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Indigenous Polynesian Agriculture in Hawaiʻi

Noa Kekuewa Lincoln and Peter Vitousek

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Summary and Keywords

Agriculture in Hawaiʻi was developed in response to the high spatial heterogeneity of climate and landscape of the archipelago, resulting in a broad range of agricultural strategies. Over time, highly intensive irrigated and rainfed systems emerged, supplemented by extensive use of more marginal lands that supported considerable populations. Due to the late colonization of the islands, the pathways of development are fairly well reconstructed in Hawaiʻi. The earliest agricultural developments took advantage of highly fertile areas with abundant freshwater, utilizing relatively simple techniques such as gardening and shifting cultivation. Over time, investments into land-based infrastructure led to the emergence of irrigated pondfield agriculture found elsewhere in Polynesia. This agricultural form was confined by climatic and geomorphological parameters, and typically occurred in wetter, older landscapes that had developed deep river valleys and alluvial plains. Once initiated, these wetland systems saw regular, continuous development and redevelopment. As populations expanded into areas unable to support irrigated agriculture, highly diverse rainfed agricultural systems emerged that were adapted to local environmental and climatic variables. Development of simple infrastructure over vast areas created intensive rainfed agricultural systems that were unique in Polynesia. Intensification of rainfed agriculture was confined to areas of naturally occurring soil fertility that typically occurred in drier and younger landscapes in the southern end of the archipelago. Both irrigated and rainfed agricultural areas applied supplementary agricultural strategies in surrounding areas such as agroforestry, home gardens, and built soils. Differences in yield, labor, surplus, and resilience of agricultural forms helped shape differentiated political economies, hierarchies, and motivations that played a key role in the development of sociopolitical complexity in the islands.

Keywords: agriculture, agroforestry, biogeochemistry, cropping systems, dryland, Hawaiʻi, indigenous, irrigated, Polynesian, rainfed, traditional, wetland

Prologue

I walk through a cattle pasture in the North Kohala district of Hawaiʻi Island as Peter animatedly describes the intensive dryland agricultural system that once blanketed this landscape. Looking out across the knee-high ocean of grass, I find it hard to envision. We take a sharp turn and begin to hike up the puʻu (cinder cone) towering over the otherwise smooth landscape. As we trudge up the steep hill, battling 35 mile-an-hour tradewinds, I glance at the sparse ironwood trees bent over by the wind and wonder how anything productive could grow in this harsh environment. Finally, after reaching the summit, I pause to catch my breath and turn to enjoy the view. What I see takes my breath away. Where moments ago there was nothing but a grassy expanse, the elevated perspective reveals, like a magic 3-D eye book, row after row after row of ancient agricultural infrastructure extending as far as can be seen, off into the horizon. These are the field walls that formed the backbone of Hawaiian dryland agriculture. In that moment, gazing out from the center of the 25 square-mile Kohala field system, my perception of ancient Hawaiʻi instantly changes. Even as a Kanaka Maoli (Native Hawaiian) who was taught our stories and history as a child, even as a mahi ʻai (traditional farmer) who has learned from my elders in the traditional fashion, and even as an academic who has studied Hawaiian agriculture from a scientific perspective, my understanding of what my ancestors were doing in the islands before European contact was woefully inadequate when faced with this reality of their accomplishments. Although I had previously explored the remnants of traditional Hawaiian farming across the state, its breadth is nowhere recognizable like it is in Kohala. Here, on top of Puʻu Kehena, looking out at the endless expanse of archaeology laid out before me, I realize for the first time the immense scale and scope of what occurred here. Such a feat of landscape alteration could only have been accomplished by a massive labor force within a highly organized society. This was not the works of villages and family clans, or small chiefly hierarchies. This was the work of a nation.

Ten years after my first glimpse of the ancient Kohala field system, our collective understanding as scientists, historians, and cultural practitioners of the Hawaiians' agricultural accomplishments remains incomplete. Through archaeological digs, soil sampling, biogeochemical mapping, and ethnographical recordings, we continue to uncover some of the adaptations, innovations, and mechanisms used to achieve an incredible scale of food production—one that sustained a population greater than exists on most of the Hawaiian Islands today, and was accomplished without the use of any external inputs. Our aim now is not only to use this information to better understand the past, but to apply the lessons learned from our ancestors to inform and help guide modern agriculture development in Hawaiʻi today.

Key Hawaiian Words Used in Text

Loʻi—Flooded or irrigated agricultural terraces
Māla—Dryland (rainfed) agricultural areas
Ahupuaʻa—Traditional land division that extended from the uplands to the ocean, subset of a region
Moku—Traditional land division; region
Akua—Gods
Aliʻi—Chiefs
Moʻolelo—Stories/History

Common Hawaiian Crop Names Used in Text

ʻAwa—Kawakawa, *Piper methysticum*
ʻAwapuhi—Shampoo Ginger, *Zingiber zerumbet*
Ipu—Bitter Gourd, *Lagenaria siceraria*
Hala—Screwpine, *Pandanus tectorius*
Kalo—Taro, *Colocasia esculenta*
Kī—Ti Leaf, *Cordyline fruticosa*
Kō—Sugarcane, *Saccharum officinarum*
Kukui—Candlenut, *Aleurites molloccana*
Maiʻa—Plantains/Bananas, *Musa spp*.
Niu—Coconut, *Cocos nucifera*
Noni—Cheese fruit, *Morinda citrifolia*
ʻOhe—Bamboo, *Schizostachyum glaucifolium*
ʻŌhiʻaʻai—Mountain Apple, *Syzygium malaccense*
ʻOlena—Turmeric, *Curcuma longa*
Pia—Polynesian Arrowroot, *Tacca leontopetaloides*
ʻUala—Sweet Potato, *Ipomoea batatas*
Uhi—Greater Yam, *Dioscorea alata*
ʻUlu—Breadfruit, *Artocarpus altilis*
Wauke—Paper Mulberry, *Broussonetia papyifera*

Background—Hawaiʻi as a Model System

Hawaiʻi offers a near-perfect matrix of biogeochemical factors. Spawning from a stationary hotspot, each island subsequently emerges in an orderly age and orientation; the eight youngest islands (the permanently inhabited ones) represent substrates ranging from fresh lava to highly weathered soils approximately 5.5 million years old (Juvik & Juvik, 1998). The high mountain peaks and dominant northeastern tradewinds interact to form some of the strongest rainfall gradients in the world, producing semi-desert, rainforest, and bog ecosystems separated by only a few hours walk (Giambelluca et al., 2013). This orthogonal combination of age and rainfall gradients creates highly diverse, yet predictably organized, patterns of soil fertility and geomorphology that, in turn, construct very different opportunities and constraints for the development of agriculture (Ladefoged et al., 2009; Vitousek, 2004).

Hawaiʻi also is unique in its sociopolitical history. The relatively late Polynesian colonization of the islands allows for its entire human history to be traced, while the near-total isolation of the culture provides a relatively closed system for societal evolution (Kirch, 2007). Yet, Hawaiʻi developed high-density populations and sophisticated systems of governance and land management (Hommon, 2013; Kirch, 2005, 2010A). In fact, Hawaiʻi is one of the few places considered to have developed into a "state" system, with vast areas controlled through a complex political hierarchy (Hommon, 1976, 2013; Kirch, 2010A). This multifaceted development process was supported by agricultural surplus that provided the resources needed to invest time and energy in societal progress. In turn, varying degrees of political stability and hierarchy throughout the islands influenced further agricultural developments by allowing the large-scale mobilization of labor and investment into land-based capital improvements (e.g., Kolb, 1997). Perhaps nowhere in the world can the interactions between the environment, agriculture, and social systems be observed so readily as they can in Hawaiʻi. Because of this, Hawaiian agriculture has been described as a "model system" for understanding the complex interaction between people and place; the archipelago offers an unparalleled combination of complexity and tractability that allows for the isolation and understanding of key factors in ecosystems and human societies (Kirch, 2007).

Polynesian agriculture reached a zenith within Hawaiʻi. More than any other Polynesian islanders, Hawaiians predominantly relied on agriculture rather than marine resources for food (Handy & Handy, 1972). They intensified virtually every arable habitat (Ladefoged et al., 2011), made productive extremely marginal environments (e.g., Schilt, 1984), utilized innovation to develop unique farming methods (McCoy & Graves, 2010A), and sustained production for hundreds of years without the use of external inputs, metals or draft animals, or legume or cover crops. Not only are these achievements yet to be widely recognized, but, in many cases, the mechanisms behind them are still poorly understood. Nevertheless, the extraordinary nature of Hawaiian agriculture has not gone unnoticed. Early visitors to the islands noted that Hawaiian agriculture practices "far exceed in point of perfection the produce of any civilized country within the tropics" (Menzies, 1920, p. 81), and archaeologists have marveled that "the Kona Field System is without equal in Hawaiʻi, and probably in the nation, in terms of the extensiveness of a prehistoric modification of the land" (Newman, 1974, p. 8).

Agriculture in pre-European Hawaiʻi was *the result of the interaction between a people and their environment* and cannot be understood without a basic understanding of the ecology, culture, and social complexity of the islands. The ultimate state of labor and political organization allowed for the construction of massive intensive agricultural developments, while the rapid growth and transformation of Hawaiian society allowed for the preservation of specific, place-based agricultural techniques. In this way, indigenous Hawaiian agriculture is an *extraordinary example of cultural evolution, innovation, and adaptation within an environmental context*. Before inhabiting the fertile volcanic slopes of Hawaiʻi, the original settlers had a millennia-long legacy of inhabiting islands incapable of supporting agriculture at the scale seen in Hawaiʻi (Yen, 1993). With the settlement of Hawaiʻi, *agricultural practices that were new and unique to Polynesia, and indeed to the world, were developed in coordination with the environment in order to maximize the productivity and resilience of the new landscape*.

In this chapter we explore the social and cultural pathways of Hawaiian agricultural developments and how they relate to the opportunities and limitations presented by the landscape. Using oral histories, observations, traditional knowledge, and scientific findings we trace, to the extent possible, the rapid expansion and intensification of Hawaiian agriculture from the arrival of Polynesians to its apex, as observed upon the arrival of Europeans. We focus on plant-based agriculture (ignoring animal husbandry and aquaculture that were both large contributions to food production) to provide an overview of planting styles and methods while exemplifying how they were adapted to place-specific considerations. Throughout this chapter, we attempt to weave the inseparable cultural values attached to the crops and agricultural systems themselves. Finally, we examine the interplay between agriculture, culture, and society in Hawaiʻi, in which we hope to illustrate the complex interactions and multifaceted influences that comprise ancient Hawaiian agriculture.

Kuamoʻo ʻŌlelo—A History of Hawaiʻi and Hawaiian Agriculture

Wā Waʻa—The Time of the Canoe

The master navigators who initially located and settled Hawaiʻi stemmed from Southeast Indochina (Pierson et al., 2006), through the large island of New Guinea (Soares et al., 2011) and then westward across the Pacific (Kirch, 2000; Pearce & Pearce, 2010). Colonization of the extremely remote Pacific Islands is one of the great accomplishments of humankind. Earliest human movements into Near Oceania began about 40,000 years ago, followed by Austronesian speakers out of Southeast Asia about 4,000 years ago that led to the emergence of the famous Lapita cultural complex (Kirch, 2010B). The Lapita expansion into Remote Oceania, commencing about 1200 BC, led ultimately to the settlement of the vast Eastern Pacific, concluding with the colonization of Hawaiʻi (for discussion see Box 1), Rapa Nui, and ultimately New Zealand about 1250 AD (Kirch, 2010B).

Box 1. When Did Polynesians Settle Hawaiʻi?

The date of human settlement of Hawaiʻi is a contested topic. While some analyses push for a colonization date as late as 1250 A.D. (Rieth et al., 2011), extensive and widespread samples indicate that Hawaiian populations were already well established in many environments by that time. Current archaeological evidence suggests that Hawaiʻi was certainly inhabited by the 11th century A.D. (Kirch, 2011, 2014). Kirch (2014) expresses that Hawaiʻi may have been colonized within the 10th century, but doubts establishment occurred any earlier due to the timeline of settlement of Polynesia at large. Oral histories indicate that 89 generations passed prior to the arrival of Captain Cook, which targets a similar, but earlier, date of settlement (Cachola-Abad, 1993, 2000).

With people came essential plants and animals needed to establish new settlements. Like the humans who transported them, the introduced plants primarily originated from the East (except the sweet potato—see Box 2). As the Polynesians colonized subsequent islands from the “entrance” of Polynesia (Tonga) (Burley, Barton, Dickinson, Connaughton, & Taché, 2010), they carried fewer and fewer plants with them (Whistler, 2009) because only a portion of the plants and people who initially settled, adapted, and developed progeny on each island moved on (or were transported) to the next. This process of island hopping played an important role in defining the horticultural assortment of Hawaiʻi, with systematically less genetic diversity arriving to each successive settlement (e.g., Chang et al., 2015; Zerega, Ragone, & Motley, 2004). In particular, there was a reduction of plants propagated by seeds, which were particularly vulnerable on the long ocean voyages. By the time settlers reached Hawaiʻi, the vast majority of the food and resource plants were propagated through vegetative means, such as by tubers, root suckers, or cuttings (Whistler, 2009; Zerega, Ragone, & Motley, 2006). Great care was taken to properly protect these precious plants through the open-ocean voyages. For instance, root suckers were "wrapped in well rotted coconut husk fiber … the whole thing … wrapped in dried leaves … then a … basket woven around the entire[ty]" (Schattenburg, 1976, p. 44). The canoes themselves were not only vessels carrying the agricultural crops, but examples of their worth: the sails were woven from the leaves of the hala, the cordage braided from the niu husk, and the hulls caulked with the sap of the ʻulu.

Upon arriving in Hawaiʻi, the Polynesians encountered lush river valleys and sweeping volcanic plains situated upon tall mountain peaks—an ideal landscape for agriculture. They also encountered an endemic flora that included very few fruits, tubers, or otherwise edible plants. The development of agriculture was therefore based almost entirely on introduced crops. At least 23 plants were introduced into the agricultural economy of the Hawaiian people; an additional five species lack distinction, and may have either been Polynesian introduced or indigenous to Hawaiʻi (Table 1) (Whistler, 2009). Table 1 provides a short summary of each crop introduction along with some of the endemic plants that were absorbed into the Hawaiians' horticultural practices (Abbott, 1992; Krauss, 1993; Lincoln, 2009; Lincoln, Chadwick, & Vitousek, 2014; Whistler, 2009).

Although many of the crops arrived with the initial voyage(s), some crops, such as ʻuala, ʻulu, and ipu were introduced considerably later through postcolonization, round-trip voyages (Ladefoged, Graves, & Coil, 2005; McCoy, Graves, & Murakami, 2010). That Polynesian voyagers made consistent, long-distant trips to conduct trade and other missions is well documented (e.g., Collerson & Weisler, 2007). Multiple origin stories point to seafarers from Hawaiʻi departing and returning with ʻulu trees; some stories indicate people blown off course to sea, while others indicate targeted voyages made specifically to acquire a crop (Meilleur, Jones, Tichenal, & Huang, 2015). Often times these voyages are connected to stories of individual sacrifice and relief from famine, a theme occasionally found in traditional moʻolelo (Green & Pukui, 1929; Thrum, 1923).

Table 1: Summary of Key Hawaiian Crops

Crop	Status	Brief Description of Primary Uses	Agricultural Zone (As in Kona, Hawai			
			Kula	Kaluulu	Apaa	Ama
Aleurites moluccana (Kukui)	*P*	Dye, wood, ink, oil, medicine	-	xx	x	x
Alocasia macrorrhizos (Ape)	*P*	Food	-	x	x	x
Artocarpus artilis (Ulu)	*P*	Food, caulking, wood, sandpaper	-	xxx	xx	-
Broussonetia papyifera (Wauke)	*P*	Fiber	x	xxx	x	
Calophyllum inophyllum (Kamani)	*X*	Wood	x	-	-	-
Cocos nucifera (Niu)	*P*	Food, wood, fiber, water, medicine	xxx	-	-	-
Colocasia esculenta (Kalo)	*P*	Food	-	x	xxx	x
Cordia subcordata (Kou)	*I*	Wood	xx	-	-	-
Cordyline fruticosa (Ki)	*P*	Physical resource, food	-	x	xxx	x
Curcuma longa (Olena)	*P*	Medicine, food	-	x	x	-
Dioscorea alata (Uhi)	*P*	Food	-	-	xx	xx
Dioscorea bulbifera (Hoi)	*P*	Food	-	x	x	x
Dioscorea pentaphylla (Pi'a)	*P*	Food	-	x	x	x
Heteropogon contortus (Pili)	*I*	Thatching	xxx	-	-	-
Hibiscus tiliaceus (Hau)	*X*	Fiber, medicine	xx	-	-	-
Ipomea batatas (Uala)	*P*	Food	xx	xxx	xxx	-
Lagenaria siceraria (Ipu)	*P*	Physical resource, food	xx	x	-	-
Morinda citrifolia (Noni)	*P*	Medicine, dye, food	xxx	-	-	-
Musa spp (Maia)	*P*	Food	-	xxx	xxx	xx
Pandanus tectorius (Hala)	*I*	Plaiting, fiber, food	xx	x	-	-
Piper methysticum (Awa)	*P*	Mild narcotic	-	xx	xx	x
Pipturus albidus (Mamaki)	*E*	Medicine	-	-	-	xx
Saccharum officinarum (Ko)	*P*	Food, medicine	-	x	xxx	x
Schizostachyum glaucifolium (Ohe)	*P*	Physical resource	-	-	xx	x
Syzygium mallaccense (Ohia ai)	*P*	Food, wood	-	xx	x	x
Tacca leontopetaloides (Pia)	*P*	Food	-	xx	-	-
Tephrosia purpurea (Auhuhu)	*P*	Fish poison	xx	-	-	-
Thespesia populnea (Milo)	*X*	Wood	xx	-	-	-
Touchardia latifolia (Olona)	*I*	Fiber	-	-	-	xx
Zingiber zerumbet (Awapuhi)	*P*	Medicine, cosmetic	-	x	x	x
P=Polynesian Introduced, I=Indigenous, X=Unclear			*xxx=prevalent, xx=occasional, x=prob*			

Box 2. The Sweet Potato Enigma

The sweet potato was originally domesticated in tropical America, where it is known as kumara (Zhang et al., 2004). Genetic and linguistic evidence supports that the sweet potato in Polynesia came directly from South America (Denham, 2013; Roullier et al., 2013). Similar genetic studies have well documented the dispersal of Polynesian crops from Southeast Asia and Indochina. Associated implications for human migrations are often drawn from the plants, such as from breadfruit (Zerega et al., 2004, 2006) and paper mulberry (Chang et al., 2015, Gonzalez-Lorca et al., 2015; Seelenfreund et al., 2011). It was thought that, along with the sweet potato, gourds and chickens in the Pacific also originated in the Americas, but, although still debated, recent genetic analyses appear to indicate Eastern Pacific origins for both (Clarke et al., 2006; Fitzpatrick & Callaghan, 2009; Thomson et al., 2014). With the general acceptance that sweet potato is the sole exception to the origin of Polynesian crops, the argument turns to how it arrived into the Pacific—via American voyaging (e.g., Heyerdahl, 1950), via natural plant rafting (e.g., Montenegro, Avis, & Weaver, 2008), or via round-trip voyaging of Polynesians to the Americas (e.g., Finney, 1994). Given the voyaging prowess of the Polynesians, and their colonization of Rapa Nui (Easter Island) relatively close to South America, the authors favor the final hypothesis.

Less clear is how many individual cultivars of each crop might have been introduced. Genetic analyses appear to indicate that relatively few varieties were introduced, with only 5–8 closely related groups of kalo (Irwin, Kaufusi, Banks, De La Peña, & Cho, 1998; James, Bolick, & Imada, 2012) and kō (Schenck et al., 2004) arising. From the handful of introduced crop cultivars, Hawaiian agriculturalists developed a diversity of varieties within each individual crop. Over 300 varietal names of kalo have been recorded, with nearly 80 distinct varieties remaining in collections today (Whitney, Bowers, & Takahashi, 1939). Similarly, some 200 names of ‘uala and 40 varieties of kō have been documented (Handy, 1940; Lincoln, IN PRESS). The development of a new variety was done in two ways—by selecting a mutation from a bud or slip and then isolating and rearing it, or by controlling pollination (Palmer, 2001). Handy and Handy (1972) explain the process of creating and selecting varieties of plants through mutation:

> In a matter of shrewd observation of varieties and careful, conscious selection of mutants in the creation of subvarieties of their plants, the Hawaiians were truly experimental horticulturalists. New varieties are still consciously created by selecting sports[1] from bud or slip mutation. A variant sport, growing as a banana or taro shoot, or from a potato slip, is termed a keiki (child). If the mutant produces desirable food, or is liked for its color, leaf form, or vigor, it is replanted and given a name, generally that of a grower or locality; and if it is really of value, it will be shared with friends. Thus, presumably, have the hundreds of named

> varieties of old Hawaiian taro and sweet potato, and the less numerous varieties of banana, sugarcane and ʻawa, been originated.
>
> (p. 21)

The crop varieties excelled in different climates and soils, and exhibited different levels of resistance to diseases and pests. Several varieties of a crop were planted together, which accomplished multiple goals. Utilizing numerous cultivars increased the resilience against interannual variations in climate by spreading the risk and assuring a moderate harvest. Presumably, the different cultivars also offered variable protection against the occasional outbreak of pests and diseases. Finally, variable time of development allowed a longer harvest period. For instance, some kalo varieties mature in as little as six months, while others can stay in the ground for nearly two years; planting different varieties together gives a large window of time in which to harvest from a single planting event, allowing farmers to take advantage of the rainy season to establish crops without a similarly narrow window of harvest.

Menehune and Maiʻa—Mythical Peoples and Plantains

Akua (deities) in Hawaiian culture are multitudinous, and their stories are intertwined, sometimes seemingly contradictory, and not easy to unravel (e.g., Beckwith, 1940; Malo, 1903). Very ancient beings are dually represented as both akua and people; oftentimes the names are shared by both figures. This is significant because, as Beckwith (1940) explains, "even Wākea and Papa, whose figures play a dominating part in Hawaiian myth and story, are represented as parents upon the genealogical line, not as the Sky and Earth deities their names imply" (p. 5), adding a historical element to Hawaiian lore. In addition to Wākea and Papa, there are four primary deities associated with the ancient arrival of humans—Kāne, Kanaloa, Lono, and Kū[2]. Kāne and Kanaloa are the first to have traveled to Hawaiʻi, where they settled in a large river valley, cultivated several crops, and lived simply. While multiple crops are associated with the arrival of these two ancient ancestors—including kalo, kō, ʻohe, and ʻawa—maiʻa is the only food recorded as being eaten upon their arrival in Hawaiʻi (Beckwith, 1940).

Hawaiian folklore offers multiple stories depicting early discoveries of the islands, likely representing newly arrived voyagers. One such discoverer is Luanuʻu (lit. the second cycle of time), who arrived in the islands from a Marquesan pedigree. Legend holds that Luanuʻu dwelt in the same lands settled by Kāne and Kanaloa, and that he even fed on the bananas planted by those deities. Luanuʻu mingled with the Nāwao[3] and became the progenitor of the Menehune, said to be a group of peoples who dwelt in the forest and subsisted on bananas (Fornander, 1880). These people and their descendants were referred to as the Mū ʻai maiʻa—the banana eating Mū. While it is dangerous to attempt to untangle such ancient stories as factual history, Beckwith (1940) confidently states the following:

> It is evident that … in the legend of Luanuʻu and his forest-dwelling … progeny we deal with that period of early settlement … directly following the dawn of the day and the appearance of Kāne … and Kanaloa, when the ancestors dwelt in the uplands on the edge of damp forests favorable to … bananas, which were their principal food.
>
> (p. 323)

Over time, more active forms of agriculture evolved and reliance on bananas subsided. In particular, kalo holds a central role in Hawaiian horticulture, and is known affectionately as the "staff of life" (Handy & Handy, 1972). The kalo plant emerged in association with Wākea,[4] known in deity form as the sky-father (Beckwith, 1949, 1981). The stillborn child of Wākea and his daughter was buried behind their house, from which emerged the first kalo plant; Wākea had many other children, from whom stem the Hawaiian people. Kalo is, therefore, the elder sibling of the Hawaiian people, and this endows upon it a paramount place from the perspective of familial relationships. The elder sibling is to be respected, while it is his responsibility to care for the younger relatives. This metaphor is taken further by using the kalo plant to represent a healthy family: the main stalk is called makua (lit. parent), while the offshoots are referred to as ʻohā (fig. offspring or youngsters), forming the root word for family—ʻohana. Multiple permeations through Hawaiian culture intertwine kalo with lessons and values about coexisting peacefully in a familial way (e.g., Pukui, Haertig, & Lee, 1972). Thus, a central value of the Hawaiian people is expressed through agriculture—kinship with our environment, to the same degree as kinship among a family, both of which require reciprocity and respect in order to function properly.

Many stories of Wākea's feats are recorded; among them are his struggle for power, the establishment of the priestly office, and his siring of one of the principal chiefly lineages of the Hawaiian people (Fornander, 1880; Malo, 1903). His importance as a developer of social order signifies a significant shift in the societal structure. Wākea is also famed for establishing one of the ancient and central laws—the ʻaikapu (eating taboo). The ʻaikapu segregated power and roles between men and women both physically and in ritual. Among the many restrictions it imposed on women was bananas. Although we are again dwelling in the hazy overlap between mythology and history, this story informs an important transition from forest dwelling and banana eating to kalo-based agriculturalists and rudimentary land claims that occurred during the time of Wākea, noted as the 28th generation following the settlement of the islands (Cachola-Abad, 1993).

Wai and Waiwai—Water and Wealth

As with Kāne and Kanaloa, the earliest settlements tended to occur in large, broad river valleys. Here ample fresh water was available, marine resources were abundant, and rich alluvial soils allowed for productive agriculture. The earliest indications of agriculture were simple plantings around households, near rivers, and along valley slopes (Yen, Rosendahl, & Riley, 1972). Detailed studies at Hālawa Valley, Moloka'i suggested evolving agricultural practices over time, from simple plantings, to slash and burn agriculture, and finally to more complex systems of terraces and irrigation (see Box 3 for a timeline of wetland agricultural development) (Kirch & Kelly, 1975).

Irrigated terraces (such as the archaeological remains seen in Figure 1), known as lo'i, were a dominant agricultural feature wherever suitable areas within river valleys or open floodplains were accessible by the gravitational flow of water. Lo'i occurred in intermittent stream beds, taluvial slopes, and alluvial floodplains, and could be fed by water from streams, stream diversions, springs, or the water table (artificially accessed through cutting into hillsides). Kirch (1977) partitions the forms of lo'i; based on the presence or absence of specific features, he classifies four types of lo'i: (i) narrow channel barrage systems consisting of stone built features within stream beds; (ii) single ditch, direct feed systems that divert streamflow directly into one or more pond fields in series; (iii) peripheral ditch, multiple feed systems that diverted streamflow along a cultivable area to feed a series of pondfields in parallel; and (iv) multiple ditch, multiple feed systems that included parallel feed of multiple pondfields plus drainage ditches to return excess flow to the stream.

Click to view larger

Figure 1. Classic stonework representing the stepped terrace system used in lo'i agriculture from Mānoa Valley, Kauai (photo credit Timothy Earle).

Construction of lo'i was a considerable undertaking that required significant labor and social organization. The land had to be cleared of stones, often consisting of large boulders, which were then used to create walls and form terraces. The soil within would be compacted by stomping to make the surface as impermeable as possible. Forms of lo'i varied depending on the terrain and water source; they could comprise simple ponds dug into the earth or elaborate surface structures with massive stonewalls reinforced with compacted earth to be watertight. Depending on the quality of the lo'i, different planting methods were employed. In a lo'i with good soil and good water flow, submerged rows were planted in an orderly fashion, much like rice in a paddy. A lo'i in a swampy or stagnant area, meanwhile, would be planted above the water level in mounds so that stagnant water would not cause the corm to rot. Along the banks or around a lo'i, other crops would be grown, such as mai'a, kō, and kī (Handy & Handy, 1972). The elegance of these systems on Kauai is stressed by early European observers, such as King (1784):

> these plantations were divided by deep and regular ditches; the fences were made with a neatness approaching elegance, and the roads through them would have done credit to any European engineer.
>
> (p. 116)

Box 3. Timeline of Loʻi Development

There is clear evidence for the establishment of loʻi by 1200 A.D. (Dega & Kirch, 2002; Dye, 2016; McElroy, 2007). Extensive organized systems of pondfields existed by 1400 A.D., by which time there is also evidence of redevelopment of earlier loʻi, indicating that intensification of existing improvements was becoming more important than the continued expansion (McElroy, 2007). The patterns of development are variable. In Makaha, Oʻahu archaeological investigations indicate that inland areas were developed first (Yen et al., 1972), while in Kohala, Hawaiʻi, lowland development occurred initially that then encroached up the valleys (Field & Graves, 2008). All sites show a pattern of larger loʻi developed on flatter areas first, then progressively smaller loʻi on steeper landscapes developed over time.

Eventually, moderate slopes of every river valley and flat lowland plains were converted into highly productive terraces. The vast alteration of these valley landscapes for agriculture is well captured by many historical observers, such as these remarks describing Wainiha, Kauai:

> All … along the river, wherever the encroaching [steep mountain slopes] on either side leave the least available space, the land has been terraced and walled up … so the whole valley is a slowly ascending stairway of steps, broad in the tread and low in the rise, all the way to [the back of the valley], where the last available space was won.
>
> (Lydgate, 1912, p. 126)

An essential aspect of loʻi was the ʻauwai—canals that transferred water from the river through the pondfields and back (Gingerich, Yeung, Ibarra, & Engott, 2007). ʻAuwai were often simply channels of compacted earth, but more elaborate systems were paved with well-fitted stones and even used carved wooden conduits to pass over short expanses (Handy & Handy, 1972). Some ʻauwai were reported to be upwards of 3km long (McAllister, 1973). The sides were sloped inwards to prevent erosion and often lined with plantings to stabilize the soil. At critical junctures there were keystones that could be used to adjust the flow of water, or eliminate flow altogether. The poʻo wai (lit. headwater) refers to the place where the water was drawn from the river. Here the water would be slowed by the construction of mānowai—constructions that allowed for sufficient water pooling while employing mechanisms to prevent excess flow during high water events. For instance, stone dams were built to raise the water level for appropriate intake; these dams were constructed so that during flood events they would break away, lowering the water level and preventing the ʻauwai from being washed out. A detailed observation of one loʻi in Wailau, Molokaʻi captures some the engineering that was considered in loʻi water management:

> There's a stone wall edging … four feet wide, level with the terraces … but nine feet high on the side facing … below. Also, there were large pohaku (stones), standing like sentinels … in the middle of a terrace … at seemingly random locations … and stonework that gave the odd impression of short walls abruptly left unfinished. [After a terrific storm] … the purpose of the stonework was seen … all had been engineered to break the force of water, gently move[ing it] through the system of cleared terraces with such perfection that it was not even discolored. Not a speck of soil was washed out, not a single plant uprooted, and not a single stone dislodged from its place.
>
> (Sykes in ʻOnipaʻa Nā Hui Kalo, 2004, p. 199)

Once diverted from the river, water would be directed through several loʻi, passing from one to the next via small connections known as makawai (lit. water eye). Finally, the water was invariably returned to the river. ʻAuwai embodied multiple aspects of the communal values that permeated Hawaiian society (Goodyear-Kaʻōpua, 2011). Their construction and maintenance was completed through socially organized labor; if a family did not contribute to the building or maintenance of an ʻauwai, they risked being excluded from its usage (Handy & Handy, 1972; Nakuina, 1893). Similarly, a system of locks allowed for control of water to individual series of terraces; during times of drought the water was managed so that all users, despite their downstream location, were given a fair share of water as determined by their contribution to the system. The Hawaiians' recognition of water's supreme importance for personal and social well-being can be seen in the close relation between the words for water (wai) and wealth (waiwai) (Pukui & Elbert, 1986).

The primary crop of wetland agriculture was kalo, which was generally considered the preferred staple of Hawaiʻi (see Box 4 for a discussion of water and nutrients in loʻi kalo). Depending on the variety, all parts of this sturdy and vital plant are eaten, but must be cooked in order to break down the needle-like calcium oxalate crystals present in the leaves, stem, and corm. These can be irritating to the throat and mouth lining, causing an acrid burning and stinging sensation. The leaves and stems are cooked as greens, while the tubers are baked, boiled or steamed, or cooked and mashed with water to make poi. Once cooked and mashed, the corms keep almost indefinitely in a form known as paʻi ʻai. Once the leaves, stems, and tuber are removed, the remaining part of the plant consisting of a bit of corm and a few inches of stalk, known as a huli (lit. to turn), can be replanted to grow into the next crop.

Box 4. Water and Nutrients in Loʻi

Kalo requires well-circulated water, and proper management and engineering of the water flow was essential to loʻi productivity. The plant requires an average daily temperature above 21 °C for normal production (Onwuema, 1999), but also performs best in water cooler than 25 °C to prevent rot and disease (Gingerich et al., 2007). To maintain these temperatures, water flow rates of 100–400,000 gallons a day are required. Generally, the older, wetter landscapes representing loʻi agriculture consist of soils heavily depleted in mineral nutrients. Mineral nutrients to the soil are therefore supplied either via a rejuvenation of weathering caused by erosion, which removes nutrient depleted soil and exposes fresher material near the surface, or by the routing of water through less-weathered layers deep within the soil and its subsequent emergence at the surface in springs and streams. The size and slope of the valley walls relate to the level of nutrient rejuvenation; large, deep valleys provide substantially more nutrients via erosion than small or shallow valleys (Vitousek et al., 2010). While erosion alone may supply sufficient nutrients in some large deep valleys, it is insufficient for sustained intensive agriculture in smaller ones (Palmer et al., 2009; Vitousek et al., 2010). Here, over 90% of the water-born nutrients P and Ca are derived from the rock (as opposed to rainfall, ocean spray, or other depositional sources), and the nutrient levels are generally sufficient to meet crop demands (Palmer et al., 2009).

Loʻi set the tone for Hawaiian management of land. The initial development of loʻi were controlled by kinship networks and family clans (Hommon, 2013). The natural geological boundaries of Hawaiian valleys, the high ridges delineating the watershed, became clear boundaries separating individual groups. Early on, evidence of power struggles for the leadership of these clans is demonstrated, even in the story of Wākea—one of the earliest progenitors of the Hawaiian people. Wākea’s father, Kahiko, is said to have “divided and separated the islands,” potentially indicating an early parceling out of lands (Beckwith, 1940). This system of land division was formalized under Māʻilikūkahi during the 16th century, a strong chief hailing from a wetland region of Oʻahu, who developed the ahupuaʻa system of management. Ahupuaʻa were the smallest politically controlled units, nested within larger and larger political units that were controlled by higher and higher chiefs. Like the rivers they were originally based on, most ahupuaʻa ran from the upland out through the nearshore marine environment, which ensured each unit had access to a range of necessary resources. Kirch (2012) summarizes the importance of this shift in land management:

> Māʻilikūkahi made the momentous decision to impose a new hierarchical order over the entire island. Rather than let the people work out their territorial rights according to ancestral claims … he would assign the land to the chiefs, lesser chiefs, and through them down to the common farmers and fishermen. This was a radical departure from the old Polynesian system, in which rights to land were

> tied to kinship. From this point on, the land tenure system became one of chiefly territories, in which the common people’s rights to land depended on their relationship with their chief. This new system would become fundamental to the economic and political order of the islands.
>
> (p. 139)

Lepo and Lono—Soils and Lono

While the first settlements occurred in river valleys, many early settlements arose in other high resource areas (Hommon, 2013). These sites typically had less surface water, but often included extensive springs or even spring-fed rivers. Here, where water was scarcer, dryland (rainfed) agriculture was essential. Evidence suggests that the earliest forms of farming in dryland areas were home gardens close to coastal settlements; however, over time the development of massive, systematic dryland agriculture is seen—first in highly productive microhabitats then across the entire arable landscape (e.g., Ladefoged & Graves, 2008). The expansion of rainfed agriculture coincides with the late introduction of ʻuala and possibly ipu (see Box 5 for timeline of development). Both crops are associated with Lono, one of the four paramount deities whose principal affiliation is to rain and clouds—critical resources for rainfed agricultural. Lono's arrival is clearly placed after the time of Kāne and Kanaloa, and after the time of Wākea (Fornander, 1919). His association with the immigrant chief Pāʻao (along with the akua Kū) in the 12th or 13th century, who brought with him a new religious order and chiefly lines, speaks to Lono's late arrival to the Hawaiian pantheon (Kalakaua, 1888). The introduction of new crops and social order allowed for developments in both agriculture and politics, and in this time period there was an elaboration of ritual systems and a greater differentiation between chiefs and commoners. In addition to dryland agriculture, Lono is credited with the initiation of the Makahiki, or harvest festival. The Makahiki was a time of peace, prosperity, and frivolity, but also initiated a clear system of taxation to support the aliʻi, provided an opportunity to assess each area's productivity, and allowed for further development of political hierarchy.

The expansion of dryland systems appear to have had a political component to it, seen in their architecture. Initial construction of dryland systems was not uniform, but rather patchwork development adapted to the local topography. Subsurface features typically consisted of simple retaining walls, often only a single boulder high (Allen, 2001; Tomonari-Tuggle, 2006), that served to capture soil and moisture (Coil & Kirch, 2005). In particular, these early endeavors took advantage of productive micro-areas (Kirch et al., 2013). Archaeological work in Kona, Hawaiʻi often shows layers built on top of each other as the landscape progressed towards a more intensive state of production. Over time the construction of the dryland systems became very homogenous, and can be characterized by common infrastructure, possibly indicating politically mobilized construction. The dominant surface features were long walls or embankments referred to as kuaiwi,[5] literally meaning "backbone" (such as the walls seen in Figure 2). The name is significant, referring not only to the walls' appearance on the landscape but also to their critical role in supporting Hawaiian society. The kuaiwi, made of earth or stone or both, were typically one to two meters wide and one-half to one meter high; they could extend continuously, in a kinked manner, for over a kilometer (Allen, 2001; Escott & Spear, 2003; Ladefoged et al., 2011). The kuaiwi were spaced to encompass cleared fields, typically 12 to 20 meters wide, though as narrow as 8 and as wide as 60 meters. Generally, the walls were planted with taller secondary crops such as kō, maiʻa, and kī, while the cleared fields between them were used to cultivate the primary crops of ʻuala and kalo (Handy & Handy, 1972; Kelly, 1983). Various sources indicate the kuaiwi had a purpose beyond mere rock repositories, such as rock mulch or water capture, though their function has not yet been well studied (Allen, 2001; Escott & Spear, 2003). It is clear that kuaiwi were used to delineate individuals' plots.

Box 5. Timeline of Māla Development

While house gardens and slash and burn agriculture is prevalent by the 12th century, large-scale construction of mala did not occur until much later (Ladefoged et al., 2008). Permanent upland garden sites emerge beginning in the 14th century in productive areas (Allen, 2001; Ladefoged et al., 2008). Continuous expansion of dryland agriculture emerges in the 15th century, followed by extensive, relatively homogenous, buildout of dryland "systems" that blanketed vast sections of the landscape in the 17th and 18th centuries (Allen, 2001, 2004; Bayman & Dye, 2013; Dye, 2016; Ladefoged et al., 2008; Ladefoged et al., 2009). ʻUala was critical for the development of these systems, surviving in much drier climates than kalo. There is little direct dating of ʻuala in Hawaiʻi, with the earliest dates indicating that it was grown inland on Hawaiʻi Island by the 14th century (Ladefoged et al., 2005). The timeline stemming from the Southern Polynesia suggests that ʻuala was introduced to Hawaiʻi around the 12th or 13th centuries.

At their peak māla were vast. Kohala, Hawaiʻi consisted of 25 square miles of contiguous agriculture and Kona, Hawaiʻi covered some 60 square miles (Ladefoged et al., 2009). Similarly, extensive systems existed on the slopes of Haleakalā, Maui (Kirch et al., 2009), with smaller pockets of development across the state, such as at Kalaupapa, Molokaʻi (McCoy, 2005). The development of intensely cropped dryland systems was limited to areas with adequate rainfall and nutrients (see Box 6 for a discussion of the biogeochemical parameters of dryland systems). The intensity and perfection of these systems is captured by Menzies (1920), one of the first Western botanists to visit the archipelago, in his description of the agriculture of Kona, Hawaiʻi:

> For several miles round us there was not a spot that would admit of it but what was with great labor and industry cleared of the loose stones and planted with esculent roots or some useful vegetable or other […] being in a high state of cultivation […] [S]eeing now these upper regions so industriously cultivated [… and] by extending their cultivation to different regions of the air, they secure a continued succession of crops and therefore can never be destitute of supply […] [W]e could not help admiring the manner in which the little fields on both sides of us were laid out to the greatest advantage and the […] great attention […] in adapting every vegetable they cultivate [… to] its proper soil and natural situation

by which their fields [...] are productive of good crops that far exceed in point of perfection the produce of any civilized country within the tropics.

(pp. 75–76)

Click to view larger

Figure 2. An aerial perspective reveals the intensive and extensive infrastructure that comprised the dryland field systems in Kohala, Hawaiʻi (photo credit Robert Shallenberger).

The application and adaptation of particular kuaiwi infrastructure to their unique environments is evident. For instance, in Kohala, Hawaiʻi, where the prevailing tradewinds are exceptionally strong and mist-laden, the kuaiwi run perpendicular to the slope and the winds. While only preliminary work has been done to date, these particular walls appear to have functioned as a windbreak and mist trap, particularly during initial plantings. In contrast, in Kona, Hawaiʻi the walls are parallel to both slope and wind; the author believes that this orientation is to facilitate the management of solar radiation and evaporation (the walls run on a WSW orientation, aligning with the sunset in the winter while providing shade to the fields during the summer). The walls are again different in Kula, Maui, being perpendicular to the slope but parallel to the prevailing winds. Although we can (and do) make educated hypotheses regarding the wall orientations, the reasoning has so far been largely anecdotal and preliminary.

Box 6. The “Sweet Spot” for Māla Development

Intensively cropped māla took advantage of naturally occurring “sweet spots,” poised between areas too dry to reward farming (~750 mm/yr) and so wet that millennia of weathering and leaching had depleted soil nutrients (Kirch et al., 2005; Lincoln et al., 2014B; Vitousek et al., 2004). Along the wetter edge of māla, the sweet spot was bounded by a ‘soil threshold’ where buffering mechanisms are overcome and soil properties change very rapidly, causing a cliff in the soil fertility (Vitousek & Chadwick, 2013). The extent of māla intensification can be well predicted by a threshold value of pH, exchangeable calcium, base saturation, or plant available phosphorus (Vitousek et al., 2014). Because soils undergo a cumulative weathering process, over time the fertility cliff occurs at a lower and lower rainfall, such that the sweet spot between the wet and dry boundaries narrows and eventually disappears. Thus intensive dryland agriculture is not possible on old soils. Very young soils may also be limited in nutrients due to the inability of coarse material to retain nutrients as they are released through weathering (Lincoln et al., 2014B).

While wall orientation clearly differs at each of these sites, it is only one of many local adaptations that were made. Kepelino, in Beckwith (1932, pp. 152–155) exemplifies some of the differences in planting methods by classifying six methods of dryland farming:

1. ʻŌhiki, a “prodding method” in which the soil is pried up with the ʻoʻo until it is soft, after which the taro tops are planted;
2. ʻŌkupe, in this case the earth is pushed to one side and the plant inserted in the hole;
3. Pāʻeli, a “covering method” involving “good large holes” of softened earth;
4. Puʻepuʻe, a “mounding method” in which earth is piled up into “good-sized mounds”;
5. ʻUmoki, the “stopping-up method” used in the uplands “where tree-ferns grow,” and in which “the sharp stick is thrust into the soil, the hole widened, then the plant is thrown into the hole made”; and
6. Pākukui, where large holes were dug and filled with a mix of kukui leaves and earth.

These different planting methods are largely adaptations to different soil types. The pākukui, for instance, is largely referenced in areas with highly clayey soils that would have had poor drainage and low organic matter, likely necessitating considerable amendment with kukui leaves. In contrast, ʻōhiki method often arises in connection to drier areas, where soils can be compacted and hardened.

The dense concentration of diverse microhabitats in Hawaiʻi necessitated different types of cropping systems and temporal uses of dryland areas (Kirch, 1994). The ecology of dryland agriculture was more variable due to the wider range of elevation, temperature, rainfall, wind speed, and soil nutrients encompassed by these systems (Kagawa &

Vitousek, 2012; Vitousek et al., 2004). In some areas, these distinctions were made explicit in the Hawaiian language and knowledge base through the differentiation of unique planting zones or habitats. Hawaiians exploited each of these zones according to their societal needs and the ecological requirements of their food and fiber crops. An overview of agroecology in Kona, Hawaiʻi—adapted from Handy and Handy (1972), Kelly (1983), and Bayman and Dye (2013)—is presented here.

> *Kula*—The kula is the lowland dry plains immediately inland of the coastal and habitation zones, from just above sea level to ~200 m elevation. This area typically receives less than 1000 mm/yr of rainfall and was largely used for the cultivation of non-edible resource crops, including wauke, hala, pili (*Heteropogon contortus*) and ipu. Fire was used in some areas to encourage the growth of native pili grass, which was Hawaiians' preferred thatch (Cuddihly & Stone, 1990; Hommon, 2013). The kula supported small home gardens and animal pens, as well as the densest concentration of houses (Escott & Spear, 2003; Haun & Henry, 2010).

> *Kaluʻulu*—The kaluʻulu was an agroforestry development with an open canopy dominated by breadfruit, and co-planted with kukui and ʻōhiʻa ʻai. It was a distinct belt approximately 0.8 to 1.5 km wide that fell between ~200 and ~450 m elevation (Lincoln & Ladefoged, 2014); it gave way abruptly on both the mountain- and ocean-side boundaries and was continuous along the north-south axis (Beaglehole, 1967; Ellis, 1917; Menzies, 1920). Plants grown in the understory included ʻuala, uhi, maiʻa, ʻolena, pia, ʻawapuhi, ʻawa, and kalo, among others.

> *ʻĀpaʻa*—In Kona, the ʻāpaʻa was the most intensively cultivated area. Here the stereotypical dryland agricultural infrastructure, practices and cropping occurs, with tall crops of kō, kī, and maiʻa planted along the kuaiwi walls and staple crops of uhi, ʻuala and kalo in cleared fields between them. The ʻāpaʻa occurred upslope of the kaluʻulu, transitioning at a rainfall of approximately 1300 mm/yr (Lincoln & Ladefoged, 2014).

> *ʻAmaʻu*—The uppermost zone of cultivation, the ʻamaʻu, modified the existing native forest to grow crops within the subcanopy. It is named for the native ʻamaʻu treefern (*Sadleria spp.)* that grew in the ʻōhiʻa (*Metrosideros polymorpha*) dominated forests. Cultivated crops such as maiʻa, kī and uhi were planted, and naturally occurring medicinal and resource plants such as mamaki (*Pipturus albidus*) and olonā (*Touchardia latifolia*) were encouraged and harvested. Crops planted here were occasionally left to grow wild as a security measure against drought and famine.

The delineation of distinct planting zones with different crops, planting regimes, and temporal aspects, illustrates some of the variability within dryland agriculture. While the descriptions of these zones above are specific to Kona, Hawaiʻi, variations within individual dryland systems can be seen across the islands. In Kohala, Hawaiʻi, which encompasses a substantial rainfall gradient, the Hawaiians likely employed both temporal variations (utilizing similar cropping systems in different parts of the system throughout the year) as well as spatial variations (utilizing different crops and cropping systems in different locations within the system) (Kagawa & Vitousek, 2012; Lee, Tuljapurkar, & Vitousek, 2006). Much of the planting variation is in response to environmental and nutrient constraints, although some transitions also appear to be mediated by preferences in crops (e.g., Lincoln, Chadwick, & Vitousek, 2014).

As seen throughout much of Polynesia, arboriculture played a significant role in Hawaiian agriculture (Huebert, 2014; Kirch, 1994; Millerstrom & Coil, 2008). Many of the Polynesian introduced crops survive and produce well in diversified forest conditions, including ʻulu, noni, kukui, wauke, ʻōhiʻa ʻai, niu, ʻawa, maiʻa, ʻawapuhi, and hala. Endemic plants used for resources and medicine also thrive. Agroforestry was particularly prevalent in areas that were too steep, too rocky, too infertile, or too salty for kalo and ʻuala production, and were therefore common in colluvial areas, areas with very young soils, along the coast, and high in the upland slopes.

The valley walls provide an example of places that were often too infertile or steep to support intensive rainfed agriculture (see Box 7 for discussion of colluvial slope nutrients). If fertile, colluvial soils were sometimes worked to form rudimentary terraces (Kirch, 1977, Kurashima & Kirch, 2011), but more often were established with semi-wild tree and shrub plantings that would provide necessary resources, seasonal products, and unmanaged reserves against disasters that might cause the loss of intensive systems nearby. The planting of breadfruit, in particular, in the valley slopes is evidenced by dozens of historical and prehistorical references (Meilleur, Jones, Tichenal, & Huang, 2015). These valley plantings accounted for the bulk of the agricultural production in some areas, and was a key component to resilience and production throughout the islands (Allen, 2004; Kurashima & Kirch, 2011).

Box 7. Nutrients in Colluvial Areas

Inputs from erosion in valleys support the rejuvenation of colluvial soils along the valley walls, particularly in wet areas where leaching of nutrients on the shield surface create relatively infertile soils. Erosion exposes fresh material and therefore a new supply of nutrients (Porder et al., 2005). The effects of this process are sufficient to support intensive rainfed agriculture along the slopes of large but not small valleys (Palmer et al., 2009). Moreover, because older islands are subsiding much more slowly than the younger islands (Moore & Clague, 1992), the morphology of large valleys on older islands supports a larger fraction of lower-slope landforms conducive to planting (Vitousek et al., 2010). These colluvial slope forms have been shown to play an important role in agricultural supply, being a significant contribution to food production and thereby enhancing the variety and production of agriculture on at least some of the older islands (Kurashima & Kirch, 2011).

Other marginal habitats were also given over to arboriculture, such as very young, rocky soils with inadequate soil to cultivate ʻuala or kalo. Kona, Hawaiʻi and Puna, Hawaiʻi, famous for their breadfruit and coconut groves, exemplify the application of this strategy (Lincoln & Ladefoged, 2014; Meilleur, Jones, Tichenal, & Huang, 2015), such as was captured by a European explorer in 1773:

> [They] commenced [their] march … over a … track of a gradual ascent, consisting of little else than rugged porous lava and volcanic dregs, for about three miles, when [they] entered the bread fruit plantations whose spreading trees with beautiful foliage were scattered about that distance from the shore along the side of the mountain as far as [they] could see on both sides.
>
> (Menzies, 1920, p. 74)

Coastal areas were another place where agroforestry often dominated. Groves were developed that supplied resources as well as pleasurable habitats. Hala is particularly famous for its pleasant ambiance that provided a comfortable place to work within the shade of the trees open to the cool ocean breeze. Several tree crops fare well in the salt intrusion zone, including niu, hala, milo (*Thespesia populnea*), noni, hau (*Hibiscus tiliaceus*), and kou (*Cordia subcordata*). The adoration of these coastal plantings is expressed in a traditional saying, "Puna, kai nehe i ka ulu hala - Puna, where the sea murmurs to the hala grove" (Pukui, 1983).

In some regions, it is clear that Hawaiians planted trees specifically to accumulate fertility. In these systems, known as pā, very fast-growing woody plants that decomposed quickly such as kukui and hau were cultivated. One such system, the pākukui, is described:

> Kīhāpai, or small gardens, in pā kukui were prepared by felling a number of kukui trees in a concentrated area, and allowing for the trees to decompose, creating rich humus for planting. Large holes, up to 10 feet (3 m) in circumference and 3 feet (0.9 m) in depth, were then dug and filled with kukui leaves, which, once decomposed, was turned and planted. Kalo cultivated in pā kukui were said to have grown to heights of up to 7 feet (2.1 m), with corms of up to 20 pounds (9.1 kg).
>
> (Handy & Handy, 1972, p. 110)

In essence, the pākukui system is managed shifting cultivation in which both the "fallow" (kukui, whose nuts provide an oil used for lighting and hau, a primary source material for fiber) and "cropping" (here kalo) phases provided useful products.

Hawaiians also made use of natural forests for various forms of agriculture. Maps of homesteads submitted at the time of the Māhele[6] show multiple variations of this. In Hāmākua, Hawaiʻi areas of ʻōhiʻa, the dominant canopy tree in most native Hawaiian environments, were maintained with dense understory plantings of useful ferns and shrubs. This practice capitalized on increased nutrient cycles associated with forests, and increase moisture throughput due to interception. Recent science confirms the efficacy of this ancient practice (Brauman, Freyberg, & Daily, 2010), supporting that "Hahai nō ka ua i ka ulu lāʻau—Rain always follows the forest" (Pukui, 1983) (although in this case it is interception of cloudwater by the forest canopy that is the dominant source of water). In this way, upland forest plantings in Kona were used to add a measure of resilience to the agricultural landscape, as described by Menzies in 1793:

> After going on about two miles by a narrow path through an uncultivated track, overgrown with ferns and small bushes, we entered the forest, the verge of which was adorned with rich and fruitful plantations of bananas and plantains, from which we supplied ourselves with a good stock for our journey.
>
> (Menzies, 1920, p. 155)

As the population continued to expand, increasingly marginal areas were cultivated. In some cases, most notably in Kaupō, Maui, vast areas were utilized that scarcely seem able to have supported agriculture. Hawaiians began to cultivate such areas beginning around the 15th century (Kirch et al., 2004; Kirch et al., 2005) and likely developed them continuously until the time of European contact (Coil & Kirch, 2005). Initial usage of this land relied on productive micro-sites where more widely applied agricultural techniques were used (Kirch, Holson, Legacy, Cleghorn, & Chadwick, 2013); however, over time, the application of unique infrastructure and techniques, as well as the intentional and unintentional alteration of the landscape, was also important for the cultivation of such marginal areas.

Swales were commonly used to concentrate water and soil resources. These were often simple dams constructed in highly intermittent streams or U-shaped enclosures that captured water-born or wind-blown dust and were capable of creating significantly more soil than naturally existed (Schilt, 1984; Tomonari-Tuggle, 2006). In the lowlands of Kona, Hawaiʻi, it is noted that virtually every natural low point, such as basins and intermittent stream beds—no matter how small, had multiple enhanced swales to increase the arable land area. These swales varied in size and application, with individual farming plots ranging from ~1 to ~7000 m^2 (Schilt, 1984). Multiple small swales were engineered where the potential for soil capture was high, leading to "fish scale" walls comprised of small, interlocking C-shaped structures. Conversely, a single wall corralling an intermittent floodplain could quickly form a large area with farmable soils. Overall, the use of swales enabled a high level of agricultural intensification across a small area of the total landscape.

The use of soil capture techniques became even more important as nearby lands (particularly upslope) were developed. As the typically wetter uplands were developed for agriculture, downslope erosion increased, thereby facilitating new farming opportunities in the lowlands. As noted in the lowland of Kona, Hawaiʻi:

> One of the more interesting findings of … studies in the project area is that most cultivation on the kula occurred in soils that had been transported primarily by water erosion from higher slopes, probably as mauka [upland] subzones of the Kona Field System were being developed.
>
> (Schilt, 1984, p. 84)

Where use of soil capture techniques was not a readily available option, Hawaiian farmers created their own soil. Using natural formations or simple infrastructure, soil and other organic and inorganic amendments were collected and used to grow crops. Pocket agriculture was the process of using either natural or manmade infrastructure to collect soil into "pockets," within which it was amended with organic matter. Natural "blisters," or air pockets in the lava, were particularly effective for this technique because their thick sides kept the soil cool and their low porosity helped to preserve water. An extreme example is a collapsed lava tube that could be altered into a farmable habitat. Charcoal is very often associated with planting basins and other forms of pocket farming, as are shards of volcanic glass and sparse midden, all of which aided in adding volume and nutrients to the soil mixture (Schilt, 1984). The in situ creation of organic soil was a critical component of pocket agriculture for the influx of nutrients, increased water holding capacity, and volume added to the rooting zone. In some cases, constructed soils were used nearly exclusively. An interviewee in an early newspaper reminisces about such practices:

> Rocky lands in the olden days were walled up around with the big and small stones … and in the enclosure were put weeds of every kind … and then topped well with soil … to enrich it, or in other words to rot the rubbish and weeds and make soil. After several long months, the rotted weeds were truly converted into soil of the best grade. (Ka Nūpepa Kūʻokoʻa, March 24, 1922, in Handy, 1940, p. 147)

Grasses and other weeds growing in small pockets of soil were both excavated to create planting holes for crops and also used as a source of mulch, as described by a visiting ship captain:

> We passed some plots of ground curiously prepared … by pulling up, by the roots, the long tufts of grass and leaving them upon the ground to keep in the moisture. In the furrows or holes thus opened stalks of the potato are inserted, which, in the course of a few weeks, produce abundant roots.
>
> (Tyerman & Bennet, 1840, p. 111)

The types of plants grown in pocket agriculture varied depending on the specific local conditions. This method was important in the production of ʻuala and ipu—both are crawling species that would root in the pockets of dirt and spread out across the surrounding rocks. A large area of spaced pockets could form a contiguous patch of gourds that grew together, effectively bringing the entire area into cultivation despite having only a small percentage of land with adequate soil.

Similarly, rock mounds were widely built in soil-scarce or dry regions. While they were also used extensively in fertile areas, such as Kona, Hawaiʻi (Allen, 2001), their application was much more widespread in marginal habitats. Several acres could be blanketed in mounds approximately 1 meter in diameter. These mounds increase yields primarily by helping to preserve moisture and regulate heat. The mounds enclosed soil or organic matter, and largely planted with ʻuala (Horrocks & Rechtman, 2009). Ellis, in his 1820 tour of Hawaiʻi Island presents:

> We thought the people generally industrious; for in several less fertile parts of the district we saw small pieces of lava thrown up in heaps, and potato vines growing very well in the midst of them, though we could scarcely perceive a particle of soil.
>
> (Ellis, 1917, p. 337)

The diversity of techniques used by Hawaiian farmers allowed them to successfully cultivate a wide range of habitats across the islands. Cropping systems, agricultural infrastructure, planting methods, and management of planting were all adjusted according to the local climate and the macro- and micro-topography. Often planting styles could be found in close proximity to each other, making the most of all available resources (e.g., Schilt, 1984).

Kū and Kanaka—The God of War and People

The akua Kū is associated with the forest and many of the tree crops, such as ʻulu and niu. These crops are seen as masculine, and their productivity represented sedentariness. In this vein, Kū is associated with prosperity, but as an opposing force, Kū is also the primary deity of war. To cut down a grove of trees, particularly niu—a symbol of royalty and wealth—was a grave offence and an impetus for confrontation. As populations of Hawaiʻi grew, the balance between these dualities—prosperity and war—became increasingly important.

The 15th and 16th centuries were a golden age in the history of Hawaiʻi. Continued hierarchical development had led to the consolidation of multiple districts under single chiefs by this time, reducing the frequency of conflicts (Graves, Cacola-Abad, & Ladefoged, 2011; Kirch et al., 2005; Kolb, 1994). Previous investments into landscape capital provided constant returns. A burgeoning population provided the opportunity for further investments to ensure production and resilience, and innovations in the political system provided the stability for investment. The ahupuaʻa system of land management developed by Māʻilikūkahi quickly spread to the other islands, providing a degree of permanence and security for those on the land.

The increased political oversight influenced or possibly dictated forms of agricultural development. On Maui, precise dating of temples in Kahikinui, Maui show an extremely rapid establishment of permanent markers in the mid to late 16th century (Dye, 2016; Kirch & Sharp, 2005; Kirch, Mertz-Kraus, & Sharp, 2015) that coincided with increased development of agricultural infrastructure in the region. At the same time, the extensive and rapid buildout of the dryland system in Kohala, Hawaiʻi, occurred. In Kona, Hawaiʻi, we see a strong interaction between regional boundaries and the establishment agricultural infrastructure (Allen, 2004; Lincoln & Ladefoged, 2014). The organization and mobilization of labor, accessible through initial investments in agriculture and facilitated by political hierarchy and organization, allowed for the increased investments into long-term benefits (Kolb, 1997). In the 15th and 16th centuries, the Oʻahu chief Kākuhihewa established a massive grove of niu at Helemoa, Oahu estimated to contain 10,000 trees, while the Hawaiʻi Island chief ʻUmi a Līloa established a breadfruit grove in Kona, Hawaiʻi that covered over 25 square km (Lincoln & Ladefoged, 2014; Meilleur, Jones, Tichenal, & Huang, 2015). These groves provided an important source of wealth and stability to the political system, which in turn sought to create social stability to protect their power. One example of such social changes is the koʻele system of taxation instituted by ʻUmi a Līloa, a famous chief from Hawaiʻi Island, which designated aliʻi plots within each ahupuaʻa that were worked by the residents. This increased the fairness of taxation by setting aside relative amounts of land and labor rather than goods. Therefore, a productive area and a marginal area were held to equitable expectations (by providing an established amount of land and labor rather than goods), and in a lean year when the commoners produced less an aliʻi's koʻele plot also yielded fewer taxes—the burden was shared equally by chiefs and commoners.

As resources and population continued to grow, increased political intensity became increasingly necessary to maintain stability and hierarchy. Kohala, Hawaiʻi, provides an excellent example of the changing politics that accompanied increased agricultural development. While established boundaries of ahupuaʻa do not move after their initial establishment, it is clear that in some areas—especially in the dryland agricultural system—ahupuaʻa continued to be split into increasingly fine divisions over time (Ladefoged & Graves, 2006; Mulroony & Ladefoged, 2005). Other political tactics, such as intermarriage of chiefly lines, also became increasingly common (Cachola-Abad, 2000).

After several hundreds of years of occupying and cultivating the islands, Hawaiians made use of virtually every arable habitat. Outsiders were amazed at the ability of Hawaiians to thrive in these conditions, as a Captain in the mid-19th century quipped:

> Cultivation is carried on in many places where it would be deemed almost impracticable in any other country.
>
> (Wilkes, 1845, p. 25)

While the cultivation of these extremely marginal habitats was impressive, it was also precarious (Allen, 2004; Kirch et al., 2004). The highly variable production of marginal areas and moderately variable capacity of dryland systems in general would have produced boom and bust cycles dependent on rainfall. The effects of hard times could be mitigated by trade with neighboring polities, but could also provide an incentive for war against more productive and resilient areas. Following the "golden age" in the 15th and 16th centuries, detailed analysis of oral histories shows rapid changes in the political structures and social interactions (Graves et al., 2011). With the advent of emergent states in the 17th and 18th centuries and the rapid intensification of agricultural production in increasingly marginal areas, state-sponsored religion flourished and the division between the aliʻi and the commoners became absolute. As the need for cooperation or competition became increasingly fierce, the increase of conflict within and between islands grew exponentially (Cachola-Abad, 2000).

While many factors led to the development of Hawaiian politics and the consolidation of power, the uneven distribution of climatic and environmental resources certainly played a role (Kirch, 1994). Recognizing nature's influence on the opportunities and limitations available to them, Hawaiian farmers perceived the division of agricultural types as tied to fundamental environmental parameters. This is illustrated by a 19th-century native farmer's statement that "Elua ano a ka aina, he maloo a he wai - There are two kinds of lands, there are dry and there are wet" (Fornander, 1919, p. 160). This distinction does not refer only to the amount of rainfall, but whether or not there is flowing surface water—which may depend as much on substrate and geomorphology as on total rainfall. An area such as Kona, Hawaiʻi Island with moderate rainfall and no surface water because of the young, porous lava, supported primarily dryland agriculture, while a very dry area such as Mākaha, Oʻahu Island, with perennial streams fed from the mountains supported extensive wetland systems.

The spatial distribution of environments conducive to these systems was not distributed equally. Soil and topography associated with the forms of Hawaiian agricultural intensification have been well studied (e.g., Kurashima & Kirch, 2011; Ladefoged et al., 2009; Lee et al., 2006; Palmer et al., 2009; Vitousek et al., 2004). Loʻi depend on surface streams that primarily exist in older and wetter parts of the islands due to the cumulative effects of erosion and sediment deposition. In contrast, māla require moderate rainfall and adequate soil fertility, the latter of which, in general, decreases with increasing rainfall and substrate age (Chadwick et al., 2003; Vitousek, 2004). Hence, rainfed systems developed primarily on the younger Hawaiian Islands, while wetland agriculture dominated the older islands (Ladefoged et al., 2009).

Kirch (1994) postulates that the spatial and environmental separation of the intensive wet and dry agricultural systems played a key role in sociopolitical dynamics and interactions. Many theoretical frameworks have been proposed to outline the social mechanisms that contributed to the high state of sociopolitical complexity Hawaiʻi achieved (e.g., Earle, 1978; Hommon, 2013; Ladefoged & Graves, 2000). The higher surplus and resilience associated with wetland agriculture allowed for the rapid development and stability of the political system (Earle, 1978). At the same time, the topography of wetland areas, which, typically, are clearly delineated by steep ridges, facilitated the establishment of distinct political units (Kirch, 1990). Areas dominated by wetland agriculture created well-established hierarchies early on, and more peaceful, but tiered, social management structures. On Kauai in particular, the chiefly lines remained unbroken through time, indicating a high level of control and stability (Fornander, 1919). That the chief first credited with establishing permanent land boundaries and a strong hierarchical state system—Māʻilikūkahi—hailed from Oʻahu, a wetland dominated island is likely no coincidence (Kirch, 2012).

In contrast, dryland systems provided less surplus of yield and were highly variable in production over time. The reduced surplus allowed for less hierarchical control, while the lack of resilience provided opportunities for political instability. The preservation of, or competition for, chiefly title can be seen in the traditional genealogies, which indicate a higher level of competition and turnover within areas that relied more heavily on dryland agriculture (Graves et al., 2011). While the political boundaries were established early and remained stable in wetland dominated areas, dryland systems continued to distinguish finer levels of political control over time. This can be seen in the dating of boundary markers as well as in the physical layout of the ahupuaʻa; within the areas supporting dryland agriculture we see more "capped" or "cutout" land divisions that indicate fractionation of land and control over time (Ladefoged & Graves, 2006).

These development pathways have been used to examine the complex relationships between society, agriculture, and politics over time (Kirch & Zimmerman, 2011; Ladefoged, Lee, & Graves, 2008). Ultimately the societies based on dryland systems, which supported much larger, but likely more precarious, populations, appear to have been the greater instigators of predatory warfare (e.g., Kirch & Zimmerman, 2011). Alternatively, taking the "good year" hypothesis, the excess abundance that was likely produced from dryland systems in climatically favorable times may have allowed for greater accumulation of wealth assets that would have played a role in building and maintaining alliances and power (e.g., Dye, 2014). Ultimately, Kamehameha I, the chief who unified the island through conquest, stemmed from a dryland dominated landscape on Hawaiʻi Island.

The earliest colonizers of Hawaiʻi were no doubt driven by their will to survive; as increasing alterations to the landscape were made, cultural norms were developed and reinforced to support the protection of the land. It is evident that the Hawaiians maintained the healthy functioning of their environment as a cornerstone of their value system. A well-known saying summarizes: "He aliʻi ke ʻāina, he kauwa wale ke kanaka—the land is chief, and the people merely servants" (Pukui, 1983). The embodiment of akua within plants, animals, and natural features represents a deep reverence for the natural world. Certain areas were seen as being a part of wao akua—the realm of the gods, in direct contrast to wao kanaka—the realm of man. Within the Hawaiian landscape, areas above ~3,000 ft. elevation were reserved for the akua, where man did not tread heavily and only under specific circumstances of need. Whether by design or by circumstance, this practice protected watersheds and biodiversity, aiding in the management of natural resources necessary for survival and wants.

Cook and Conquest

The story of Hawaiian agriculture recognizes fundamental differences in the investment, return, and resilience of different agricultural systems. The loʻi system required significant initial investment to construct, but once established was highly productive and required relatively little maintenance to operate. Flowing water supplied much of the necessary crop nutrients and suppressed weeds (Deenik, Penton, & Bruland, 2013; Deenik, Penton, Popp, & Bruland, 2013; Palmer et al., 2009). The capital investment in irrigation reduced vulnerability to environmental variations (i.e., droughts) and the low-labor requirements also reduced vulnerability to social disturbances (i.e., war). This contrasts with the māla system, which involved less infrastructure investment but required extensive labor to maintain in the forms of mulching, weeding, and watering. The dependence on rain made māla inherently more vulnerable to the environment, while the dependence on labor made it more vulnerable to social disturbances (Kolb, 1997, Tuggle & Tomonari-Tuggle, 1980). Ultimately, loʻi were more resilient systems that produced a larger food surplus in comparison to the labor required that powered the rapid development of stable polities and social orders (Kirch, 1994).

Earlier research helped identify factors required for the development of intensive wetland and dryland agriculture. For loʻi these factors relate to topography (i.e., slope of the land), elevation, and flowing water; for māla, the rainfall, substrate age, and slope define the usable areas (Ladefoged et al., 2009). By mapping these variables researchers have modeled the extent of intensive Hawaiian agriculture with remarkable accuracy (Kurashima & Kirch, 2011; Ladefoged et al., 2009). The different agricultural systems show high spatial segregation, with dryland agriculture dominating the youngest islands of Hawaiʻi and Maui, a mix of agricultural systems on mid-aged Molokaʻi, and almost exclusively wetland agriculture on the oldest island of Kauai.

In the modern study of Hawaiian agriculture, these simplified groupings have been useful to examine a range of interactions between the environment, agriculture, and sociopolitical development. While historical testimony and cultural knowledge tell us a great deal about the agricultural forms, practices and values, there are larger processes at work that can only readily be observed in hindsight. This topic has captured the attention of many, who have examined the broader story of Hawaiian agriculture from an interdisciplinary perspective (e.g., Field et al., 2010; Kirch et al., 2003; Kirch & Zimmerman, 2011; Kirch & O'Day, 2012; Ladefoged & Graves, 2000; Vitousek et al., 2004).

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The story of ancient Hawaiian agriculture is greatly altered by the arrival of Captain James Cook in 1778 and the Hawaiians' ensuing interaction with the Western world. Introduced diseases decimated the Hawaiian population by an estimated 90–95% over the ensuing century (Swanson, 2014), while global commerce and political influence rapidly changed the way of Hawaiian life. The vast māla systems, which required extensive labor to maintain, struggled on for several decades before collapsing. The loʻi systems, with their durable stone infrastructure, persisted much longer—some have been farmed constantly to the present day. Portions of both systems were adapted and utilized by immigrants, with pockets of Hawaiian agriculturalists maintaining their practices into contemporary times. With the privatization of land, establishment of plantation agriculture, and the marginalization of native peoples in Hawaiʻi the practice and knowledge of these systems has been pushed to the side, but not forgotten.

Although Hawaiian agriculture and associated practices were largely diminished, they continue in an adapted form. And perhaps this is fitting, for clearly Hawaiians evolved their practices over time and in response to changing environmental and social conditions; there is no reason to think this process of adaptation would have at some point ceased. There is evidence for Hawaiian innovation in agriculture throughout its history, and evidence it was still occurring at the time of contact (McCoy, Graves, & Murakami, 2010). In early valley agriculture, Hawaiians discovered the practice of simple flooding, cutting into the valley walls to reach the water table and irrigate nearby soils (Kirch, 1977). Construction of superior ʻauwai in the 18th century shows that Hawaiians were beginning to use canals, even tunnels, to divert water out of the river valleys onto the plateaus, likely to increase intensity and resilience of already established rainfed agriculture systems (McCoy & Graves, 2008). Where Hawaiian agricultural practices would have evolved to had Europeans not arrived will forever remain a mystery, but given the ingenuity and adaptation, the environmental values embodied into the culture, and continued evolution of the Hawaiian social–political system we can assume that it would have proceeded along a trajectory unlike any seen in the world.

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Notes:

(1.) A sport, traditionally traditionally called lusus, is a part of a plant that shows morphological differences from the rest of the plant. Sports may differ by foliage shape or color, flowers, or branch structure.

(2.) There are others that could be included, particularly the ancient goddess Hina, that have been left out in consideration of brevity. Please see Beckwith (1940) for an excellent overview of ancient Hawaiian lore and the many gods and goddesses.

(3.) The Nāwao were an ancient race of forest dwellers, and several references make them sound more like natural elements and biota rather than people. Interestingly, this word is also used to describe a cultivated kalo (*Colocasia esculenta*) that has gone wild in the forest. The Nāwao are also called the Mū (silent) and the Wa (shouting). The Menehune are called "human" as distinguished from the "wild" Nāwao people (Beckwith, 1940).

(4.) Wākea seems to have been, in historic times at least, the officially accepted progenitor of the Hawaiian people, and is regarded as a man in Hawaiʻi rather than a deity as in the Southern Polynesian islands.

(5.) Several similar names have been recorded describing the agricultural walls, including kuaiwi, kuamoʻo, kuaʻāina, iwiʻāina, iwikuamoʻo, and moʻoʻāina. All the terms envoke the meaning backbone or ridge, using the terms iwi (bones), kua (back), ʻāina (land), and moʻo (ridge or narrow strip of land).

(6.) The political act that ended the traditional land tenure system and established fee-simple land ownership. The Monarchy of Hawaiʻi enacted the Māhele in 1848, with two follow-up provisions that allowed for additional claims to be submitted by Hawaiian nationals.

Noa Kekuewa Lincoln

Tropical Plant and Soils Sciences, University of Hawaiʻi Mānoa

Peter Vitousek

Department of Biology, Stanford University