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Social and Ecological Factors Affect Long-Term Resilience of Voyaging Canoes in Pre-contact Eastern Polynesia: A Multiproxy Approach From the ArchaeoEcology Project

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While Eastern Polynesian archaeologists rarely recover archaeological remains of canoes (*va'a)*, ethnohistoric texts document how such vessels played a central role in the daily lives of commoners and chiefs alike. Here, we refocus discussions of *va'a* in Polynesian societies through synthesizing proxy information (archaeological data, evidence from ethnographic and ethnohistoric sources, ecological modeling, human-centered interaction networks) on canoe use in the Society Islands of French Polynesia. While all communities who initially settled Eastern Polynesia archipelagoes must have done so with large double-hulled canoes, their use was absent in some societies by the time of European contact. We question why some Eastern Polynesian societies retained the use of large ocean-going canoes, while others did not. For high island archipelagoes like the Society Islands, sources document how large double-hulled canoes facilitated and supported elite intra-archipelago voyaging, warfare, and exchange with near and remote hinterlands up until European contact in the mid-eighteenth century. While smaller canoes were used by commoners on a daily basis for subsistence fishing and island-wide transport, larger ocean-going canoes were strictly the purview of high-ranking elites. Our human-centered interaction network models help us to identify how social processes put constraints on the manufacture and continued use of large ocean-going *va'a* in Eastern Polynesian contexts. We deploy such data to outline steps in the production, use, and re-use of canoes. We employ network science to better understand the relationships between animal and plant species used by the Mā'ohi in canoe manufacture, quantifying the number of resources used, the number of social personae involved, and the amount of labor/energy involved in their manufacture. Finally, we use Mo'orea settlement pattern data, as well as landscape and elevation data, to visually model the extent to which local ecologies or habitats constrained access to long-lived hard wood trees, key raw materials in the construction of ocean-going vessels. We consider the additional variables of soil pH and tree regrowth rates in our modeling of the ecological limits of preferred *va'a* species. We then query differential patterns of continued use of ocean-going vessels in two Eastern Polynesian archipelagoes: the

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Gambier archipelago and the Society Islands. Utilizing these multiple sources of data, we return to the age-old question of what roles social and natural processes played in the resiliency of the socio-political systems of Polynesian chiefdoms. We view ocean-going canoes as critical social tools in terms of resilience, as use of these water craft reduced island isolation and allowed for contact with near, and sometimes far, neighbors who served as critical buffering agents, particularly in times of ecological crises, such as drought, famine, or tsunamis.

Keywords: Eastern Polynesia, canoe societies, resilience, ecology and habitat modeling, ethnohistory, prestige goods, human-centered interaction network, archaeoecology

> "This people are very ingenious in building their Proes, or Canoes, and seek to take as much care of them having large shades of houses to put them in built for the purpose and in these houses they likewise build and repair them and in this they shew a great deal of ingenuity, far more than one an expect: they are built full bellied. In these Pahee's…these people sail in those seas from Island to Island for several hundred Leagues ……" (Cook in Beaglehole, 1955/1961/1967, pp. 153–154).

INTRODUCTION

As the quote above from Captain Cook's first voyage to the Society Islands between 1768 and 1771 attests, large ocean-worthy canoes played a key role in Māʻohi society at the time of European contact. Yet Eastern Polynesian archaeologists rarely recover archaeological remains of canoes, despite ethnohistoric texts documenting how large ocean-going watercraft and smaller everyday vessels played a central role in the lives of commoners and chiefs. Arguably, only one archaeological example of a truly ocean-going canoe has been recovered in Eastern Polynesia (from New Zealand). Here, we refocus discussions of *vaʻa* (canoes) in Eastern Polynesian societies through synthesizing varied forms of proxy information (archaeological data, ethnographic and ethnohistoric data). We then harness these data to simulate models (human-centered interaction networks and spatial patterns of ecological limits) on canoe use in the Society Islands of French Polynesia. While all communities who initially settled Eastern Polynesia must have done so with large double-hulled canoes, their use was absent in some societies by the time of European contact. We question why did some Eastern Polynesian societies retain the use of large ocean-going canoes, while others did not?

Such questions are intertwined with human-environmental relations, as anthropogenic deforestation has been seen as a causal factor in the loss of timber for canoe manufacture and subsequently, the loss of the ability for ocean-going voyaging (Van Tilburg, 1994; Weisler, 1994, pp. 98–99; Rolett, 2002). The size of Eastern Polynesian canoes was largely based on the availability of large trees, with ocean-going canoes requiring the largest of trees to craft immense hulls (Ranney, 2018, p. 30). Thus, we privilege the ability of certain islands to grow large hardwood trees as a necessary condition for continued ocean-going voyaging capabilities in pre-contact Eastern Polynesia or at a minimum, access to canoes manufactured within such island's long-distance trade networks. Historically, Tongan political influence over the Lau island group in Fiji for extraction of *Intsia bijuga* provides a good example for the latter in Western Polynesia (Banack and Cox, 1987), while in our Eastern Polynesian case study, the Society Island-Mehetia-Tuamotu interaction sphere provides a good example of such a practice in Eastern Polynesia.

We launch our canoe-centric study by synthesizing ethnographic and ethnohistoric data on canoe use in the Society Islands and more broadly in Eastern Polynesia at the time of European contact. For high island archipelagoes like the Society Islands, sources document how large double-hulled canoes facilitated and supported elite intra-archipelago voyaging, the waging of war, and exchange with near and remote hinterlands up until European contact in the mid-eighteenth century. While smaller canoes were used by (mainly male) commoners on a daily basis for subsistence fishing and island-wide transport, larger ocean-going canoes were strictly the purview of high-ranking elites (again, mainly male). In the most complex of Polynesian chiefdoms, like the Society Islands, ocean-going canoes were highly valued functional items, but also symbolic items, as the size of a canoe materially expressed chiefly status. Only high-ranking chiefs had the wealth required to support the manufacture of such *vaʻa* by craft specialists. As such, we can identify large double-hulled royal canoes and war canoes as highly prized and restricted elite prestige items.

Our human-centered interaction network research helps us to identify how social processes put constraints on the manufacture and continued use of large ocean-going *vaʻa* in Eastern Polynesian contexts. We deploy such data to outline steps in the production, use, and re-use of canoes. We quantify the number of resources used, the number of social personae involved, and the amount of labor/energy involved in their manufacture. Finally, we use Moʻorea settlement pattern data, landscape data on elevation, and modern botanical survey data to visually model the extent to which local ecologies or habitats constrained access to long-lived hardwood trees, key raw materials in the construction of ocean-going vessels. We then query differential patterns of continued use of ocean-going vessels in two Eastern Polynesian archipelagoes: the Gambier archipelago and the Society Islands. Utilizing these multiple sources of data, we return to the age-old question of what role both social and natural processes, working in tandem, played in the resilience of the socio-political systems of Polynesian chiefdoms. Here we follow a perspective viewing ocean-going canoes as critical tools in terms of resilience.

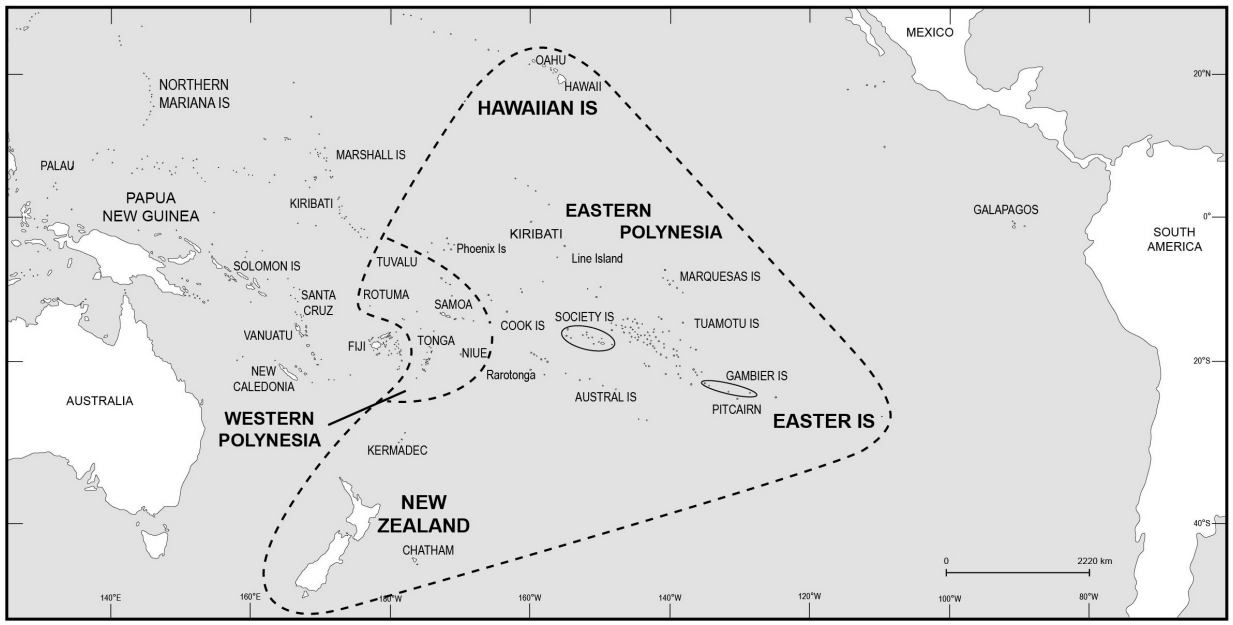

FIGURE 1 | Map of Eastern Polynesia and location of the Society Islands and Gambier Islands (Mangareva).

Use of these watercraft reduced island isolation and allowed for contact with near, and sometimes far, neighbors who served as critical buffering agents, particularly in times of ecological crises, like drought, famine, or tsunamis, otherwise known as the "rescue effect." As such, our work has broad relevance for studies of other pre-contact "canoe cultures," like those found in the Caribbean (Shearn, 2020) and the Northwest Coast (Mathews and Turner, 2017).

Eastern Polynesia as a Study Area and the Society and Gambier Case Studies

Eastern Polynesia is comprised of five main Central Eastern Polynesian archipelagoes (Cook, Society, Marquesas, Gambier, Tuamotu), in addition to the Pitcairn Group, Equatorial Islands, Kermadecs, Chatham Island, and the remote Eastern Polynesia islands (Hawaiian Islands, New Zealand, and Easter Island) (**Figure 1**). This area stretches over a vast ocean, spanning tropical to sub-tropical climates. All Eastern Polynesian islands are characterized by isolation and limited size (Kirch, 1984, p. 20), yet these are relative, as are differential physical resources given island type, age, and height. Geologically young high island archipelagoes, like the Hawaiian Islands and the Societies, offered the largest land masses, well-watered valleys with permanent streams, and moderate to well-developed lagoons (Kirch, 2010; Hommon, 2013; Kahn, in press), thus affording new settlers with the richest landscapes in terms of natural resources. While not the largest, youngest, or tallest island in the Society chain (this would be Tahiti at 1,045 km^2 in size, 0.3–1.3 myr in age, 2,241 m in elevation), Moʻorea is a geologically young island of moderate size and elevation (134 km^2 in size, 1.3–1.8 myr in age, 1,207 m in elevation). In contrast, the geologically older islands in the Gambier chain are both much smaller in size and much lower in elevation than Moʻorea (see **Table 1**). Geologically older archipelagoes, like the Gambiers, were more impoverished in terms of available natural resources. Their old age and small island size limited their terrestrial biodiversity, however, this was offset by enormous lagoons and rich marine resources (Conte and Kirch, 2004), in addition to the plants and animals introduced as canoe species ("Polynesian Introductions"). The Gambier Islands' reduced elevations resulted in a local context where only the largest valleys had permanent watercourses (Conte and Kirch, 2004, pp. 18–19).

TABLE 1 | Environmental and cultural characteristics of the Society Islands and the Gambier Islands (after Conte and Kirch, 2004; Kahn, 2018, in press).

Archipelago	Size (km^2)	Type	Max elevation (m)	Climate	Mean annual precipitation (mm)	Degree of isolation	Complexity	Comments
Society Islands	1590	Volcanic	2,241	Tropical	1,820–4,500	Low	Complex	Dynamic shorelines; highest level of social complexity; integrated complex chiefdoms
Gambier Islands	31	Volcanic	441	Tropical (cooler than Societies)	1,400–1,900	High	Open	Older islands, massive lagoon; moderate level of social complexity

As seen in **Table 1**, the geologically young high island archipelago of the Society Islands benefits from higher elevations that generate orographically induced rainfall. Their low degree of isolation provided colonizing communities with relatively high biodiversity of terrestrial and marine flora and fauna. It likewise situated Mā'ohi communities to exploit nearby islands, islets, and atolls in sometimes an extractive fashion (as with the uninhabited Fenua'ura Islands) and sometimes as mutually beneficial exchange (as with Mehetia and the western Tuamotus) (see **Figure 2**; Hermann et al., 2019; Molle et al., 2019; Kahn, 2020). In contrast, the more isolated Gambiers, situated in a cooler tropical climate, suffered from lower biodiversity in terms of plants and animals as well as from having lower annual rainfall. When coupled with their higher degree of isolation, such physical characteristics likely constrained social efforts of Gambier's pre-contact communities to buffer environmental shifts, whether natural or the result of anthropogenic causes.

Culturally, all Eastern Polynesian societies can be considered one phylogenetic unit, as each derives from the same set of ancestral cultures found in the Western Polynesian homeland (Kirch and Green, 2001). However, once each island or archipelago was colonized, new settlers adapted to local environments and resource bases, effectively leading to changes in material culture, subsistence intensification, hierarchy, and social relations (Kirch, 1984; Kahn, 2018). At first contact in the late eighteenth century, Eastern Polynesia exhibited a diversity of social-environmental systems. These ranged from hierarchically structured polities in the Society Islands with high population densities and intensive agricultural landscapes, to islands such as the Gambiers, which lacked centralized political authority and whose terrestrial landscapes were markedly degraded (Sahlins, 1958; Goldman, 1970; Kirch, 1984; Conte and Kirch, 2004, p. 21–22; Kahn, in press). In terms of cultural evolution, Sahlins (1958) was the first to suggest a correlation between resource availability, degree of social complexity, and instability of climate/natural resources in Eastern Polynesia (see also Kirch, 1984). We explore these variables with relation to the Society Islands and the Gambier Islands to examine the degree to which differing island size, slope, precipitation, and soil pH affected islander's abilities to manufacture large ocean-going canoes. Finally, we explore to what extent isolation derived from the lack of ocean-going canoes, and hence intra-archipelago interaction, constrained some Polynesian communities' choices vis-à-vis long-term sociopolitical resilience.

MATERIALS AND METHODS

Textual Sources

As we argue, the dearth of direct archaeological evidence for canoe technologies has contributed to an under-representation of the processes surrounding the manufacture and voyaging of canoes and their impact on the structure of Eastern Polynesian settlement patterns, social hierarchies, and economic interactions

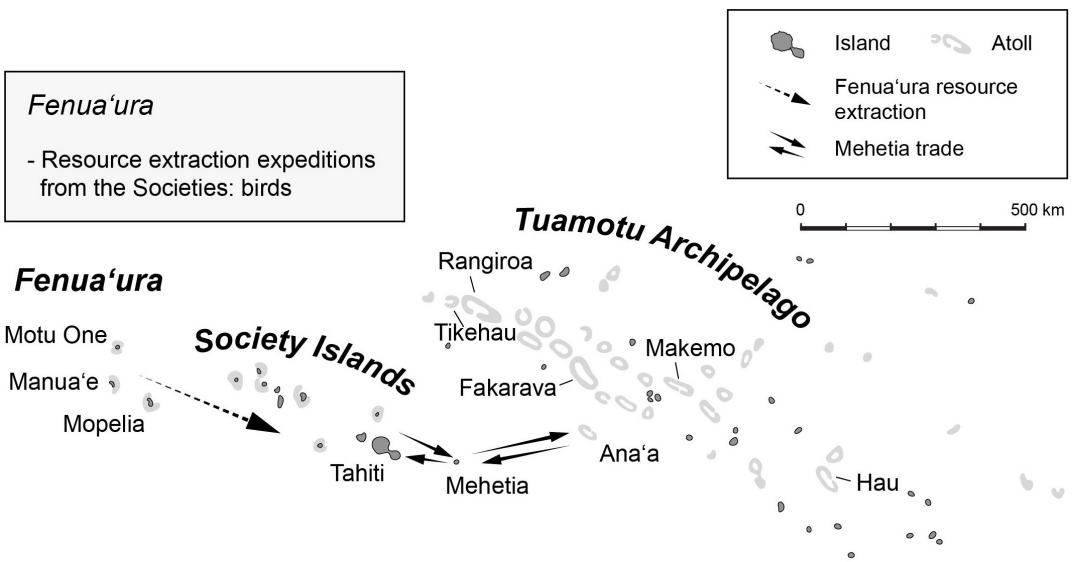

FIGURE 2 | Visual map of the Society Islands as the principal agent in Fenua-Ura resource extraction and as a key node in the Society Island-Mehetia-Tuamotu. Phrases followed by (?) denote possible interpretations that we have less solid foundation for regional interaction sphere.

as well as intra-archipelago interactions involving the exchange of material goods and ideas. Thus, understanding canoe cultures in Eastern Polynesia, as well as which societies lacked large ocean-going canoes at contact, requires the use of proxy data. Following this, we gathered data concerning pre-contact Eastern Polynesian canoe manufacture, use, and re-use from 43 published textual sources ranging from botanical articles/books; archaeological, anthropological, and linguistic works; traditional myths and oral traditions; and European explorer, missionary, and later historic accounts.

Presence and Absence of Ocean-Going Canoes at Contact

Several scholars have identified historical references to Eastern Polynesian societies at European contact who lacked ocean-going canoes (Mulloy, 1975; Weisler, 1994; Rolett, 2002); generally, this is seen as the de-evolution of more formally complex canoe technologies, although alternative views do exist (Anderson, 2008, 2017). We gathered data about the presence and absence of Ocean-going canoes in Eastern Polynesian societies at the time of European contact from both primary (European explorers and missionaries, early Tahitian dictionary) and secondary sources (later published syntheses). Generally, ocean-going canoes are defined as large double-hulled canoes used outside the lagoon, in contrast to smaller single-hulled canoes with or without outriggers used inside the lagoon (Finney, 2006, p. 113).

Human-Centered Interaction Network and Human-Centered Canoe Web

As part of the ArchaeoEcology Project[1], we developed a use web coding uses of all plants and animals recovered in Society Island archaeological sites. For each taxon present in archaeological sites, we recorded use data as reported in textual sources (European explorer texts, later historic accounts, ethnographies, botanical and ethnobotanical sources and surveys; the Tahitian dictionary, oral traditions, and genealogies). Our objective was to understand "human-centered interaction networks" (HCIN), including how relationships between pre-contact Māʻohi communities and island flora and fauna were organized, what these relationships can tell us about diachronic shifts in human-environmental interactions, and how such network approaches can identify changes in socio-economic systems (see Verhagen et al., 2021, p. 2). From our larger HCIN database, we developed a human-centered canoe-web database, intending to define the number of steps in the life cycles of canoes; which animals, plants, and tools were used in such steps; and which social personae were involved in each step.

Social Personae

We define social personae as social roles that are present in specific interactions in a society and which are recognized by other members of the social group as responsibilities of that individual. Broadly within Eastern Polynesia, social personae might include chiefs, commoners, and occupational specialists; the latter can be broken down into craft specialists (e.g., canoe manufacturer, adze manufacturer), other experts with specific knowledge (sea expert, navigator, expert fishermen), and ritual specialists (priests) (Kirch and Green, 2001, pp. 221–2279, Tables 8.7, 8.9; see Kahn, 2005 for the Society Islands, Taomia, 2000 for the Cook Islands). Social personae mentioned specifically in terms of Society Island canoe manufacture and use included chiefs, *ahi-tu* (the assistants of a canoe builder, canoe builders for chiefs on temple grounds), and *tahuʻa tari vaʻa* and *tahuʻa tari pāhi* (specialized canoemakers). These Tahitian glosses are derived from the first Tahitian dictionary published in 1851 (Davies, 1991).

Life Cycles

We classified canoe life cycles according to four generalized categories: construction, launching, sailing, re-use. Construction was broken down into two sub-categories, extraction of raw materials used and processing of the raw materials used. Within each of these, we likewise coded for tools used (e.g., adze, auger, chisel, fire) and activity (hollowing out the hull, boring holes). The launching category was broken down into the physical act of launching and ceremonies surrounding this event. Sailing was coded along three sub-categories: navigation (otherwise known as wayfinding), sailing, and voyaging (the latter refers to open ocean voyaging). The re-use category recorded data related to secondary repurposing events. Importantly, ritual activities were coded as sub-categories of each of the four life-cycles whenever ceremonial activities were deemed present, such as rubbing rigging cords on the stones of temples to determine the fate of the canoe before launching.

For each life-cycle category, we recorded which tools or items were used for which specific activity within each life-cycle, such as a wind compass used to determine the direction of the prevailing winds or an amulet offered to the sea gods upon safe arrival back to shore. Wherever possible we recorded the specific nature and names of social personae involved in life cycle events and ritual activities, as with *ahi-tu*, the builders of sacred canoes who lived consecrated lives and who would not cut their hair until a canoe was complete. We likewise recorded the specific places where events in the life-cycle took place (e.g., special huts near temples where the canoe was constructed).

Species Used

Based on work developing our HCIN database (Kahn et al., forthcoming), we reduced the ocean-going canoe body element category (associated with the hull elements) to two species: *Calophyllum inophyllum* (glossed in Tahitian as *Tamanu*) and *Neonauclea forsteri* (*Mara*); these species have known historic preference for use in double-hulled canoe manufacture in the Society Islands, Mangareva, or both. We recorded use across 12 categories: food, structural, ritual, health, clothing, fuel, housing, ornamental, artifact, companions, cosmology, and trade (for category definitions see **Supplementary Table 1**).

[1] http://www.archsynth.org/the-archaeoecology-project.html (accessed 7/15/2021)

For our canoe database (available online, see Kahn and Escue, 2021), we captured which particular plant and animal taxa were used across five categories: structure, purpose, vessel, maintenance, and use. Here, the structure category is defined as species used to create the original canoe structure excluding removable parts like paddles, sails, and masts. It has five sub-fields, including ornamentation, processing, body elements, extraction, and general, with sub-categories including tools and ritual. Ornamentation refers generally to aesthetic, social, or spiritual elements of the canoe, like carved figureheads or shell inlays or other sorts of decoration of the hull, rather than functional elements of the canoe, such as the shape of the mast or the hull (see Rogers and Ehrlich, 2008). The purpose category relates to particular use-events recorded around canoes, with the five-sub-fields of trade (use of canoes to transport trade items or to transport people with items to trade), hunting/fishing, ritual, cosmology, and navigation. Hunting of marine mammals like dolphins and whales is differentiated from fishing which includes capture of fish or shellfish. Ritual relates to generalized ceremonial activities, while cosmology relates specifically to beliefs or activities related to origin myths and world-views. Navigation relates to any practice linked with wayfinding. Sub-categories of the purpose category include vessel (items related to the physical canoe), equipment (auxiliary items not part of the actual canoe like masts, paddles), sacrificial (transportation of items like human bodies, pigs), and general (unspecified use).

The vessel category relates to specific mention of canoe type, whether single-hulled, double-hulled, or general (type unspecified). The double-hulled category has three sub-fields, canoes for use in war, those for use in voyaging, and those for use in ritual. The maintenance category relates to post-manufacture refabrication practices, with sub-categories of repair (practices to prolong use), recycling (practices to refabricate materials for other use), ritual (a species used for ritual to repair a canoe, but these were lacking in our study), and general (maintenance activity unspecified). The use elements category relates to the raw materials used for specific canoe elements, with the sub-categories of sail, mast, paddles, and general (unspecified). Wherever possible, use data was reported at the species level, yet some entries only provided data to the genus level.

Social Network Modeling

We generated a useweb model of the canoe production system by subsetting the larger HCIN dataset described in the previous section. Our first subset limited the species for construction to those categorized as used in constructing double-hulled canoes, namely *Tamanu* and *Mara*. We then converted this dataset into nodes (species, objects, personae, and events, $n = 105$) and links (processes, $n = 1{,}493$) to generate a human-centered interaction network model; as part of our supplementary data we include the R code file and the Excel data file so users can examine the canoe networks reported herein (see **Supplementary Tables 2**, **3**). The nodes were further classified as ornamentation, construction, general, body elements, launching, sailing, and ritual, and the links were classified as extraction, processing, construction, and ritual. We used these data to generate an igraph in R Studio 3.6.3. We then quantified this network model by summarizing the number of links per node using the degree function, which results in a list of centralization scores.

Archaeological Data

We coded data from textual sources whenever physical materials recovered in archaeological sites or housed in museums mentioned particular plant and animal taxa used in constructing canoe types (vessel, single-hulled, double-hulled), canoe elements (sail, mast, paddles, and general), or mentioned particular plant and animal taxa used to fabricate tools used in canoe manufacture, use, maintenance, and recycling events. The transportation of stone architectural elements and tools, particularly adzes, away from islands serving as their source of origin likewise provides indirect proxy data for intra-island, inter-island, and intra-archipelago voyaging; the latter two in many, if not most cases, required large ocean-going canoes.

Ecology and Landscape Data and Habitat Modeling

To test how island settlement densities, agricultural development, and demographic processes would impact access to species used in canoe hull manufacture, we generated habitat suitability maps in ArcMap 10.4 for the island of Moʻorea. Moʻorea was chosen as a test case, as it has a relatively rich biota (300 native and endemic taxa) and has high-resolution settlement data, particularly from the ʻOpunohu Valley.

Our first habitat model focuses on settlement densities by elevation. Knowledge of site densities across the island were gathered from published and unpublished sources[2], with modern data on 53 archaeological sites, a high concentration of which derive from the ʻOpunohu valley ($n = 41$). These data derive from 10 archaeological survey and excavation projects directed by Kahn over the last two decades. Such data were used to generate three zones of site density: high, moderate, and low. We must note that the low site density category often occurs in high altitude contexts, many of which, but not all, have very rare instances of known archaeological sites.

Our second and third habitat models illustrate erosional data and elevational limits of species known to have been used in constructing the hulls of double-hulled canoes, *Tamanu* and *Mara*. The depth of erosional deposits were derived from all known excavated archaeological contexts with available data (Green et al., 1967; Lepofsky, 1994; Kahn, 2005, 2010, 2012; Kahn and Kirch, 2011, 2014; Kahn et al., 2015). We theorized that soil erosion from the interior onto the coastal plain, which appears to have generally ceased around 1250–1400 CE (Lepofsky and Kahn, 2011; Kahn et al., 2015), impacted the regrowth potential of large, slow-growing, hardwood trees preferred for ocean-going *vaʻa* hulls. *Tamanu* and *Mara* have specific elevational limits (425 and 1,000 m, respectively) and require specific growing conditions like pH and soil type (4.0–7.4 pH respectively, in sandy well-draining soils for *Tamanu* and hydrophilic forests with well-draining soils for *Mara*). At the outer limits of these boundaries, trees may be viable, but growth potential may be impacted, resulting in smaller stature trees. To map these constraints, we

[2]Kahn, J. G. (unpublished data). *Moʻorea Field Notebooks, 1999–2017*.

used the Raster Calculation tool to produce overlays for *Tamanu* and *Mara* limits by elevation. We traced the erosion values based on the data derived from the excavation units.

RESULTS

The methods that we use can be replicated easily and extrapolated to other regions. In **Supplementary Table 1** we include our code and network analysis datasets, while in Kahn and Escue (2021) we publish the canoe dataset used in this publication. While our methods could be used with our data to replicate our findings, more importantly, our methods are open access and can be used to understand other regions where habitat growth could have negative impacts on critical species.

Our model results suggest that there were varying abilities to regrow large trees required for double-hulled ocean-going canoes. Erosion would have been a primary concern for Polynesians, potentially creating a snowball effect that would be difficult to ameliorate. Removing large trees for ocean-going canoes would decrease the resilience of the soil, and only through reforestation—a long and lengthy process—could Polynesians regrow the essential resources. As our models show, pH changes in areas of deforestation suggest that some islands would have a difficult time rebounding to early conditions.

Our use web models suggest the critical nature of many organic materials for the function of Polynesian societies. As availability of these resources became strained, Eastern Polynesians would have needed to rely on their larger networks, if they could.

Use Webs and Human-Centered Interaction Networks: How Do Social Processes Constrain Canoe Manufacture and Use?

General Use Categories

In considering the greater impacts of tree availability, it is key to understand the range of uses for large tree taxa like *Tamanu* and *Mara*, as canoe manufacture is likely not their only realm of human use. Our HCIN databases documented the number of concurrent uses reported for these taxa in the Society Islands and Mangareva. Both trees and their elements are highly used in the Societies. Seven to eight uses are reported, with *Tamanu* used for artifact, cosmology, food, fuel, health, structural, and transportation and *Mara* used quite similarly for artifact, cosmology, health, ornamental, structural, trade, and transportation. In Mangareva, *Tamanu* is also highly used[3], having four use categories (fuel, housing, artifact, transportation), while *Mara* is absent from the archipelagoes' native flora. Mangareva shares 75% of *Tamanu* use categories with the Societies, yet lacks *Mara*.

[3]Mangarevan flora, in general, have lower use rates than in the Societies. The highest use rate for Mangarevan plants is across six categories, whereas in the Societies it is across 11 categories. Thus, while seven to eight use categories in the Societies is substantial, four use categories in Mangareva is comparatively substantial.

In terms of the ability to resource switch, Mangareva's more depauperate flora reduced access to the species for large canoe building. In the Societies, the use of parts of the living tree of *Tamanu* for food and medicine may have put additional constraints on the availability of parts of this tree, but likely would not have affected the actual size of the trunk. The Mā'ohi also had the benefit of being able to resource switch to use *Mara* in canoe construction if *Tamanu* became scarce or smaller in size due to over-harvesting or erosion. Because of this, *Tamanu's* concurrent uses in Mangareva likely created heavier constraints on long-term harvesting potential there than in the Societies. This is especially true given that *Tamanu's* 7–8 year growth cycle, which may have led to harvesting trunks before their full size and thus impeding the construction of large ocean-going hulls.

Canoe Use Categories and Complex Life Cycles

In our canoe use network, we had a total of 1,385 links relating to activities occurring during canoe life cycles. In terms of life cycles, the construction category had the most links (n = 722, 53%), while sailing had the least (n = 59, 4%). The presence of a four-part use-life to large double-hulled canoes signals complex stages of construction, from felling the tree, hollowing out the hull, smoothing the side planks, ritualized movement of the canoe to the water and ceremonies involved in first launching and sailing of the canoe, in addition to ritualized re-use episodes. For example, the fact that old canoe parts were placed on altars before launching new canoes and were used to create sacred fires at temple sites illustrates how in all their four life stages, canoes and their constituent material parts were considered sacred.

In terms of the structure category, or species used to create the original canoe structure excluding removable parts like paddles, sails, and masts, the node with the highest number of links is *Mara* (n = 84). *Tamanu* has the second highest number of links along with clothing worn by canoe building specialists (n = 72). That *Tamanu* and *Mara* are among the nodes with the most links in the entire network shows their integral use in constructing diverse aspects of the main hull and canoe structure. That canoes were multi-component technologies is clearly illustrated in the presence of 16 named body elements, ranging from the projecting bow, the hull, the side board, the outrigger, and the pegs on the outrigger, etc.

In the processing sub-category of construction, coral (n = 55) and stingray (n = 48) were the nodes with the highest number of use links, illustrating the importance of tools made from these raw materials in the processing of canoe parts. Such tools were likely used to polish and burnish canoe surfaces in preparation for other ornamental treatments. Tool use across all four use-life categories (construction, launching, sailing, re-use) involved 25 items, ranging from simple tools like coral rasps and whetstones (the latter were used to sharpen stone adzes), to complex multi-component tools, like paint comprised of numerous elements, or sennit cord (twined and braided organic cordage used as rigging), which itself had several stages in its time-consuming manufacture. Because some of the materials used in canoe construction and use themselves

had time-consuming production rates, we can view the staged construction of large-ocean growing canoes as substantial, both in terms of the raw materials needed and the time need to process them.

In the ornamentation sub-category of canoe structure, the nodes with the highest number of use links include candlenut (*Aleurites moluccana*) and *Chamaecyse celastroides* (a flowering shrub) (n = 20). Candlenut ornamental use included extraction of liquid from its inner bark to color cloth and mats and for use as an element in canoe paint (Butaud, 297; Medeiros et al., n.d.). *Chamaecyse celastroides* was also used as an ingredient in canoe paint (Medeiros et al., n.d.). Forms of ornamentation were found across the first three of the four use-life categories (construction, launching, sailing), ranging from painting the canoe hull black, hanging white tapa cloth on canoes carrying sacrifices, placing small wooden figures representing the gods in canoe sterns, and placing ornate sculptures on canoes prows as figureheads. These data highlight how canoes were more than just functional tools to transport people and things, as they were used in vibrant social displays in varied social contexts (warfare, canoe/visiting elites' arrival ceremonies, presentation of tribute, etc.).

Ritual activities are well-represented (n = 17) across the four stages of the canoe life cycle, demonstrating the ceremonial importance of all steps in canoe production. It is then no surprise that in the ritual sub-grouping of each life-cycle, feasting (n = 65) and sleeping rituals for stone adzes used in canoe construction (*haʻamoe raʻa toʻi*) (n = 53) have the highest number of use links. Such high linkage in the network for different types of rituals supports how canoe production was performed under highly circumscribed ritual practices. Importantly, ritualized production occurred from the outset of construction. Stone adzes used to fell the tree trunk cut for the hull and later used in hull carving were "put to sleep" at night (*haʻamoe raʻa toʻi*) in temple walls by canoe specialists. Priests decided which tree to fell in the forest and recited prayers during tree felling. The launching life-cycle category, referring to ceremonies surrounding use and first use of the canoe, is particularly replete with rituals, like rubbing sennit cord on the stones of temples to determine the fate of the canoe before launching, using feathers to invoke spirits and as presentation to the gods at launching feasts, and *faʻainuraa i te vaʻa*, making the canoe drink to consecrate the boat. Furthermore, in the sailing group, amulets (n = 13), and drums (n = 14), items used in ceremonies performed to ensure successful voyages or successful acts of war, are the nodes with the highest number of links.

That in the launching category, pig (*Sus scrofa*) (n = 19), feathers (n = 19), and offerings (n = 19) are the nodes having the highest number of links is telling. These data not only illustrate the importance of canoes in transporting high prestige items as tribute to Māʻohi socio-ritual elites, but the significant use of highly valued prestige items as offerings made to the gods during the ritual life-cycles of canoes. Pigs and red feathers were among the most highly prized goods in elite Māʻohi society. Of Māʻohi staple goods, pigs were the most highly valued prestige items, figuring prominently in sociopolitical and ritual life. They served as frequent items of gift exchange and intra-island exchange (Kahn, in press). Feathers were raw materials integral to items of wealth finance, like the *toʻo*, or feathered god figures. In the pre-contact Society Islands, feathers (black, yellow, and especially red) and feathered objects were not just highly valued objects, but were symbols of power, fecundity, and the divine (Kahn, in press). Pigs and red feathers were also ritual symbols associated with the ʻOro state religion and the *ʻarioi* cult, members of which were frequent passengers in double-hulled canoes voyaging between islands in the archipelago. Here again we see how ritual, ideology, and sacred power were bundled together with the symbolic and economic uses of ocean-going canoes. This is underscored by results from the social personae category, where the *ahi-tu* node, canoe builders for chiefs on temple grounds, has 75 links, and the *tahuʻa tarai vaʻa* node, specialist canoe builders, likewise has a high number of links (n = 72). Highly ritually prescribed stages of craft production are more likely to be carried out by highly skilled and highly specialized craft specialists than more mundane tasks.

Our network visualization (**Figure 3**) shows the links between the three dominant life stages (construction, launching, sailing), and sub-categories therein (structure-body elements, ornamentation, processing), as well as all links related to ritual. We split out activities related to chiefs vs. activities related to other social personae (specialist canoe builders). There are several pertinent points to highlight. First, processing shares many taxa with construction, suggesting that this life-stage may be better conceived of as a sub-set of a more generalized construction life cycle. Second, ritual forms important nodes in all three life stages. As an example, the amulet links the ritual and launching group to the sailing group. Third, specialized canoe builders (depicted in white as personae) play a significant role in the first three life stages of the canoe, as they form nodes linking construction, launching, sailing, and ritual events. Finally, chiefs (represented by red) serve as an important node with 37 links, connecting launching and ritual to construction, as well as the sets of tools used in the construction of the hulls. Other patterns that can be observed include two clusters of construction suggestive of potential sub-categories to this life cycle and some partitioning of ornamentation events

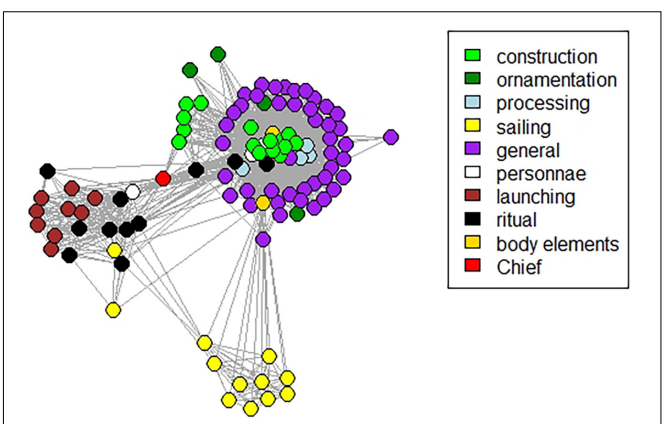

FIGURE 3 | Network visualization for the canoe use web.

that might suggest that canoe ornamentation perhaps was carried out by different craft specialists than hull construction, although these secondary patterns are more speculative and need further testing.

DISCUSSION

Ethnohistoric and Linguistic Data and Eastern Polynesian Canoes

Polynesian historical linguistics studies have clearly reconstructed a Proto-Polynesian term for double-hulled canoe, in addition to terms for large ocean-going sailing canoes, smaller single outrigger canoes, and dugout canoes (see Kirch and Green, 2001, pp. 197–198, Table 7.8). By the time of European contact, several European Explorers noted how some Eastern Polynesian islands and archipelagoes, such as Easter Island, the Gambier Islands, and some of the Tuamotu Islands, lacked large ocean-going canoes, relying instead on single-hulled canoes or other types of water craft for near shore travel and fishing (**Supplementary Table 4**). The Gambiers represent an extreme example, as at the time of contact, rafts fashioned from tree bark twines lashed together were the only style of watercraft seen. Similarly, Easter Island lacked true ocean-going canoes, as Europeans described only small single-hulled canoes that heavily leaked (Roggeveen, 1908, p. 19; Haddon and Hornell, 1936, pp. 96–97).

Some shifts in Eastern Polynesian canoe design likely represented adaptions to long-term isolation post-colonization. In New Zealand, watercraft shifted from double-hulled colonization canoes to single-hulled canoes and war canoes (*waka taua)* better adapted to intra-island voyaging and marine combat (Irwin et al., 2017, p. 32). As Irwin et al. (2017, p. 32) argue, Māori canoe technology adapted to "the changing cultural and geographical context of communications." Others have argued that a reduction in Māori voyaging in the pre-contact era derived from local conditions (unpredictable winds) and a large landmass that dampened demographic pressures to out-migrate (Biggs, 2006). There likely were varied reasons why Eastern Polynesian canoe societies modified the form and size of their watercraft after initial island colonization.

While there are suggestions that some shifts to smaller single-hull or plank canoes in Eastern Polynesian cultures may have been linked to social factors, other data indicate changing ecological conditions were a forcing factor. Indeed, Irwin and Flay (2015, p. 437–438) have argued that the adoption of "complex plank canoes with internal frames" served as an ecological adaptation on Polynesian islands lacking large trees. As **Supplementary Table 4** illustrates, there is a tendency for smaller islands and archipelagoes with low elevation and high isolation to have lacked double-hulled voyaging canoe manufacture and use at European contact. Several studies have linked this trend to higher levels of deforestation on smaller, low, and isolated islands (Weisler, 1994; Rolett, 2002; Diamond, 2014), while others have noted that some islands, like Easter Island, likely never had high numbers of large trees needed to build ocean-going canoes (Finney, 1993). As Rolett (2002) rightly highlights, deforestation as a limiting factor would have intensified through time, yet so too would have socio-political factors, like human population pressure supporting out-migration, expansionist chiefs requiring double-hulled war canoes for military campaigns, or atoll communities needing to maintain links to neighboring high islands. So what, we might ask, were the primary reasons for the loss of double-hulled canoes in some Eastern Polynesian societies? Namely, did social hierarchies (i.e., powerful chiefs) promulgate their continued production or use? Or did certain ecological contexts permit their continued production or use? Or is the answer somewhere in between?

Archaeological Data and Eastern Polynesian Canoes

The wet, tropical environments of Eastern Polynesia create challenging conditions for the preservation of the organic materials used in canoe production. Yet Sinoto's excavations at the waterlogged Vaitoʻotia and Faʻahia sites on Huahine (Society Islands) yielded exceptionally well-preserved wooden artifacts he interpreted as canoes parts and canoe accessories like paddles and bailers (Sinoto and McCoy, 1975; Sinoto and Han, 1985; Sinoto, 1988)[4]. At Faʻahia, Sinoto argued that two long wooden objects of similar length (c. 7 m) and shape were platform planks from a double-hulled canoe measuring c. 26 m in length (Sinoto, 1979, p. 13, Figure 1). Anderson et al.'s (2019, pp. 6–7) re-excavation of Faʻahia cast some doubt on this interpretation, noting that the two planks lack many features commonly found in hull pieces of large canoes, notably curvature, ribs, or lashing holes associated with fitted ribs. While Anderson et al. (2019) concur that some canoe construction likely took place at the site, they reason that whether the recovered canoe pieces belonged to a single, large, ocean-going canoe cannot be established given the lack of published stratigraphic details for the finds and the lack of direct chronometric dating.

At Anaweka Bay on the South Island of New Zealand, a large section of a complex composite canoe was discovered and radiocarbon dated to c. A.D. 1400 (Johns et al., 2014). The recovered section represents part of a hull measuring 6.08 m long and carved from a single timber. Given the vessels' hull form, size (thought to be at a minimum 12 m long), and sophistication, Johns et al. (2014, p. 14729) interpreted the Anaweka vessel as most likely part of a double-hulled ocean-going sailing canoe. The presence of a carved sea turtle motif on the outer portion of the canoe's hull supports our earlier assessment that Eastern Polynesian canoes often had

[4]Anderson et al. (2019) have recently argued that Sinoto's purported remains of a large ocean-going canoe were, in fact, pieces that could date to different time periods or could represent parts of different canoes. Based on form, they argue Sinoto's probable canoe planks likely had other functions and perhaps derived from domestic or ritual structures. They likewise argue that Sinoto's purported canoe mast may represent a piece of unmodified driftwood, examples of which were common across the site. Based on their reading, Anderson et al. (2019) argue that the construction of canoe parts may have taken place on the site but that there is no definitive evidence for the recovery of a large ocean-going canoe.

symbolic association. Despite several finds of other canoe pieces in New Zealand, the Anaweka find represented the only example of a "truly-ocean going canoe" (Irwin et al., 2017, p. 42). While few archaeological traces of Eastern Polynesian voyaging canoes have been recovered, current finds suggests the presence of moderate-sized voyaging canoes similar to Māʻohi *tipaerua*.

Society Islands Case Study: High Island Archipelago With Complex Chiefdoms

Since the Society Islands have some of the richest ethnohistoric references to double-hulled canoes at the time of European contact, it provides an excellent in-depth case study of a highly complex chiefdom retaining such vessels. The Māʻohi voyaged in specialized sea-going vessels termed *pāhi*. These vessels were differentiated in size and form from single-hulled canoes (*vaʻa, pu hoʻe*) used for everyday fishing and local travel by commoners (Corney, 1913/1914/1918 (I), p. 334; Guiot, 2001, p. 4). *Pāhi* were immense double-hulled canoes (up to 30+ m) with double masts and composite plank keels who carried small shelters on their platforms (Forster, 1778, pp. 459–460; Cook, 1893, p. 98; Banks, 1896, pp. 115–116, 159; Oliver, 1974, pp. 195–196, 173; Corney, 1913/1914/1918 (I), p. 358; (II), p. 82). Other moderately sized craft (20–26 m) termed *tipaerua* were also used by the Māʻohi in open sea voyaging.

Māʻohi war canoes were large (up to 32 m+) double-hulled vessels with up curved sterns (see **Figure 4**; Oliver, 1974, pp. 400–401). On their fore part, a fighting stage was installed. On Cook's second voyage, George Forster and Sparrman viewed a large double-hulled war canoe under construction. This vessel was 27 m long, with room for 144 paddlers to sit on the beams and 8–10 steersmen (Salmond, 2009; Thomas et al., 2016). Its fighting stage was 7 m × 3 m; the edges of this stage as well as the prow and stern were intricately carved with anthropomorphic figures. Europeans commented on how the manufacture of canoes cost communities "infinite labor," no doubt why their access and storage were highly controlled. Communities must have invested great time and effort to produce chiefs' war fleets. While ethnohistoric sources at times conflate *pāhi* with large war canoes, it seems as if all moderately large (6–9 m) to large (>9–30 m) double-hulled canoes were valuable chiefly prestige items chiefs (Ellis, 1829(I), p. 170).

Varied historic sources document how Māʻohi high chiefs (*ariʻi nui, ariʻi rahi*) controlled the production of long-distance canoes and war canoes. *Pāhi* manufacture was considered a "public work" carried out by specialized canoe makers under the control of high chiefs and financed through corvée labor, tribute, and other means (Ellis, 1829(I), p. 175; Henry, 1928, pp. 180–182; Morrison, 1935, pp. 165, 205–206; see Guiot, 2006). High chiefs likewise underwrote the construction of war canoes. Priests would inform the chiefs of the god's request for canoes; chiefs subsequently extracted tribute from the greater community to hold a series of feasts, to gather foodstuffs to support the ritual and craft specialists during the period of canoe manufacture, and to procure a human sacrifice for the launching event (Morrison, 1935, pp. 205–206).

Multiple lines of evidence speak to the highly ritualized nature of Māʻohi ocean-going canoes, both in terms of their manufacture and use. *Pāhi* and war canoes were manufactured on temple grounds or near the coast in specialized structures under formalized rules of ritualized production (Wilson, 1799, pp. 190, 377; Henry, 1928, pp. 146–147, 180–182; Orliac, 1982, p. 99); when finished they were launched with elaborate rituals and feasting. Traditional Māʻohi chants and ethnohistoric texts frequently reference expert canoe makers. Henry (1928) proposes that there were two classes of canoe builders, those for the general public (*tahuʻa papai vaʻa*, *tahuʻa tarai vaʻa*) and those who worked for the chiefs building sacred canoes on temple grounds (*ahi-tu*). Specialist canoe-builders had their own temples or shrines in which they made offerings and prayers to their patron deities (Henry, 1928, pp. 146–148). High chiefs' royal compounds, associated with national *marae* (temples) and formal meeting places and assembly grounds (*tahua*), also housed *fare vaʻa*, storage structures for the immense double-hulled royal canoes used to travel between the islands (Corney, 1913/1914/1918(I), pp. 334, 336, 1915(II), p. 56; Orliac, 2000). Like royal insignia such as feathered girdles, that *pāhi* and war canoes were manufactured under prescribed rules indicates their role as highly valued wealth items, similar to war canoes (Henry, 1928, p. 189). That high-ranking chiefs could demand canoes as a form of tribute, particularly as a preparation for war (Oliver, 1974, pp. 998–999), reflects some direct control over the political economy.

Why were large ocean-going canoes and war canoes so highly valued in Māʻohi society? Such canoes were instrumental in facilitating island-to-island exchange within the archipelago. They were likewise critical for ocean-going voyages of inter-archipelago exchange between the Society Islands and their far hinterland neighbors, the Tuamotu atolls, similar to practices seen in the Western Pacific (the *sawei* system in Micronesia, see Hunter-Anderson and Zan, 1996). They also made possible resource extraction trips to the Society Island's near hinterlands, Fenua-Ura (**Figure 2**). So from a purely economic and mobility perspective, ocean-going canoes were key transport vessels.

Yet, if we broaden our perspective to include social processes, canoes served as key elements in this realm of life as well. In fact, access to large ocean-going canoes was instrumental in the expansion of the late pre-contact 'Oro war cult out of Raʻiātea and its spread to the rest of the islands in the archipelago, primarily through members of the *ʻarioi*, a high-status fertility cult linked to 'Oro worship. Grand groups of traveling *ʻarioi*, high priests, and chiefs, with canoes laden with material goods, play prominent mention in European Explorers' accounts (G. Forster in Salmond, 2009). When the 'Oro god figures traveled for ceremonies, these royal sacra were transported in their own canoe (*te vaʻa a roa i te mataʻi*, the long canoe in the wind), with a special chamber for the god house and bunches of red feathers and decorative wooden sculptures on the prow (Henry, 1928, pp. 136, 190). In Māʻohi oral traditions, famed canoes carrying male chiefs and high priests between islands were named and regaled, such as Manuatere, Tainui, and Te-apori. Such data support the functional import of long-distance voyaging canoes in pre-contact Māʻohi culture and their association with the movement of elites (largely male elites), and the adoption of the

FIGURE 4 | Engraving of large double-hulled canoes amassed on the coast of Tahiti waiting to launch and wage war on Mo'orea. "The Fleet of Otaheite assembled at Oparee," 1776. Artist William Hodges, courtesy of National Maritime Museum, Greenwich, London (BHC2395).

'Oro war cult (Ellis, 1829 (I), pp. 168–170; Salmon, 1910; Henry, 1928, p. 459). Indeed, the advent of the 'Oro war cult likely spurred specialized production of *pāhi,* given that *'arioi* had to frequently travel from island to island during the ritual calendar. European explorers describe *'arioi* in flotillas of 60–70 canoes carrying some 700 persons; others suggest even higher numbers, with 150 boats carrying a group of 4,500–6,000 persons (Oliver, 1974, p. 918, f 25).

Large ocean-going canoes likewise played a key role in Mā'ohi high chiefs' abilities to control the political economy. Large canoes commonly transported immense amounts of staple goods and prestige goods, moving such tribute from the populace to the chiefs during *rites de passage*, during the construction of specialized and monumental architecture, and during the ritual cycle. A case from Huahine describing a public work serves as an example:

> The people from different parts are assembling in our neighborhood in order to thatch the big house called Nanu which is built at great public expense. The people of both Huahines. . .brought their several divisions of thatch and also a great quantity of food for the Chiefs consisting of baked hogs, mahe, Yams, Taro, Cocoanuts, pia, plantains, Xc. There are in all about 120 Canoes come, each of which had with his division of food either a hog or baked fish, about 100 hogs of different sizes all baked were heaped up on the beach today with the baskets of Yams, Taro, Mahe & delivered up to the Chiefs with great ceremony (Davies, cited in Oliver, 1974, pp. 997–998).

The term *tavau* glosses a fleet of canoes bringing items to the principal chief in the form of tribute; such events moved substantial foodstuffs and wealth items such as red feathers, feathered breastplates, feathered headdresses, canoes, and large bundles of mats and barkcloth from commoner communities to ruling chiefs (Oliver, 1974, pp. 1003–1005). Annual *Pararaʻa Matahiti* ceremonies likewise involved the movement of people and things. Such ceremonies began with the arrival of *'arioi* cult members in district canoes with public offerings of staple goods (pigs, dogs, fish, breadfruit, bananas, mountain banana, fermented coconut sauce) and wealth finance objects (mats, canoes, *tapa*) to high ranking chiefs at national *marae* (Moerenhout, 1837(I), pp. 518–521; Oliver, 1974, pp. 260–261; Babadzan, 1993, p. 244). In this way, large ocean-going canoes facilitated the movement of elites and vast amounts of goods following the annual and ritual calendars, thereby forming key elements of elite power-building strategies (Kahn, in press). They likewise permitted exploitation of near hinterlands like Fenua-Ura for the extraction of bird feathers, some of which were used in elite regalia and costumes, in addition to facilitating the continuation of regional exchange networks between the Society Islands, Mehetia, and the Tuamotu Islands. Such regional exchange networks were key to Tuamotuan Islander efforts to buffer the negative impacts of living on resource poor atolls. Yet, this regional exchange network likewise filtered important resources into the Societies, such as Tuamotuan expert boatbuilder knowledge (Klem, 2017)[5] and white dog's hair used in fabricating *taumi*, the elite breastplates worn as a sign of upper-class male status.

It also seems clear that Mā'ohi chiefly access to war canoe production and use consolidated their control over military campaigns. Oral traditions and historic accounts illustrate that at the time of European contact, the Society Islands were characterized by endemic and institutionalized warfare between independent chiefdoms or confederations thereof. In the Society Islands, naval battles were the dominant form of warfare prior to European contact (Moerenhout, 1837(II), p. 40). Such skirmishes involved large double-hulled war canoes manned by large numbers of paddlers and fighters in addition to battle shapers and exhorters (Morrison, 1935, p. 175; Moerenhout, 1837(II), p. 40,

[5]Klem (2017, pp. 4–5, 7–8) provides a discussion of ethnohistoric sources recounting how Tuamotuans were revered for their expertise in canoe building and may have had residence in the Society Islands as expert boat builders. Historic sources from which such descriptions derive all date to the post-contact period. Given historic sources document the presence of the Society-Mehetia-Tuamotua interaction sphere in the pre-contact era, there is some likelihood that expert Tuamotuan boat-builders resided in the Societies in pre-contact times.

see Oliver, 1974, pp. 401–405). Thus, we can view war canoes as key avenues by which Paramount chiefs amassed military might.

Warfare undoubtedly served numerous roles, here we want to emphasize its economic, political, and ideological impacts. Victors in war had access to the spoils of war and the ability to wreak havoc on their enemies' varied sources of power. Victors not only could seize land and other highly valued wealth items such as pigs, they could also take one's royal sacra (god idols, feathered loin cloths) by force. Long-lasting reduction of an opponent's economic power and ideological power could be had by burning agricultural fields and the pole and thatch structures on their ritual sites (Salmond, 2009). Thus, control over warfare *via* control over the manufacture and use of war canoes gave Māʻohi high chiefs access to widespread sources of power. Given that the ʻOro war cult of the mid-eighteenth century ushered in a period whereby the highest ranking socio-ritual elites actively and often effectively used coercive force as a means to grow and consolidate their sacred and secular sources of power, the key role of war canoes in late pre-contact Māʻohi society cannot be overstated.

Yet the symbolic association of the ʻOro war cult, high-status chiefs, and canoes likely had as great an import as the functional associations of ocean-going canoes with transport, tribute, and warfare. That large royal canoes in the Society Islands were named and had memories connected to them suggests they served as inalienable objects. That royal canoes and ʻOro canoes were decorated to be visually stunning and that their size required great labor investments indicates that such vessels served as highly visible symbols of elite wealth and sanctity. For example, like the ʻOro god figures, high status chiefs had "state canoes" called *anuanua*, glossed as the rainbow (Henry, 1928, p. 39; Handy, 1930, pp. 120, 190; see also Oliver, 1974, p. 787), reflecting the chiefs' close association with the gods who lived in the skies. Given their symbolic power, it is thus unsurprising that many steps in the manufacture of royal or ʻOro state canoes were highly ritualized (Henry, 1928, p. 119).

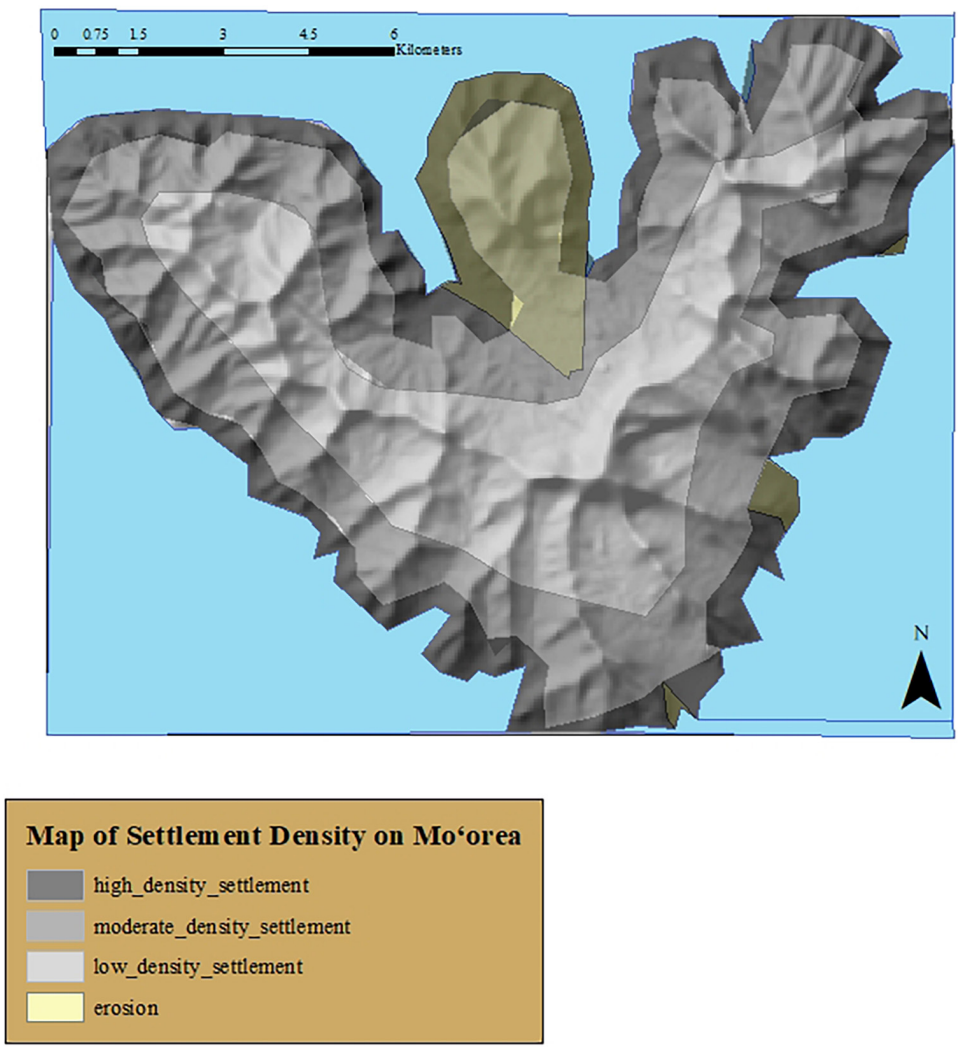

FIGURE 5 | Visualization of archaeological site densities and elevation for the Island of Moʻorea.

In sum, ethnohistoric and linguistic data demonstrate how the Society Islands, like other societies of Eastern Polynesia, used canoes as powerful metaphors for daily social relations, ritual practices, and cosmological worldviews. Equally important, the manufacture and use of large double-hulled canoes in many archipelagoes indexed clear socio-economic boundaries related to social hierarchy (chief vs. commoner), gender (male vs. female), and occupational specialization (fisher/farmer vs. craft specialists, specialized fisherman, priests, *'arioi*, warriors, etc.). In the most complex of Eastern Polynesian chiefdoms, such as the Society Islands, and archaic states, such as the Hawaiian Islands, large double-hulled canoes were prestige items expressly under the control of Paramount chiefs and Divine kings, used for both intra-archipelago elite travel and for military campaigns. Such data speaks to large ocean-going canoes having multi-faceted importance and to their role as highly valued prestige goods. Now we must turn to other proxy data concerning factors limiting the availability of large timber for large double-hulled canoe construction.

Settlement Pattern Densities, Landscape Elevation, Erosion, and Local Ecologies as Constraining Factors

As previously discussed, in Eastern Polynesia timber accessibility is key to canoe form, as the size of a canoe is based on the availability of large trees. This is all the more important when constructing a double-hulled canoe, as vessels for ocean-going voyaging were large in size. Given that certain islands and archipelagoes only had a few key tree species conducive to the manufacture of large double-hulled canoes, we can query to what extent island ecology and habitat, in addition to localized settlement patterns and settlement densities, put constraints on the production of ocean-going canoes.

Figure 5 provides a visualization of Mo'orea pre-contact settlement densities as mapped onto island elevation. Three categories are represented. High settlement density extends from c. 2 msl from the coast to lower to mid-valley reaches c. 100 msl. Moderately high settlement densities are found in the upper slopes of interior valleys c. 101–200 msl, where slope tends to be more severe and where land has to be more highly terraformed for ritual, residential, or agricultural use. Finally, the highest portions of the upper valley (c. 201–300 msl) have the lowest settlement densities, yet sometimes ritual mortuary, agricultural, and fortified sites are found in these upper elevations and rarely at even higher elevations (Kahn, 2005). If we assume that the Gambiers and the Societies had similar pre-contact settlement densities, the fact that Mangareva, the most elevated island in the Gambiers at 441 m, is one-quarter the height of Mo'orea is significant. As human populations increased on Mangareva, they had less vertical room to expand. This likely led to a situation where upper valley reaches in the Gambiers were more heavily settled and cultivated than those in the Societies.

Figures 6A,B visually model the ecological range of *Tamanu* and *Mara*, slow-growing hardwood trees used by the Mā'ohi to fashion large double-hulled canoes. It also depicts areas on Mo'orea island with high erosion, as derived from data reported in excavated archaeological sites. In some locations, excavations revealed significant volumes of colluvium overlaying prior living surfaces (ranging from 0.03 m in the upper limits of the 'Opunohu valley to 2.75 m in the bottom-most slopes

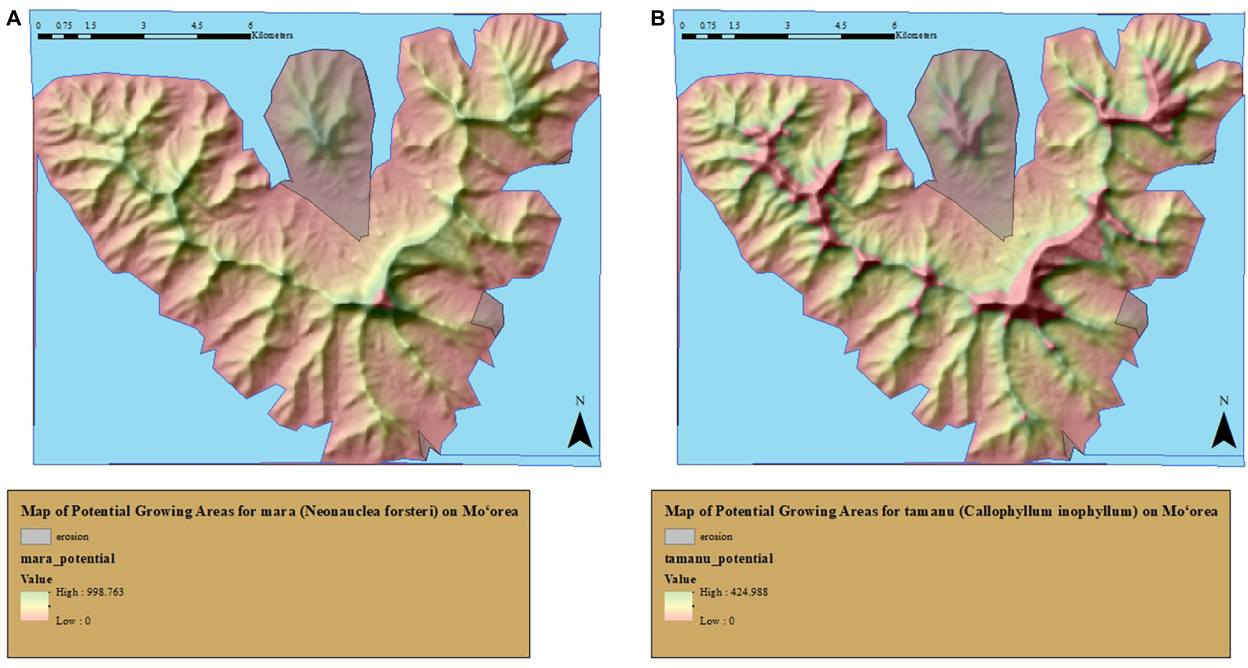

FIGURE 6 | (A) Visual habitat suitability model for *Tamanu* on the Island of Mo'orea; **(B)** visual habitat suitability model for *Mara* on the island of Mo'orea.

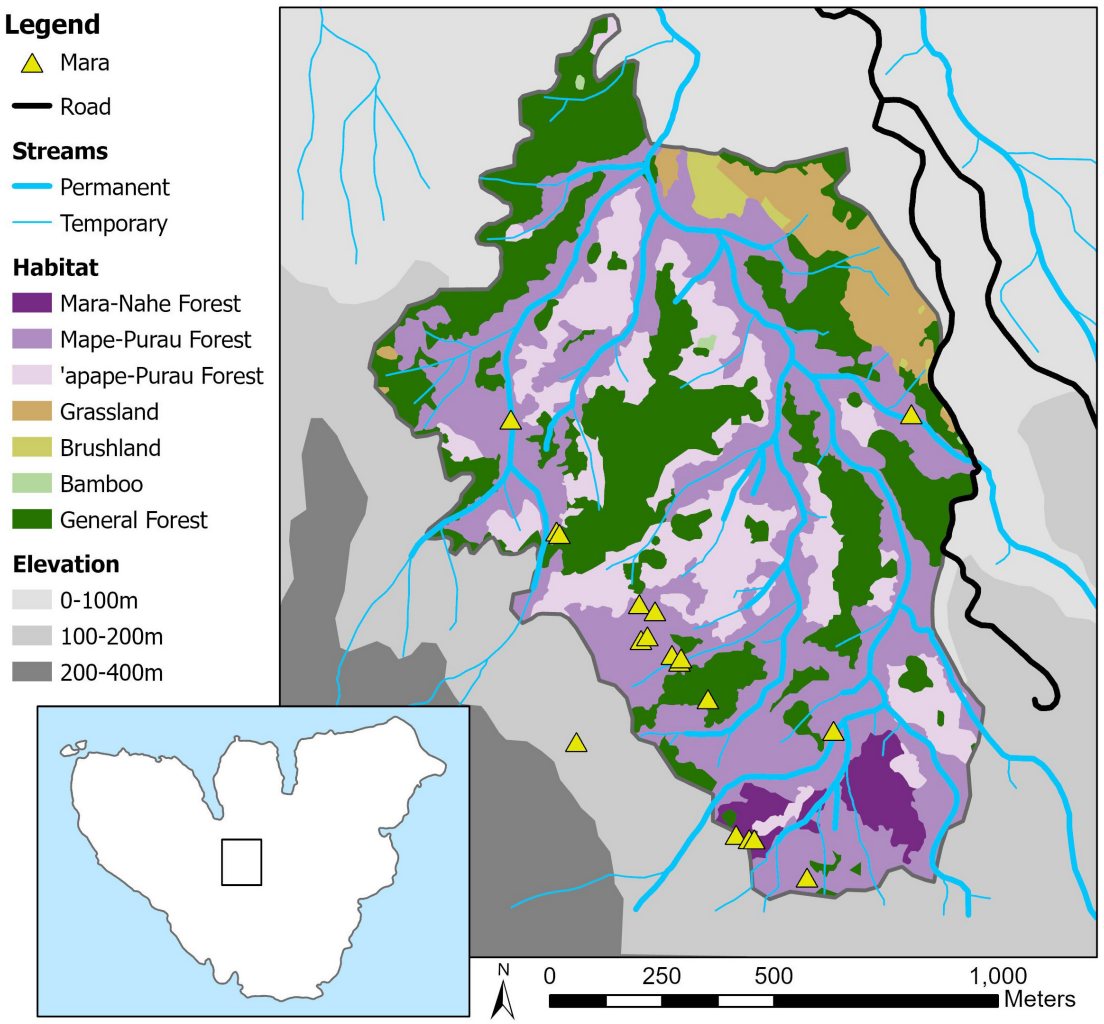

FIGURE 7 | Modern botanical survey of the middle sector of the ʻOpunohu Valley with *Mara-Nahe* forest elevational distribution and *Mara* isolates.

of the valley), supplying evidence for the heavy impact of swidden agriculture during the first few centuries following island settlement (c. 950 CE). We theorized that this process, which appears to have generally ceased around 1250–1400 CE, would have impacted the regrowth potential of large trees preferred for *vaʻa* hulls. This is because in addition to elevational limits for these trees (425 m for *Tamanu*, 1,000 m for *Mara*), there are also pH and soil type limits (4.0–7.4 in sandy well-draining soils for *Tamanu* and hydrophilic forests with well-drained soils for *Mara*). At the ecological limits for these trees, even if trees are viable, their growth potential may be impacted resulting in smaller statured trees. *Tamanu* in particular is a fairly slow-growing tree, which takes seven to eight years to mature, meaning harvesting the tree too early can result in lower re-seeding potential.

As can be seen in **Figures 6A,B**, *Tamanu* grows best at lower elevations than *Mara*. On Moʻorea, *Tamanu* habitats more closely overlap with areas of moderate settlement density, while *Mara* habitats are found at higher elevations associated with low-density settlement. The latter is well-illustrated in **Figure 7**, which provides results from a recent botanical survey in the Middle sector of the ʻOpunohu Valley (see JACG, 2011). Areas with the densest remnant *Mara-Nahe* (fern) forest are situated in upper elevations at the back of the valley (c. 200 msl), yet *Mara* trees are found growing as isolates at lower elevations. When comparing erosion patterns, settlement density, and preferred tree habitats, we can infer that it is highly likely that anthropogenically caused erosion impacted *Tamanu* growth rates on Moʻorea in the pre-contact era. In contrast, suitable habitats for *Mara* were likely less impacted, both by human-induced erosion and human settlement. As previously mentioned, Mangareva lacks *Mara* trees. Given the island's lower elevation, *Tamanu* growth on this island was likely more severely impacted by human-induced erosion and human settlement, likely contributing to generalized deforestation and the inability to sustain large double-hulled canoe manufacture.

CONCLUSION

Our canoe use web illustrates that in terms of technology, we should view ocean-going canoes as one of the most, if not the most, complex technologies found in Eastern Polynesia. In the Society Islands, such canoe construction and use required considerable raw material resources, expert knowledge for their construction, use, and maintenance, and the provisioning of expert boat builders and other community members during the course of their work. Clearly, social, economic, symbolic, and ritual actions were entangled in double-hull canoe manufacture, maintenance, use, and repair. Conventional narratives viewing ocean-going canoes as solely economic vessels used in voyaging, transport, and exchange fail to see their important use as wealth and prestige items of the elite class. Furthermore, we cannot ignore that their sustained production and use was a result of significant communal and specialized labor, nor that their symbolic links to the gods was one aspect of Māʻohi chiefs' social and ritual power.

Following this, in the complex chiefdoms of the Society Islands we view the continued construction and use of double-hulled canoes at European contact as implicated in critical facets of chiefly economic, sociopolitical, and ideological power. While use of canoes as proxies for chiefly symbolic power may have positioned Māʻohi communities to better safeguard the specific tree species used in their manufacture, island ecology and habitats in the geologically youthful high islands of the Society archipelago likewise positioned its residents to having more resilient habitats for long growing hard wood trees used in ocean-going canoe construction. In contrast, in the Open chiefdoms of Mangareva, local topography and ecology worked against sustainable harvesting of canoe species over the long term. We might also query whether double-hulled canoes never reached quite the same apogee of use as visual symbols of chiefly ideological and economic power in this archipelago, thereby negating some of the social forcing factors sustaining ocean-going canoe use in the Society Islands.

Since the 1970s, Polynesian societies have been deeply engaged in reviving their long-distance canoe cultures as a means of invigorating their cultural identity and pride. These efforts also serve as a means of returning to sustainable non-fossil fuel sea transport in the modern era (Nuttall, 2012), key issues in sea transport policy and financing in the region (Newell et al., 2017). By proxy, archaeologists have long established that the construction and use of large double-hulled voyaging canoes was directly responsible for supporting human population dispersals into Eastern Polynesia from a homeland in Western Polynesia. Likewise, a Central Eastern Polynesia interaction sphere lasting some 400–500 years after initial colonization of the region depended on the use of large ocean-going canoes. Yet, while Weisler (2002) documented a Mangarevan-Pitcairn group interaction sphere undoubtedly supported by ocean-going canoes, these networks of trade were abandoned in the fifteenth century. As we and others have argued, deforestation on Mangareva and a lack of timber for ocean-going canoe construction appears to have had regional impacts beyond Mangareva, likely serving as one cause leading to the abandonment of Pitcairn and Henderson islands (Weisler, 2002). Thus, we must view ocean-going canoes as critical items in the maintenance of pre-contact intra-archipelago social networks in Eastern Polynesia, all the more important as archipelagoes here are further distant from each other than in Western Polynesia, thus leading to greater island isolation.

As we argue, the dearth of direct archaeological evidence for canoe technologies has contributed to an under-representation of the processes surrounding the manufacture and voyaging of canoes and their impact on the structure of Eastern Polynesian settlement patterns, social hierarchies, and economic interactions as well as intra-archipelago interactions involving the exchange of material goods and ideas over eight centuries of pre-contact settlement. As we have demonstrated, ethnohistoric and linguistic data illustrate how some archipelagoes of Eastern Polynesia, like the Society Islands, used canoes as powerful metaphors for daily social relations, ritual practices, and cosmological worldviews. Equally important, the manufacture and use of large double-hulled canoes indexed clear socio-economic boundaries related to social hierarchy (chief vs. commoner), gender (male vs. female), and occupational specialization (fisher/farmer vs. craft specialists, specialized fisherman, priests, warriors, etc.). Like our ethnohistoric analysis, our canoe use webs illustrate how in the most complex of Eastern Polynesian chiefdoms, as with the Society Islands, large-double-hulled canoes were prestige items expressly under the control of Paramount chiefs, used for both intra-archipelago elite travel, military campaigns, and the amassing of tribute. Our network analysis reveals a highly connected set of interactions among elite social personae like chiefs and canoe builders for the chiefs, plants, and animals in the process of manufacturing and using large double-hulled-canoes. This is consonant with expectations for highly valued prestige items.

In returning to our larger question of why did some Eastern Polynesian societies retain the use of large ocean-going canoes, while others did not, we argue there are complex issues when managing forests today, as in the past (Vogt, 2006). Varied factors, like island height and isolation, island-wide settlement pattern densities, erosion patterns, and suitable habitats for canoe timber likely all played a role in the maintenance, or lack thereof, of double-hulled canoe technologies. As such, we posit that social processes as well as environmental factors constrained canoe manufacture and use in some Eastern Polynesian contexts, yet permitted double-hulled canoe manufacture in others. We end by acknowledging that future studies might investigate suitable habitats for other tree species used to fashion other types of canoes, such as *Artocarpus altilis* (breadfruit), and *Terminalia* sp. Furthermore, other aspects of canoe use, like the labor and skill needed for their production as derived from modern experimental studies, might be incorporated into future models examining large ocean-going canoes as wealth items in Eastern Polynesia.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/ **Supplementary Material**.

AUTHOR CONTRIBUTIONS

JK, AB, CE, and SC contributed to conception and design of the study. JK, AB, and CE organized the database. AB performed the network analysis. JK wrote the first draft of the manuscript. JK and AB wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.750351/full#supplementary-material

Supplementary Table 1 | Use Categories for Human-Centered Interaction Networks database. Entries after Verhagen et al. (2021, **Table 2**), excepting Cosmology, which is specific to the Society Island-Gambier Island HCIN databases and Ornamental, whose meaning has been modified in the current paper.

Supplementary Table 2 | Canoe Network Node Data Used in the Network Analysis.

Supplementary Table 3 | Details of select Eastern Polynesian societies and canoe types at the time of European Contact, after Forester, 1777; Wilkes, 1845; Roggeveen, 1908; Morrison, 1935; Haddon and Hornell, 1936; Lamb, 1984; Finney, 1994; Van Tilburg, 1994; Rolett, 2002; Howe, 2004; Irwin, 2006; Irwin and Flay, 2015; Thomas et al., 2016; Anderson, 2017; Irwin et al., 2017.

Supplementary Data Sheet 1 | R Code Used in the Network Analysis.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.