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Erosion, Geological History, and Indigenous Agriculture: A Tale of Two Valleys

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ABSTRACT

Irrigated pondfields and rainfed field systems represented alternative pathways of agricultural intensification that were unevenly distributed across the Hawaiian Archipelago prior to European contact, with pondfields on wetter soils and older islands and rainfed systems on fertile, moderate-rainfall upland sites on younger islands. The spatial separation of these systems is thought to have contributed to the dynamics of social and political organization in pre-contact Hawai'i. However, deep stream valleys on older Hawaiian Islands often retain the remains of rainfed dryland agriculture on their lower slopes. We evaluated why rainfed agriculture developed on valley slopes on older but not younger islands by comparing soils of Pololū Valley on the young island of Hawai'i with those of Hālawā Valley on the older island of Moloka'i. Alluvial valley-bottom and colluvial slope soils of both valleys are enriched 4–5-fold in base saturation and in P that can be weathered, and greater than 10-fold in resin-extractable P and weatherable

Ca, compared to soils of their surrounding uplands. However, due to an interaction of volcanically driven subsidence of the young island of Hawai'i with post-glacial sea level rise, the side walls of Pololū Valley plunge directly into a flat valley floor, whereas the alluvial floor of Hālawā Valley is surrounded by a band of fertile colluvial soils where rainfed agricultural features were concentrated. Only 5% of Pololū Valley supports colluvial soils with slopes between 5° and 12° (suitable for rainfed agriculture), whereas 16% of Hālawā Valley does so. The potential for integrated pondfield/rainfed valley systems of the older Hawaiian Islands increased their advantage in productivity and sustainability over the predominantly rainfed systems of the younger islands.

Key words: erosion; geomorphology; Hawai'i; human–environment interaction; intensive agriculture; irrigation; soil fertility; subsidence; weathering.

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INTRODUCTION

Prior to European contact, the Hawaiian Archipelago supported a diversity of highly intensive agricultural systems—in keeping with the high degree of social and cultural complexity of Hawaiian society (Kirch 2000), and the exceptional environmental

heterogeneity of the islands (Chadwick and others 2003; Vitousek 2004). The most widespread of these agricultural systems have been separated into two major classes—irrigated pondfields in which taro (*Colocasia esculenta*; in Hawaiian *kalo*) was the major crop, and rainfed uplands based on sweet potato (*Ipomoea batatas*; 'uala), dryland taro, and yams (*Dioscorea* sp; uhi) (Kirch 1994). Pondfields were established earlier in Hawaiian history; there is clear evidence for their existence by AD 1200 (Kirch 2002; McElroy 2007), and organized systems of pondfields were developed by AD 1400 (Allen 1992). In contrast, rainfed systems largely developed after AD 1400, and show evidence for increased intensification after AD 1650 (Allen 2001; Coil and Kirch 2005; Kirch and others 2005; McCoy 2006; Ladefoged and Graves 2008).

These two classes of agro-ecosystems have profoundly different environmental requirements, and they were distributed unevenly across the archipelago at the time of European contact (Kirch 1994; Ladefoged and others 2009). Pondfields depend upon reliable sources of irrigation water and gentle slopes; they were developed extensively in well-watered alluvial and colluvial soils. Streams develop and the cumulative effects of erosion and sediment deposition increase with increasing rainfall and substrate age across the Hawaiian archipelago—and consequently pondfields largely were restricted to older northwestern islands, and to the oldest and wettest portions of the younger southeastern islands (Ladefoged and others 2009). In contrast, intensive rainfed systems require at least moderate rainfall ($>750 \text{ mm y}^{-1}$) and relatively fertile soils (Vitousek and others 2004). Soil fertility on stable geomorphic surfaces decreases with increasing rainfall and substrate age (Chadwick and others 2003; Vitousek 2004); hence, rainfed systems developed primarily in leeward portions of the younger Hawaiian Islands, in environments very different from irrigated pondfields (Ladefoged and others 2009). The spatial and environmental separation between these two modes of intensive agricultural production could have played a substantial role in the dynamics and interactions of Hawaiian societies occupying the younger versus older islands in the archipelago (Kirch 1994; Graves and others, in press).

Despite the opposing nature of the conditions favoring irrigated and intensive rainfed systems, examples of what appear to be integrated systems including both the modes have been reported in valleys on older islands in the archipelago, with irrigated pondfields in valley bottoms and dryland agricultural features on lower slopes just above

them (Kirch 1977; McElroy 2007). One mechanism that could underlie the development of such systems is the dual role that erosion can play in influencing soil fertility. Erosion removes soil and associated nutrients from surface soils, often limiting the productive capacity of agricultural ecosystems. However, erosion also exposes rock and little-weathered soil near the surface, making the effective age of the soil much younger than that of the geological substrate from which it was formed. This effect has the potential to enhance the fertility of both erosional and depositional areas. Studies that have used strontium isotopes as tracers of nutrient sources within native forest ecosystems in Hawai'i show that although the supply of nutrients derived from the weathering of soil minerals is depleted on stable geomorphic surfaces of the older islands (Kennedy and others 1998), the weathering source is rejuvenated and soil fertility is enhanced on lower slopes and in alluvial areas of those same landscapes (Vitousek and others 2003; Porder and others 2005). Similar enrichment of eroded slopes by rock-derived nutrients was observed on volcanic landscapes in Costa Rica (Porder and others 2006).

Palmer and others (2009) evaluated soil fertility, erosion, and their potential contribution to pre-contact agriculture on constructional geomorphic surfaces, slopes and valley bottoms on the wet windward side of Kohala volcano of the Island of Hawai'i—the oldest portion (150–600 ky) of the youngest island in the archipelago. Leeward Kohala supports a large rainfed agricultural system that is bounded by well-defined thresholds in climate and soil fertility (Vitousek and others 2004; Ladefoged and Graves 2008); the soil fertility threshold occurs where cumulative weathering and leaching have depleted soil minerals to the point that they no longer supply substantial quantities of nutrients or buffer atmospheric acidity (Chadwick and others 2003). This threshold shifts to progressively lower rainfall levels in progressively older substrates across the Hawaiian archipelago (Ladefoged and others 2009; Porder and Chadwick 2009).

Based on soil properties at the leeward soil fertility threshold, Palmer and others (2009) concluded that: (i) soils on constructional surfaces of windward Kohala are too infertile to support intensive rainfed agriculture, at least as it was practiced in leeward Kohala; (ii) erosion has a positive but small effect on soil fertility on slopes and alluvial areas in small ($<30\text{-m}$ deep) stream valleys; and (iii) rock-derived nutrients dissolved in the streamwater used to irrigate pondfields sufficed to meet the nutrient demands of intensive pond-

field agriculture in these smaller valleys. Palmer and others also analyzed soils in Pololū Valley, a large (>200-m deep) valley in windward Kohala; there, soil fertility on lower slopes and alluvium was enriched substantially relative to constructional surfaces or to smaller valleys. They suggested that most of the material transported by erosion in the small valleys was derived from low-fertility soils in the surrounding uplands, whereas most of the material in the large valley came from its steep and little-weathered walls.

Despite the fertility of lower-slope soils in the large Pololū Valley, its slopes are extremely steep all the way to the alluvium on the valley floor, and there is no evidence of intensive rainfed agriculture having been practiced on these slopes. Similar slope profiles occur in Waipi'o and Waimanu Valleys in windward Kohala; these are the largest valleys on the Island of Hawai'i, and their alluvial valley floors supported the most intensively irrigated areas on the island. In contrast, most large valleys on older islands in the archipelago have very different slope profiles, with an accumulation of gradually sloping colluvial material between their steep walls and relatively flat alluvial floors (MacDonald and others 1983). Why do large valleys on the older versus the younger islands in the Hawaiian Archipelago differ in structure? Are soils of the colluvial lower slopes on older islands fertile enough to support intensive rainfed agriculture? Could differences in valley structure have shaped pathways of agricultural development and intensification in pre-contact Hawai'i?

In this article, we compare topography, soil fertility, and associated agricultural potential in two large Hawaiian valleys, Pololū on the island of Hawai'i and Hālawā on the much older island of Moloka'i. We test the hypothesis that the geological processes of erosion and subsidence influenced pathways of agricultural development and intensification in these landscapes.

METHODS

Sites

We focused on Pololū and Hālawā Valleys because they are comparable in size, relatively accessible, and because the archaeological remnants of Hawaiian agriculture have been surveyed in both. Pololū Valley (20° 12' N, 155° 44' W) is the westernmost of seven large valleys on the windward northeastern flank of Kohala Volcano, the oldest subaerial portion of the Island of Hawai'i. Most of

the lava within Pololū Valley is from the Pololū volcanic formation, older tholeiitic basalts that erupted from 400 to 600 ky before present; younger flows of the later alkalic Hāwī formation (150–220 ky) cover much of the surrounding uplands and spill into the Valley. Wave-cut sea cliffs flank Pololū Valley on both sides, and the valley itself is from 200- to 400-m deep (Figure 1). Pololū has a long history of Hawaiian occupation (Handy and Handy 1972); it was colonized by AD 1200 (Field and Graves 2008), and evidence of both irrigated pondfields and rainfed agricultural systems (as well as later post-contact features) can be found on the broad, relatively flat floor of the valley (Tuggle and Tomonari-Tuggle 1980).

Hālawā Valley (21° 12' 20" N, 156° 45' W) is the easternmost of four large valleys on the windward flank of east Moloka'i. The east Moloka'i volcano emerged approximately 1.8 million y (my) before present, and later alkalic eruptions covered most of its surface around 1.4 my ago. Like Pololū, Hālawā Valley is flanked by sea cliffs, and the main valley itself is approximately 300-m deep (Figure 1). Hālawā has a pre-contact cultural sequence dating from at least AD 1300 (Riley 1973; Kirch and Kelly 1975; Kirch 1990; Kirch and McCoy 2007). Its extensive irrigation systems are intact; a total of 693 pondfield terraces have been recorded in nine separate irrigation complexes (Riley 1975). The colluvial slopes above the irrigation systems on the valley floor exhibit dense archaeological landscapes of residential and rainfed agricultural features (Rosendahl 1975).

Topography and Geological History

We characterized the modern topography of Pololū and Hālawā Valleys using a 10-m digital elevation model (DEM) provided by the National Elevation Dataset (NED). Four 200-m-wide topographic swaths were selected to represent slope profiles in each valley, one near the valley outlet to the ocean, two in the center, and one just below the major waterfalls that bound the upper margin of the valley cores (Figure 1). Together, these transects sample more than 25% of each valley. The minimum, maximum, and mean elevations in the across-swath direction were computed for each point along the long dimension of the topographic swath. We compared mean elevations from each of the swaths by normalizing elevation and distance along the swath, and centering the swaths on the minimum swath elevation.

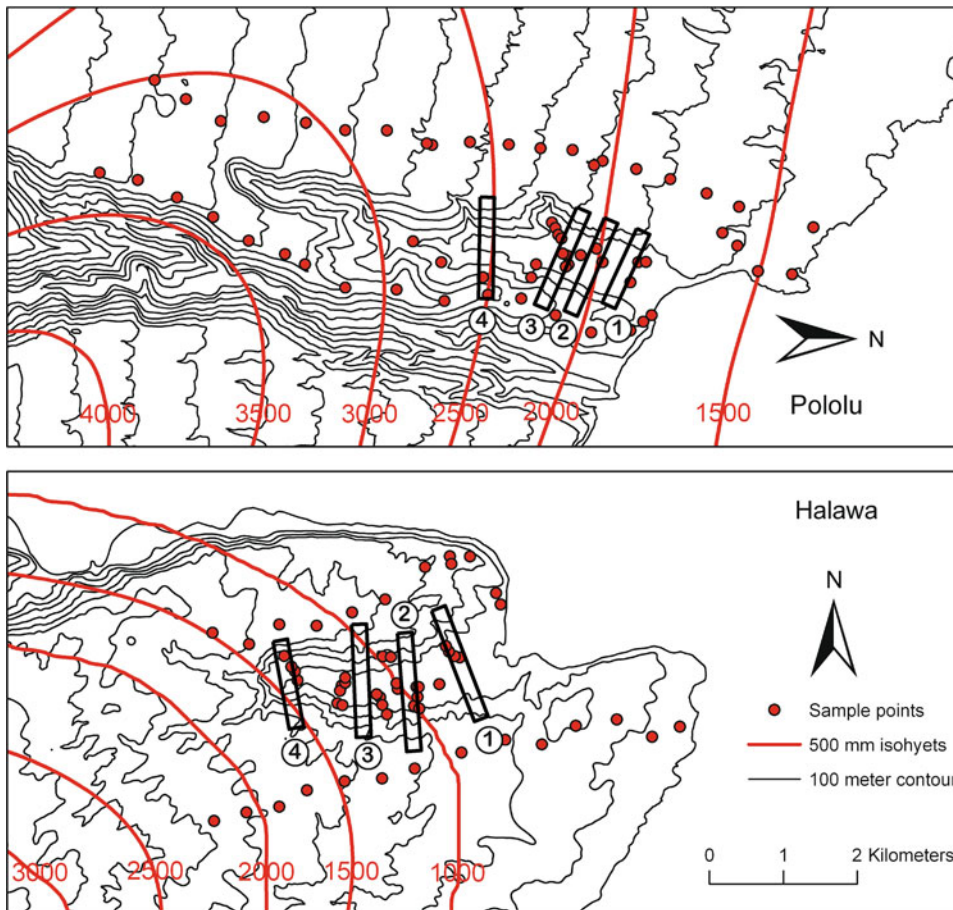


Figure 1. Pololū and Hālawā Valleys, on the Islands of Hawai'i and Moloka'i, respectively. The figures display elevation contours (*thin lines*), rainfall isohyets (*thicker lines labelled with annual rainfall*), and points where soil samples were collected (*dots*). Rectangles delineate swaths in which slope properties were determined (Figure 2).

Second, we calculated the distribution of slope angles across the full surface of each valley using a low-pass filter on the NED-DEM with a cut-off frequency of 0.05 m^{-1} (200-m wavenumber) to characterize the overall valley morphology by removing topography related to small individual gullies and ephemeral streams. From this filtered DEM, we extracted all filtered slope values within Pololū and Hālawā, summarizing these values as a cumulative distribution that denotes the fraction of the mapped valleys whose slopes are less than a given value.

Soil Sampling

We sampled alluvial and colluvial soils within each of the valleys, and along transects on upland soils on both sides of each valley; locations where soils were collected are shown in Figure 1. We collected integrated soil samples from 0- to 30-cm depth following protocols similar to those of Vitousek and others (2004), using a tiling shovel to expose a 30-cm profile and collecting an integrated sample across this depth. This depth generally encompassed the soil that was churned by cultivator's digging

sticks (Kirch and others 2005)—and in earlier studies (Vitousek and others 2004; Palmer and others 2009), the chemistry of these integrated 30-cm samples correlated well with deeper (1–4 m) profiles collected across Kohala Volcano (Chadwick and others 2003; Porder and Chadwick 2009). Moreover, analyses of the 30-cm samples provided consistent thresholds that defined the distribution of pre-contact rainfed agricultural systems (Kirch and others 2004, Vitousek and others 2004). Samples on the upland transects were collected systematically at approximately 500-m intervals, and sample positions were recorded via GPS. In Hālawā Valley, slope and alluvial samples were collected on transects reaching from alluvial soils near the main stream up to sloping colluvial soils, continuing up-slope above any remnants of Hawaiian agriculture to the base of the cliffs that surround the valley. The basal slopes of Pololū are much steeper, and transect sampling was not feasible; instead, we collected alluvial and lower-slope soils widely across the valley and at the lowest portion of its steep slopes. Most of the alluvial and (in Hālawā) lower-slope samples were collected within long-abandoned (multiple decades) Hawaiian agricultural systems.

Soil Analyses

Soils were air-dried, sieved (2 mm), and then divided into three homogenous subsamples, and all analyses were carried out as described in the supplemental material to Vitousek and others (2004). Briefly, one subsample was analyzed for total C and N using an elemental analyzer; a portion of this subsample also was extracted using the method of Kuo (1996) and analyzed for resin-extractable phosphorus using an Alpkem RFA/2 AutoAnalyzer. A second subsample was analyzed for cation exchange capacity (CEC) and exchangeable Ca, Mg, Na, and K at the University of California, Santa Barbara, using the NH_4OAc method at pH 7.0 (Lavkulich 1981). The third subsample was shipped to ALS Chemex (Sparks, Nevada, USA) and analyzed for total concentrations of Ca, Mg, Na, K, P, Sr, and Nb using lithium borate fusion and X-ray fluorescence spectrometry. Duplicate samples were incorporated in each procedure.

These measurements include some that reflect the forms of elements that are available to biota on relatively short time scales (resin P, exchangeable cations), and others that represent the total pools of elements and/or the cumulative effects of weathering. Available forms of elements can be dynamic; measurements reflect what was in the soil at the time of sampling, but those pools can change on annual time scales (or more frequently) and certainly are likely to have been influenced by human land use, both pre- and post-European contact. Total element pools are a more conservative measure; they include forms that are not immediately available to organisms, but they reflect the integrated outcome of additions and losses of elements playing out at time scales of decades or longer.

Data Analyses

With reference to an immobile index element, total element pools can be used to calculate the net loss or gain of elements from the soil. We used niobium (Nb) as an index element because (with tantalum) it is the least mobile of the elements analyzed in Hawaiian soils (Kurtz and others 2000). The percentage of an element that remained in the soil sample relative to its basaltic parent material was calculated as:

$$L_{i,j} = 100 \times (C_{i,j}/C_{\text{Nb},j}) / (C_{i,\text{pm}}/C_{\text{Nb},\text{pm}})$$

where $L_{i,j}$ is the percentage of element i remaining in soil sample j ; $C_{i,j}$ and $C_{\text{Nb},j}$ are the concentrations of element i and of Nb, respectively, in sample j ;

and $C_{i,\text{pm}}$ and $C_{\text{Nb},\text{pm}}$ are the element concentrations in basaltic parent material (Brimhall and others 1992). Values can exceed 100% where elements have been added to soils, either from outside the system or by vertical translocation within soil. This calculation assumes homogeneity in parent material, which is a more reasonable assumption on volcanic islands than it is in most places. Nevertheless, the Ca/Nb ratio in parent material of different eruptive phases of Hawaiian volcanoes (younger tholeiitic versus older alkalic basalts) differs substantially; we assumed tholeiitic parent material was dominant at Pololū and alkalic parent material dominated Hālawā. The P/Nb ratios in tholeiitic versus alkalic basalt are similar, so our assumptions about the provenance of soils are less important for P than for Ca. These calculations of elements remaining from parent material provide a conservative estimate of the potential for soil minerals to supply more nutrients via weathering, and they should be relatively robust to changes in land use over time.

Statistical analyses were performed using Systat (Systat Software version 8; Systat, Chicago, Illinois, USA). All data were log-transformed to approximate the assumptions of analysis of variance (normality, homogeneity of variance). We employed one-way analyses of variance to test for significant variation in soil properties between sample locations (three factors: upland sites outside the valleys, and slope and alluvial sites within the valleys) for each valley and its surroundings. Where significant F values from the overall ANOVA were obtained ($P < 0.05$), multiple pairwise comparisons were performed between groups using the conservative Bonferroni's correction for the t test. We did not test the significance of differences between valleys; as illustrated below, the valleys differed in both rainfall and substrate age, and differences in soil properties between the valleys were influenced by both sources of variation.

RESULTS

Topography and Geological History

The topographic profiles of Pololū and Hālawā Valleys are summarized in Figure 2. As is apparent to observers in the field, the valley sidewalls in Pololū are generally steeper than those of Hālawā; although, the upstream portion of Hālawā Valley is steep relative to both its downstream portions and to Pololū Valley. Pololū and other large valleys on Kohala Volcano show an abrupt transition from steep, relatively planar valley sidewalls to a

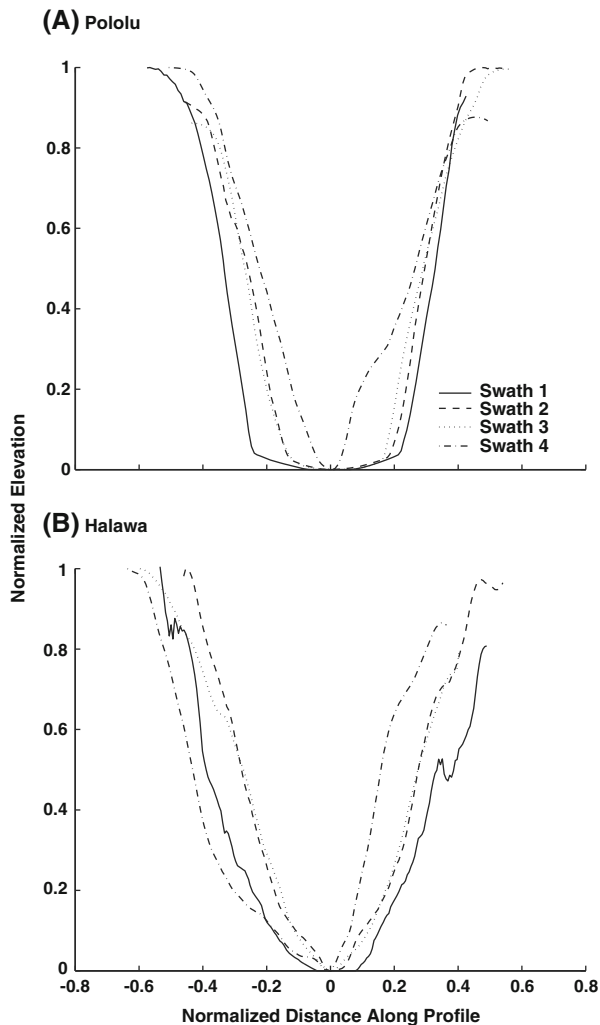


Figure 2. Normalized slope profiles for the *rectangles* displayed in Figure 1. Swath 1 is towards the mouth of each valley, swath 4 near the valley headwall. **A** Pololū and **B** Hālawā.

flat-bottomed valley floor that currently lies at or close to sea level (Macdonald and others 1983). In contrast, Hālawā and other large valleys on windward Molokaʻi have valley sidewalls that transition from eroded cliffs to colluvial slopes to the alluvial valley floor, creating a continuous, concave-up landscape.

These different morphologies result from the differing subsidence histories experienced by the two islands over the last several hundred thousand years. Hawaiʻi Island is subsiding at a rate of approximately 2 mm y^{-1} (Moore and Clague 1992), as a consequence of loading by the active volcanoes to the southeast of Kohala. In contrast, most eruptive activity on Molokaʻi ceased over a million years ago, and the island currently is subsiding very little. Moreover, both the islands are

now near the maximum of 120-m sea-level fluctuations through glacial–interglacial cycles.

We can use this information on subsidence and sea level fluctuation to reconstruct the history of valley filling in Pololū since the last glacial maximum (Figure 3). Valley sidewall morphology was extrapolated to depth for each of the aggradational swaths in the front and in the center of Pololū Valley (Swaths 1–3; Figure 2), using the swath that was far enough from the coast to be buffered from aggradation associated with the marine transgression (Swath 4). Swaths 1–3 were backfilled using past sea-level reconstructions since about 20 ka (Chappell and Shackleton 1986). Reconstructed valley bottom elevations along the northernmost swath in Pololū Valley correspond remarkably well with the 18-ka sea-level low stand, suggesting that the (overall) marine regression since around 120 ka was instrumental in excavating material from the valley as the base level lowered. Since the last glacial maximum, ongoing rapid valley aggradation has filled Pololū with alluvial and colluvial sediments. In contrast, valley morphologies in Hālawā are consistent with continuous transport across a colluvial apron that is buffered from the high-frequency base-level variations associated with the recent history of sea-level changes.

In both Pololū and Hālawā, the maximum topographic slopes calculated from the low-pass-filtered DEM tend to increase near the headwaters of these canyons, whereas downstream valley sidewalls are far less steep (especially in Hālawā, Figure 2). This observation is consistent with a scenario in which the headward-migrating canyon wall leaves progressively shallower valley sidewalls in its wake, as these initially steep slopes decrease and preserve an apron of colluvium across these portions of the landscape. This effect is far less pronounced in Pololū Valley, probably due to the youthfulness of this canyon system relative to Hālawā and to valley aggradation that buries the colluvial side-slopes.

Soils

Soils were collected across broad (and differing) rainfall gradients in and around the two valleys—particularly in the uplands (Figure 1), where sample locations received from about 1450–3420 mm y^{-1} of rain at Pololū and from around 875 to 2200 mm y^{-1} at Hālawā (Giambelluca and others 1986). Consequently, mean values of soil properties (by valley and slope position) must be compared with caution. The distribution of soil properties with variation in rainfall provides a more

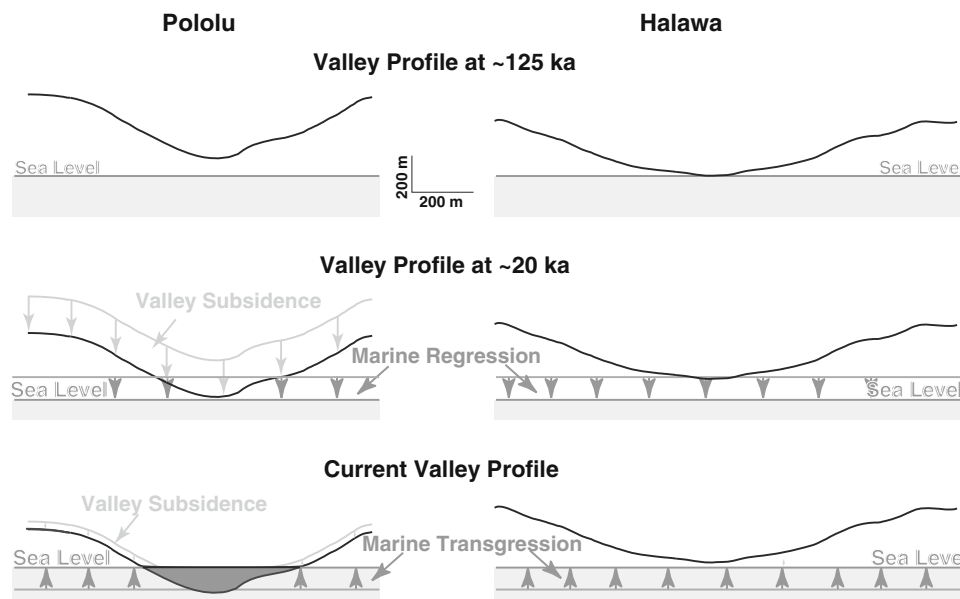


Figure 3. A model of the history of each valley for the past 125 ky. The *dark line* represents the valley profile; the area that now represents swath 1 in Pololū Valley was well above sea level during the last interglacial 125 ky ago. It subsided to the point where its base was at sea level at the last glacial maximum, approximately 20 ky ago. Subsequently, sea level rise (coupled with continuing subsidence) has taken the base of the valley below sea level, and the valley has been backfilled to its present flat-bottomed profile. In contrast, Hālawā Valley is not subsiding substantially, and its profile 125 ky ago is similar to its present profile.

direct measure of differences between valleys and among slope positions within valleys. These distributions are illustrated for base saturation and the percentage of P remaining (relative to parent material) in Figure 4; both of these measures are relatively stable indicators of soil fertility that correlate well with the boundaries of intensive rainfed agriculture in leeward Kohala (Vitousek and others 2004). Both base saturation and P remaining decline with increasing rainfall in the uplands surrounding both valleys, consistent with numerous measurements of both 30 cm and deep soils along rainfall gradients in Hawai'i (Chadwick and others 2003; Vitousek and others 2004; Palmer and others 2009; Porder and Chadwick 2009). Where rainfall ranges overlap between the valleys, Hālawā soils are substantially lower in both base saturation and P remaining than are Pololū soils—again consistent with numerous measurements that show declining soil fertility with increasing substrate age in Hawai'i (Crews and others 1995; Vitousek 2004; Chadwick and others 2009).

Alluvial and colluvial soils within both valleys had much higher base saturation and P remaining than did upland soils with similar rainfall (Figure 4). Although the uplands surrounding both Pololū and Hālawā Valleys are nutrient-depleted and infertile, with most samples falling well below

the thresholds that bounded intensive Hawaiian rainfed systems (30% base saturation, 50–60% P remaining) (Kirch and others 2004; Vitousek and others 2004), the slope and alluvial soils are well above these fertility thresholds (Figure 4). Not surprisingly, the remnants of intensive pre-contact agriculture were absent in the uplands and abundant in the alluvial areas of both valleys and the lower slopes of Hālawā.

Similar patterns of variation with rainfall and slope position were observed for most soil measurements, excluding only total C, N, and P. We summarize these comparisons in Tables 1 and 2, comparing slope and alluvial soils in each valley with upland soils that fall within a similar range of rainfall. Because Hālawā Valley is both older and has much lower rainfall than Pololū, we confine our statistical comparisons to slope positions within each valley and its surrounding uplands—although upland Hālawā soils are systematically less fertile than Pololū soils at comparable rainfall.

Analyses of variance for most soil properties (resin-extractable P, P and Ca remaining from parent material, base saturation, exchangeable Ca, Mg, and K) yielded significant ($P < 0.001$) differences with sample position in both valleys (Tables 1, 2); for these properties, in every case uplands were significantly lower in fertility/nutrient

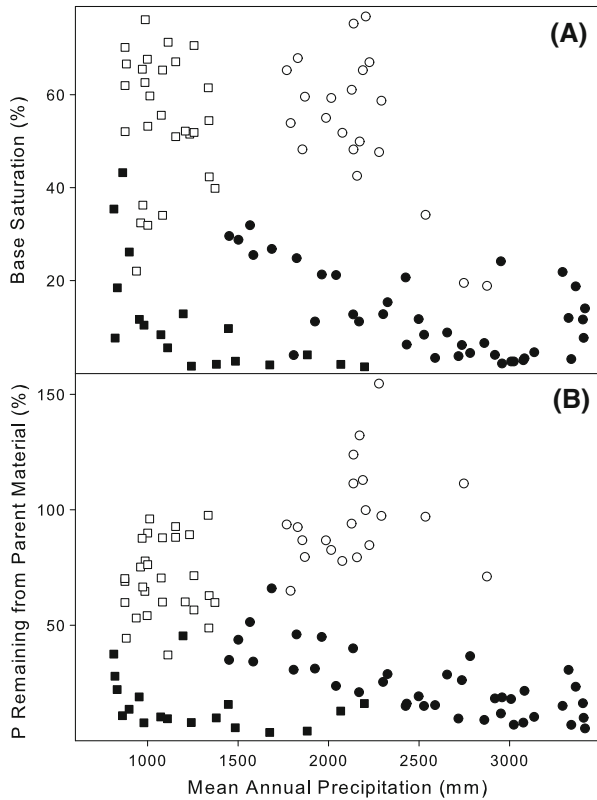


Figure 4. The distribution of base saturation **A** and the percentage of P remaining from parent material **B** versus mean annual rainfall within surface soils (to 30 cm) in and around Pololū (circles) and Hālawā (squares) Valleys. Solid symbols represent upland soils; hollow symbols represent both slope and alluvial soils.

availability than were slope and alluvial positions, and slope did not differ significantly from alluvium. Total element pools (C, N, and P) displayed different patterns. There too analyses of variance yielded significant differences with sample position in both

valleys ($P < 0.05$ for total N at Hālawā, $P < 0.01$ for total P at Pololū, $P < 0.001$ for the rest). For C and N, upland soils had significantly higher concentrations than slope and alluvial soils in both valleys; slope and alluvium did not differ significantly. For total P, upland and alluvial soils had significantly higher concentrations than slopes at Pololū, whereas upland soils had significantly lower total P than slope or alluvial soils (which did not differ significantly) at Hālawā.

We suggest that the greater total C and N pools of upland soils reflect their greater effective age, relative to slope and alluvial soils. Greater effective soil age in little-eroded uplands soils means a longer time for the accumulation of recalcitrant organic matter in older soils—and probably more importantly, it allows the accumulation of non-crystalline minerals that stabilize soil organic matter (Torn and others 1997). We further suggest that the patterns for total P are more complex because its pools reflect both weathering and loss (with cumulative effects that increase with increasing effective soil age) and retention by both organic matter and mineral adsorption, which are greater in the upland slope positions (Crews and others 1995; Miller and others 2001).c

DISCUSSION

Overall, these results illustrate that erosion and deposition have a rejuvenating effect on the supply of rock-derived nutrients in these valley landscapes (Porder and others 2005, 2006)—one that suffices to make both lower slope and alluvial soils fertile enough to support intensive pre-contact agricultural systems in both valleys despite the infertility of the upland soils surrounding them. However,

Table 1. Base Saturation and Pools of Available Elements in Soils

	Pololū–Hawai‘i			Hālawā–Moloka‘i		
	Upland (N = 18)	Slope (N = 10)	Alluvial (N = 11)	Upland (N = 10)	Slope (N = 18)	Alluvial (N = 10)
Resin P (µg/g)	0.6 (0.3)	7.3 (1.7)	11 (3.2)	0.7 (0.6)	19 (5.5)	11 (3.7)
Base saturation (%)	11 (4.3)	53 (1.9)	55 (3.0)	12 (3.0)	61 (1.9)	43 (5.1)
Exchangeable cations (meq/100 g)						
Ca	3.0 (0.5)	15 (2.5)	13 (1.5)	2.2 (0.8)	16 (0.9)	11 (2.9)
Mg	2.8 (0.4)	10 (1.1)	5.9 (0.5)	1.8 (0.5)	11 (0.9)	6.7 (0.9)
K	0.4 (0.05)	1.1 (0.2)	1.1 (0.1)	0.2 (0.1)	1.4 (0.1)	1.1 (0.3)

Pools of resin-extractable P and exchangeable nutrient cations in soils in and surrounding Pololū and Hālawā Valleys, and base saturation calculated as described in the text. The values for uplands are derived from transects on each side of the valleys, utilizing only sites with rainfall similar to the within-valley samples; slope and alluvial samples come from the lower slopes of each valley and the alluvial material in the bottom of the valley, respectively. All values are means, with standard errors in parentheses. ANOVA on log-transformed values yielded very highly significant differences ($P < 0.001$) for each measure in each valley; Bonferroni-corrected T tests showed that upland soils differed significantly from slope and alluvial soils in every case, whereas slope and alluvial soils did not differ significantly.

Table 2. Total Pools of C, N, and P, and P and Ca Remaining from Parent Material

	Pololū–Hawai'i			Hālawā–Moloka'i		
	Upland (N = 18)	Slope (N = 10)	Alluvial (N = 11)	Upland (N = 10)	Slope (N = 18)	Alluvial (N = 10)
Total element concentrations (%)						
Carbon	7.5 (0.6)	4.6 (0.5)	4.8 (0.7)	6.0 (0.7)	3.4 (0.2)	3.3 (0.2)
Nitrogen	0.66 (0.05)	0.43 (0.039)	0.45 (0.052)	0.40 (0.047)	0.30 (0.022)	0.28 (0.021)
Phosphorus	0.27 (0.022)	0.17 (0.042)	0.22 (0.008)	0.14 (0.017)	0.20 (0.020)	0.27 (0.012)
Elements remaining from parent material (%)						
Phosphorus	26 (2.6)	95 (6)	99 (8)	14 (3.9)	70 (4.5)	70 (4.1)
Calcium	1.7 (0.4)	36 (10)	37 (3)	0.53 (0.22)	21 (2.9)	21 (3.4)

Concentrations of total pools of C, N, and P in soils of Pololū and Hālawā Valleys, and the fraction of P and Ca that remains from the original parent material (calculated as described in the text). The values for uplands are derived from transects on each side of the valleys, utilizing only sites with rainfall similar to the within-valley samples; slope and alluvial samples come from the lower slopes of each valley and the alluvial material in the bottom of the valley, respectively. All values are means, with standard errors in parentheses. ANOVA on log-transformed values yielded very highly significant differences ($P < 0.001$) for each measure in each valley, except for total P in Pololū ($P < 0.01$) and total N in Hālawā ($P < 0.05$); Bonferroni-corrected T tests showed that upland soils differed significantly from slope and alluvial soils in every case except total P in Pololū, for which slope soils differed significantly from upland and alluvial soils. This represented the only case in which slope and alluvial soils differed significantly.

differences in the structures of the valleys influenced their ability to support intensive agriculture prior to European contact. Hālawā Valley and other large valleys on older islands have well-developed colluvial aprons surrounding their alluvial floors. In contrast, Pololū Valley lacked the potential for lower-slope rainfed agriculture because the high subsidence rate of Hawai'i Island causes a sharp transition between slopes too steep to cultivate and the nearly flat valley floor (Figure 2)—a process that is accentuated by the rapid glacial-melt-driven sea level rise of the past approximately 20 ky (Figure 3). Other major valleys on Kohala Volcano have similar structures—including the largest, Waipi'o Valley, which was a major center of pre-contact Hawaiian settlement.

Considering only the area bounded by the cliff tops on the valley sides and waterfalls at the head of the valleys, differences in subsidence rates and corresponding in-fill histories cause large differences in the distribution of slopes suitable for agriculture within Pololū and Hālawā (Figure 5). Assuming that slopes of less than 5° could have been made suitable for intensive pondfield systems, 17% of the 423 ha surface of Pololū Valley could support pondfields (if enough water were available); only 6% of the 692 ha surface of Hālawā Valley had slopes less than 5°. Further, assuming that 12° represents an upper threshold for intensive rainfed agriculture, 16% of Hālawā Valley has slopes between 5° and 12°, as opposed to only 5% of Pololū Valley (Figure 5).

Available archaeological evidence for pre-contact agricultural systems in Pololū and Hālawā is consistent with our findings on valley topography and

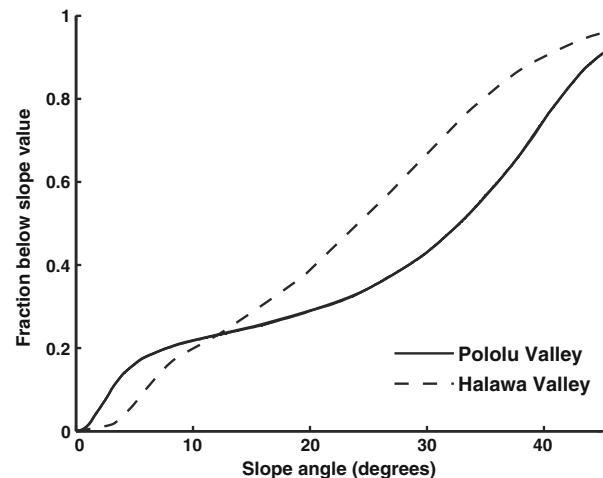


Figure 5. The cumulative distribution of slopes within Pololū and Hālawā Valleys, calculated as described in the text. Both valleys have equivalent fractions of their surface with slopes less than 12° (22%), but a much larger fraction of Pololū Valley (17 vs. 6%) has slopes less than 5° that are suitable for the development of irrigated pondfield agriculture.

soil fertility. Tuggle and Tomonari-Tuggle (1980) found evidence for both irrigated and rainfed fields on the flat alluvial floor of Pololū. They attribute the fact that not all the Pololū alluvium was irrigated (despite greater yields from irrigated systems) to the valley's hydrologic conditions; the valley floor is so large relative to its watershed area that stream flow was inadequate to have watered the entire valley floor. In Hālawā Valley, the entire area of alluvium was converted to irrigated pondfields, which also extended onto the lower colluvial slopes (Riley 1975). More importantly, well-defined rainfed

cultivation plots with stone-faced terraces and walls extend well up the colluvial slopes in Hālawā, encompassing an area greater than the total area of irrigated pondfields there. Rosendahl (1975; see also Kirch 1977) mapped the Kapana area of Hālawā Valley, providing a detailed example of intensive rainfed agricultural terraces, integrated with habitation sites and small temples. Significantly, mid-nineteenth century land records (the Mahele archives) from Hālawā demonstrate that most claimants included both irrigated (*lo'i*) as well as rainfed (*kula*) areas in their claims (Anderson 2001), showing that the two kinds of agriculture were integral parts of the overall production system at the household level.

The broader implications of this potential for intensive rainfed agriculture on colluvial slopes of the valleys on the older islands in the Hawaiian Archipelago are substantial. Analyses of the distribution of intensive agricultural systems and their consequences for the dynamics of Hawaiian society have considered irrigated and rainfed systems to have been spatially separated, due to the very different ecosystem and landscape properties that favor their development (Kirch 1994, in press; Vitousek and others 2004; Ladefoged and others 2009). Because these types of agricultural systems differ both in their ability to produce a surplus over agricultural labor and in their vulnerability to drought—with both comparisons favoring the irrigated pondfield systems—these contrasting systems could have contributed to the development of rather different societies, in areas or on islands dominated by one system or the other. The islands of Hawai'i and to a lesser extent Maui were based largely upon intensive rainfed systems, with only a few well-watered irrigated valleys. In contrast, the older islands in the archipelago have been thought to be based mostly upon irrigated pondfield systems. However, the evidence here suggests that the older islands likely maintained integrated pondfield/rainfed systems and that, as in Hālawā Valley, the peripheral rainfed systems could have covered a larger area than did irrigated pondfields. A similar pattern has been suggested in the leeward Mākaha Valley of O'ahu, where archaeological survey confirmed the presence of extensive areas of dry-land gardening on colluvial slopes, but where irrigation was confined to smaller areas in the valley interior (Hommon 1969, 1970; Yen and others 1972; Kirch 1977).

The potential for developing integrated pondfield/rainfed systems on colluvial slopes on the older islands strengthens the contrast between the agricultural production potential of Hawai'i Island

versus the older islands. It has been suggested that pressures to maintain surplus production in rainfed, drought-prone agricultural areas could have driven the elites of Hawai'i Island towards marriage alliances (Cachola-Abad 2000) with elites of the older islands, and/or towards conquest of those islands (Kirch 1994)—and the development of integrated pondfield/rainfed systems on the older islands would only have increased their attractiveness as potential acquisitions. Moreover, integrated systems on the older islands could have boosted their potential agricultural yields, and the diversity of foods they could produce, to levels approaching the total productivity of the much larger island of Hawai'i (Ladefoged and others 2009). These dynamics should be incorporated into our understanding of the dynamics of Hawaiian society, and those of other indigenous societies in which similar dynamics could occur.

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