The Ahupua'a of Puanui: A Resource for Understanding Hawaiian Rain-Fed Agriculture

Author(s): Aurora K. Kagawa and Peter M. Vitousek
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The Ahupuaʻa of Puanui: A Resource for Understanding Hawaiian Rain-Fed Agriculture[1]

Aurora K. Kagawa[2,3] *and Peter M. Vitousek*[2]

Abstract: Intensive rain-fed agricultural systems represented the foundation of the agricultural economies of the island of Hawaiʻi and parts of Maui in the centuries before European contact. These systems largely were abandoned in the nineteenth century, and our understanding of how they functioned as productive systems is sparse. We established three experimental gardens within the ahupuaʻa (traditional Hawaiian land division) of Puanui, in the Leeward Kohala Field System, where we have measured climate and soil properties and planted several Polynesian crops. We obtained relatively large yields of ʻuala (sweet potato, *Ipomoea batatas*) (from 1 to 4 kg of tubers per m^2) from spring and summer plantings in two wetter, higher-elevation gardens; growth was slow there in the winter. In a drier, lower-elevation garden, only winter plantings provided reasonable yields (0.6 kg per m^2). We suggest that Hawaiian farmers cultivated a winter crop of ʻuala in the lower, warmer, drier portion of the field system and grew spring-summer crops in the upper, wetter portion of the system. Ahupuaʻa-level management in rain-fed agricultural systems could thus have functioned to integrate environmental variability and sustain yields through the year.

The Hawaiian archipelago offers unparalleled opportunities to evaluate the structure and functioning of ecosystems, the evolution of cultures, and the interactions between ecosystems and cultures. Hawaiʻi encompasses most of the climatic variation found in the earth's tropics and a wide variety of soils and ecosystems, all organized along more or less well-defined environmental gradients and in a relatively small and circumscribed area (Vitousek 2004). The archipelago was colonized by Polynesian voyagers who expanded across the Islands and over the course of a few centuries developed several kinds of intensive agricultural systems that reflected both the creativity of the culture and the capabilities of the lands they inhabited and transformed (Allen 1991, 1992, Kirch 1994). At the same time, Hawaiian society grew substantially in social and cultural complexity (Sahlins 1972, Johnson and Earle 2000, Kirch and Green 2001), ultimately developing four to five political entities (archaic states) that were centered on the largest islands of the archipelago (Abad 2000, Cordy 2000, Kirch 2010*a*). Hawaiian societies differentiated as they developed, with social organizations that took different forms on the different landscapes and islands of the archipelago (Kirch 1994, 2010*a*).

Agricultural systems represented one important nexus where ecosystems and Hawaiian societies interacted with and influenced each other. Agriculture as practiced by mahi ʻai (farmers) was intensive and productive; it supported population densities that were remarkably high by contemporaneous global standards (Kirch and Rallu 2007, Kirch 2010*a*,*b*). Two major classes of agricultural systems can be identified: irrigated systems based on kalo (taro, *Colocasia esculenta*), and rain-fed systems based on ʻuala (sweet potato, *Ipomoea batatas*), dryland kalo, uhi (yams or *Dioscorea* spp.),

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[2] Department of Biology, Stanford University, Stanford, California 94305.
[3] Corresponding author (e-mail: akk.alum.mit.edu).

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and other crops. Hawaiians also maintained household gardens and practiced shifting cultivation; they raised domestic pigs, dogs, and chickens, drew substantial resources from marine environments, and developed unique intensive aquaculture systems in estuaries and on reef flats (Handy and Handy 1972, Kamakau 1976). However, at the time of European contact, the bulk of their food (and probably that of their domestic animals as well) is believed to have been derived from the irrigated and rain-fed dryland systems of intensive agriculture (Ladefoged et al. 2009).

The highly productive and sustainable irrigated agricultural system was brought to Hawai‘i by the Polynesian discoverers; it was (and to an extent still is) widely practiced in the Pacific, although it was carried out on a larger scale in Hawai‘i. In Hawai‘i as elsewhere (before the development of long-distance water diversions or groundwater pumping), systems of irrigated pondfields generally required landscapes that supported surface streams or substantial springs. These irrigated systems fit well in the Hawaiian land tenure system that included ahupua‘a, land divisions that often are described as wedges extending from the mountains into the sea (Blaisdell et al. 2005), although it is clear that the multiple Hawaiian land divisions were influenced not only by resources but also by politics within the chiefly class (Beamer 2008). Still, ahupua‘a in irrigated agricultural regions generally represent one or more watersheds, allowing a community to manage flowing water from its source in the forest through irrigated pondfields and in some areas through reef-flat fishponds into the sea (Blaisdell et al. 2005).

Within Polynesia, large and highly structured rain-fed agricultural systems were unique to Hawai‘i. Several of these systems covered tens of kilometers with dense networks of field walls and trails (Rosendahl 1994, Ladefoged et al. 1996, 2003, Ladefoged and Graves 2000, Allen 2004); they required sites with sufficient rainfall to support intensive agriculture but not so much rainfall that long-term weathering and leaching depleted soil fertility (Chadwick et al. 2003, Vitousek et al. 2004, Ladefoged et al. 2009). These conditions were met on the mesic leeward slopes of the younger volcanoes of the Hawaiian archipelago, where the remains of large systems have been identified in Kohala, Waimea, Kona, and Ka‘ū on the island of Hawai‘i and Hāna, Kahikinui, and Kula on Maui. The land underlying these systems also was divided into ahupua‘a that may have been defined more flexibly than in irrigated regions (given the lack of perennial streams in these dryland regions). In the Leeward Kohala Field System, there is evidence for progressive subdivision of seven original ahupua‘a to the point where portions of 33 ahupua‘a were included in the system at the time of European contact (Ladefoged and Graves 2006). These rain-fed systems were largely abandoned in the nineteenth century, due to the devastation of the Hawaiian people by introduced diseases, the social and political disruptions of European colonization, and the introduction of grazing animals and agricultural pests; how they functioned as large-scale systems of agriculture has been lost to modern memory and practice.

The Leeward Kohala Field System is the best studied of the rain-fed field systems; a number of studies have mapped and analyzed agricultural and other features within the area (Ladefoged et al. 1996, Ladefoged and Graves 2000), soil fertility in relation to agriculture (Vitousek et al. 2004, Meyer et al. 2007, Palmer et al. 2009), human demography (Lee et al. 2006, Ladefoged et al. 2008), and the stratigraphy of coastal and inland house sites (Field et al. 2011). In this article, we introduce and discuss an opportunity to evaluate rain-fed dryland agriculture within the Leeward Kohala Field System through observation and experiment, and to engage the local community in understanding and connecting to an example of the most important precontact agricultural system on the island of Hawai‘i.

MATERIALS AND METHODS

Research Site

The ahupua‘a of Puanui reaches from the northwestern ridge of Kohala Volcano to the ocean; it crosses the Leeward Kohala Field

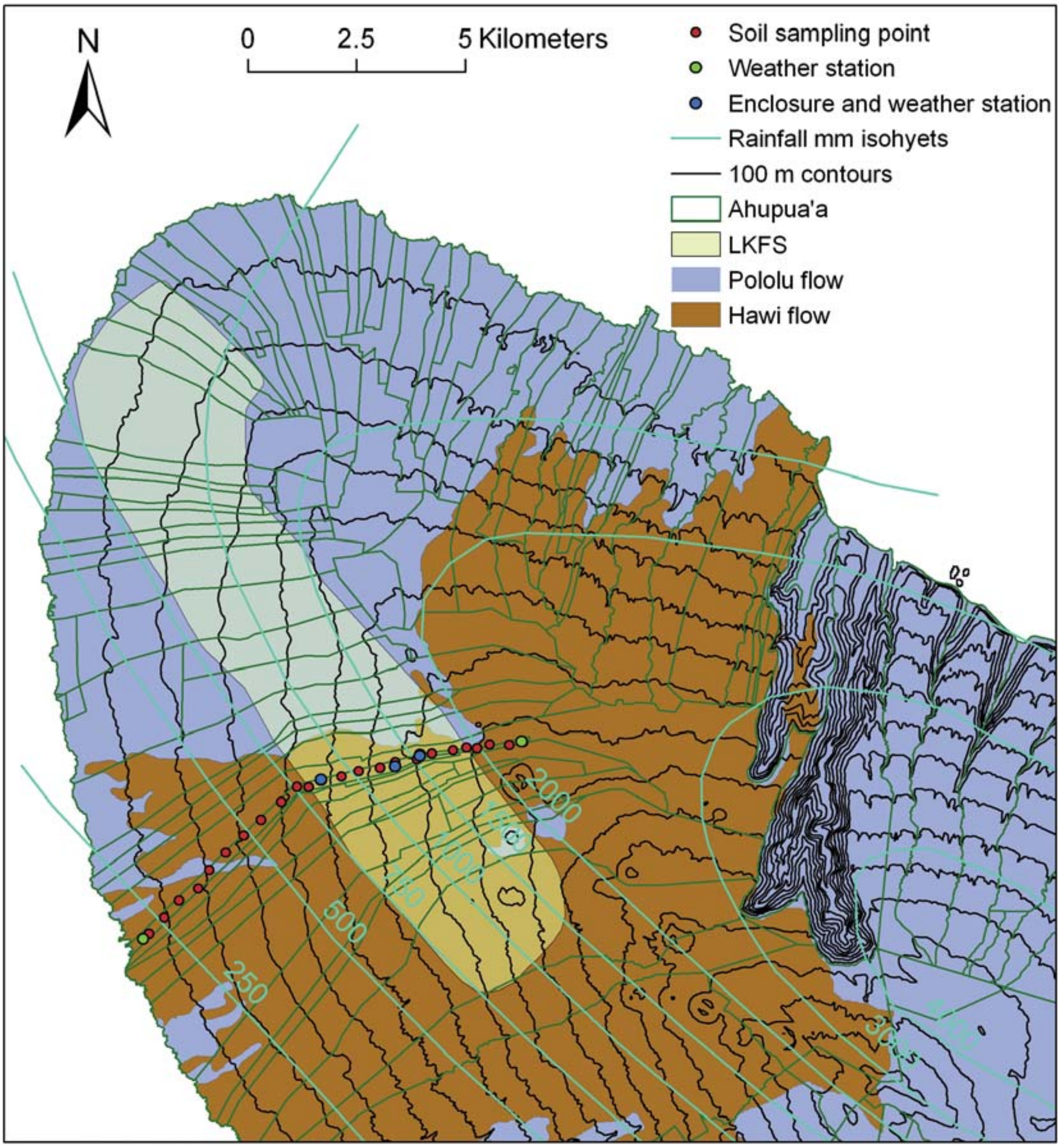

PLATE 1. Kohala Volcano. The colors represent volcanic formations; blue represents the older Pololū Formation (~400,000–600,000 yr old) and brown represents the younger Hāwī Formation (~150,000 yr old). The tan overlay represents the Leeward Kohala Field System (LKFS) (Ladefoged et al. 2003). Black lines are elevation contours (100 m), cyan lines are rainfall isohyets (from Giambelluca et al. 1986), and green lines are ahupuaʻa boundaries. All measurement sites discussed here are in the ahupuaʻa of Puanui; red dots represent locations where soils were sampled, green dots represent weather stations, and blue dots represent locations with both planting exclosures and weather stations.

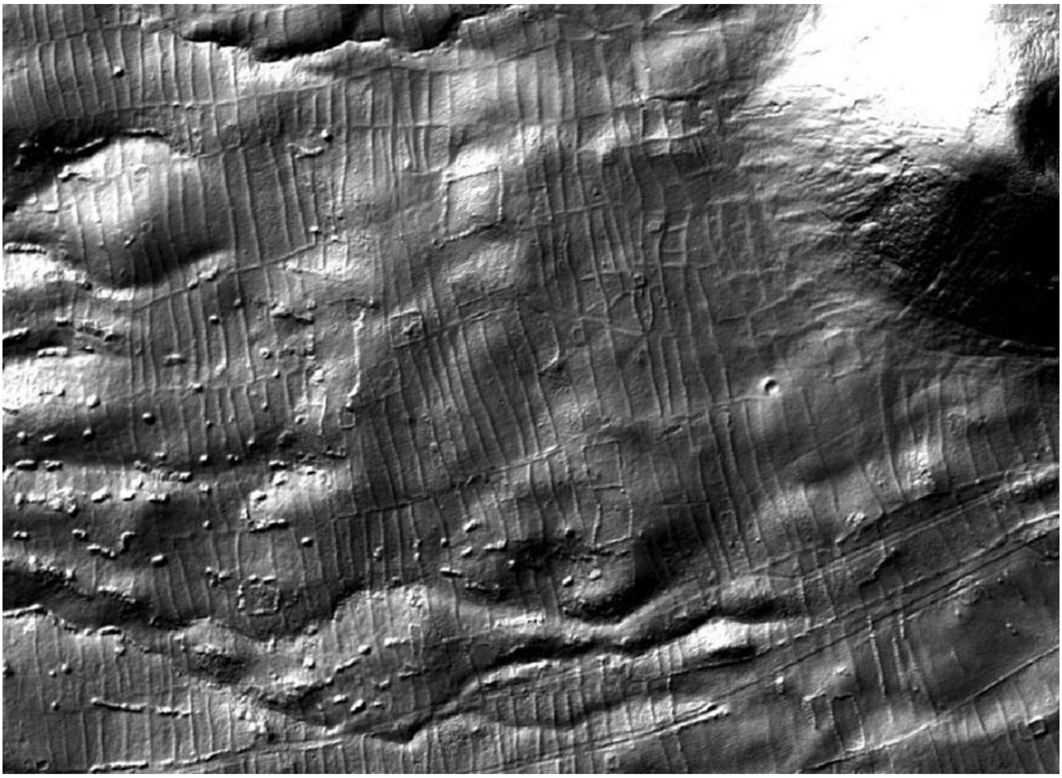

Figure 1. Features of the Leeward Kohala Field System in a portion of the ahupuaʻa of Puanui and surroundings. This image is a hillshade projection of a digital elevation model derived from light detection and ranging (LiDAR) images obtained by the Carnegie Airborne Observatory (Asner et al. 2007). North is at the top of this image; the land slopes down from right to left, and the cinder cone Puʻu Kehena is in the upper right. Puanui extends from just below Puʻu Kehena to the lower left corner of the image; the midelevation exclosure is near the lower center of the image. Densely spaced field walls run parallel to the contour throughout the image, and stone-lined trails run up and down the slopes (along with a four-wheel-drive road and fence lines in the bottom portion of the image). The mounds on the left side of the image result from past bulldozing for pasture improvement.

System about two-thirds of the way from the northern margin of the system near ʻUpolu Point to the southern margin near Kahuā Ranch (Plate I). Puanui is owned by Kamehameha Schools and leased to Parker Ranch; it has been grazed continuously by cattle for over 100 yr. Within Puanui, the walls of the field system (shown in Figure 1) can be detected from just below Kohala Mountain Road at ~780 m elevation to their lower margin near 480 m; many of the remains in the lower-elevation portion of the system were damaged by bulldozing, although not right at the lower-elevation margin. We sampled soils and established climate stations across the ahupuaʻa, and established and fenced three experimental gardens within the bounds of the ancient Hawaiian agricultural system (Plate I).

Soil Sampling

We collected 24 surface soils (integrated from the surface to 30 cm depth) at ~500 m intervals from the upper margin of Puanui to near the coast (Plate I), following procedures used elsewhere in the Leeward Kohala Field System (Vitousek et al. 2004, Palmer et al. 2009). Soils were sieved, air dried, and divided into subsamples for analyses. Analytical procedures were reported by Vitousek et al. (2004): briefly, one subsample was analyzed for resin-extractable P (a measure of available P) and total C and N at Stanford University; a second subsample was analyzed for pH, exchangeable cations, cation exchange capacity, and base saturation at the University of California Santa Barbara; and a third subsample was digested for total element analyses of P, Ca, Mg, K, Na, Al, Fe, Si, Ti, Mn, Sr, Ba, Cr, Zr, and Nb at ALS Chemex (Las Vegas, Nevada). We used Nb as an immobile index element and calculated the retention and loss of other elements with reference to Nb (Chadwick et al. 2003).

Climate Stations

We established five micrometeorological stations within Puanui, four of them in late 2008 and a fifth early in 2010. Stations were established within the three fenced gardens (exclosures) in the agricultural system, as well as near the upper and lower margins of the ahupuaʻa (Plate I). Four of the stations were Onset (Pocasset, Massachusetts) systems, each consisting of a datalogger (HOBO U30 NRC), tipping bucket rain gauge, relative humidity/temperature sensor, pyranometer, wind speed and direction sensor, and two 20 cm soil moisture sensors (ECH2O). A fifth system (located near the coast) was a Campbell Scientific (Logan, Utah) system consisting of a datalogger (CR10x), tipping bucket rain gauge (TE525), RH/temperature sensor (HMP45), combination anemometer and wind vane (034b), pyranometer (SP-110), and two soil water content reflectometers (CS616). Rainfall, temperature, relative humidity, solar radiation, wind speed and direction, and an index of soil moisture were sampled every minute and recorded every 10 min at all stations. When equipment failure necessitated gap filling, daily precipitation data were estimated using linear and multiple linear regression techniques assuming that daily rainfall of the target series had the same distribution as that of the nearest recording stations with which it was best correlated. Mean daily temperatures were calculated as the average of the daily maximum and minimum temperatures.

Gardening Exclosures

Cattle grazing continues in the ahupuaʻa of Puanui; to grow Hawaiian crop plants, we needed to build exclosures. Three exclosures were established: one near the upper margin of the Leeward Kohala Field System; another near the lower margin; and the third centered within the system, in a region where the remains of the agricultural infrastructure are most clear (Plate I and Figure 1). The upper and lower exclosures are ~40 × 40 m; the middle exclosure is larger (~80 × 80 m) to allow educational use by community and school groups. Within the exclosures, we cleared existing vegetation (with herbicide or by hand), tilled (with a rototiller or digging stick), and planted multiple Polynesian varieties of ʻuala, kalo, and kō (sugarcane, *Saccharum officinarum*). Plantings were carried out at different times of the year, and yields of ʻuala were determined by harvesting and weighing tubers from known areas.

The exclosures served as outdoor classrooms, and community visitors were recruited to assist in cultivation and harvest of the ʻuala. After hiking to the summit of nearby Puʻu Kehena to view the expanse of the field system, students and other visitors helped to weed the ʻuala, kalo, and kō cultivar collections and harvest and weigh tubers, taking home excess yield not used for laboratory analysis and often cuttings of ʻuala cultivars for their own home use and experimentation.

RESULTS

Soils

Soil properties within Puanui are similar to those reported earlier from elsewhere in leeward Kohala: soils in the wet upper-elevation areas (above the field system) are acidic and nutrient depleted, those within the agricultural system are relatively nutrient-rich (remarkably so in P), and those in the dry lower-elevation areas are intermediate in fertility. Earlier studies demonstrated that thresholds in several soil properties are correlated with the upper, wetter margin of the Leeward Kohala Field System and other rain-fed dryland systems (Kirch et al. 2004, Vitousek et al.

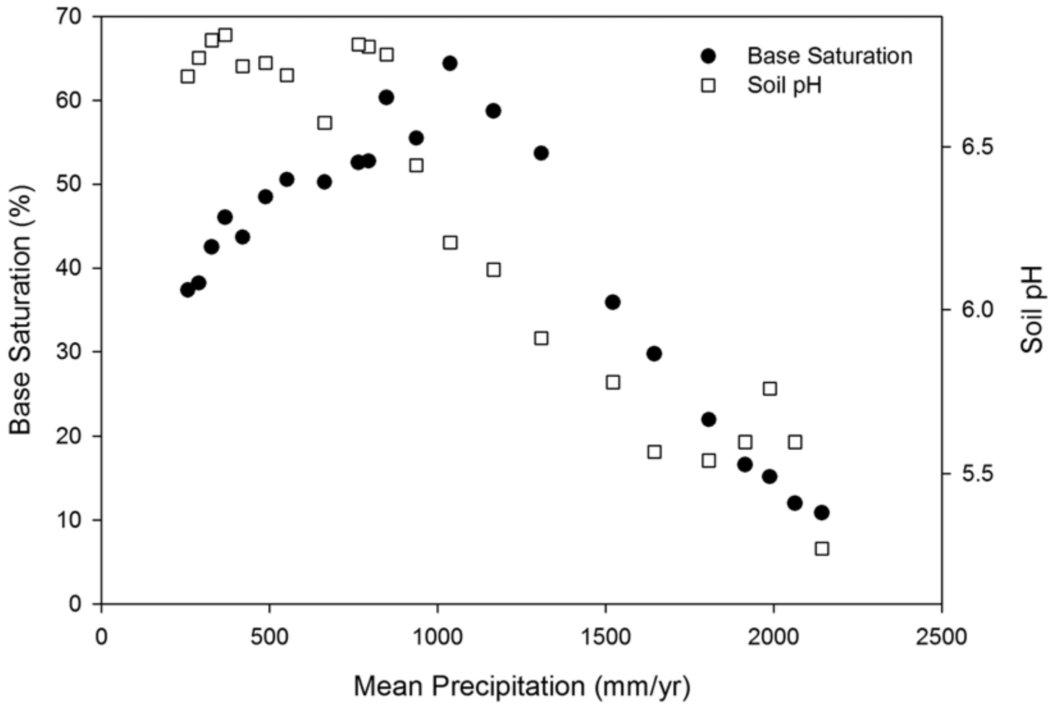

FIGURE 2. Soil pH and base saturation (the percentage of cation exchange sites that are occupied by Ca, Mg, K, and Na versus Al and H^+) across the ahupuaʻa of Puanui. Values are three-point running means. Base saturation is an integrated index of soil fertility; a threshold value of 30% was associated with the upper, wetter margin of the Leeward Kohala Field System here and elsewhere in Leeward Kohala (Vitousek et al. 2004).

2004, McCoy and Hartshorn 2007); these properties are summarized in Figures 2–4, and the complete set of soil information is accessible at http://www.stanford.edu/group/Vitousek/ [as "Puanui Soils Data (Excel)"].

Within Puanui, soil pH decreased from ~6.8 near the coast to 5.2 at the upper margin of the ahupuaʻa, and base saturation increased from 35% near the coast to over 60% within the lower portion of the field system, then declined to ~10% at the upper edge of the ahupuaʻa, as observed elsewhere in the Leeward Kohala Field System (Figure 2). There is generally a threshold value near 30% base saturation below which Hawaiians did not intensify rain-fed agriculture; this threshold is observed in Puanui as elsewhere. Resin-extractable P averaged ~40 ppm near the coast; it increased to 130–180 ppm in the lower portion of the agricultural system, then declined to <10 ppm in wet areas above the agricultural system (Figure 3). The fraction of P remaining from the original parent rock averaged ~100% above and below the agricultural system but was strikingly enriched within the system (Figure 3). This enrichment was observed elsewhere in the Leeward Kohala Field System; it is caused by biological uplift of P from deep within the soil by the forests that preceded the Hawaiian agricultural system (Porder and Chadwick 2009). Finally, organic C concentrations increased with increasing rainfall within Puanui, and the C : N ratio of soils reached a minimum between 11 and 12 (by mass) within the agricultural system and increased to 15–16 at both the dry and wet extremes of the ahupuaʻa (Figure 4). Organic N is more readily mineralized (converted into available forms for plant growth) when the C : N ratio is low; this observation suggests that the biological availability of soil N is greatest within the agricultural system.

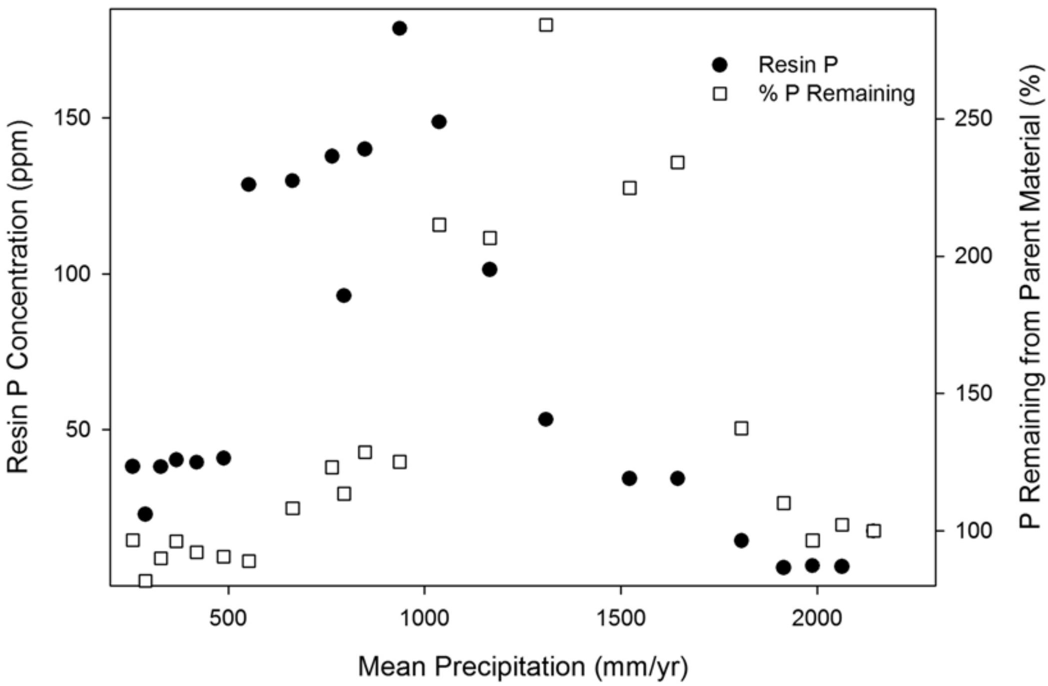

Figure 3. Resin P and P remaining from parent material across the ahupua'a of Puanui, reported as three-point running means. Resin P is readily extractable; it provides a measure of biologically available P. The P remaining from parent material is calculated with reference to the index element Nb; values are enriched above parent material abundances because biological uplift of P from the subsoil has enriched surface soil in P in the intermediate rainfall zone.

Climate

Within Puanui, temperature decreases and rainfall increases rapidly with elevation. From 1 March 2009 to 28 February 2010, the mean temperature ranged from 26°C at 50 m elevation near the coast to 18°C at 860 m elevation near the upper margin of the ahupua'a (Figure 5), equivalent to a lapse rate of 9.4°C per kilometer. Rainfall in Puanui during that period ranged from 102 mm near the coast to 1,304 mm at the upper margin of the ahupua'a (Figure 5). Precipitation was unusually low during that year of measurements; an 80-yr record from nearby Kahuā and Ponoholo Ranches shows that 2009–2010 had the lowest rainfall since the mid-1930s (Pono von Holt, pers. comm.). Interpolations based on long-term measurements suggest that average rainfall at the lowest-elevation station is ~200 mm/yr, and average rainfall at the highest-elevation station is ~2,200 mm/yr (Giambelluca et al. 1986).

Temperature and rainfall observed at Puanui exhibited strong seasonality. Across all sites, rainfall was greatest in the winter months when temperatures were low, and rainfall was lowest in summer months (Figure 6). Across all stations, mean temperature ranged ~5°C between coldest and hottest months. The lower-elevation sites receive almost all of their rain in winter frontal storms ("Kona weather"), but the upper-elevation sites receive substantial summer rainfall associated with the northeast trade winds (Figure 6). From 1 March 2009 to 28 February 2010, 50% of annual precipitation at the coastal weather station (50 m) occurred during five storm events, and 90% of total annual rainfall occurred on 19 days, versus 94 days at the highest-elevation station (860 m).

Within the agricultural system at Puanui, the spatial and seasonal climatic variation resulted in growing conditions that shifted in time and space (Figure 6). When the lower margin of the agricultural system (495 m)

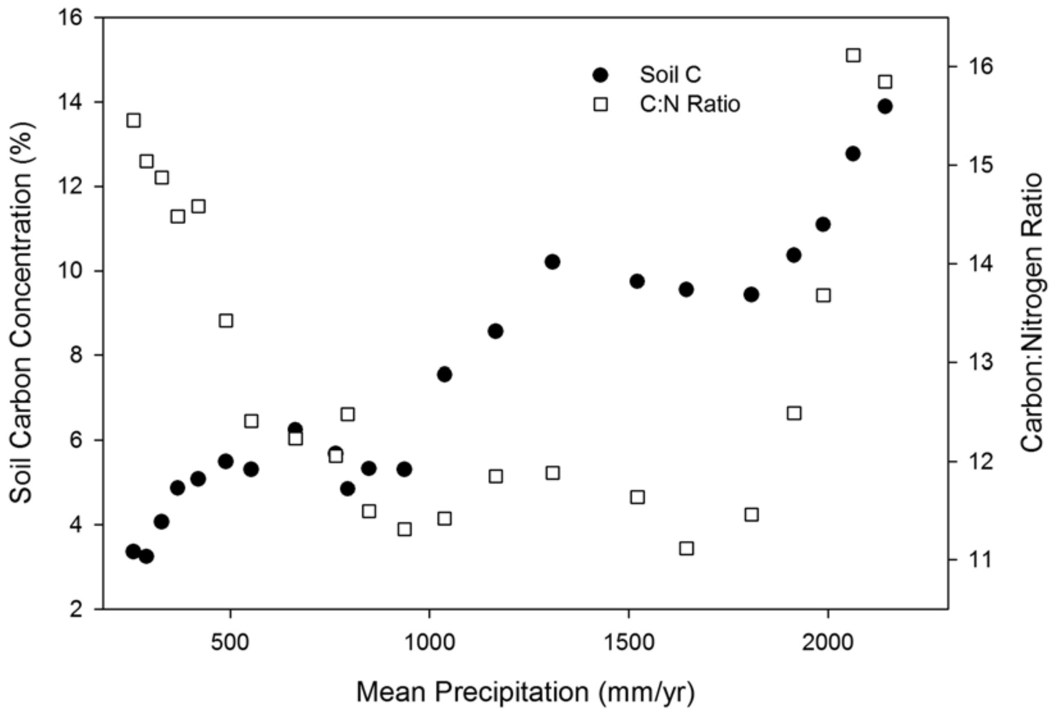

Figure 4. Soil C and C:N ratio across the ahupuaʻa of Puanui, reported as three-point running means. The C:N ratio is a strong predictor of N supply to plants; below a ratio of 12, nitrogen supply is enhanced.

experienced summer drought in June–July, the upper-middle portion of the agricultural system (685 m elevation) received ~30 mm rain per month. Alternatively, when mean January–February temperatures were 17–18°C at the upper-middle portion of the agricultural system, they were ~20°C at the lowest part of the field system (Figure 6). Thus we observed a shifting envelope of environmental conditions conducive to the growth of ʻuala (Figure 6). Micrometeorological data continue to be collected at Puanui and are available at http://www.stanford.edu/~akkagawa/data.html.

Exclosures

Kō established and grew well in the upper-elevation exclosure, less well and variably (depending on variety) in the middle-elevation exclosure, and not at all in the low-elevation exclosure. We did not succeed in growing dryland kalo at any site. However, despite the unusually low rainfall during our experiments, growth and yields of ʻuala were substantial in the two higher-rainfall exclosures. A January 2009 planting of the ʻLanikehaʼ variety in the upper-elevation exclosure yielded 1.8 and 4.0 kg/m^2 (wet weight; dry weight was ~20% of wet weight) in harvests in late June and early August 2009. Plants grew slowly through the winter, then rapidly and continuously in spring and early summer. In the intermediate-elevation exclosure, plantings in early April, late June, late July, and mid-December 2009 yielded 2.2, 1.8, 0.9, and 1.3 kg/m^2, respectively; pest issues (especially mice and pheasants) were substantial with the later plantings, and again growth was slower in the winter months. Finally, several attempts to grow ʻuala in the lowest, driest exclosure failed; only a mid-December planting succeeded, yielding 0.6 kg/m^2 of tubers.

These yields are generally higher than was assumed in a recent analysis of the productive potential of rain-fed ʻuala (Ladefoged et al. 2009); that analysis reported a range of 0.5 to 1.5 kg/m^2 (wet weight) for Pacific systems,

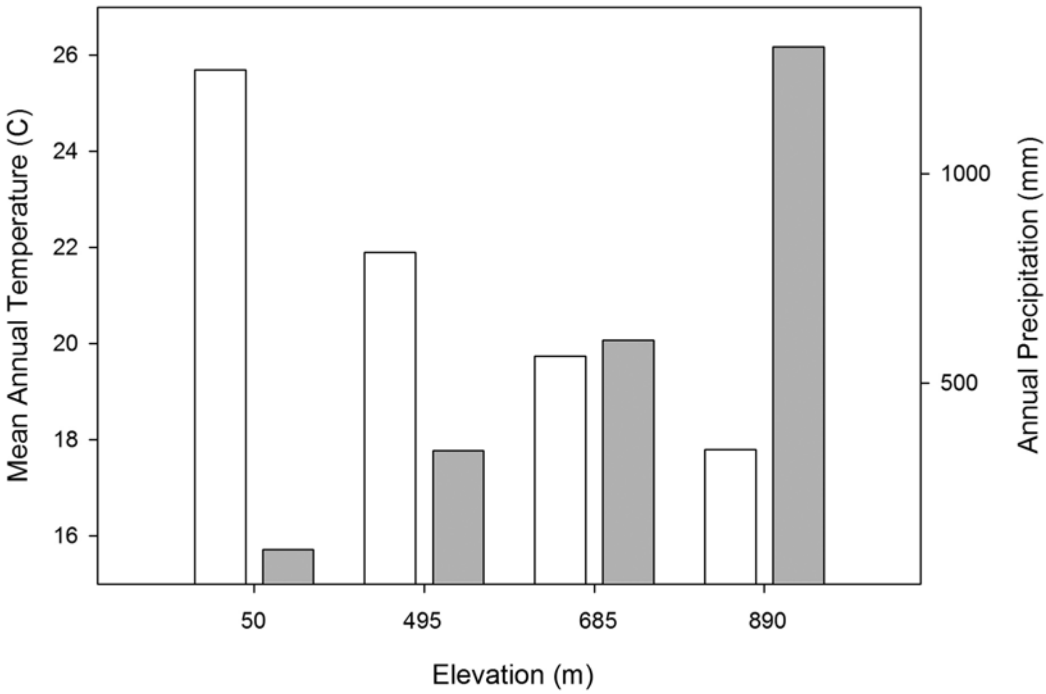

Figure 5. Temperature and precipitation at four weather stations across the ahupua'a of Puanui from March 2009 through February 2010. Temperature values (white bars) are calculated from monthly mean temperatures at each station; rainfall (gray bars) was summed across the interval.

and assumed an average value of 0.5 kg/m^2 for precontact Hawaiian rain-fed systems. We do not know if the much higher yields we obtained in the higher-elevation exclosures could be sustained through repeated crops. Possibly not, in that nutrients removed in harvest would have had to be replaced. But on the other hand there can be no doubt that the Hawaiian cultivators who lived in the field system and off of its yields for centuries were better at farming it than we are.

Beyond 'uala yields, the exclosures facilitated valuable education and exchange. The service-learning approach and communal weeding/harvesting enabled visitors to work together beyond economic and cultural gaps. The yields also became currency for building collaborations with potential partners in the community. The sheer number of visitors, over 600 in 2 yr, has enhanced awareness of and interest in traditional rain-fed systems across the island of Hawai'i.

DISCUSSION

Irrigated kalo-based agricultural systems persisted through European colonization and the dislocations of globalization; their dynamics can be understood in terms of direct observations and a living tradition as well as in terms of information derived from archaeology, environmental science, and ethnohistory. In contrast, large rain-fed agricultural systems of the sort that fed most of the population of the island of Hawai'i before European contact (Ladefoged et al. 2009), and that powered the island's ascendance in the archipelago shortly afterward, were largely abandoned in the nineteenth century. Field measurements and experiments at Puanui provide the opportunity to bring an additional line of evidence to our understanding of these rain-fed systems, complementing existing research based on soils, climate, and archaeology (Vitousek et al. 2004, Lee et al.

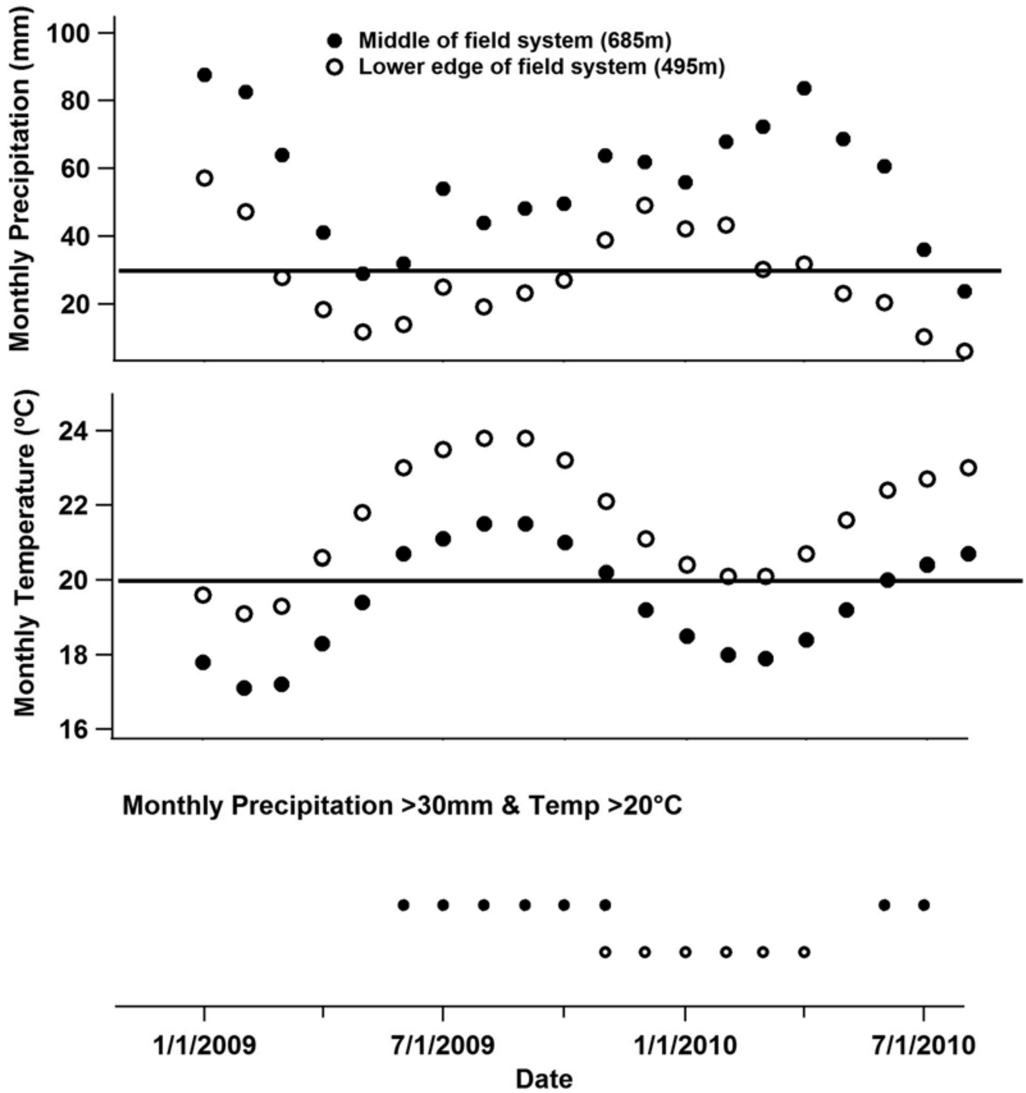

Figure 6. Monthly precipitation and temperature at two exclosures within the field system at Puanui, from January 2009 through August 2010. Data are reported as three-point running means. In the bottom panel, seasonal patterns of rainfall and temperature give rise to periods of warm, wet conditions that shift seasonally with elevation.

2006, Ladefoged et al. 2009, Kirch 2010*b*, Field et al. 2011).

Our field observations at Puanui suggest a possible utility and organizing principle for ahupuaʻa in intensive rain-fed agricultural regions. Although the value of ahupuaʻa as watershed-based management units in irrigated regions is clear (Blaisdell et al. 2005, Mueller-Dombois 2007), it is not so evident why regions without surface water should have been organized into narrow, vertically oriented strips of land, particularly where (as in Puanui) the network of temporary streams that does exist is oblique to the ahupuaʻa boundaries. We found that the vertical climate gradient provides a possible explanation.

The agricultural system itself runs from 780 m elevation and 1,750 mm/yr average precipitation at its upper boundary to 480 m and 800 mm/yr at its lower bound 3 km away. The majority of rain falls in the winter across the system. Seasonal patterns of rainfall and temperature indicate that temperatures for sweet potato production are suitable year-round at the lowest-elevation exclosure, but precipitation is limiting, particularly during the summer months (Figure 6). Planting at these sites could be done to make use of available water during and following winter Kona storms. At the upper-elevation exclosure, cold temperatures constrained growth in the winter; however, higher moisture availability and higher summer precipitation enabled late spring and summer cropping (Figure 6). Overall, we suggest that planting, tending, and harvesting shifted seasonally across the landscape, and that the ahupuaʻa-based organization of the Leeward Kohala Field System made both agronomic and cultural sense as a consequence.

Finally, the observations and experiments at Puanui provide an extraordinary opportunity for education and community outreach. The importance, even the existence, of rainfed agricultural systems and their drought-resistant crop plants has been little-appreciated in Hawaiʻi, even in communities within or adjacent to such systems. Research in Puanui has been a magnet for school and community groups interested in science, agriculture, and cultural history; over 600 people have visited Puanui, most of them from Hawaiʻi, and several student groups have been inspired to perform their own plantings and experiments within the exclosures and/or at their schools. The measurements, experiments, and educational activities are now being managed by a community group, Ulu Mau Puanui, that will sustain research and education at Puanui.

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