishing structures are frequently built in precisely the kinds of carbonate-rich littoral environments where traditional charcoal-based chronologies are difficult to obtain. If carefully sampled and contextually controlled, algal bioclasts may provide one of the most practical ways to move beyond the persistent chronological impasse that has constrained research on fishponds, weirs, and other stone-built marine features (Carson and Peterson 2012).

Carson and Peterson's approach begins with the recognition that beach and lagoonal sediments in many Pacific island settings contain abundant calcareous algal fragments, especially Halimeda spp., that can be dated directly by radiocarbon if they are recovered in the right condition and interpreted in relation to site formation. Their method therefore has two linked steps. First, they isolate intact, non-eroded bioclasts, because fresh-edged fragments are more likely to represent deposition close to the time of algal death, whereas rounded or abraded pieces may have been reworked and redeposited after an unknown interval. In this sense, the distinction between eroded and non-eroded algae is critical, since relatively unabraded bioclasts are more likely to be in situ or near-primary deposits, while eroded fragments suggest disturbance,

transport, or secondary redeposition prior to burial. Second, they interpret those dated bioclasts contextually, not as stand-alone ages, by asking whether the algal deposit lies within, below, or above the archaeological layer or feature of interest. In this way, the radiocarbon age of the calcareous algae can establish a relative chronology for the associated archaeology: bioclasts incorporated directly within a cultural layer may date that depositional event closely, bioclasts beneath a feature provide a terminus post quem for construction or occupation, and bioclasts overlying a feature provide a terminus ante quem or later bracketing age for burial and landscape change. Carson and Peterson also stress that marine calibration is essential, since the carbon in Halimeda derives from seawater rather than terrestrial reservoirs; accordingly, they apply local marine reservoir correction and compare algal dates against associated archaeological layers and other materials to evaluate accuracy. The strength of the method, then, is not simply that it dates algae, but that it uses carefully selected algal bioclasts as stratigraphically sensitive markers for bracketing the age of archaeological deposits and coastal features in settings where charcoal or other conventional samples are absent (Carson and Peterson 2012).

I am not suggesting that *Halimeda* itself constitutes a universal chronological solution. Rather, the more important point is that the methodological use of calcareous algal bioclasts as datable material deserves broader archaeological attention than it has received. Context, taphonomy, redeposition, and reservoir effects still matter, and any application of this approach must be carefully evaluated within local depositional and marine conditions (Petchey 2020). Yet in a field where the scarcity of directly datable material has repeatedly constrained interpretive progress, the development of a more systematic dating methodology centered on *Halimeda* and related calcareous algae may offer one of the most promising near-term avenues for improving chronological control. Its significance lies not simply in the possibility of dating fishing

structures, but in the broader methodological potential to refine chronologies for stone-built archaeological features in carbonate-rich coastal settings, and perhaps in some lacustrine environments where comparable depositional conditions apply (Riet and Cochrane 2018). In that sense, the promise of this approach is methodological as much as material: it opens a new line of chronological inquiry that extends beyond the immediate dissertation while remaining grounded in the archaeological problems identified here (Carson and Peterson 2012).

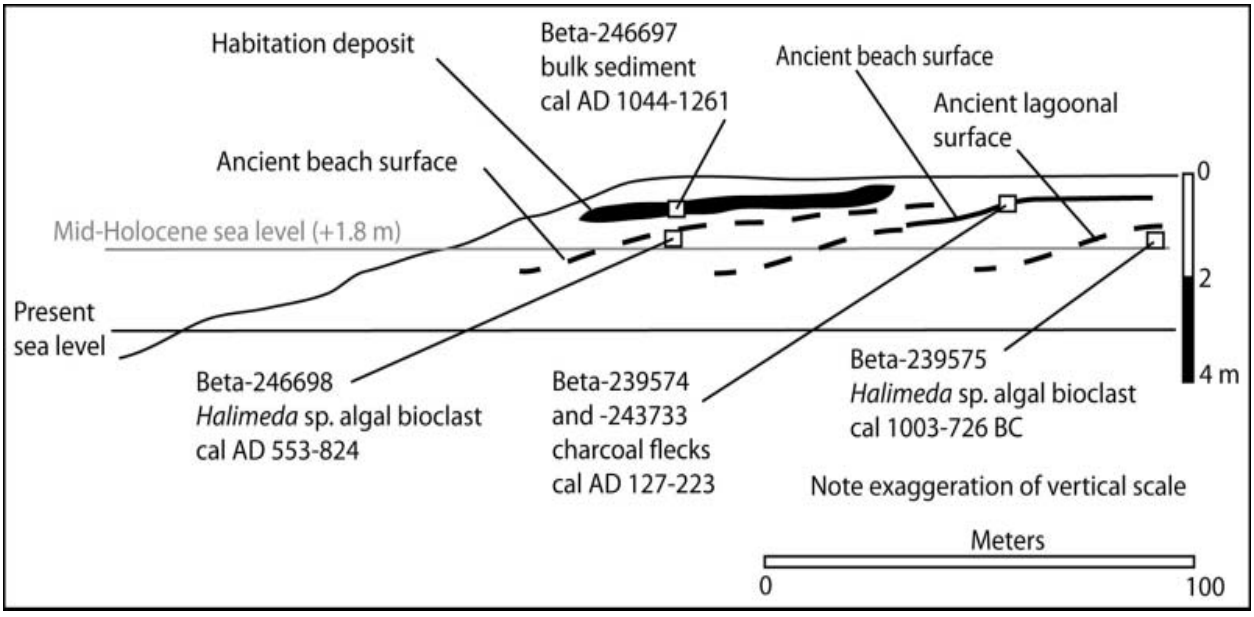

Figure 43. Illustration showing method (Carson et al. 2012) for establishing relative chronology of cultural material in a coastal setting using algal bioclasts deposited on beach.

This is one reason I suggest that customary fishing structures could become a major comparative laboratory for archaeological science (LeFebrvre et al. 2022). The field remains under researched relative to its potential. Stone-built coastal features are widespread, difficult to date, and deeply entangled with local ecology. They therefore offer unusually strong proving grounds for integrated methods that combine targeted sampling, geochronology, paleoenvironmental reconstruction, and explicit contextual reasoning (Alexandrakis et al. 2021). In that sense, the future of this research area is not only regional. It is methodological. The

challenge of dating marine infrastructure may help develop tools and protocols relevant to coastal archaeology more broadly.

Comparative work from outside Oceania strengthens this claim. Lepofsky and colleagues' work on Northwest Coast clam gardens is especially important because it demonstrates that Indigenous maricultural systems can be recognized, dated, and interpreted as long-term engineered environments rather than as ephemeral or purely opportunistic harvest aids. Their study combined Indigenous ecological knowledge, archaeology, and geomorphology to document rock-walled shellfish mariculture and establish its antiquity, thereby reshaping how archaeologists think about non-agricultural food production and marine landscape modification Later work on clam gardens has pushed this further, including the use of optical dating methods to constrain wall construction and sedimentary changes where conventional organic material is sparse (Lepofsky et al. 2015, 2021). Optically stimulated luminescence (OSL) dating, a technique used in the PNW, estimates the last time mineral grains, usually quartz or feldspar, were exposed to sunlight before burial, making it especially useful in contexts where datable organic material is absent or poorly preserved. In intertidal settings such as clam gardens and many customary fishing structures, OSL can help date sediments associated with wall construction, infilling, or shoreline modification, thereby providing a way to build chronologies for rock-walled features that are otherwise difficult to place in time (Neudorf et al. 2017). For the purposes of Oceanic archaeology, the lesson is clear: rock-walled intertidal features that once seemed chronologically intractable can, with the right methods, be brought into much sharper temporal focus (Neudorf et al. 2017; Lepofsky and Salomon 2023).

This is where dating *Halimeda sp*. becomes especially exciting. In the Pacific Northwest, different materials and geomorphic settings have guided the dating of clam gardens. In tropical

Pacific archipelagos, however, calcareous algae may offer a more regionally appropriate route (Carson and Peterson 2012). That possibility deserves a coordinated research agenda: controlled sampling of algal bioclasts from dated and undated structures; comparison with other available materials; evaluation of redepositional risk; and explicit attention to reservoir offsets and local calibration issues (Petchey 2020). Although Bayesian chronological modeling is not central to this dissertation, even a light engagement with the literature suggests that the interpretive value of new dates would be significantly improved if future projects paired better samples with more robust chronological modeling and reservoir-correction protocols (Bronk Ramsey 2009; Bayliss 2015).

Halimeda also matters beyond dating because its calcified segments become part of the broader bioclastic sediments that build and record tropical coastal environments. As a major producer of calcareous sediment in reef settings, *Halimeda* contributes to carbonate budgets, sediment generation, and in some cases the maintenance of shoreline-forming or shoreline-protective systems (Woodroffe 2003). Once deposited, those algal fragments can do more than provide datable material: they can also function as sedimentary indicators of coastal processes and as components of paleoenvironmental archives. Research on *Halimeda* bioherms shows that such deposits can preserve signals of nutrient supply and Holocene oceanographic change, while sedimentological research demonstrates more broadly how bioclastic and carbonate-rich deposits can be read stratigraphically to reconstruct marine flooding, tidal deposition, and shifting coastal settings (McNeil et al. 2021; O'Connell et al. 2021; Dorsey et al. 2023). For my research, that convergence is especially important. In customary fishing structures and other stone-built littoral features, Halimeda-derived bioclasts may serve not only as chronological markers, but also as

evidence for the depositional histories, environmental conditions, and shoreline dynamics within which those structures were built, used, and later buried or reworked.

A second major future direction is the expansion of submerged and paleoshoreline archaeology. If shoreline change has hidden part of the record, then the next generation of work cannot remain confined to the modern visible coast (Woodroffe and Murray-Wallace 2010). Research on Pacific coastal evolution and submerged archaeology makes it increasingly clear that dynamic shorelines have altered the visibility and context of human coastal infrastructures over time (Kane et al. 2017; Easton et al. 2021; Iwabuchi 2022). Future work should therefore integrate paleoshoreline modeling, underwater or nearshore survey, and geomorphological reconstruction more systematically into the study of customary fishing structures. This is not merely a preservation exercise. It is necessary for reconstructing the full spatial and functional range of marine management systems that were built in settings where coastlines have migrated, prograded, drowned, or been reworked (Monteleone et al. 2013; Robles-Montes 2024). That agenda could also support better predictive archaeological modeling. Once researchers know more about where datable calcareous deposits, preserved wall features, or stable paleoshoreline contexts are likely to occur, predictive models could help prioritize future fieldwork. Rather than treating coastal archaeology as a largely reactive enterprise, researchers could identify high-probability sectors for chronology-building, submerged-feature detection, and comparative testing. In tropical island contexts where survey resources are often limited, that would be an important practical gain (Giatsiatsou 2024).

A third future direction is to expand the comparative Pacific dataset. The archaeology of customary fishing structures remains uneven across the region. Hawai‘i and Fiji are vital case studies, but they are not the whole story. There is a strong reason to extend similar lines of

inquiry to other archipelagos where stone tidal weirs, fish traps, and related marine infrastructures remain understudied or under integrated into wider archaeological debate (Malindine 2019). Such work would help move the field away from isolated case reports and toward a broader comparative framework capable of asking when, where, and under what conditions coastal engineering became socially central. It would also improve our ability to distinguish local innovation, regional convergence, and historically contingent trajectories of marine intensification (Roberts 2015).

A fourth and equally important direction is the deeper integration of local ecological knowledge, Indigenous collaboration, and biocultural restoration into future research design (Berkes 1993; Berkes et al. 1994; Silvano and Valbo-Jørgensen 2008). The most productive future for this field will not come from archaeology working alone. Johnson and colleagues (2016) have argued persuasively for weaving Indigenous and sustainability sciences together to diversify methods and improve resilience-oriented research. Recent work on Pacific traditional knowledge and climate resilience likewise shows that place-based knowledge systems remain vital resources for adaptation, stewardship, and environmental planning in island contexts (Nunn et al. 2024). For the archaeology of customary fishing structures, this means that interpretation, restoration, survey priorities, and even dating strategies should be developed in partnership with communities who continue to work with, care for, and think through these coastal systems in the present.

This leads directly to heritage stewardship and restoration, which should stand not at the margins of future research but near its center. Restoration initiatives are already showing that fishponds and related marine infrastructures are not only archaeological subjects; they are living sites of education, food production, cultural renewal, and environmental intervention. At He‘eia,

modern restoration demonstrates that fishponds can still function as places where ecological care, historical learning, and community revitalization meet (Paepae o He‘eia 2025). Recent research further suggests that restored *loko i‘a* can increase fish density, supplement surrounding fisheries, and, under some scenarios, help mitigate some climate-related stresses through nutrient restoration and other forms of biocultural management (Innes-Gold et al. 2024; Innes-Gold 2025). That combination of cultural continuity, ecological benefit, and practical stewardship is precisely why restoration should be understood as both a research frontier and a social one.

8.4 Concluding Statement

The deeper lesson of this dissertation is that history is one of the wellsprings from which futures are drawn. The archaeological record does not offer a ready-made manual for the present, and it should never be romanticized into one. But it does preserve a long archive of human experimentation with resource stress, ecological uncertainty, collective labor, infrastructural problem-solving, and cultural persistence (Schroeder and White 2024). Customary fishing structures in Oceania matter because they show that communities facing dynamic coastal conditions did not merely endure them; they actively shaped them. They learned, adjusted, engineered, cooperated, and built institutions around them. In that sense, these structures are not just remnants of subsistence. They are records of resilience (Malindine 2019; Fitzpatrick 2020; Fitzpatrick et al. 2024).That is why the combination of archaeology and local ecological knowledge is so powerful. Archaeology offers depth in time, material patterning, and the ability to trace long-term change. LEK brings place-based experience, continuity of observation, practical insight, and forms of understanding that do not survive fully in stone alone (Sobrevila 2008; Aswani 2018). Neither mode of knowledge is sufficient on its own to address the

challenges ahead. Together, however, they widen the field of what can be known about sustainability, risk, stewardship, and adaptation. Johnson and colleagues describe this as a weaving of Indigenous and sustainability sciences; the phrase is apt because it implies not fusion into sameness, but collaboration without erasure (Johnson et al. 2016; Nunn et al. 2024).

Modern efforts at He‘eia Fishpond show what this kind of collaboration can look like in practice. Paepae o He‘eia’s long-running work to rebuild the wall, care for the pond, and connect restoration to community programs demonstrates that fishponds are not simply objects of heritage. They are active places where ecological repair, education, food systems, and cultural renewal meet. Recent research on restored *loko i‘a* strengthens this point by indicating that biocultural restoration can increase fish density, support fisheries, and help buffer some climate-related impacts in estuarine systems. The significance of He‘eia, then, is not only that it helps illuminate the past. It shows that archaeological landscapes can become living infrastructures again under conditions of community stewardship (Paepae o He‘eia 2025; Innes-Gold et al. 2024; Innes-Gold et al. 2025).

The same principle can be seen in the revitalization of Pacific voyaging. The Polynesian Voyaging Society and the legacy of the famous voyaging canoe, Hōkūle‘a, show that experimental practice, Indigenous knowledge, and public education can work together to recover ways of knowing once dismissed or doubted (Finney 1977, 1994). Hōkūle‘a helped demonstrate that ancestral navigation was not accidental drift but disciplined, purposeful seafaring, and its legacy continues to animate cultural resurgence and environmental consciousness across the Pacific (Polynesian Voyaging Society 2026). That matters here because it reveals a larger truth: practices often treated as belonging only to the past can become engines of future thinking when communities reclaim them on their own terms.

The Uto ni Yalo Trust points in a similar direction from Fiji. Its work with traditional and sustainable voyaging, public outreach, and ocean-centered stewardship reflects a broader Pacific commitment to keeping maritime knowledge active rather than merely commemorative (Uto ni Yalo Trust 2026). Its connections with organizations such as PEUMP (Pacific-European Union Marine Partnership) and the Okeanos Foundation suggest that ancestral maritime practice can be mobilized in contemporary conversations about governance, resilience, and environmental responsibility. That continuity between old technologies and new environmental futures is deeply relevant to the themes of this dissertation. It suggests that Pacific infrastructures of the past are not only worthy of archaeological reconstruction, but also of further study. They may also help shape the ethical and practical imagination of the present.

What emerges from these examples is a conclusion both simple and difficult: the future will be understood more fully when different ways of knowing are allowed to work alongside one another rather than in isolation. Archaeology has an important role to play in that conversation, but not as the sole authority. Its greatest contribution may lie in helping reveal that sustainability, resilience, and cooperative marine management have histories deeper and more diverse than many modern frameworks assume. In a century defined by climate change, shoreline instability, ecological pressure, and renewed struggles over food and water, that is no small contribution.



Figure 44. Photo of voyaging canoe “Uto ni Yalo” operated by ‘The Econesian Society’ and the University of the South Pacific-Suva in Fiji.

The final claim of this dissertation, then, is one of guarded hope. It is not the hope that the past can be copied or precisely reconstructed. It is the hope that the past enlarges our sense of what people are capable of when they work with place, with one another, and with knowledge carried across generations. Customary fishing structures in Remote Oceania testify to ingenuity, discipline, ecological intelligence, and durable collaboration. Their archaeology shows that resilience is not merely a contemporary slogan. It is a historical achievement, built stone by stone, tide by tide, and renewed whenever communities choose to learn from it again.

9. APPENDIX

Appendix A: Source Code (NetLogo) for Agent-Based Model Used in Chapter 6

```
globals [
 pdo-phase          ;; -1 (negative), 0 (neutral), +1 (positive)
 limu-productivity   ;; dynamic based on pdo-phase and storms
 storm?             ;; whether a storm occurs this turn
 open-season?       ;; true if fishing is allowed
]

turtles-own [
 energy             ;; used by both fish and humans
 strategy           ;; "cooperator", "defector", or "enforcer" (humans)
 species            ;; "fish", "human"
 home-village
]

patches-own [
 limu
 fish-biomass
 village-id
]

;; Setup procedure
to setup
 clear-all
 set-default-shape turtles "circle"
 set pdo-phase one-of [-1 0 1]
 set open-season? true
 setup-patches
 setup-turtles
 reset-ticks
end

to setup-patches
 ask patches [
   set limu random 100
   set fish-biomass random 50

   ;; Horizontal zones
```

```
  if pxcor < -5 [ set village-id 1 set pcolor green ]
  if pxcor >= -5 and pxcor <= 5 [ set village-id 2 set pcolor blue ]
  if pxcor > 5 [ set village-id 3 set pcolor red ]
 ]
end

to setup-turtles
 ;; Add humans
 create-turtles 30 [
  set species "human"
  set energy 100
  set strategy one-of ["cooperator" "defector" "enforcer"]
  set color ifelse-value strategy = "cooperator" [green]
          [ifelse-value strategy = "defector" [red] [blue]]
  setxy random-xcor random-ycor
  set home-village [village-id] of patch-here
 ]

 ;; Add fish
 create-turtles 50 [
  set species "fish"
  set energy 50
  set strategy "n/a"
  set color gray
  setxy random-xcor random-ycor
 ]
end

;; Main loop
to go
 if ticks >= max-ticks [ stop ]
 update-season
 update-pdo
 maybe-storm
 grow-limu
 grow-fish
 ask turtles [
  if species = "fish" [ fish-behave ]
  if species = "human" [ human-behave ]
 ]
 tick
end

to update-pdo
```

```
 if ticks mod 120 = 0 [
   set pdo-phase one-of [-1 0 1]
 ]
end

to maybe-storm
 set storm? false
 if random-float 1 < storm-frequency [
   set storm? true
   ask patches [
     set limu limu * 0.5
     set fish-biomass fish-biomass * 0.7
   ]
 ]
end

to grow-limu
 ask patches [
   let base-growth 2 + pdo-phase * 1
   if storm? [ set limu limu * 0.8 ]
   set limu limu + base-growth
   if limu > 100 [ set limu 100 ]
 ]
end

to fish-behave
 let current-limu limu
ifelse current-limu > 10 [
 set energy energy + 2
 ask patch-here [ set limu limu - 2 ]
] [
 rt random 60
 lt random 60
 fd 1
 set energy energy - 1
]
if energy > fish-repro-threshold [
 hatch 1 [ set energy fish-repro-threshold / 2 ]
]
 if energy <= 0 [ die ]
end

to human-behave
 rt random 60
```

```
lt random 60
fd 1

if open-season? [
  if strategy = "cooperator" [
    harvest 2
    maintain
  ]
  if strategy = "defector" [
    harvest 3
  ]
  if strategy = "enforcer" [
    harvest 2
    patrol
    maintain
  ]
]

if not open-season? [
  if strategy = "cooperator" [
    maintain
  ]
  if strategy = "enforcer" [
    patrol
    maintain
  ]
]

set energy energy - 2
if energy <= 0 [ die ]

if energy > human-repro-threshold [
  hatch 1 [
    set energy energy / 2
    rt random 360
    fd 1
    set color [color] of myself
    set strategy [strategy] of myself
    set species "human"
    set home-village [home-village] of myself
  ]
  set energy energy / 2
]
end
```

```
to maintain
 ask patch-here [ set limu limu + 1 ]
end

to patrol
 let offender one-of turtles in-radius enforcement-radius with [
  species = "human" and
  strategy = "defector" and
  [village-id] of patch-here = [home-village] of myself
 ]

 if offender != nobody [
  ask offender [ set energy energy - 15 ]
  set energy energy - 1
 ]
end

to grow-fish
 ask patches [
  let growth 1
  if limu > 50 [ set growth 2 ]
  set fish-biomass fish-biomass + growth
  if fish-biomass > 50 [ set fish-biomass 50 ]
 ]
end

to update-season
 set open-season? ((ticks mod (2 * season-length)) < season-length)
end

to harvest [amount]
 if [village-id] of patch-here != home-village [
  set energy energy - 1
 ]

 ifelse open-season? [
  let actual-amount min list amount fish-biomass
  if actual-amount > 0 [
   ask patch-here [ set fish-biomass fish-biomass - actual-amount ]
   set energy energy + actual-amount * 4
  ]
 ] [
  set energy energy - 1
```

```
 ]
end

to-report final-human-count
 report count turtles with [species = "human"]
end

to-report final-cooperator-count
 report count turtles with [species = "human" and strategy = "cooperator"]
end

to-report final-enforcer-count
 report count turtles with [species = "human" and strategy = "enforcer"]
end

to-report final-defector-count
 report count turtles with [species = "human" and strategy = "defector"]
end

to-report humans-persisted?
 report any? turtles with [species = "human"]
end

to-report defectors-eliminated?
 report not any? turtles with [species = "human" and strategy = "defector"]
end

to-report final-mean-limu
 report mean [limu] of patches
end

to-report final-mean-fish-biomass
 report mean [fish-biomass] of patches
end

to-report final-mean-human-energy
 ifelse any? turtles with [species = "human"]
 [ report mean [energy] of turtles with [species = "human"] ]
 [ report 0 ]
end

to-report final-dominant-group
 let coop-count count turtles with [species = "human" and strategy = "cooperator"]
 let enf-count count turtles with [species = "human" and strategy = "enforcer"]
```

```
 let def-count count turtles with [species = "human" and strategy = "defector"]

 if coop-count = 0 and enf-count = 0 and def-count = 0 [ report "none" ]

 if coop-count >= enf-count and coop-count >= def-count [
   if enf-count > 0 and abs (coop-count - enf-count) <= 0.1 * (coop-count + enf-count + def-count) [
     report "mixed"
   ]
   report "cooperator"
 ]

 if enf-count >= coop-count and enf-count >= def-count [
   if coop-count > 0 and abs (enf-count - coop-count) <= 0.1 * (coop-count + enf-count + def-count) [
     report "mixed"
   ]
   report "enforcer"
 ]

 report "defector"
end
```

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