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Qualities and Contributions of Agroforestry Practices and Novel Forests in Pre-European Polynesia and the Polynesian Outliers

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Abstract

Agroforestry systems have long played a central role in Polynesian societies, contributing to food production, building and craft production, and ritual activities. Until recently, however, archaeological studies of these important systems were limited. Recent methodological improvements and a growing number of macro- and micro-botanical studies have provided opportunities for a more empirical exploration of the role of agroforestry in pre-European Polynesia. Here we integrate the findings of several key studies to assess the qualities and contributions of agroforestry across the region. We highlight the expansive and enduring qualities of these systems and contrast them with other forms of production used in this region. Overall, processes of novel forest formation in Polynesia shared key characteristics that affected a suite of activities ranging from subsistence practices to the construction of cultural landscapes. Integration of agroforestry research ultimately provides a nuanced understanding of landscape transformations that are broadly characteristic of island socio-ecosystems.

Keywords Agroforestry · Archaeology · Arboriculture · Novel Forests · Polynesia

Introduction

Humans are so successful at creating novel ecosystems that entire landscapes and environments can be described as domesticated (Chase 1989; Terrell *et al*. 2003; Yen 1989). Often, the formation of domesticated landscapes modifies ecosystem structure and function through the alteration of vegetation from a natural composition to an economically dominant suite of plants. Trees are keystones of these environments, and large-scale changes in their distribution and composition affect many biotic and abiotic components of ecosystems through cascading effects (Poch and Simonetti 2013). The process of landscape domestication creates vegetation patterns referred to as novel forests, defined as persistent forests that result from human activity and include a mix of introduced and native taxa (Lugo 2013). Once created, novel forests endure and replace the ecosystem services of native forests and serve additional functions (Lugo 2009; Mascaro *et al*. 2012). They are typically perceived by outsiders to be naturalized or even "wild," but indigenous knowledge systems proclaim – and research has demonstrated – their association with former agroforestry practices in several regions of the world (e.g., Balée and Erickson 2006; Ford and Nigh 2015; Kennedy and Clarke 2004; van der Warker 2005).

Trees have long been appreciated as important components of production systems in pre-European Polynesia (Kirch 1982; Yen 1973b) and their cultivation is referred to in a variety of ways (e.g., orchard gardening, arboriculture). We use the term agroforestry to refer to cultivation practices that are predominately arboreal-based where the manipulation, maintenance, and extraction of forest ecosystems are key goals (see Hviding and Bayliss-Smith 2000; Terrell *et al*. 2003). Even though the importance of these practices is recognized, research by archaeologists on Polynesian agroforestry has been extremely limited in contrast with root crop cultivation systems (see discussion in Huebert 2014; Kennedy 2012; Maxwell 2015). Agroforestry systems are sidelined in theoretical discussions because they do not fit neatly within available conceptual categories (e.g., intensification) of food production (Kennedy 2012; but see Yen 1974). The focus on intensified cropping in contrastive wet and dry environments (irrigation

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in the former, dryland field systems in the latter) has relegated agroforestry to secondary or supplementary resources, resulting in a significant gap in our understanding of the economic and ecological consequences of human land use in pre-European Polynesia.

A surge in agroforestry research has taken place in the Pacific in the last decade. Improvements in remote sensing and archaeobotanical analyses have challenged and modified previous perspectives on the long-term history and the development of agroforestry on several islands (Dotte-Sarout and Kahn, 2017; Huebert and Allen 2016, 2019; Lincoln and Ladefoged 2014; Maxwell 2015). This research creates opportunities to address critical questions relating to the patterning, use, and importance of agroforestry at a regional scale. We argue that the best way to understand agroforestry and novel forests in Polynesia is as low-labor multi-generational resources, which comprise a particular form of *biotic* landscape capital (see discussion in Brookfield 2001:184; Erickson 2008:161), distinct from the better-known *geomorphic* landesque capital characterized by a permanent infrastructure of terraces, canals, or field systems (Blaikie and Brookfield 1987). This is a form of incremental capital (after Doolittle 1984) that possesses enduring and expansive characteristics. Several characteristics of agroforestry practices and the novel forests that result are complementary to other forms of production, while their emergent qualities affect economies and local environments over long periods. We first discuss the qualities of agroforestry across Polynesia and the Polynesian outliers, after which we explore agroforestry's contribution to economic production, long-term resource availability, and cultural landscape construction.

The Qualities of Agroforestry in Pre-European Polynesia

Polynesia forms the eastern region of Oceania (Fig. 1) and it is split into two sub-regions: West Polynesia (e.g., Tonga, Sāmoa, Futuna, Uvea) and East Polynesia (e.g., Society Islands, Marquesas, Hawai'i, New Zealand, Rapa Nui). This division is based primarily on culture-historical factors rather than simple geography, and the sub-regions have archaeological sequences of considerably different time spans. West Polynesia was settled from islands to the west (e.g., the region extending from the Bismarck Archipelago to Vanuatu) around 2850 years ago as part of the Lapita diaspora (Burley *et al*. 2015). In contrast, East Polynesia was settled ~1800 years later, with the apices of the Polynesian triangle (Hawai'i, New Zealand, and Rapa Nui) settled between the tenth to the thirteenth centuries AD (Athens *et al*. 2014; Wilmshurst *et al*. 2011). Populations in East Polynesia stem either from West Polynesia directly or via a group of islands called the Polynesian outliers (Kirch 2017; Wilson 2012). Outliers are islands whose populations speak Polynesian languages and exhibit Polynesian cultural traits, but are geographically located outside and to the west of the Polynesian Triangle. The two outliers of focus here (Tikopia and Anuta) were originally settled as part of the Lapita diaspora around 2800–3000 years ago (Kirch 1984; Kirch and Swift 2017), with later arrival and integration of groups from West Polynesia occurring in the late first and early second millennia AD.

Most of the agroforest tree species in Polynesia were first domesticated or brought under cultivation in the Southeast Asia-Near Oceania region and transported into the Pacific with human migration (Kirch 2017). Tree crops were a major element of the Lapita subsistence strategy (Kirch 1989; Matthews and Gosden 1997), and following dispersal, elements of agroforestry practices were nearly ubiquitous across Polynesia. Some of these trees might have been dispersed at times by agents other than humans (Fall *et al.* 2007: Appendix 1); however, the association of persistent novel forests with former human land use implies that their distributions were largely human-mediated (Huebert and Allen 2019; Quintus 2018). Here we focus our discussion on the best-documented cases to illustrate the diversity of agroforestry practices (Table 1). The emphasis is on food-producing trees, though taxa with other functions are also discussed (Table 2).

West Polynesia and the Polynesian Outliers

West Polynesia and the Polynesian outliers constitute the earliest occupations reviewed herein. Although they include longer agricultural sequences than elsewhere, the process of novel forest development was protracted and large-scale modified forests do not appear in most islands until the late first and early second millennia AD. By European contact, however, agroforestry systems were well established and contributed significantly to ecological and economic systems on most of these islands—especially those of smaller size.

The Polynesian outlier Tikopia offers a classic case study. Early documentation recognized a "high state of economic utilization" (Firth 1936:375), dominated by a form of tree cropping first described as "orchard gardening" (Firth 1936, 1965). A detailed ethnobotanical study by Kirch and Yen (1982) showed that the island's novel forest mosaic, consisting of 19 species of tree crops, covered 95% of the island (Kirch 2007:90). The dominant economic tree was breadfruit (*Artocarpus altilis*), with coconut (*Cocos nucifera*) also important (Kirch and Yen 1982). The agroforestry system also included the more widespread Tahitian chestnut (*Inocarpus fagifer*) and vī apple (*Spondias dulcis,* syn. *cythere*), and trees typically not found in Polynesia proper, such as the sago palm (*Metroxylon salomonense*)*,* betel nut (*Areca catechu*)*,* and Nali nut or canarium almond (*Canarium indicum*) (Kirch and Yen 1982:33; Kirch 1994:300–301).

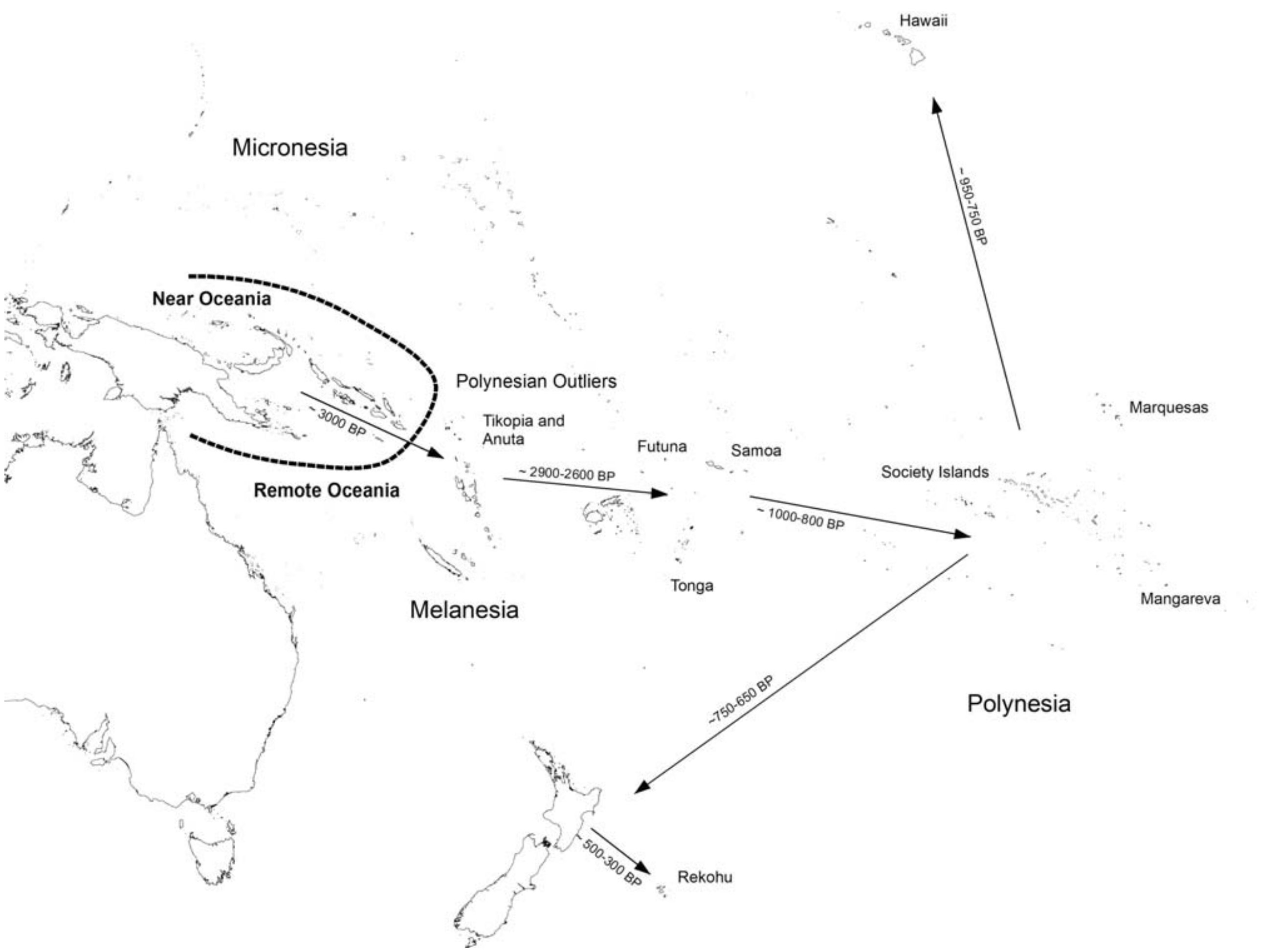

Fig. 1 Map of Oceania with major locations discussed in the text

These trees were grown in permanent multi-story gardens with understory crops of banana (*Musa* spp.), giant swamp taro (*Cyrtosperma merkusii*), and yam (*Dioscorea* spp.) grown between and under larger trees (Kirch 1994:291). Kirch and Yen (1982:38) note that these multi-story forests "mimic the mixed nature of the low-altitude forest associations typical of the Solomon Islands flora, not only in tree species, but also in the subcanopy." Humans dispersed some native trees, both on the mountain slopes and the coast, through seeding. For example, the Alexandrian laurel (*Calophyllum inophyllum*) is a natural component of the strand vegetation but was intentionally planted by seed in coastal and inland locations to increase the abundance of its desirable wood (prized for canoe hulls) and to stabilize the coastal beach ridges (Kirch and Yen 1982:28). Leaf-lined subterranean pits or silos for the fermentation of starches, notably breadfruit and banana, were used on Tikopia as an important reserve for seasonal food supplies (Kirch and Yen 1982:43–45).

Agroforestry was widespread in West Polynesia and the Polynesian outliers, but research in locations outside Tikopia is more limited. As in Tikopia, agroforestry on the West Polynesian island of Futuna was constituted by breadfruit and coconut (Kirch 1978), between and underneath which were grown banana (both *Eumusa* and *Australimusa* forms), giant taro (*Alocasia macrorrhizos*), and several species of yams (Kirch 1994:181). Tree crops were planted amongst residential units situated along the coast, as well as more extensive plantings throughout the zone of cookhouses inland of the dwellings, and again at the base of the mountain slopes (Kirch 1994:181) (Fig. 2). Similar zonal distributions and species appear to have existed in Sāmoa based on ethnographic evidence and the present extent of vegetation (Krämer 1902-03; Quintus 2018). While also similar on the western outlier of Anuta (Yen 1973a), where agroforestry with understory crops (Fig. 3) was key to maintaining one of the highest population densities in the Pacific, a slight deviation is apparent wherein root crops were grown in intensive, short-fallow plots on the higher elevation plateau of the island. The extent of unmodified forests on Anuta, as well as on Ofu/Olosega in the Manuʻa Group of American Sāmoa, is extremely limited because of small island size (Yen 1973a; Quintus 2018), making them more similar to Tikopia than to Futuna in the relative

Table 1 Natural and cultural characteristics of locations discussed in text

Island Group	Type	Location	Date Settled	Substrate Ages	Rainfall Range	Land Area	Primary Food Crop (s)	Widespread Storage?	References for Date Settled
Tikopia	Singe Island	Polynesian Outlier	3000–2700 BP	< 0.08	4000	4.6	Breadfruit, coconut, betel nut, Tahitian chestnut, vī apple, sago palm	Present	Kirch and Swift 2018
Anuta	Single Island	Polynesian Outlier	2800–2400 BP	*	3000–3500	0.4	Breadfruit, coconut, betel nut, Tahitian chestnut	Present	Kirch 1984
Futuna	Single Island	West Polynesia	2800–2600 BP	*	2500–3500	83	Breadfruit, coconut, Tahitian chestnut, vī apple, mountain apple, Sago palm	Present	Frimigacci 1990
Sāmoa	Archipelago	West Polynesia	2800–2600 BP	0–5.2	2500–6000	3050	Breadfruit, coconut, Tahitian chestnut, vī apple, mountain apple	Present	Petchey 2001
Tonga	Archipelago	West Polynesia	2850–2750 BP	0–4	1700–2970	700	Breadfruit, coconut, Tahitian chestnut, vī apple, mountain apple	Present	Burley *et al.* 2015
Society Islands	Archipelago	Central East Polynesia	1000–800 BP	<1.0–4.5	1200–2000	1700	Breadfruit, coconut, vī apple, mountain apple	Present	Stevenson *et al.* 2017
Mangareva	Island Group	Central East Polynesia	1000–900 BP	5	2500–3500	29.6	Breadfruit, coconut, Tahitian chestnut	Present	Kirch *et al.* 2010
Marquesas	Archipelago	Central East Polynesia	900–700 BP	0.4–5.5	700–1500	1050	Breadfruit, coconut	Present	Allen 2014
Hawaiʻi	Archipelago	North Polynesia	950–750 BP	0–5.1	200–10,200	16,650	Breadfruit, coconut, candlenut	Absent	Athens *et al.* 2014
Rēkohu	Archipelago	South Polynesia	500–300 BP	4	900–1500	950	Kōpi	Present	Maxwell 2015

degree of vegetation modification. Close associations between domestic and tree-cropping areas have been noted for Tonga as well, where haphazard arrangements of breadfruit and coconut trees were associated with residential units (Beaglehole 1967:934), while other early visitors documented the presence of economic trees at the margins of tuber gardens (La Billardiere 1800:378; La Perouse 1799:171).

The temporal development of novel forests in West Polynesia and the Outliers remains poorly understood. First millennium BC introductions of breadfruit, *vī* apple, and Tahitian chestnut have been demonstrated for Tonga (Ussher 2015:221–232). The archaeobotanical record further suggests multi-story gardens that integrated arboreal species with understory crops were created early in the Tongan sequence (Ussher 2015:235–236, 251, 266), with economic trees present thereafter in different quantities (Fall 2010:263–267). In the Manuʻa islands of Sāmoa, charred breadfruit wood has been directly dated to only within the last 1000 years (Quintus 2018); similarly, agroforestry on Tikopia did not become dominant until after about AD 900 (Kirch and Yen 1982:350–355; Kirch 1994:301–302). There, a decline and then total cessation of the use of fire (i.e., swidden, or shifting cultivation) in the island's production systems marks the transition.

The remains of fermentation pits also provide some evidence of temporal trends. On Tikopia, these pits become common after AD 1200, reflecting an increased reliance on breadfruit or bananas (Kirch 1994:303; Kirch and Yen 1982:333). On Futuna, multiple storage pits have been dated to the end of the first millennium AD (Frimigacci 1990:168–169) implying more intensive tree cropping by that time. Finally, on the western islands of the Sāmoan archipelago, storage pits may date to as early as the first millennium BC (Green 2002), potentially suggesting early reliance on some tree species, or possibly banana.

Central East Polynesia

Nowhere in Polynesia has agroforestry been better documented, both ethnographically and archaeologically, than in the Marquesas and Society Islands. European explorers commented repeatedly on the magnitude and productivity of agroforestry systems in these islands, where breadfruit was emphasized (de Bougainville, 1772; Forster 2000; Robarts 1974). Several visitors were struck by the spatial extent of these systems, particularly in the Marquesas, where they gave the appearance of an entirely cultivated landscape (von Krusenstern, 1813:124–14).

The prominence of breadfruit in the Marquesas and Society Islands is inferred, in part, by the prevalence of fermentation pits (see Huebert 2014 for Marquesas; Kahn 2005:160–163 for Society Islands). This is especially true for the Marquesas where such pits reached diameters as large as 10 m (Handy

Table 2 List of taxa mentioned in text, with notes on primary uses and geographic range

Scientific Name	Common Name	Key Uses[a]	Natural Range	Relevant Extended Range
Aleurites moluccana	Candlenut	Raw material (lighting, dye/ink), lighting	Tropical Asia	Tropical Polynesia and Hawai'i
Areca catechu	Betel Nut	Secondary food	East Asia	Polynesian Outliers and West Polynesia
Artocarpus altilis	Breadfruit	Food, raw material, ritual	Near Oceania and Southeast Asia	Tropical Polynesia and Hawai'i
Broussonetia papyrifera	Indian mulberry	Raw material (bark cloth)	Japan or China	Asia to Polynesia
Calophyllum inophyllum	Alexandrian Laurel	Raw material (timber, oil)	Tropical East Africa to parts of East Polynesia	Hawai'i
Canarium indicum	Nali nut	Food, raw material	Island Southeast Asia through Near Oceania	Polynesian Outliers
Cocos nucifera	Coconut	Food, raw material (fiber), adornment	Old World Tropics to parts of East Polynesia	Polynesia
Corynocarpus laevigatus	Kōpi (karaka in New Zealand)	Food	New Zealand	Rēkohu
Fagraea berteroana	Pua, pua kenikeni (Hawai'i), perfume-flower tree	Raw material (timber), ornamental	Fiji to the Marquesas	Hawai'i (Modern)
Ficus prolixa	Polynesian banyan	Raw material (bark cloth), ritual	New Caledonia to the Marquesas	NA
Hibiscus rosa-sinensis	Red hibiscus	Ornamental	Old World Tropics	Tropical Polynesia
Hibiscus tiliaceus	Beach hibiscus	Raw material (fiber)	Old World Tropics to Eastern Polynesia	Hawai'i
Inocarpus fagifer	Tahitian chestnut	Food, raw material (timber)	Indo-Malaysia	Tropical Polynesia
Metrosideros polymorpha	ōhi a lehua	Raw material, ornamental	Hawai'i	NA
Metroxylon vitiense	Sago palm (ota in Futunan)	Food, raw material	Fiji	Futuna
Metroxylon salomonense	Sago palm	Food, raw material	Near Oceania	Polynesian Outliers
Morinda citrifolia	Noni, Indian mulberry	Raw material (dye), medicinal, secondary food	Southeast Asia	Tropical Polynesia and Hawai'i
Pandanus tectorius	Screwpine	Raw material (fiber), secondary food, adornment	Tropical Africa to Polynesia	NA
Pipturus albidus	Waimea pipturus	Medicinal	Hawai'i	NA
Pritchardia pacifica	Pacific fan palm	Secondary food, ornamental	Tonga	West Polynesia
Schizostachyum glaucifolium	Polynesian bamboo	Raw material	Fiji	Tropical Polynesia and Hawai'i
Spondias dulcis syn. *Cythere*	Vī apple (also, Otaheite apple)	Food	Indo-Malaysia	Tropical Polynesia
Syzygium malaccense	Mountain apple	Food, raw material	Indonesia	Tropical Polynesia and Hawai'i
Thespesia populnea	Pacific rosewood	Raw material (timber), dye	Tropical Africa to parts of East Polynesia	Areas of East Polynesia
Touchardia latifolia	Olonā	Raw material (fiber)	Hawai'i	NA

[a] Many plants had medicinal and minor utilitarian uses not noted herein

Fig. 2 Zonation of arboriculture and irrigation on Futuna in 1974. In the foreground is the Aloalo (hillslope) arboriculture zone, dominated by breadfruit (the main crowns visible) with some coconut and understory of bananas and yams. Beyond that is the zone of irrigated pondfields, and then the village arboricultural zone, with breadfruit, coconut, and various other fruit and nut trees. Photograph taken by Patrick Kirch

1923:188–189). Storage at such a scale was necessary given environmental and climatic fluctuations that resulted in variability in food production in the Marquesan archipelago (Allen 2010; Kirch 1982:3), but large stores were also an important source of chiefly influence in both the Marquesas and Society Islands (Kahn *et al*. 2014:256; Kirch 1991:128–129). In addition to breadfruit, coconut was a significant part of these systems, as were other arboreal crops including candlenut (*Aleurites moluccana*), mountain apple (*Syzygium malaccense*), and Tahitian chestnut (albeit possibly at a later time; see Huebert and Allen 2016; Dotte-Sarout and Kahn 2017:17), with understory crops also playing an important role (e.g., banana, taro) (Lepofsky 1999, 2003; also see Addison 2006).

At least two agroforestry techniques were utilized in these island groups: house gardens and expansive patches of novel forests. House gardens were located close to habitations and were more intensively managed (Lepofsky 1999). Early European visitors noted that in these house gardens, understory crops such as taro and paper mulberry were planted alongside fruit trees in dense concentrations (von Krusenstern, 1813:125; Lisiansky 1814:73). The expansive systems, in contrast, appear to have been less diverse and focused largely on breadfruit, coconut, and banana, covering most valley floors and hillslopes at the time of European contact (Forster 2000:336; Lepofsky 1999).

Trees evidenced by archaeobotanical materials found in the region (Dotte-Sarout and Kahn 2017; Huebert 2014) provided a variety of other resources as well. In Central East Polynesia, these plants include several types of hibiscus (*Hibiscus* spp.), screwpine (*Pandanus* spp.), Pacific rosewood (*Thespesia populnea*), Alexandrian laurel, Polynesian bamboo, noni (*Morinda citrifolia*), and several others (Table 2). Breadfruit wood, for example, was used as posts for dwellings in elite structures (Kahn and Coil 2006). There is also evidence that

Fig. 3 A view directly into the agroforestry zones of Anuta in 1971. Visible is the understory of giant swamp taro as well as a canopy of breadfruit and betel palms. Photograph taken by Patrick Kirch

trees defined culturally important spaces, as the planting of Alexandrian laurel might have been restricted to places used by persons of higher social status (Huebert 2014:273; Kahn and Coil 2006).

Agroforestry systems, and consequent novel forests, were widespread in Central East Polynesia outside the better-documented cases. For instance, the Mangareva (Gambier) Islands of southeastern Polynesia documented a subsistence system in which breadfruit and other tree crops, including coconut and Tahitian chestnut, played a dominant role. Hiroa (1938) describes the traditional subsistence system in which breadfruit (again frequently ensiled in storage pits, Fig. 4) was the most important crop, augmented by other tree crops and by small irrigated systems for taro cultivation. Such examples, even if not well documented at present, attest to a wide distribution and overall importance of novel forests and agroforestry practices in this area.

Recent archaeological research has begun unraveling the temporal development of these systems in Central East Polynesia. For Maupiti Island in the Societies, forest structure appears to have changed shortly after the first settlement of the island in the thirteenth to fourteenth centuries, with novel forest landscapes in place by the seventeenth century (Dotte-Sarout and Kahn 2017). The diversity of plant species found in archaeobotanical assemblages is indicative of a mixed exploitation strategy in a mosaic landscape that incorporated

Fig. 4 A large pit for breadfruit fermentation and storage in Rikitea, Mangareva. The pit is part of a complex, including the Catholic cathedral (built in the 1840s) and the king's residence. The cathedral was built upon the foundation of the former marae (the most important marae in Mangareva), thus the pit itself could well pre-date the missionary period. Photograph taken by Patrick Kirch in 2012

different stages of agroforest development, including fallow (Dotte-Sarout and Kahn 2017:17–18). Vegetation changes were not only geared toward creating food-producing landscapes; evidence suggests propagation of ritually charged—but also economically important—plants (e.g., banyan trees, pua kenikeni or perfume-flower tree [*Fagraea berteroana*]) to define social space over time (Dotte-Sarout and Kahn, 2017:16–17). Evidence of the temporal development of agroforestry is also available from Moʻorea and Tahiti. Breadfruit and Tahitian chestnut were present after the fifteenth century in the ʻOpunohu Valley of Moʻorea (Lepofsky 1994:291–292; Lepofsky *et al*. 1996), and agroforestry practices had expanded across inland slopes of the island by the fifteenth to the seventeenth centuries (Kahn *et al*. 2015). On Tahiti, breadfruit is noted by the fourteenth century and continues into contemporary times, with the presence of Tahitian chestnut noted later (Orliac 1997).

A protracted developmental sequence of forest development, involving several overlapping processes, is also well documented for the Marquesas (Huebert and Allen 2016, 2019). Reductions and even extirpation of some native arboreal species were noted in coastal and lowland forests of Nuku Hiva within a few centuries of settlement (Huebert 2015). This spatially extensive analysis also demonstrated that economic trees were established very early in the cultural sequence, alongside several root crops (Allen and Ussher 2013). Evidence points to a rapid dispersal and increasing uptake of tree crops in the fifteenth century in multiple locations, following forest clearance and repetitive burning, with arboriculture centered on breadfruit coming to dominate these landscapes by the mid-seventeenth century. Huebert and Allen (2016:92) also noted that several cultivated trees, most importantly Tahitian chestnut, might not have been introduced until late prehistory, as other researchers have noted for Central East Polynesia.

Finally, a stratified sequence of macro- and micro-botanical remains from Agakauitai Island in the Mangareva group documents the gradual emergence of a novel forest over six centuries, beginning around AD 1200 (Kirch *et al*. 2015). The early archaeobotanical assemblage is dominated by indigenous trees such as Beach hibiscus and Pacific rosewood, but also includes Polynesian-introduced coconut, candlenut, and the medicinal shrub or small tree noni. The frequency of breadfruit wood charcoal rises significantly over time, suggestive of its increasing prevalence in agroforestry.

North Polynesia

The Hawaiian archipelago defines the northern extent of Polynesia. Much attention has been paid to the archipelago's labor-intensive rain-fed and irrigated systems that were developed across the islands (Ladefoged *et al*. 2009), as these have been linked to the rise of social inequality and political complexity (Hommon 2013; Kirch 2010). Less attention has been devoted to agroforestry even though multiple known agroecological zones were associated with such practices (e.g., Lincoln and Ladefoged 2014; Winter and Lucas 2017).

As elsewhere in Polynesia, breadfruit is known to have been one of the staple starches in the Hawaiian diet, but it was not preferred (Handy *et al*. 1972). Somewhat unique to Hawaʻi, however, was the presence of named breadfruit groves on several islands (Cook 1784: 120; Handy *et al*. 1972:152–153; Meilleur *et al*. 2004:17), suggesting they were seen as capital investments for food and non-food products. On Hawaiʻi Island, European explorers noted the high productivity of tree crops, and the growth of understory crops, in an agroforestry belt termed the kaluʻulu (Kelly 1983; Menzies 1920). In addition to breadfruit, coconut and candlenut, among others, are known to have been cultivated in this zone (Lincoln and Ladefoged 2014:195). This system was spatially distinct and dependent on elevation-based ecosystem changes (Lincoln *et al*. 2018). Here, trees were spaced further apart, forming an open canopy that allowed greater light penetration with intensive tree management that included pruning to maintain a lower canopy height (Cook 1784). This form of agroforestry contrasts with that practiced in West and Central East Polynesia, as does the limited use, or even total absence, of pit fermentation and storage of breadfruit. The reason for this lack of storage is not known but could relate to the more limited importance of breadfruit in the diet or the practice of feeding excess breadfruit to pigs (Lincoln and Ladefoged 2014).

Outside defined agroforestry zones, a mix of more intensive cultivation strategies and agroforestry were found in areas of human habitation (Winter and Lucas 2017:470–472). Coconut was grown widely, especially along the coast and

Fig. 5 A maintained agroforestry system on Maui island representative of multi-story systems. This system includes giant taro, taro, coconut, candlenut, pandanus, *ōhi a ai*, Polynesian bamboo, banana, ti, and hibiscus. The maintained system is on *kuleana* land, implying that it has been passed down within a family. Photograph taken by Noa Lincoln

near coastal villages, as was pandanus. Large tracts of candlenut groves were grown to enhance soil fertility for the growth of taro (Handy *et al*. 1972:51). Recent research suggests that the transition from these candlenut forests to mixed agroforestry practices is associated with underlying soil fertility (Lincoln in press). Colluvial slopes of river valleys and gentle slopes in windward regions were planted with economic trees, among other crops (Kurashima and Kirch 2011), in a way that matched the closely spaced multi-story agroforests in West and Central East Polynesia (Fig. 5). There is evidence from Land Commission Award maps from the mid-nineteenth century that patches of native forest were retained within some heavily cultivated areas. In these situations, a native canopy, typically of ōhi a lehua (*Metrosideros polymorpha*), was retained as a habitat for medicinal and raw material plants (e.g., *Pipturus albidus, Touchardia latifolia*). Tended novel forests were present at higher elevations as well, outside areas of direct human habitation, and were constituted by a mixture of introduced and native species used for food, construction materials, and medicine (Winter and Lucas 2017:462).

Coconut was transported with the initial island settlers, as was candlenut (Athens *et al*. 2014:147). According to oral traditions and a limited number of dated samples, breadfruit was brought late in the thirteenth century or slightly later (McCoy *et al*. 2010), though the tree is uncommon until the fifteenth-sixteenth century (Allen and Murakami 1999:90). Extensive investigation of archaeological charcoal in fire pits on Oʻahu shows an increase in the use of introduced trees over time, especially in and after the fifteenth century (Dye and Sholin 2013). This temporal development is broadly consistent with increases in the diversity of economic trees on Kauaʻi in the sixteenth and seventeenth centuries (Kahn *et al*. 2016). Both of these studies speak to the relatively late development of novel forests. Similarly, given the spatial scale of the kaluʻulu, it is likely that it was only established after the social developments that gave rise to considerable intergroup cooperation, most likely no earlier than the sixteenth or seventeenth century (Allen 2004:219; Lincoln and Ladefoged 2014:200).

South Polynesia

South Polynesia, defined as the southern sub-tropics, is at the margin of food production in the region. As one consequence, agroforestry in New Zealand focused on plants not available in tropical Polynesia such as karaka (Māori) / kōpi (Moriori) (*Corynocarpus laevigatus*), an endemic broad-leaf that produces an edible drupe (though the edible seeds required additional processing to remove toxins [see Bell 1974:329–329]). Leach and Stowe (2005: 21-23) argue convincingly for the importance and partial domestication of karaka by pre-European Maori. While native in the northern North Island, the tree was widely translocated beyond its natural range and is seen in dense concentrations often associated with settlement areas (Leach and Stowe 2005:14–17) and sweet potato production (Leach and Stowe 2005:18–19). Ethnographic accounts of karaka document that the tree crop was part of a larger subsistence practice that included gardening (Harris and Te Whaiti 1996: 274, 276, 280). The practice, therefore, was similar to those described elsewhere in the Eastern Pacific but incorporated a local species in the place of tropical Polynesian tree crops.

The pre-European importance and development of karaka/ kōpi agroforestry is best documented for Rēkohu (Chatham Island) (Maxwell 2015; Maxwell *et al*. 2016), where it is known ethnographically as an important resource (Skinner and Baucke, 1923; Williams 1898). The tree is not native to the island and was transferred from mainland New Zealand (Atherton *et al.* 2015). Once there, kōpi provided a significant portion of food resources for the human population (Maxwell 2015:246–249) and it exhibits larger drupes compared to mainland New Zealand (Maxwell and Tromp 2016). The trees were of such subsistence importance that they were avoided as sources of fuel; forest management on Rēkohu also encouraged successional plants useful for fuel and species that were wind resistant (Maxwell *et al*. 2016:323). Maxwell (2015:261-262) demonstrated that kōpi required careful management for propagation to dominate the forest and the increased propagation of the tree was a strategy to increase survival in this island environment. The onset of forest modification to induce the growth of kōpi appears to have begun shortly after island settlement in the fifteenth to the seventeenth centuries and continued through human selection of management to European contact. Kōpi became a major portion of the broadleaf forest by late pre-European times (Fig. 6) (Maxwell *et al*. 2016:308).

The Contributions of Agroforestry Practices and Novel Forests

Novel ecosystems were widely created to facilitate—and enhance—production across Polynesia. Landscape modifications such as terraces increased soil capture and reduced erosion (Allen 2004). If mulched as well, these practices presumably facilitated soil development and enhanced soil nutrients (Lincoln and Vitousek 2016). In wet environments, terraces were used to construct artificial pondfields connected to canals that directed water into systems from streams and other sources (Addison 2006; Campbell 2003; Kirch 1977; Lepofsky 1994). Other forms of infrastructure, such as embankments, mounds, and mulches, counteracted the impacts of wind evaporation in dry landscapes (Barber 2013; Lincoln *et al*. 2018; Marshall *et al*. 2017). Finally, pits were excavated and organic media were created to cultivate root crops on atolls (Chazine 2012) and also on young lava flows (Lincoln in press).

What is often overlooked is the constructive nature of agroforestry practices that filled spatial gaps between and complemented other production systems (Table 3). As with walls, terraces, or other forms of production, trees are assets that serve a variety of functions over long time periods (Brookfield 2001), best characterized as incrementally created landscape capital (see Doolittle 1984). Agroforestry practices created novel forests that were extended and modified through a process of accretion; over time, these actions transformed previously unusable tracts of land into productive economic landscapes. Few have recognized the importance of incremental forms of agroecological change characteristic of agroforestry systems in the Pacific in contrast to the systematic and formal construction of new dryland and wetland infrastructure. The biotic components of incremental landscape capital provided enduring resources that structured and transformed ecological systems and cultural practices throughout Polynesia.

Fig. 6 One of the last remaining stands of old growth forests of kōpi on Rēkohu, Kaingaroa Forest in 2017. Visible in the foreground is a rākau momori (lit. Memorial tree). Photograph taken by Justin Maxwell

The modern forests of most Polynesian islands offer evidence of economic landscape development sequences that began with initial human settlement (see Figs. 2, 3, 5, 6), and there was a re-assortment and reduction in the number species as populations moved eastward (see Kirch 1982; Yen 1973b). In contrast to rapid forest replacement, recent research shows that the formation of novel forests on these islands was the result of long-term processes of selection and management that spanned centuries (e.g., Dotte-Sarout and Kahn 2017; Dye and Sholin 2013; Huebert and Allen 2016; Kirch *et al.* 2015; Maxwell *et al*. 2016). Still, the process occurred more rapidly in the east than in the west. The use of many types of plants, though principally breadfruit and coconut in most places but kōpi in Rēkohu, created production systems where labor, maintenance, and exploitation costs were low compared to other types of cultivation (Lincoln and Ladefoged 2014). In addition to supplying food, these systems formed reservoirs of raw materials for construction, medicine, and ornamental use. This enduring landscape capital enhanced economic and social production as well as ecosystem resilience.

Trees and Economic Production

An underappreciated aspect of agroforestry in Polynesia is its broad spatial extent. Constraints of substrate age, precipitation, elevation, soil quality, and evapotranspiration restricted the distribution of intensive root crop production on Polynesian islands (Vitousek *et al*. 2014), but agroforestry spanned nearly the entire range of diverse island and archipelago landscapes encountered by settlers (Table 1). Such adaptability allowed trees to fill spatial gaps in production systems, principally vertical space and steep terrain, but also excessively rocky, infertile, cold, or saline lands; this ultimately increased landscape-level productivity. It is no coincidence that some of the highest population densities in the Pacific were found on islands where agroforestry dominated, such as Tikopia and Anuta (Kirch and Yen 1982; Yen 1973a). In the Society Islands, early European visitors were struck by the distribution of economic resources in generally rough terrain (Lepofsky 1999, 2003). In locations with rugged topography, as in the case of some Marquesan valleys or Sāmoan and Tikopian hillslopes, agroforestry provided a means to cultivate without environmental degradation, as tree roots helped to stabilize soils. Perhaps more importantly, the low labor effort required for agroforestry provided a way to cultivate steep

Table 3 Contrasts and complements between agroforestry and Oceanic root crop cultivation. Most of the contributions of agroforestry and novel forests results from the extensive and enduring nature of these systems

	Contribution of Agroforestry and Novel Forests	Key Contrast(s) and Complements with Oceanic Root Crop Cultivation
Spatial Extent of Production	Extended cultivation outside nutrient sweet spots; used coastal plains with high salinity and sand content; vertical production	High degree of adaptability and high species diversity relative to root crops, agroforestry not wholly constrained by nutrient thresholds
Political Economy	High marginal returns increased surplus; fruits used to feed wealth assets; forests were controlled by elites; woods as means of craft production and ritual reproduction	Long-lived tree resources become multi-generational and regenerating wealth assets contrasting with annual root crops
Long-Term Production	Deep root systems increased nutrient availability; trees leaves acted as mulch; trees potential fixed atmospheric nitrogen	Improved growth of understory crops; created more efficient nutrient cycling for sustainable production relative to intensive root crop systems
Variance Reduction	Created regenerating banks of resources; breadfruit was key storage crop; diversity of exploited ecological locations staggered harvest times	Storage of root crops relatively rare outside of New Zealand and Anuta; root crop cultivation is generally not self-propagating
Cultural Landscape	Contributed to maintenance of group and individual memory; thought of as ancestral objects; used as points of spatial reference	Long-lived resources attached to the social memory of groups and individuals contrasted with annual plants and herbaceous perennials

terrain with limited labor inputs. Root crops can be grown in these areas, but labor requirements increased as land becomes steeper while land clearance destabilized slopes. This was also the case in Hawai‘i, where breadfruit and other trees and shrubs were grown on steeper valley slopes (Lincoln and Vitousek 2017:22–23). Across the region, coastal plains also were covered with breadfruit and coconut, which could grow in nutrient-deficient calcareous sediments exposed to sea spray and/or brackish water. In Hawai‘i, very young lava flows with minimal soil development were brought into cultivation only with the use of arboreal species, both directly (Lincoln and Ladefoged 2014) and indirectly, as they were sources of compost for built soils (Lincoln in press). This filling of spatial gaps was especially important on small islands such as Tikopia, Anuta, and the Manu‘a Group of American Sāmoa where high population densities were supported by extensive tree cropping (see Yen 1974).

Novel forests replace ecological functions of natural forests (Smith *et al*. 2012) and may even exceed levels of previous functionality in some areas (Mascaro *et al*. 2012). The maintenance and enhancement of ecosystem functions can increase the long-term productivity of environments, in terms of human economic practices, through a variety of mechanisms. Trees generally possess deep root systems that result in the uplift of nutrients from considerable depth in the soil profile to the surface (Jobbagy and Jackson 2001; Smith *et al.* 2012). Trees and other vegetation may also increase the rate at which parent material is weathered and reduce nutrient leaching (Jobbagy and Jackson 2001). Nutrient-enhancement functions were important where the conjunction of high rainfall and relatively old substrate ages (e.g., Sāmoa, Societies, Marquesas) reduced nutrient availability through leaching to a point where root crop production could not otherwise be practiced. The inclusion of trees that fix atmospheric nitrogen, specifically the introduced and leguminous Tahitian chestnut (Pauku 2006:6), enhanced these outcomes. Introduced nitrogen-fixing trees can potentially lead to increased ecosystem productivity (Mascaro *et al*. 2012:234), and their incorporation likely helped to sustain nitrogen concentrations needed for intensive cultivation. More generally, the use of trees in multi-story gardens created a useful mulch used both in house gardens and more expansive agroforestry systems (Handy *et al*. 1972; Lepofsky 1999; Lincoln in press). These ecosystem services are not restricted to the past, and novel forests continue to contribute to maintaining the functionality of modern ecosystems in Polynesia.

The capacity of agroforests to produce food is critical to discussions of surplus and its role in Polynesian political economies. Agroforestry production enhanced surplus through enduring, high marginal returns (see Lincoln and Ladefoged 2014), especially because of the expansive nature of long-lived resources such as trees. The contributions of tree-cultivation systems reduced economic dependence on other production strategies and provided the means to feed herds of pigs that acted as wealth assets, especially in Hawai’i (Allen 2004:216; Dye 2014; Lincoln and Ladefoged 2014:200). Trees, groves, and plantations were seen as wealth assets in their own right as well, controlled and employed by elites and others. Elite control is indicated by the association of these resources with named individuals in Hawai‘i, the most well-known of which is the coconut grove Helemoa planted by order of Kākuhihewa in what is now Honolulu (Lincoln and Vitousek 2017). The spatial association between agroforestry plots and political boundaries further suggests that these resources were closely managed (Lincoln and Ladefoged 2014; Lincoln in press). In the Marquesas, house gardens were owned by individual families, but the large and extensive plantations were controlled by the chiefs (Handy 1923:182). Control of fermented breadfruit stores also became a political strategy in the Society Islands, the Marquesas, and Mangareva, exploiting the qualities of breadfruit as seasonal and storable (Kahn *et al*. 2014; Kirch 1991). This is illustrated especially well in Mangareva where large district fermentation pits were given proper names, in a similar fashion to groves of trees elsewhere, marking them as the property of corporate groups under the control of chiefs (Hiroa 1938:207).

The use of trees and their products as wealth assets extends beyond food production, and cultivated forest species were associated with manifestations of power (e.g., monumental architecture, ritual activities) (Dotte-Sarout and Kahn 2017; Kahn and Coil 2006; Kolb and Murakami 1994; Millerstrom 2006). At times, the intersection between raw material use and food production was used to create symbols of wealth. Breadfruit wood was a prestigious construction material in throughout the region (Hiroa 1930:19–20; Kahn and Coil 2006:342); Whistler (2001:90) opines for Sāmoa that this might relate to the fact that cutting the tree for use in building results in a loss of productivity. Similarly, in the Society Islands the use of highly prized native tree timbers (i.e., *Calophyllum inophyllum, Fagraea berteroana*) in construction is associated with prestige (Kahn and Coil 2006). The political or ritual consumption of woods for non-subsistence use demonstrated the control of both functional and symbolic components of novel forests (e.g., the means of craft production and the ritual means of cosmogonic reproduction). Such control was highlighted through proxemics (Kahn and Coil 2006; Millerstrom 2006); archaeologically, this is manifested in the spatial correlation of some species, in relic or archaeobotanical form, with ritual architecture or elite structures (Dotte-Sarout and Kahn 2017).

Diversification and the Enduring Production Reservoirs of Novel Forests

The ability of agroforestry to buffer environmental variability in Oceania, both in and outside of Polynesia, has been noted previously (Allen 2004; Latinis 2000; Yen 1974). These practices can be employed to minimize temporal variance as well as reduce the risk of catastrophic loss. Planting of trees increased crop diversity, the spatial diversity of a production system, and the seasonal spread of harvest. Subsistence system diversification, as defined by Latinis (2000), aids in reducing the effects of hazards that impact particular crops or cultivation techniques. Several authors have argued that variance-minimization might have been the impetus for the original investments in Polynesian agroforestry (Allen 2004; Huebert 2014). For instance, Huebert (2014:292) notes the ability of some trees to persist through droughts (e.g., breadfruit) and others to produce in inundated environments (e.g., Tahitian chestnut). Over time, the expansive qualities of agroforests created an opportunity for the exploitation of multiple ecological zones. Not only are place-specific hazards mitigated by this strategy, but ecological differences in the location of agroforestry resources can also result in staggered harvest times that maintain the availability of food resources (Lepofsky 2003:86).

Enduring novel forests enable food buffering in a way other techniques do not, owing to their regeneration year after year with minimal (or no) labor inputs. The preservation of native forest within otherwise cultivated zones in Hawaiʻi indicates a desire to create easily exploitable resource reservoirs. In times of need, these enduring "stored" or "banked" resources can be called upon. For example, tree fruits and seeds such as pandanus, noni, and Pacific fan palm (*Pritchardia pacifica*) — plants that are generally not part of the subsistence economy — were used in times of famine in Sāmoa (Whistler 2001:46–47). The continued management of these tree species owes much to their myriad uses for raw materials or in medicinal preparations, and, as a by-product, result in their availability to provide famine foods. Similarly, the economic trees that are part of fallow systems after root crops are no longer actively cultivated, as in the case of Futuna (Kirch 1994), create production reservoirs that can be tapped in times of shortfall.

A component of these systems is the capacity for fruits such as breadfruit to be stored in subterranean pits (Cox 1980), or processed kōpi drupes to provide storable food for as long as several years (Salmon 2001). There is little doubt that the capacity for storage led to the widespread cultivation of breadfruit (Kirch 2006:204), especially in locations susceptible to environmental unpredictability such as the Marquesas (Allen 2010; Huebert, 2014:292–293) and Tikopia (Kirch and Yen 1982:43–46). Furthermore, storage allowed for the efficient use of seasonal crops like breadfruit, mitigating seasonal gluts and avoiding substantial losses from rot. Storage of kōpi on temperate Rēkohu functioned in a similar way, though with starker seasonality. In fact, given its nutritional characteristics and the limited alternative sources of starch and carbohydrates, the long-term sustainability of settlement was predicated on this process (Maxwell 2015:279–281).

Construction of Cultural Landscapes

In addition to their key role with respect to economic and ecological systems, agroforestry shaped the creation of social landscapes in Polynesia. People use trees to create places (Jones and Cloke 2002) through the production of meaning and reference points that are socially important (Pearce *et al.* 2015). Generation of novel forests inscribed history and created a relationship with the past (Hviding and Bayliss-Smith 2000:8–11), represented by place names and associations with extended families. In Polynesia, the symbolic construction of environments is a component of the transported landscape (after Kirch 1982). The growth of native and introduced trees was one of the mechanisms by which humans constructed these symbolic landscapes, principally along with stone architecture, which were tied to cultural memory and spatial logic.

Novel forests created and structured the cultural environment within which people lived in ways that were unlike other cultivated spaces because they endured over generations. Individuals planted economic trees on the property of others to enhance their reputations across generations (Firth 1965:263). The planting of the tree, and the subsequent production reaped by the family on whose land on which it was planted, translated to the construction of individual and group social capital in a way not documented for other forms of production. This was done only with long-lived trees to prolong the memorial to the individual who planted it.

Across Polynesia and the Outliers, populations constructed sacred places through the management of trees. In some cases, sacred groves were homes to spirits, with the consumption of products from these forests tightly controlled (Olson 1997). In other places, native and introduced trees served as ritual markers in conjunction with architecture (Dotte-Sarout and Kahn 2017:10–17; Handy 1923:119; Kahn and Coil 2006; Millerstrom 2006:290). Trees were used also to humanize the environment, illustrated on Rēkohu through the practice of carving on living trees (Fig. 6). These carvings, or rākau momori, provided a tangible link between different time periods, and modern-day groups inhabiting Rēkohu maintain an interpretation of these carvings as representations of ancestors and events (Barber 2012:447). The association of these trees with ancestors and the past more generally contributes to the maintenance of individual and group identity.

Polynesian spatial logic moderated normal activity outside defined sacred areas and novel forests served as reference points as people moved through these different spaces. Different vegetation compositions were components of socio-ecological zonation that structured human activity (Kirch 1994; Olson 1997; Winter and Lucas 2017). This is not to say that boundaries were immutable, as they certainly were dynamic, but rather that boundaries depended partially on the active use of enduring resources. Trees remain an important component of modern cultural landscape construction in Polynesia (Barber *et al*. 2014) that should, and does, inform contemporary forest management policies (Maxwell 2017; Winter and Lucas 2017).

Conclusions

Research in the tropics and sub-tropics has globally illustrated how human production systems have come to dominate ecosystems through long-term management and selection processes (Balée and Erickson 2006; Ford and Nigh 2015). The development of these landscapes is, at least in some sense, a form of enduring capital investment subsequently transmitted to the next generation for future modification (see Brookfield 2001; Erickson 2008:161), and trees were an important part of these systems. Agroforestry was once widespread in Polynesia, which allows us to better understand and appreciate the composition of contemporary vegetation communities—and ultimately the ecosystem functionality that exists today throughout the region. Trees are multi-generational resources grown in a wide range of ecological conditions. We have demonstrated that in Polynesia, these systems share key fundamental characteristics but have variable components, which have made them an important avenue to investigate the various ways novel forests relate to long-term economic and ecological processes. For centuries, agroforestry practices and the novel forests that endured on these landscapes provided the bulk of raw materials people used for subsistence, craft, construction, and ritual activities. Fully acknowledging the role of agroforestry in Polynesia and integrating details of its development and use into studies of human history provides a more nuanced understanding of the ecological and cultural histories of the islands and contributes to contemporary management of the region's diverse forests. This research also makes a contribution to our understanding of key long-term processes that occur in island socio-ecosystems.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no financial or non-financial conflicts of interest.

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