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Opportunities and constraints for intensive agriculture in the Hawaiian archipelago prior to European contact

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ABSTRACT

Intensive agricultural systems interact strongly and reciprocally with features of the lands they occupy, and with features of the societies that they support. We modeled the distribution of two forms of pre-European contact intensive agriculture – irrigated pondfields and rain-fed dryland systems – across the Hawaiian archipelago using a GIS approach based on climate, hydrology, topography, substrate age, and soil fertility. Model results closely match the archaeological evidence in defined locations. On a broader scale, we calculate that the youngest island, Hawai'i, could have supported 572 km^2 of intensive agriculture, 97% as rain-fed dryland field systems, while Kaua'i, the oldest island, could have supported 58 km^2, all as irrigated wetland systems. Irrigated systems have higher, more reliable yields and lower labor requirements than rain-fed dryland systems, so the total potential yield from Kaua'i (∼49k metric tons) was almost half that of Hawai'i (∼97k metric tons), although Kaua'i systems required only ∼0.05 of the agricultural labor (∼8400 workers, versus ∼165,000 on Hawai'i) to produce the crops. We conclude that environmental constraints to intensive agriculture across the archipelago created asymmetric production efficiencies, and therefore varying potentials for agricultural surplus. The implications both for the emergence of complex sociopolitical formations and for anthropogenic transformation of Hawaiian ecosystems are substantial.

1. Introduction

The suitability of tropical lands for sustained intensive agriculture – in the millennia before fossil fuels and industrial fertilizer – is a challenging and often contentious question. European colonizers in the New World and the Pacific Islands frequently observed landscapes that already had lost many indigenous inhabitants to introduced disease and social disruption, and the distribution and intensity of indigenous agriculture had diminished as a consequence (e.g., Sand (2000) for a discussion of New Caledonia, Spriggs (2007) for a discussion of Vanuatu, and Schilt (1984) for the Kona field system in Hawai'i). These diminished populations and dis-intensified agricultural systems then formed the basis for Western descriptions of low-density populations and strongly constrained agricultural systems. However, saying that constraints to pre-European contact agriculture have been overstated does not mean that such constraints were absent, nor does it provide much guidance in determining what they might have been.

The Hawaiian Islands are an especially useful place to evaluate constraints to pre-industrial intensive agriculture. Hawai'i is relatively isolated and bounded, and so the dynamics of agricultural development were largely local, and the fact that the agricultural land base was limited must have been apparent to the population of 200,000 to 800,000+ people who occupied the archipelago prior to European contact (see Kirch, 2007b for a review of population estimates). The islands exhibit a broad range of geologic settings and climates over a relatively small area (Pratt et al., 1998), and the implications of this variation for soil fertility and ecosystem biogeochemistry are well-characterized (Chadwick et al., 2003; Vitousek, 2004). There is considerable information on intensive agricultural systems prior to European contact (Kirch, 1985, 1994). Finally, there is a substantial history of interdisciplinary work combining ecology, geography, soils,

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culture, and archaeology in the study of indigenous agriculture (Kirch, 2007a; Kirch et al., 2004, 2007; Vitousek et al., 2004; Ladefoged et al., 2008) that provides an essential starting point for our analyses.

Indigenous Hawaiians were highly effective cultivators. Their Polynesian ancestors introduced a set of largely Southeast Asian derived tropical root, tuber, and tree crops, augmented by the introduction of the sweet potato (*Ipomoea batatas*) from the Americas. With this cultigen set, Hawaiians intensified and sustained agriculture by several distinctive pathways across the disparate environments of the archipelago. Most of these intensive systems fall into one of two major classes: irrigated wetland and rain-fed dryland systems (Handy, 1940; Handy and Handy, 1972; Kirch, 1994), although these classes were the endpoints of a continuum bracketing a variety of intermediate intensive techniques. The contrasts between irrigated wetland and rain-fed dryland agriculture – between wet and dry – have been suggested to have contributed to the complex political dynamics of Hawaiian societies, in the centuries before European contact (Kirch, 1994).

Earlier studies described the general distribution of intensive agricultural systems across the Hawaiian archipelago in qualitative terms (Newman, 1970; Earle, 1980; Kirch, 1994). These efforts, however, were hampered by incomplete ethnohistoric data (especially for the rain-fed systems), and by lack of archaeological survey data for large parts of the islands. Here we develop quantitative models for the distribution of intensive agricultural systems, based on the requirements of irrigated and rain-fed crops, and the measured and mapped environmental characteristics of the Hawaiian Islands. We assess the model results with detailed archaeological data from defined locations throughout the islands, and evaluate their implications for sociopolitical transformations in the Hawaiian Islands.

2. Hawaiian agriculture before European contact

Irrigated taro (*Colocasia esculenta*) pondfields in Hawai'i were highly productive systems capable of being operated over seemingly indefinite time spans (Allen, 1991; Earle, 1978; Kirch, 1977; Kirch and Kelly, 1975; McElroy, 2007; Palmer et al., 2009; Spriggs and Kirch, 1992). This type of agriculture was widely practiced throughout the Pacific (see Kirch and Lepofsky, 1993; Kuhlken, 2002 for reviews), although it was carried out on a larger scale in Hawai'i than elsewhere in Polynesia (Kirch, 1994). Irrigated pondfields represent a form of "landesque capital" intensification; initially substantial inputs of labor were required to build and maintain agricultural infrastructure (in this case stream diversions, irrigation ditches, and the pondfields themselves), but once that infrastructure was in place cultivation could yield very substantial surpluses over the requirements of agricultural labor (Brookfield, 1972, 1984; Blaikie and Brookfield, 1987).

Rain-fed dryland systems represented the other major terrestrial production system; they were based largely on sweet potato (*Ipomoea batatas*) and to a lesser extent dryland taro (*Colocasia esculenta*), yams (*Dioscorea* spp.), banana (*Musa* hybrids), sugar cane (*Saccharum officinarum*), and other crops. Again, these systems achieved a scale and scope in Hawai'i that was unmatched elsewhere in Polynesia (with the possible exception of New Zealand); in several places, they occupied contiguous areas of tens of square kilometers with a dense network of fields separated by earth and rock walls, and linked together with rock lined and paved trails. Most rain-fed systems were abandoned early in the 19th century, following the decimation of the Hawaiian population by introduced diseases. Hence, in contrast to the pondfield systems that continue to operate in valley localities into modern times (albeit in restricted scale), the rain-fed systems were no longer operating and were not described in detail during early ethnographic archipelago-wide surveys of the early 20th century (Handy, 1940; Handy and Handy, 1972).

In addition, smaller systems were widespread in Hawai'i; examples include gardens, shifting cultivation, the cultivation of heavily mulched depressions within relatively young lava flows in the Puna district of the Island of Hawai'i (Ladefoged et al., 1987), and the cultivation of terraced (but not irrigated) areas within gulches on several islands (Kirch, 1977, 1985). However, the large intensive systems occupied the most suitable lands for agriculture, and it is clear that these were the systems whose dynamics were closely coupled to the complex, hierarchical polities of the late precontact period.

Archaeological investigations suggest an approximate chronology of the development of intensive agriculture across the archipelago. Given the higher yields and lower labor inputs of taro irrigation, it is not surprising that these systems developed earlier. Irrigation systems in the windward valleys of Moloka'i were in place by AD 1200 (McElroy, 2007; Kirch, 2002), and were extensively developed and organized on a "supralocal level" on O'ahu Island by AD 1400 (Allen, 1991, 1992), In contrast, the first evidence for rain-fed dryland cultivation does not appear until AD 1300, and systems with fixed fields developed mostly after AD 1400, and only reached highly intensified levels after AD 1650 (Allen, 2001; Kirch et al., 2005; McCoy, 2006; Ladefoged and Graves, 2008).

3. GIS modeling of the distribution of agriculture

We developed models for irrigated and rain-fed systems in an iterative process based on the environmental requirements of the primary cultigens and the results of previous archaeological research. Variables and parameters were determined based on the literature and on observations, appraised, and then refined. For the rain-fed model we integrated the results of our extensive work in the leeward Kohala field system. The final results of the models were assessed by comparing the boundaries defined by the models to those depicted in detailed archeological studies. The boundaries depicted in these archaeological studies were not directly used in the formulation of the models, however, they did influence our notions about where the development of intensive agriculture was possible. The data from these studies therefore provide a relatively independent assessment of the accuracy of the models, although we acknowledge that there was interplay between the creation and testing of the models.

3.1. Irrigated pondfields

The development of large systems of intensively cultivated taro requires consistent and plentiful surface water, large areas of arable soil with shallow slopes, and elevations low enough to yield warm temperatures and high insolation. While taro can be grown in dryland systems if rainfall is sufficient, it produces its highest yields under very wet or flooded conditions, as long as a steady flow across a pondfield can be sustained. The optimal hydrologic throughput has been estimated as 280,000 l/ha per day, referred to as the "Hawaiian Legal Requirement" (de la Pena, 1983). Taro requires an average daily temperature above 21 °C for normal production (Onwueme, 1999), making it essentially a lowland crop in Hawai'i. Our irrigated pondfield model is based on the geospatial intersection of five major variables: water source, elevation, slope, gravitational flow, and geomorphology.

3.1.1. Water source

Continuous perennial streams provided the primary source of water for pondfields, although springs and zones of groundwater emergence or stream re-emergence near the coastal zone also supplied water. Model construction began with the Hawai'i Statewide GIS Program (http://www.state.hi.us/dbedt/gis/index.html) shapefile stream coverage ("darstreams.shp") which classifies watercourses into a number of categories including "perennial," "intermittent," and "non-perennial," reflecting decreasing amounts of water flow. Unfortunately, there are a number of coding errors in the GIS coverage, and some of the largest and most consistent streams in Hawai'i are erroneously classified as "intermittent" as opposed to "perennial". Our model thus starts with all the streams classified as "perennial" or "intermittent". From that set we selected only those streams with at least 1 km in length above the 1500 mm rainfall isohyet, which we considered the minimum to supply a stream with sufficient streamflow to provide a reliable water source to potential pondfields. We differentiated that set of streams into those that could supply water along their full course, and those that could only supply water along a portion of their length, distinguishing these based on whether a stream extended to the 3000 mm isohyet. We assumed streams that did not extend to the 3000 mm isohyet only received enough water to supply areas up to 5 km below the 2000 mm isohyet. The rainfall data comes from an isohyet GIS coverage ("rainfall_n83.shp") available at the Hawai'i Statewide GIS Program website; this was used to interpolate a rainfall GIS raster coverage (100×100 m resolution), from which we further interpolated a 500 mm isohyet coverage. The model assumes that all of the appropriate streams and stream segments could distribute water to areas extending up to 500 m from the stream.

3.1.2. Elevation

Although rain-fed taro can be grown at higher elevations, it is most productively cultivated in areas with mean annual temperatures above 21 °C, which corresponds to areas below 300 m. It is within this elevational zone that intensive wetland agriculture was most likely to occur. These areas were defined using a digital elevation model or DEM (10×10 m resolution) available at the US Department of Agriculture website.

3.1.3. Slope

Taro pondfield systems typically have very gentle slope gradients that deviate only slightly from horizontal, allowing for both flooding and the continuous movement of water across the growing plants. The alluvial floodplains of valleys and extensive alluvial and colluvial coastal plains provide the most favorable conditions for such pondfields. Hawaiians also created pondfields by cut-and-fill stone-faced terracing on steeper slopes, such as the colluvial slopes that are found in many windward valleys, but the area of these was more limited. Based on archaeological survey data provided by McElroy (2007) and Earle (1980), we defined a slope threshold of $\leq$10 degrees for large intensive taro pondfield systems.

3.1.4. Gravitational flow

Even where there is sufficient water flow, proper elevational contexts, and suitable slopes, the detailed topography of riparian corridors can prevent water from reaching areas where pondfields could otherwise be developed. We modeled areas of potential pondfield development by calculating the difference in elevation between a point on the landscape (as defined by a 10×10 m cell) and the elevation of the closest stream (again, as defined by a 10×10 m cell). If the elevation of the stream was higher than the elevation of an adjacent locale then the locale was classified as a potential area for pondfields. In the model, water flows from this locale to other adjacent areas of lower elevation. Given the coarseness of our DEM, we found it necessary to decrease the elevation of surrounding areas by 7 m, otherwise streams generally appeared too entrenched to permit water dispersion onto adjoining land.

3.1.5. Geomorphic setting

Intensive irrigated pondfields can only be constructed in a limited number of geomorphic settings. Soils must be malleable enough to be formed into pondfields and located in areas suitable for water manipulation and diversion. A series of Soil Survey Geographic (SSURGO) database layers were downloaded from the US Department of Agriculture website and combined. The coding in these layers specifies 36 categories for the variable "geomdesc" (geomorphic description). Seventeen of these categories were classified as being suitable for intensive irrigated agriculture, including "alluvial fans", "flood plains", "alluvial flats", "alluvial plains", "gulches", "valleys", and "streams". The primary categories that we excluded were "mountains", "mountain slopes", and "uplands".

3.2. Rain-fed dryland systems

Sweet potato, rain-fed taro, and to a lesser extent yams were the staple crops of the intensive rain-fed dryland agricultural systems of pre-contact Hawai'i (Handy, 1940; Yen, 1974). Sweet potato tolerates cooler temperatures than irrigated taro, and so could be grown at higher elevations; it also tolerates – indeed requires – drier soils than irrigated or rain-fed taro. Long-sustained rain-fed systems also required relatively high levels of soil fertility. Accordingly, our rain-fed agriculture model is based on the intersection of GIS-derived rainfall and elevation, as well as proxy measures of soil fertility.

3.2.1. Rainfall

Intensive rain-fed sweet potato production requires enough moisture for the plants to grow over a 3- to 9-month period. Optimum annual rainfall is 750–1000 mm, with 500 mm in the growing season being a minimum (Purseglove, 1968; Woolfe, 1992; Yen et al., 1972). The available state-wide rainfall data is annual precipitation isohyets, and we defined 750 mm/year rainfall as the lowest average rainfall at which the effort of building and maintaining an intensive rain-fed system was rewarded with good yields frequently enough to be worthwhile to the cultivators.

3.2.2. Elevation

We use 900 m as the upper elevation boundary for intensive rain-fed systems; this corresponds to a mean annual temperature of $\sim$18 °C, which is similar to the boundary of intensive sweet potato cultivation in other regions of the world (Ngeve et al., 1992), although less intensive cultivation can occur at much higher elevations.

3.2.3. Soil fertility

Intensive rain-fed agriculture requires suitable soil fertility, which in Hawai'i can be characterized by base saturation above 25–30% in the top 30 cm of soil (Vitousek et al., 2004); this value often occurs as a distinct threshold along gradients in rainfall (Chadwick et al., 2003). To derive spatial data on soil fertility we rely on data from >500 sites across the Hawaiian Islands that range in age from 0.3 to 4100 ky and in rainfall from 180 to >5000 mm/year. These samples indicate that base saturation is greatest on geologically young substrates; it decreases very rapidly with increasing age in wetter sites, but remains high for up to hundreds of thousands of years in drier sites.

Soil nutrient dynamics are also influenced by temperature; soil minerals weather more rapidly at high temperature than low, all else being equal (Dessert et al., 2003). Elevation provides an excellent proxy for temperature. However, the relationship between soil nutrient depletion and temperature is not linear, as younger substrates have had less time to be affected by higher temperatures than older substrates. We modeled the influences of rainfall, temperature and age of substrate on soil nutrient depletion by calculating a rainfall elevation index (REI) for every hectare of the archipelago (Table 1). We assumed that sites with substrates <4 ky had not accumulated sufficient soil for intensive rain-fed agricultural systems. We varied the REI at the soil fertility threshold from 2400 for 4–9 ky substrates, to 2300 (9–40 ky), to 2200 (40–175 ky), to 2000 (175–300 ky), to 1800 (300–500 ky), to 1300 (500–700 ky). Sites older than 700 ky were excluded because nutrient levels there typically are depleted below the minimum for intensive rain-fed agriculture by rainfalls greater than the 750 mm necessary to grow sweet potatoes (Vitousek et al., 2004).

We obtained substrate ages from the most recent digital geological map that divides the archipelago into ∼9800 polygons (Sherrod et al., 2007; http://pubs.usgs.gov/of/2007/1089). In cases where polygons were missing ages or had inconsistent ages, we assigned ages that preserved expected stratigraphic or geographic patterns. For example, polygons labeled "beach/dune deposits" were assigned an age of 500 years, and polygons labeled "older dune deposits" were assigned 3000 years. Our model results are unlikely to have been affected by these age assignments for two reasons: only a small fraction of the total number of polygons required new age assignments, and our intervals for substrate ages are relatively broad.

4. Results

The spatial predictions of our irrigated model (Fig. 1) indicate that the potential distribution of pondfields varies as a function of island age and climate; the youngest volcanoes on Hawai'i Island (surface ages <5000 years) should support pondfields only in limited areas, while slightly older volcanoes with surface ages up to hundreds of thousands of years (Mauna Kea, Kohala, Haleakalā) should support pondfields only in a fringe on their windward northeast flanks, especially in the occasional deep valleys. Still older islands with extensive alluvial and colluvial plains, and streams that flow from high-rainfall mountain areas into leeward environments exhibit much greater potential for pondfield development; on these islands irrigation systems would have been both more extensive and more widely distributed into lower-rainfall leeward areas.

As with pondfield systems, our model for rain-fed systems predicts a spatial distribution pattern that varies as a function of climate and island age, although with a very different pattern (Fig. 1). The potential for rain-fed systems is greatest in leeward upland areas of the younger islands of the archipelago; as islands age, rain-fed agricultural potential increasingly is confined to unusually young (and so fertile) substrates in a matrix of older, less fertile – and so less suitable – sites.

Table 1
Geologic substrate ages and rainfall elevation indices used to calculate threshold values for soil fertility across the archipelago.

Age range (years) of substrate	Rainfall ELEVATION INDEX equation
4000 and 8999	REI = rainfall − (elevation − (0.2 × 900))
9000 and 39999	REI = rainfall − (elevation − (0.4 × 900))
40000 and 174999	REI = rainfall − (elevation − (0.6 × 900))
175000 and 299999	REI = rainfall − (elevation − (0.8 × 900))
300000 and 499999	REI = rainfall − (elevation − (1.0 × 900))
500000 and 700000	REI = rainfall − (elevation − (1.2 × 900))

The value of 900 is the maximum elevation for intensive sweet potato cultivation, and serves as a scaling mechanism for the other two variables.

4.1. Assessing the predictive power of the models

We compared the results of our models with independent archaeological evidence for the spatial distribution of pre-contact Hawaiian agriculture. Detailed archaeological maps of the spatial distribution of intensive agricultural systems are sparse and spatially restricted in Hawai'i – but there are a few studies that provide the opportunity to assess the boundaries of intensive agriculture defined by our GIS models.

4.1.1. Pondfield agricultural systems

There are three areas in the archipelago where the archaeological remains of irrigated pondfields have been mapped over substantial areas. For Kaua'i Island, Earle (1978:59) depicts the distribution of 28 ha of pondfields in Wainiha Valley. A scan of this map was georeferenced and 98.5% of the features depicted in the map coincide with areas defined by the wetland agriculture model (Fig. 2a). On Moloka'i two archaeological projects have mapped the distribution of pondfields. An early study by Kirch and Kelly (1975) surveyed 31.3 ha in lower Hālawa Valley. A scan of their paper map was georeferenced according to the river course and coastline, which introduced some ambiguities into the comparison. Nevertheless, 78% of the distribution of the archaeological features mapped by Kirch and Kelly (1975:205) are in areas defined as high potential for wetland agriculture by the model (Fig. 2b). The model misses some terracing along the south side of the valley, as the slope values in that area are too high. It seems likely that the model removes some potentially suitable microtopographic areas due to the resolution of the DEM in the calculation of slope values. In Wailau Valley, 66% of the 20.5 ha of pondfields mapped by McElroy (2007:201) are in areas identified by the wetland model (Fig. 2c). The model did not identify areas mapped by McElroy to the north of a western tributary stream ('Eliali'i) coming into the valley, and areas in the southeast of the western arm of the main valley; these were identified in the model as having too steep slopes, as for Hālawa Valley.

In addition, the model predicts a high potential for wetland agriculture in all three areas in zones that are not depicted as containing archaeological features in the published sources. This is most marked in the cases of Wainiha and Wailau, where non-contiguous zones of production are depicted in the published maps. These semi-isolated production patches probably reflect survey sampling, not the true absence of archaeological features in between mapped zones of production.

Model results also can be compared to ethnographic and ethnohistorical accounts of agricultural production, and archaeological evidence other than detailed maps. These lines of data can provide an appreciation of the presence or absence of production in general areas. Overall, there is good agreement between the models and this distributional information. For Kaua'i and Maui, the results of the pondfield model coincide well with Handy's (1940:58–73; 103–109) description of wetland planting areas. On O'ahu there is good general fit between modeled and suggested pondfield distributions based on Kirch's (1994) synthesis of ethnohistorical data and limited archaeological work. Finally, on Hawai'i Island the model indicates that only the windward northeastern side of the island has any potential for irrigated agriculture, and this is supported by ethnohistorical accounts (Ellis, 1979:256, Bingham, 1847:379) and recent archaeological work (McCoy and Graves, under review).

There are, however, a number of discrepancies between the results of the pondfield model and the ethnohistoric, ethnographic, and archeological evidence. In an early archaeological survey, Bennett (1931) noted extensive pondfield terracing along the northwest Nāpali coast of Kaua'i, and our model may underestimate the extent of terracing in the area due to restriction of

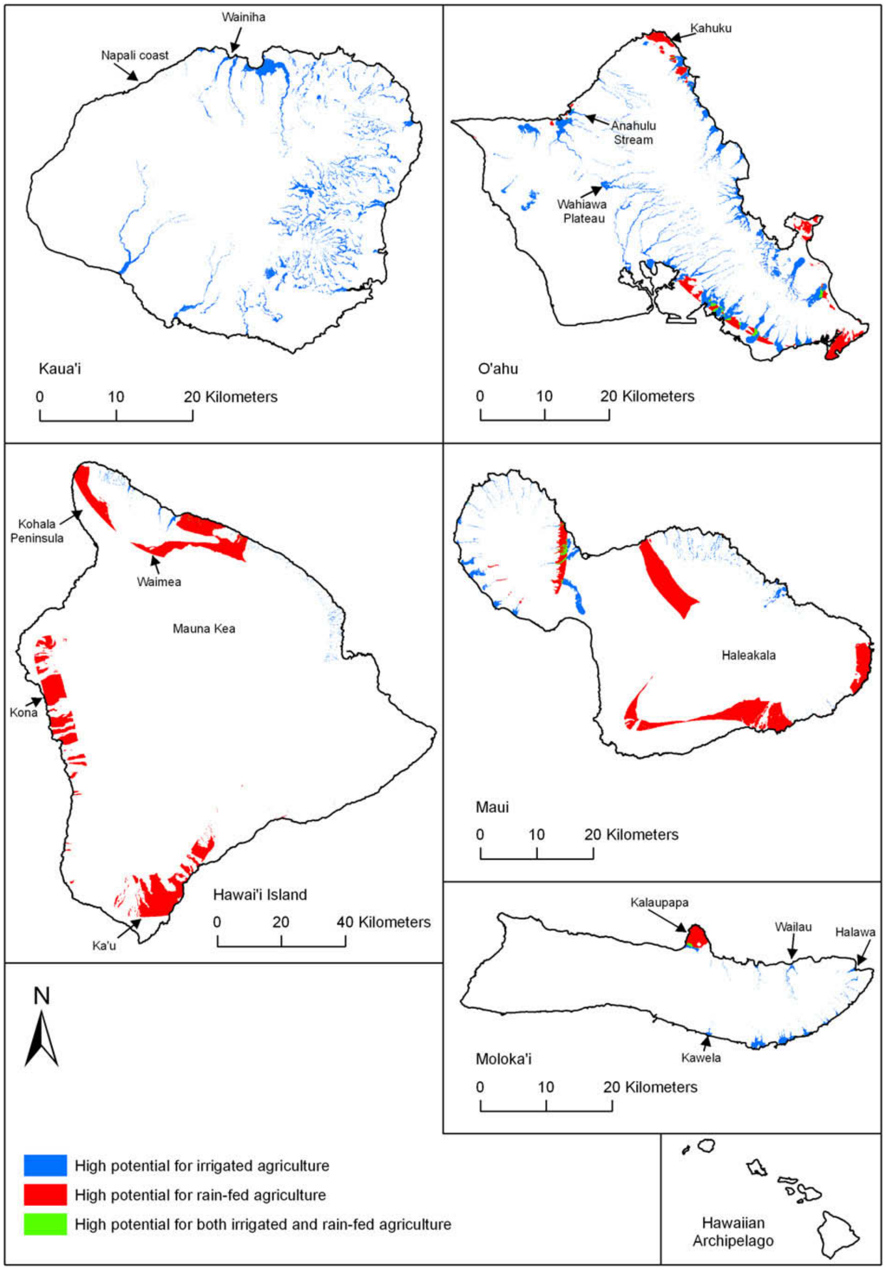

Fig. 1. Irrigated and rain-fed model results for the five major islands of the Hawaiian archipelago.

threshold slope to 10 degrees and to the coarseness of the DEM. On O'ahu, our model predicts intensive pondfields in the vicinity of the Wahiawā Plateau, but there is no evidence that they existed. We believe that historic era damming and diversions for plantation irrigation altered the topography and hydrology of this area, making it appear more suitable for pre-contact agriculture than in fact it was. On the southern leeward coast of Moloka'i our model predicts an area of high irrigation potential at the mouth of Kawela valley, but archaeological and ethnohistoric evidence (Weisler and Kirch, 1985:135–138) suggests seasonal flood-water irrigation, rather than permanent pondfields. The Kawela stream probably was mis-classified; it belongs in the "non-perennial" class in our dataset, with low potential for pondfield agriculture. The model identifies no potential for irrigated agriculture on the islands of Lānaʻi or Kaho'olawe, because rainfall there is so low that no streams have headwaters in areas receiving more than 1500 mm of rain. Despite this, Handy (1940:103) notes that on Lānaʻi "Wet taro was cultivated throughout … (an) upper valley … and in a small area midway up from the sea in … (a) deep valley." The discrepancy might reflect sporadic use of areas in wet years, or to the existence of spring-fed systems that are not captured by the model.

4.1.2. Rain-fed agricultural systems

The results of the rain-fed model can be assessed with data from two well-documented rain-fed field systems, the leeward Kohala field system on Hawaii Island (Rosendahl, 1972; Tomonari-Tuggle, n.d.; Tuggle and Tomonari-Tuggle, 1980; Newman, 1970; Ladefoged et al., 1996, 2003, 2008; Ladefoged and Graves, 2000, 2007, 2008 Meyer et al., 2007) and the Kalaupapa field system on Moloka'i (Kirch, 2002; McCoy, 2005, 2006; McCoy and Hartshorn, 2007). In

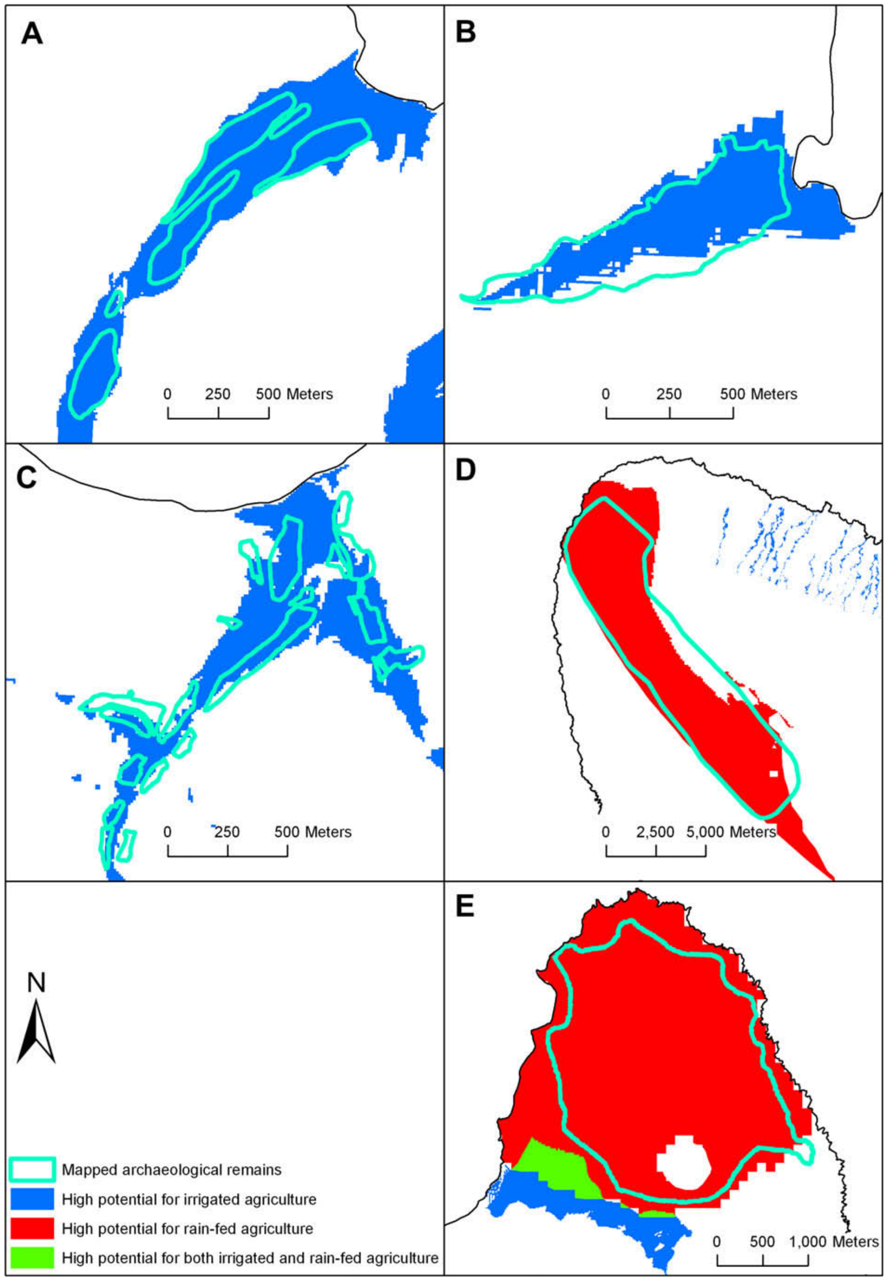

Fig. 2. The comparison of model results with archaeologically defined field systems. (A) Wainiha; (B) Halawa; (C) Wailau; (D) leeward Kohala; (E) Kalaupapa.

leeward Kohala, nearly 90% of the mapped distribution falls within the modeled intensive rain-fed agriculture area (Fig. 2d). The model captures the fact that the system occupies a belt that diagonally slopes from near the coastline to 300 m elevation in the north, to 600–900 m in the south. It also captures the shift from younger Hāwī Volcanics lava in the southern portion of the field system to older Pololū Volcanics in the north – perhaps too starkly, in that the one area of the field system not captured by the model is on the wet, upper elevation edge of the Pololū Volcanics. In practice, cinder cones deposited Hāwī-age tephra on portions of the Pololū substrate. The model and known distribution of the leeward Kohala field system are less coherent on the northern and southern margins of the field system, with the model predicting a higher elevation extension of the field system south of the region where extensive agricultural features are observed, and a larger extent of the system on the northern margin as well. The southern margin of the system abuts on a rough flow of 'a'ā lava with relatively little soil; in practice, agricultural features are observed in swales on this flow, but not across its whole surface. In the northern region, the field system may in fact have been larger than it has been mapped; the effects of modern plantation agriculture make it difficult to pin down this boundary with any certainty.

On Moloka'i the only area the model identifies as having potential for intensive rain-fed agriculture is on the Kalaupapa Peninsula, an area of late-stage volcanic rejuvenation dating to ~300 ky (Sherrod et al., 2007). Archaeological survey and excavations in Kalaupapa have firmly established the existence of an intensive field system covering much of the peninsula that began to develop as early as AD 1400 (Kirch, 2002; McCoy, 2005, 2006; McCoy and Hartshorn, 2007), with intensification continuing into the historic era (Handy, 1940:158; Ladefoged, 1993). Over 99% of the area depicted by McCoy (2006:104) as containing remnants of the field system fall within the modeled distribution of intensive rain-fed agriculture (Fig. 2e); most of the area in which the model identifies a potential for intensive rain-fed agriculture but no field evidence has been located is in a coastal fringe around the peninsula. Sea spray may be a constraint to intensive rain-fed agriculture that is not represented in the model, as sweet potato is sensitive to saline conditions (Woolfe, 1992).

Additional ethnographic, ethnohistoric, and limited archaeological data can be used to assess the results of the rain-fed model. In Kona, Hawai'i Island, the model suggests intensive agriculture could have been practiced over a more extensive but less continuous area than where generalized maps locate rain-fed systems (Newman, 1970; Kirch, 1985; Allen, 2004); the model identifies lava flows that were too young to support intensive agriculture and *kīpuka* (patches of older substrate surrounded by younger flows) in which intensive agriculture would have been feasible. In south Ka'ū district there is overlap between the area of rain-fed agriculture predicted by the model and generalized maps of field system distributions (Newman, 1970; Kirch, 1985; Allen, 2004); however, much of this area has been altered by modern plantation agriculture, and it is difficult to evaluate any discrepancies. For Maui, the model predicts four major zones of high potential for rain-fed field systems, and the presence of rain-fed agriculture in these areas is confirmed by Handy (1940) and extensive archaeological survey in the southern zone (Coil, 2004; Coil and Kirch, 2005; Dixon et al., 1999; Kirch et al., 2004; Hartshorn et al., 2006). In particular, recent fieldwork on the young lavas making up the Kaupō fan emanating from Haleakalā Volcano have confirmed the presence of a substantial field system (Kirch et al., 2009). In southeast O'ahu the model predicts high rain-fed farming potential corresponding to areas underlain by late rejuvenation phase lavas and pyroclastics, and Handy (1940:156) refers to some of these areas as "the most favorable locality on O'ahu for sweet potato cultivation". Neither model predictions nor ethnographic or ethnohistorical accounts suggest the presence of large rain-fed systems on the island of Kaua'i, the oldest of the large high islands.

There are a number of discrepancies between the rain-fed model and available evidence. On Hawai'i Island the modeled distribution of the Waimea Field System is much larger and displaced well to the east of mapped agricultural areas (Burtchard and Tomonari-Tuggle, 2004). Unlike most rain-fed systems, portions of Waimea Field System are known to have been irrigated (not flooded), likely explaining its distribution well below the 750 mm/year rainfall isohyet that typically bounds rain-fed systems. Furthermore, there is a large modeled zone extending southeast from Waimea into the Hāmākua District at relatively high elevation, with another zone along the Hāmākua coast. The archaeological evidence for or against agriculture in these areas is minimal; modern sugarcane plantations occupied most of this land, and might have destroyed most traces of pre-contact agriculture. No areas on Lāna'i or Kaho'olawe are identified by the model as being able to support intensive rain-fed agriculture. This result is inconsistent with descriptions of widespread sweet potato cultivation (Handy 1940:158–159), and may be attributed to a distinction between small mulched gardens and the development of an intensive agricultural system – or the rain-fed model may not capture the potential for dryland cultivation of young colluvial and alluvial substrates. On O'ahu the steep slopes of tuff cones on eastern O'ahu and lithified dunes in the northern Kahuku region are predicted as having high potential for rain-fed farming; no evidence for rain-fed systems exists in these areas, and their agricultural potential is questionable. The lithified dunes are calcareous paleodune deposits of Holocene and Pleistocene age (Sherrod et al., 2007), not the volcanic substrates on which our model is based; these dunes have very low nutrient supply and we doubt that they were ever intensively cultivated.

5. Discussion

The reasonably good correspondence between a number of detailed archaeological studies and the model results suggest that the variables and parameters of the models identify zones with high potential for intensive agriculture reasonably accurately. There are, however, some discrepancies between the model results and empirical observations (ethnographic, ethnohistorical, and archaeological) of the distribution of agriculture. These discrepancies are difficult to evaluate. In some instances they may reflect erroneous parameters or variables of the models. In other cases, areas of intensive agriculture outside zones identified by the model could represent Hawaiians extending agricultural development beyond optimal zones of intensive production. The areas of terracing on steep slopes in Wailau Valley (Moloka'i) could be locations where social pressures to extend intensive agriculture were being exerted. Conversely, there are areas identified by the model as having a high potential for intensive agriculture where there is little surface evidence of such activities. These could be the result of recent historic disturbance, or perhaps could represent potential agricultural lands that were only partially developed by Hawaiian farmers. One of these zones is the large area that runs from Waimea to Hāmākua on the island of Hawai'i, extending along the windward coast. The inland portions of this zone extend upwards of 16 km from the coast, and as noted by Ladefoged and Graves (2000) travel distance to coastal settlements was likely a significant factor in decisions about intensifying production. This zone in Hāmākua may be an example of an area where further expansion and intensification were possible, but not actualized. This possibility should encourage additional field work to determine if traces of rain-fed Hawaiian agriculture are present in the area, and if the soils are indeed as fertile as the model suggests.

Assuming that all suitable areas were in fact cultivated at the end of the pre-contact era (i.e., the period of maximum population density), this analysis implies that production capacities differed strikingly across the archipelago (Table 2). Almost 557 km^2 of Hawai'i Island could have supported intensified rain-fed agriculture, with an additional 14 km^2 of irrigated production. Productive land on Maui was only ca. 30% of Hawai'i Island, but 26 km^2 of Maui could have supported pondfield systems. In comparison, O'ahu had ca. 21% of the intensive agricultural land of Hawai'i Island, but most of this would have been in pondfield agriculture, and Kaua'i had 10% of the productive land of Hawai'i Island, all of it being irrigated. Moloka'i had the smallest area of productive land, with a fairly even split between the wet and dry modes. According to the models, Lāna'i and Kaho'olawe lacked areas capable of supporting either intensive wet or dry agricultural systems. This would suggest that agricultural systems on these two leeward islands were probably based on either swidden practices or (more likely) carefully mulched garden-scale plots.

The total tonnage of crops that could have been grown within intensive systems on each island is also estimated in Table 2. Traditional taro pondfield yields in Oceanic agricultural systems can reach 25 (even 50) metric tons (mt)/ha per year wet weight (Spriggs, 1981, 1984), and we assigned a production value of 25 mt/ha per year to the model wetland agriculture areas. Rain-fed system yields in Oceania, by contrast, range from 5 to 15 mt/ha per year (Kirch 1994; Massal and Barrau 1956), and we assigned them a production value of 5 mt/ha per year. These yield estimates are reported as wet weight; dry weight conversions for taro (0.34) and

Table 2
Predicted areal distributions of wetland and rain-fed field systems and estimated yields and labor costs across the Hawaiian archipelago.

Island	High potential for irrigated agriculture (km^2)	High potential for rain-fed agriculture (km^2)	High potential for irrigated and rain-fed agriculture (km^2)	Total agriculture area (km^2)	Irrigated agriculture production, metric tons (wet weight, assuming 25 mt/ha per year)	Irrigated agriculture production, metric tons (dry weight)	Rain-fed agriculture production, metric tons (wet weight, assuming 5 mt/ha per year)	Rain-fed agriculture production, metric tons (dry weight)	Total annual metric tons of food (dry weight)	Annual irrigated agriculture labor input	Annual rain-fed agriculture labor input	Total annual labor input	Average annual production per worker
Hawai'i	14.37	556.56	0.98	572	38383	13050	278278	83483	96534	2239	162329	164568	0.6
Maui	25.74	139.36	2.45	168	70483	23964	69678	20904	44868	4112	40646	44757	1.0
Molokai	8.75	7.49	0.35	17	22764	7740	3743	1123	8863	1328	2183	3511	2.5
Oahu	83.31	34.06	3.22	121	216329	73552	17029	5109	78660	12619	9933	22553	3.5
Kauai	57.62	0.00	0.00	58	144043	48975	0	0	48975	8403	0	8403	5.8

sweet potato (0.30) (Baes et al., 1984; Huang et al., 2006) lead to dry weight yields of 8.5 mt/ha for irrigated taro and 1.5 mt/ha for rain-fed sweet potato. We believe these values approximate what could have on spatial and temporal average been achieved by experienced farmers. We assumed that in areas where either wetland or rain-fed systems could be developed, Hawaiian farmers would have chosen to develop irrigated pondfields (an assumption that does not greatly affect the results). Given these assumptions, Hawai'i Island had the highest potential annual productivity within the archipelago, with a total of 96,500 mt (dry weight). Kaua'i had 10% of the intensive agricultural land of Hawai'i Island, but because all of it was relatively productive irrigated agriculture, it produced more than half as much food.

The contrast in labor requirements between irrigated and rain-fed agricultural systems is even more striking. Yen's ethnographic study of Anuta (1973), a traditional Polynesian intensive rain-fed system, suggests rain-fed agriculture requires approximately 7000 person hours/ha per year or 875 work days/ha per year (assuming an 8 hour workday) of input. This equates to the annual labor of 2.9 workers per hectare, assuming that 300 days a year were devoted to subsistence activities. In contrast, irrigated agriculture requires about half of that labor (Spriggs, 1984), or 437.5 work days/ha per year; the equivalent of an annual labor input of 1.45 workers per hectare, assuming 300 days a year of subsistence activities. On Hawai'i Island, the ca. 83,500 mt of rain-fed crops would have required an annual labor input of ca. 162,000 workers, and the 13,000 mt of wetland crops would have required an annual labor input of ca. 2200 workers (see Table 2), yielding an overall average of ca. 0.6 mt per agricultural worker per year. In stark contrast, on Kaua'i the estimated 49,000 mt of food would have required an annual labor input of 8400 workers, with average production of ca. 5.8 mt per agricultural worker per year. O'ahu is closer to Kaua'i in terms of its production regime, whereas Maui is closer to Hawai'i Island.

Under these assumptions the rain-fed system could produce ~5640 kcal of yield per agricultural worker per day (assuming a caloric content of 4 kcal/g) – enough to sustain farmers and their dependents, with some surplus. The potential surplus over agricultural labor was far greater in irrigated systems – and for the Islands of Kaua'i and O'ahu, whose production systems were based largely on irrigation. An average agricultural worker could produce ~10 times more crop yield on Kaua'i than could workers on Hawai'i Island. For other areas of the Pacific, Spriggs (1981) notes that when additional labor is required for agricultural production, women often work in the fields. This seems to have been the case in Hawai'i. According to the 19th century Hawaiian scholar Kamakau (1961:239), on Kaua'i, O'ahu, and Moloka'i agricultural activities were restricted to men, but on the islands of Maui and Hawai'i Island where rain-fed systems dominated, women also worked in the fields. Even though the restriction of agricultural labor to men meant that producers on O'ahu and Kaua'i had more dependents, the elites on these older islands would have found it far easier to acquire surpluses to support their own subsistence needs and rituals, and to support retainers, craft specialists, and warriors.

In addition to greater labor costs, communities reliant on rain-fed agriculture would presumably have been more vulnerable to environmental perturbations, particularly droughts (Allen, 2004; Ladefoged and Graves, 2000; Ladefoged et al., 2008; Lee et al., 2006). During drought, farmers in rain-fed systems could offset some consequences by increasing labor inputs, but what labor can accomplish if drought persists is limited. We expect the hardest hit areas during a drought would have been those receiving close to 750 mm of annual rainfall, the minimum needed to sustain intensive rain-fed production. Drier areas also tend to have greater annual variability in rainfall, which would constrain crop production by rain-fed farmers more often than for farmers in the wetter windward sides of the islands. Moreover, at least in windward areas there is more water in irrigated systems – even during droughts – than in the rain-fed systems; reducing rainfall by half in an irrigated system (e.g., from 3000 mm to 1500 mm annual rainfall) does not affect production to nearly the same extent as reducing rainfall by half in a rain-fed system (e.g., from 800 mm to 400 mm annual rainfall – well within the historic range). Wetland agriculture further has the advantage in that its main crop, taro, can also be grown as a rain-fed crop.

Large contrasts in both the potential surplus production and the vulnerability of that production to climate perturbations in rain-fed versus irrigated agriculture would have influenced interactions between societies based on these contrasting modes of production, both within islands and among islands dominated by one system or the other. These contrasts could have fostered the development of trade between irrigated and wetland systems, and ultimately supported the social-political integration of Hawaiian societies – particularly within islands that contained both rain-fed and irrigated systems. Alternatively, the dependence of Hawai'i Island and to a lesser extent Maui on rain-fed production meant that prior to European contact, these islands had a combination of large populations, relatively small surpluses, and vulnerability of yields to perturbations. It is reasonable to speculate that pressures to maintain surplus production in rain-fed, drought-prone agricultural areas could have impelled the elites who controlled these islands towards marriage alliances (Cachola Abad, 2000) with elites based in areas with more stable agroecosystems, and towards conquest of other territories or islands (Kirch, 1994). The predatory aspirations of prehistoric leeward polities on both Maui and Hawai'i Island towards windward localities and towards the older northwestern islands are well documented in Hawaiian oral traditions (Kamakau, 1961; Cachola Abad, 2000), and the early post-contact conquest of the Maui and O'ahu kingdoms by Hawai'i Island's Kamehameha I may represent a case in point.

Of course these estimates of land, labor, and yields are very approximate, For example, not all of the suitable land in any given area would have been farmed each year, with intensive rain-fed areas incorporating a short-fallow rotation. Furthermore, sweet potato in particular would not have required or rewarded intensive labor inputs for the entire year. On the other hand, additional major sources of food and associated demands for labor – gardens, swidden, fishing, aquaculture – are not included in this accounting. Nonetheless, we believe that the differences among production systems and among islands are robust enough to allow reasonable quantitatively-based comparisons of their implications for the generation of surpluses over agricultural labor and interactions between islands with differing agricultural bases.

Modeling the agricultural potential of different regions across this archipelago offers insights regarding the constraints on pre-contact Hawaiian agricultural development and on how populations located in different regions responded to these challenges. These modeling efforts not only help us understand past agricultural and sociopolitical practices, but can also guide future fieldwork by providing testable hypotheses about environmental constraints on prehistoric agricultural systems. While this analysis is specific to the Hawaiian archipelago, the dynamics we address are not uniquely Hawaiian, or Polynesian; we believe that this approach can contribute to our understanding of interactions among land, agriculture, and societies in many regions.

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