Ecological Applications, 19(6), 2009, pp. 1444–1453

Sources of nutrients to windward agricultural systems in pre-contact Hawai'i

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Abstract. Prior to European contact in 1778, Hawaiians developed intensive irrigated pondfield agricultural systems in windward Kohala, Hawai'i. We evaluated three potential sources of nutrients to windward systems that could have sustained intensive agriculture: (1) in situ weathering of primary and secondary minerals in upland soils; (2) rejuvenation of the supply of rock-derived nutrients on eroded slopes and in alluvium; and (3) transport of rock-derived nutrients to crops via irrigation water. Our results show that most windward soils are infertile and suggest that weathering of minerals within upland soils was insufficient to sustain intensive agriculture without substantial cultural inputs. Erosion enhances weathering and so increases nutrient supply, with soils of the largest alluvial valleys (>200 m deep) retaining 37% of calcium from parent material (compared to 2% in upland sites). However, soils of smaller valleys that also supported pre-contact agricultural systems are substantially less enriched. Isotopic $^{87}Sr/^{86}Sr$ analyses of stream water demonstrate that at low to moderate stream flow over 90% of dissolved strontium derives from weathering of basalt rather than deposition of atmospheric sources; most other dissolved cations also derive from basalt weathering. We calculate that irrigation water could have supplied $\sim$200 $kg \cdot ha^{-1} \cdot yr^{-1}$ of calcium to pondfield systems, nearly 100 times more than was supplied by weathering in soils on stable geomorphic surfaces. In effect, irrigation waters brought nutrients from rocks to the windward crops.

Key words: biogeochemistry; erosion; intensive agriculture; irrigation; nutrient availability; precontact Hawai'i; strontium isotopes; weathering.

Introduction

Hawaiians had established the largest and most complex agricultural systems in the Polynesian islands well before European contact in 1778 (Kirch 1994, 2000), including highly organized systems of intensive rain-fed sweet potato (*Ipomoea batatas*) and other crops in drier, leeward landscapes, and irrigated taro (*Colocasia esculenta*) pondfields in wetter windward regions. The distribution of these systems across the archipelago was not uniform; irrigated systems were centered in colluvial slopes and alluvial valleys of the deeply weathered and dissected older islands, while the rain-fed systems were largely confined to the relatively undissected volcanic terrains of the younger islands (Kirch 1985, Vitousek et al. 2004). Kirch (1994, 2007) suggested that these disparate modes of agricultural production and intensification influenced the political, cultural, and economic development of Hawaiian societies. While nutrient constraints to rain-fed agricultural systems in the Hawaiian archipelago have been characterized (Kirch et al. 2004, Vitousek et al. 2004, Hartshorn et al. 2006), the sources of the nutrients that sustained Polynesian agriculture for generations in high-rainfall windward areas have not been evaluated. Many of these systems now are coming back into production in Hawai'i and elsewhere, and understanding how they were sustained in the past could help to guide their management in the future.

Several recent publications have evaluated the distribution and dynamics of large rain-fed agricultural systems in Hawai'i (Ladefoged et al. 1996, Ladefoged and Graves 2000, Allen 2004, Kirch et al. 2004, Vitousek et al. 2004, Hartshorn et al. 2006, McCoy and Hartshorn 2007, Ladefoged et al. 2008), concluding that they are restricted to leeward portions of younger volcanoes by interactions of water and nutrient supply. These systems make use of a "sweet spot" in soil fertility poised between areas too dry to reward intensive cultivation, and areas so wet that millennia of weathering and leaching have depleted the supply of nutrients available

Manuscript received 26 May 2008; revised 20 November 2008; accepted 5 December 2008. Corresponding Editor: D. R. Zak.

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to crops (Chadwick et al. 2003). Substrate age also plays a role in constraining their distribution: older soils have been subject to the cumulative effects of weathering and leaching for longer, and the rainfall at which soil fertility is too depleted for large-scale intensive agriculture shifts to progressively lower levels on older substrates. Consequently, the "sweet spot" of soil fertility that sustained intensive rain-fed agriculture narrows and eventually disappears on older substrates, essentially confining large rain-fed agricultural systems to the younger islands (Vitousek et al. 2004). In contrast, irrigated systems were located near relatively permanent streams or springs, typically on alluvial or colluvial soils; most of these systems received more rainfall than did the rain-fed agricultural systems, especially on the younger islands. The importance of soil nutrient supply in constraining the distribution of rain-fed agricultural systems raises the question: what are the sources of nutrients for crops within irrigated pondfields in higher-rainfall (and older) environments?

Here we evaluate three major processes that could have supplied nutrients to windward crops. First, some low-elevation windward areas receive less rainfall than do portions of leeward rain-fed systems on similar-aged substrates (Giambelluca et al. 1986), and in those areas mineral weathering in situ might supply sufficient nutrients for intensive agriculture (irrigated or rain-fed). Second, erosion of volcanic shield surfaces could enrich valley soils as the parallel retreat of steep valley sides exposes and mobilizes fresh rock, effectively reducing the age of the soil and rejuvenating the supply of rock-derived nutrients to slope and alluvial/colluvial soils below (Vitousek et al. 2003, Porder et al. 2005). Third, the pathways of water movement to groundwater and streams—and ultimately into irrigation systems—may bring that water into contact with little-weathered minerals deep within windward soils and substrates, so that irrigation water itself could bring the products of mineral weathering to crops. Additionally, Hawaiian cultivators could have enriched nutrient supply locally by harvesting organic materials from surrounding areas and concentrating it in agricultural systems.

Methods

Research area

We carried out this research on Kohala, the oldest of five volcanoes on the island of Hawai'i. Kohala Volcano is made up of two geologic substrates: (1) Pololu lava, an older, mainly tholeiitic basalt that erupted to build the volcano from 350 000 to 600 000 years ago; and (2) Hawi lava, a younger, more alkalic basalt that erupted during a post-shield stage 150 000 to 220 000 years ago (Fig. 1) (Moore and Clague 1992). Kohala supports a dramatic orographic precipitation gradient from its wet, windward northeast slope to its leeward southwest slope, with annual rainfall ranging from an average of 1200 mm at the windward coast to >4000 mm at higher elevations before dropping to as low as 180 mm/yr on the leeward coast (Giambelluca et al. 1986). There is a striking threshold in soil fertility at an annual rainfall of ~1400–1800 mm on the younger Hawi substrate (Chadwick and Chorover 2001, Chadwick et al. 2003). Sites drier than this threshold derive most of their nutrients from the weathering of basaltic parent material, while in wetter sites most rock-derived magnesium (Mg), calcium (Ca), and potassium (K) have been lost via leaching, and the small remaining pools of these elements largely derive from atmospheric deposition of marine aerosol (Chadwick et al. 2003). The windward slopes of Kohala are dissected as well as depleted; slides and fluvial erosion have created several deep and many smaller valleys (Fig. 1).

Archaeological surveys indicate that valleys on the wet windward side of Kohala contained the most extensive irrigated pondfields on the island of Hawai'i, while the leeward slope supported a well-developed 60-km^2 rain-fed field system (see Tuggle and Tomonari-Tuggle 1980, Ladefoged et al. 2008). Pololu Valley, the largest and deepest in the study area, was settled as early as AD 1200–1300, with continuous occupation supported by both irrigated pondfields and rain-fed lowland systems through the period of European contact (1778) and the arrival of American missionaries (1821). Smaller windward valleys supported a number of pondfield complexes as well; these were initiated as early as AD 1450–1550, with construction extending well into the historic era (M. Graves, *unpublished data*). Unique to Kohala, Hawaiian cultivators also irrigated some portions of the windward interfluvial surfaces of Kohala Volcano (Handy 1940, Cachola-Abad 2000). The close proximity of four contrasting agricultural systems (the leeward rain-fed field system, windward irrigated uplands, windward valley irrigated pondfields, and windward valley rain-fed systems) on the same geological substrates allow us to use features of the well-defined and well-characterized leeward rain-fed system to inform our analysis of windward agricultural systems.

Field sampling

We established multiple transects from the windward coast to the summit ridge (the northeast rift zone) of Kohala Volcano, where they joined earlier transects across the leeward field system to the leeward coast (Fig. 1; see Vitousek et al. 2004). Current land use across the windward transects is predominantly cattle ranching, with some native forest in the east and alien-dominated forest and low-density residential areas in the west; small macadamia orchards are present as well. Field sampling methods for soils followed similar protocols to those of Vitousek et al. (2004). Briefly, integrated soil samples from 0-30 cm depth were collected approximately 500 m apart, pacing off distances; sample positions were recorded via GPS. Soils designated "shield surface" were collected on geomorphically stable constructional surfaces, and care was taken to avoid areas with signs of erosion or deposition. "Slope" soils were collected on

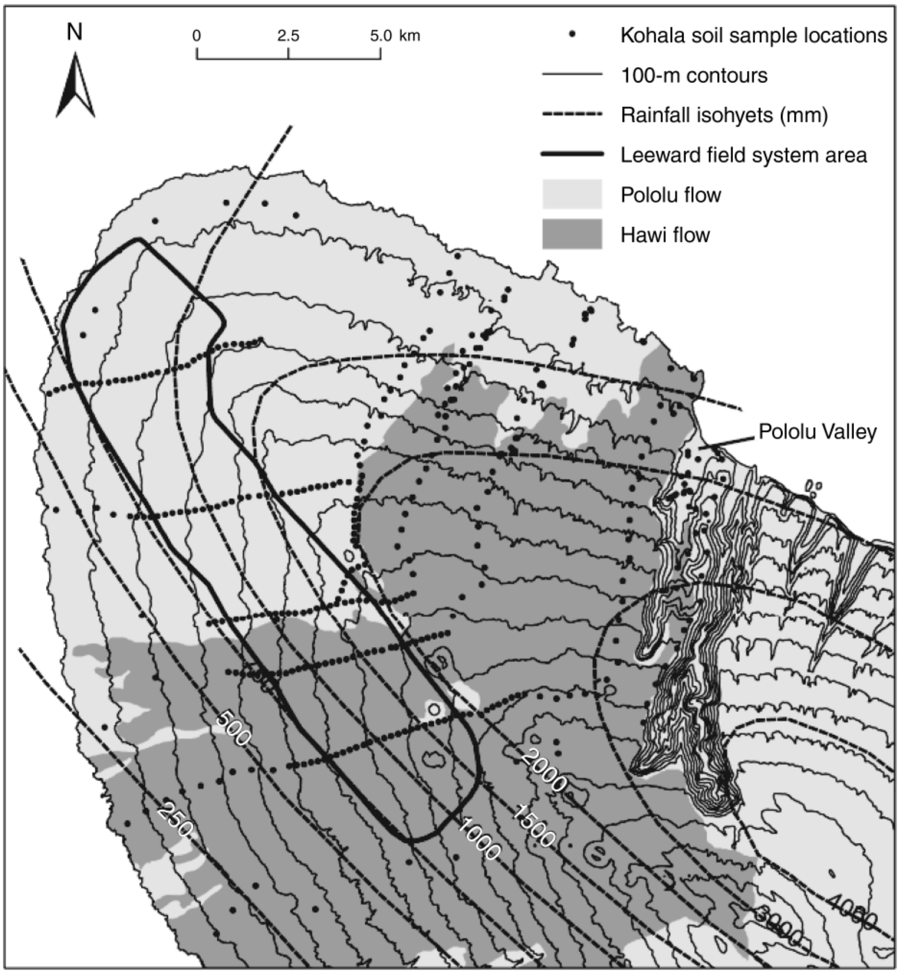

FIG. 1. Sample locations on windward and leeward Kohala Volcano, Hawai'i, USA, showing elevation (thin lines), rainfall isohyets (dashed lines), geological substrates (dark gray, Hawi, 150 000 years old; light gray, Pololu, 400 000 years old), the locations of the leeward Kohala field system (thick lines) and Pololu Valley, and points where soil samples were collected (dots).

the lower half of steeply sloping sides of valleys that dissect the shield surfaces. "Alluvial" samples were gathered in flat-lying areas along streams and in the valley floors, including in areas where remnants of precontact agriculture are clearly visible. Five main transects were established on the shield surface, and slope and alluvial samples were collected in small valleys (<50 m deep) near these transects. Additional samples were obtained throughout Pololu Valley, a large (>200 m deep) valley with a broad alluvial floor on the eastern margin of the study area. In total, 188 30-cm depth-integrated soil samples were collected in windward Kohala from 2005 to 2007: 134 shield surface, 28 slope (11 from the large valley), and 26 alluvial (11 large valley).

Stream samples were collected at multiple points in the Waikama Stream watershed, near the eastern margin of the study area, and analyzed for dissolved elements. This watershed is covered by pasture at high and low elevations, and native forest at mid-elevations. In total, seven sites were sampled along the stream at both high and moderate flow, once during high-flow conditions in early July 2005 and again at moderate flow in late August of the same year. In addition, one site was sampled under low-flow conditions at the end of December 2005. A groundwater seep was sampled on both high and moderate flow days, and a sample of surface runoff was collected at high flow. At each site, one 125-mL sample was collected using a pre-rinsed 0.2-μm syringe filter for nutrient analyses, and a 1-L sample was collected for strontium (Sr) isotopic analyses; sample bottles were acid-washed and pre-rinsed with filtered stream water. Finally, we made use of Hawai'i Department of Health water quality information on total phosphorus concentrations in Waikama Stream (State of Hawaii, Department of Health, *unpublished data*).

Soil chemical analyses

Soils were sieved and divided into three homogenous subsamples. All analyses were carried out as described in the supplemental material to Vitousek et al. (2004). Briefly, one subsample was analyzed in duplicate for resin-extractable phosphorous (P) at Stanford University using the method of Kuo (1996) and analyzed on an Alpkem RFA/2 AutoAnalyzer (Perstorp Analytical, Silver Spring, Maryland, USA). 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); percent base saturation was calculated as

$$\left(\frac{\text{Exchangeable Ca} + \text{Mg} + \text{K} + \text{Na}}{\text{CEC}}\right) \times 100.$$

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 for x-ray fluorescence spectrometry or inductively coupled plasma-mass spectrometry.

Resin-extractable P correlates with the availability to plants of this essential nutrient (Sibbesen 1978), while base saturation provides an integrated measure of cation supply and acidity (Burt 1995). Both of these properties exhibit distinct thresholds that define the wet, upper edge of the leeward field system; soils with base saturation below ~30% and resin P below ~40 μg/g did not support intensive rain-fed agriculture (Vitousek et al. 2004). We use these values as thresholds below which windward soils probably would not be able to support intensive agriculture without additional inputs or substantial effort.

There are two uncertainties associated with our use of these thresholds. First, there is no similarly robust measure for N, the other element likely to limit plant production in these systems. Second, for resin P and base saturation (though probably not the total element analyses), land uses in the past 150–200 years, particularly fertilization, liming, and 150 years of plantation sugar cultivation, could have altered these relatively dynamic soil properties. However, the strength of threshold responses in modern analyses of soils in the nearby leeward system, where these properties also were analyzed on integrated 30-cm soil samples, provides a useful basis for comparison.

Stream water chemical analyses

The 125-mL stream water samples were analyzed at Stanford University using a TJA IRIS Advantage/1000 Radial ICAP spectrometer (TJA Solutions, Franklin, Massachusetts, USA) for Sr and major cations. The larger stream water samples were analyzed for Sr isotopes; Sr is chemically similar to Ca, and the major sources of Sr to Hawaiian ecosystems (atmospheric deposition and basalt weathering) differ reliably and systematically in their ratio of $^{87}Sr/^{86}Sr$ (Kennedy et al. 1998, Stewart et al. 2001). Samples for Sr isotopic analysis were separated by ion chromatography using BIO-RAD AG-50 resin (Bio-Rad Laboratories, Hercules, California, USA) (see Porder et al. 2005, 2006 for details), and water containing approximately 1 μg of Sr was loaded onto a column, eluted with 2 mol/L distilled HCl, dried, and analyzed on a Finnigan MAT 261 solid source mass spectrometer (Thermo Finnigan, Waltham, Massachusetts, USA) at the United States Geological Survey in Menlo Park, California, USA. Analyses of standard reference material (NBS-987) were never more than 0.00005 from the accepted value. We calculated the proportion of Sr in each water sample ($^{87}Sr/^{86}Sr_{sample}$) that was derived from the weathering of basalt rock (RF) as

$$\mathrm{RF} = (^{87}\mathrm{Sr}_{\mathrm{sample}}/^{86}\mathrm{Sr}_{\mathrm{sample}} - 0.7092)/(0.7036 - 0.7092)$$

where 0.7036 and 0.7092 are $^{87}Sr/^{86}Sr$ in Hawaiian basalt and in marine aerosol, respectively. We also calculated the fraction of major elements derived from non-sea-salt (NSS) sources, as

$$\mathrm{NSS}_{i,j} = 1000 \times \{X_j - [\mathrm{Cl}_j \times (X_{\mathrm{sw}}/\mathrm{Cl}_{\mathrm{sw}})]\}$$

where X is concentration of the element in question, j is the sample, and sw represents the standard X/Cl ratio in seawater.

Data analysis

Net loss or gain of P and Ca from the soil were calculated with reference to the concentration of an immobile index element; we used niobium (Nb) because (with tantalum) it is the least mobile of the elements analyzed in Hawaiian soils (Kurtz et al. 2000). The percentage of an element that remained in the soil sample relative to its basaltic parent material was calculated as

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

where $L_{i,j}$ is the percentage of element i remaining in soil sample j; $C_{i,j}$ and $C_{\mathrm{Nb},j}$ are the concentrations of element i and of Nb in sample j; and $C_{i,\mathrm{pm}}$ and $C_{\mathrm{Nb,pm}}$ are the element concentrations in basaltic parent material. For reference, the Ca:Nb ratios (g:g) in Hawi vs. Pololu basalt average 628:1 and 4352:1, respectively, while P:Nb ratios average 109:1 and 83:1.

Losses of elements relative to parent material reflect removals via leaching or harvest, while gains represent additions of these elements from off-site or translocation from deeper levels in the soil profile. These properties provide a conservative measure of the potential for soil minerals to supply more nutrients via weathering; they should be relatively robust to changes in land use over time.

Statistical analyses were performed using SigmaStat (Systat Software version 3.5; Systat, Chicago, Illinois, USA). All data were log-transformed to approximate the assumptions of analysis of variance (normality, homogeneity of variance). For the comparison of windward vs. leeward Kohala shield surfaces, results were analyzed using a two-way analysis of variance to

TABLE 1. Soil properties in windward vs. leeward Kohala, Hawai'i, USA, grouped by substrate age.

	Hawi substrate (150 000 yr)		
Soil property	Within leeward field system ($N = 41$)	Above leeward field system ($N = 14$)	Windward Kohala shield ($N = 62$)
Base saturation (%)	52.2 ± 2.5	19.7 ± 1.6	8.5 ± 0.8
Resin P (mg/kg)	231 ± 28	34.1 ± 10.4	3.6 ± 1.1
P remaining (%)	118.9 ± 10.4	66.2 ± 8.0	25.3 ± 1.8
Ca remaining (%)	52.9 ± 5.4	8.9 ± 2.6	2.2 ± 0.2

Notes: Soil properties were measured on the constructional (shield) surfaces of windward and leeward Kohala, the latter both within and above a pre-contact rain-fed field system. Two geological substrates are represented in this landscape: younger Hawi and older Pololu lavas. Values are means ± SE; leeward field system data are from Vitousek et al. (2004). P and Ca remaining are calculated as a percentage of the original amount in parent material, determined using the immobile index element Nb as described in *Methods: Data analysis*. The last column indicates significance values (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$) obtained by two-way ANOVA on log-transformed data; L represents the effect of location (within the leeward field system, above the leeward field system, or within windward Kohala), and S represents the effect of substrate (Hawi or Pololu).

test for significant variation in soil properties among substrate types (two factors: Hawi or Pololu) and sample locations (three factors: within the leeward field system, leeward but above the field system, or in windward Kohala; see Table 1). 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. For the soils in windward Kohala, results were analyzed using one-way ANOVA to test for differences based on slope position (shield vs. slope and alluvium in large and small valleys). Bonferroni's correction again was used for multiple pairwise comparisons among the five groups where significant F values from the ANOVA ($P < 0.05$) were obtained. Three adjacent shield samples from one transect were not included in these analysis; their Ca concentrations and Ca:Mg ratios suggest a history of liming.

RESULTS

Earlier studies of the leeward field system were used to define thresholds in soil fertility (Vitousek et al. 2004). Soils within the leeward rain-fed field system have an average base saturation of 52.2% and 47.3% on Hawi and Pololu substrates, respectively (Table 1), but leeward areas above the upper, wet edge of the field system average 19.7% (Hawi) and 24.8% (Pololu) base saturation. Resin-extractable phosphorus in the leeward sites follows a similar trend (Table 1). Many of the leeward Hawi soils are enriched in total P remaining relative to parent material (hence the >100% value) due to many millennia of nutrient translocation by native forests (Table 1) (Vitousek et al. 2004). Even in leeward areas above the wet upper edge of the leeward field system, two-thirds or more of parent material P still remains in soil (Table 1), but this fraction falls to less than half in windward shield surface soils. The amount of calcium remaining is relatively high on the young Hawi soils within the leeward field system (52.9%) but drops off sharply above the upper edge (8.9%) (Table 1).

Windward shield surfaces

As expected, soils on the shield surface of windward Kohala are infertile; most fall below the base saturation threshold of 30%, although some lower-rainfall windward Pololu soils are above this threshold (Fig. 2). Resin-extractable P concentrations of windward soils also fall far below the leeward field system threshold, averaging 3.6 mg/kg (Hawi) and 6.9 mg/kg (Pololu) (Table 1, Fig. 3). The counterintuitive result that the older (Pololu) windward surface has higher base saturation and resin P on average than the younger (Hawi) surface (Table 1) occurs because the Pololu substrate occupies all of the drier northwestern portion of windward Kohala. The few high-resin P values we

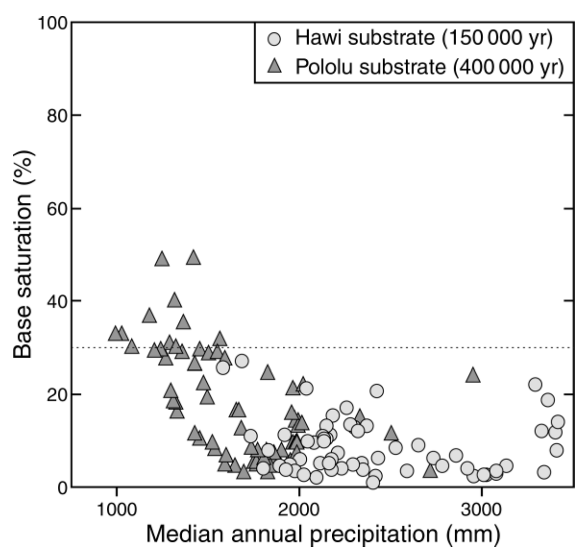

FIG. 2. Base saturation on the windward shield surface vs. median annual precipitation (MAP) for Hawi (over 150 000 yr; circles) and Pololu (over 400 000 yr; triangles) substrates of windward Kohala soils. The dotted horizontal line denotes a threshold of base saturation at 30%, based on the upper, wet edge of the leeward field system (Vitousek et al. 2004). Several low-elevation windward sites on the Pololu formation have base saturation above this threshold, but most sites in windward Kohala fall below it.

TABLE 1. Extended.

Pololu substrate (400 000 yr)			
Within leeward field system ($N = 57$)	Above leeward field system ($N = 12$)	Windward Kohala shield ($N = 72$)	Statistical significance
47.3 ± 1.5	24.8 ± 3.1	17.4 ± 1.4	L***, S**, L×S***
116 ± 14	47.8 ± 11.3	6.9 ± 2.4	L***, L×S**
74.8 ± 7.1	78.2 ± 7.4	42.0 ± 3.1	L***, L×S***
2.4 ± 0.2	2.5 ± 0.2	2.0 ± 0.4	L***, S***, L×S ***

observed in windward Kohala (Fig. 3) may reflect the residue of fertilization; most are not accompanied by high levels of total P in the soil (Fig. 4).

Similarly, the amount of total P remaining (relative to parent material) is significantly lower in windward than in leeward Kohala (Fig. 4, Table 1; $P < 0.001$). Total Ca remaining is much more depleted in older and wetter shield soils than is P, with only ~2% remaining in windward soils regardless of substrate type (Fig. 5, Table 1).

Slope and alluvial samples

Soil properties in windward valleys are summarized in Table 2, broken down by valley size and slope position; we do not separate substrate types here because these stream valleys often cut down through both Hawi and Pololu substrates. Slope and alluvial samples are enriched relative to windward shield surfaces, but the degree of enrichment is variable, especially in the smaller valleys. Base saturation is significantly greater compared to windward shield soils for both large and small valleys in both slope and alluvium ($P < 0.001$ for all four groups; Table 2); soils in the large valley in particular are well above the 30% threshold defined by the upper, wet edge of the leeward field system (49.2% on slopes and 54.5% in alluvium). Soils in smaller valleys are closer to the threshold (32.1% on slopes and 39.2% in alluvium), although small valleys do not differ significantly from the large valley for either slope position.

Resin-extractable P in alluvial soils is enriched significantly in both small and large valleys (12.9 mg/kg in small and 10.9 mg/kg in large valleys, vs. 5.4 mg/kg on shield surfaces; $P < 0.05$ and 0.01, respectively), but shield and slope do not differ significantly for either valley size (Table 2). None of these values approaches the 40 mg/kg threshold defined by the leeward field system.

Calculating P and Ca remaining in the soil relative to parent material is more challenging in slopes and alluvium than on shield surfaces, because both Hawi and Pololu material may be present in a single valley and because these substrates differ in element : Nb ratios (considerably so in the case of Ca). We assumed a most likely source of material for each sample, and calculated

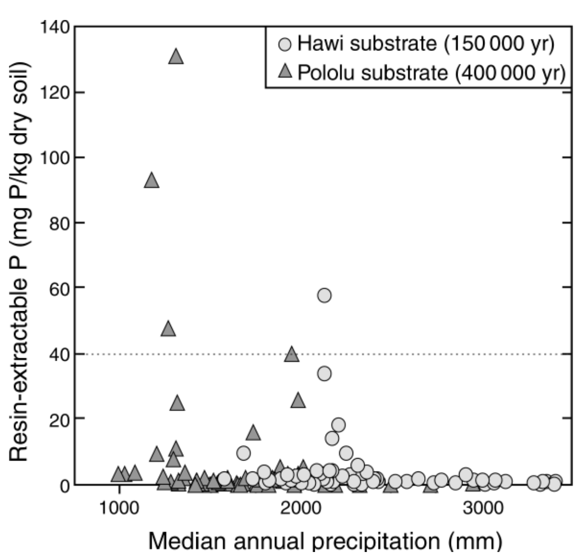

FIG. 3. Resin-extractable phosphorus on the windward shield surface vs. MAP for Hawi (over 150 000 yr; circles) and Pololu (over 400 000 yr; triangles) substrates of windward Kohala soils. The dotted horizontal line denotes a threshold of resin-extractable P at 40 mg/kg.

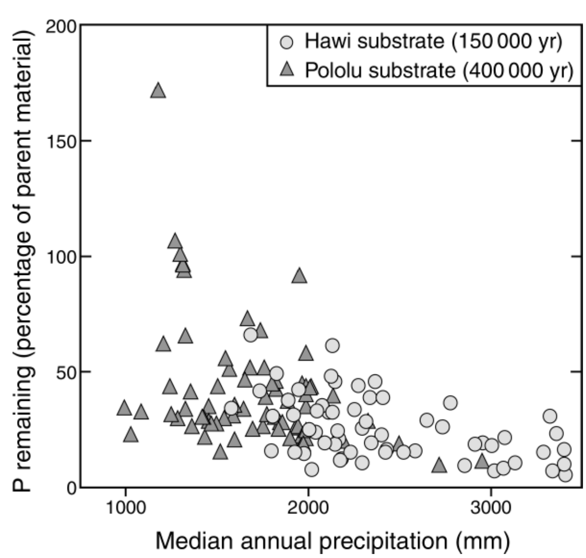

FIG. 4. Total phosphorus remaining on the windward shield surface as a percentage of P originally present in parent material, calculated using an immobile index element (Nb) as described in *Methods: Data analysis*, for Hawi (over 150 000 yr; circles) and Pololu (over 400 000 yr; triangles) substrates of windward shield soils. Values greater than 100% reflect either external inputs or the translocation of P from deeper in the soil.

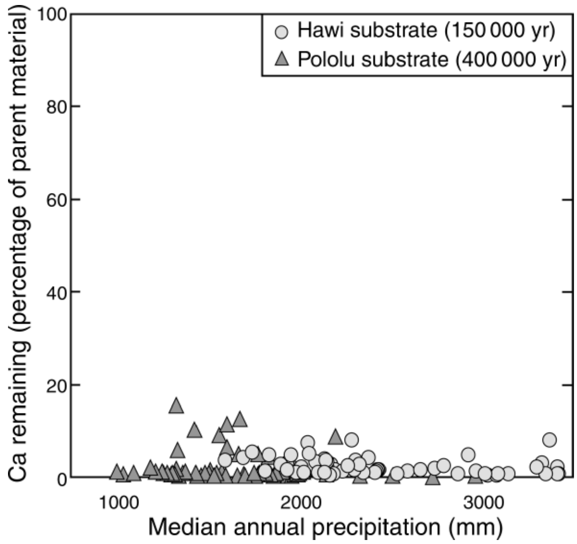

FIG. 5. Total calcium remaining on the windward shield surface as a percentage of Ca in parent material, calculated as described in Fig. 4, for Hawi (over 150 000 yr; circles) and Pololu (over 400 000 yr; triangles) substrates of windward shield soils.

elements remaining on that basis. P remaining in soil is substantially greater in the large valley relative to windward shield surfaces, increasing significantly ($P < 0.001$) from 34.4% on shield surfaces to 90.5% and 98.6% on slopes and alluvium, respectively (Table 2); these differences are much larger than those between Hawi and Pololu basalt. These results show that erosional downcutting in deeper valleys reaches into little-weathered rock, and that much of their alluvium derives from that fresh rock. Small valleys (<50 m deep) are not similarly enriched in P by downcutting; slope and alluvial soils there do not differ from shield surfaces in P remaining. In contrast, slopes and alluvium in both small and large valleys are enriched in total Ca relative to the windward shield surface ($P < 0.001$ for all four groups; Table 2). Among groups, large-valley alluvial soils (36.6%) retain more calcium than small-valley slope (10.1%, $P < 0.001$) and alluvial (14.3%, $P < 0.05$) soils, though this result depends in part on accurate identification of whether Pololu or Hawi volcanics represent the relevant parent material.

Stream water

Analyses of the $^{87}Sr/^{86}Sr$ isotopic ratios in stream water demonstrate that at low to moderate stream flow, over 90% of dissolved Sr comes from basaltic rather than atmospheric sources (Fig. 6). The contribution of Sr from atmospheric deposition of marine aerosol increases at higher flow. Strontium isotope ratios in the groundwater spring reflect a >90% rock contribution and change very little between moderate and high flow conditions, while one sample of surface runoff at high flow (the only time it occurs) yielded 54% Sr derived from atmospheric sources ($^{87}Sr/^{86}Sr = 0.70661$). Even at high flow, less than 30% of Sr in streams derives from marine aerosol, with lower values in agricultural areas near the coast (generally <10% even at high flow) and higher values in wetter, higher elevation sites.

The non-sea-salt (NSS) fraction of Ca provides an additional measure of weathering vs. atmospheric sources of elements. Results were similar to those from Sr isotopes; at low to moderate flows, the percentage of NSS (rock-derived) Ca is ~90% (Fig. 6), and the groundwater spring had a higher fraction of NSS calcium than did the sample of surface runoff.

DISCUSSION

Nearly all soils on shield surfaces in windward Kohala are low in base saturation and available P, with levels far below thresholds in fertility defined by the nearby leeward field system. Moreover, the total pools (and thus the potential supplies) of P and particularly Ca from parent material have been depleted by many millennia of leaching across most of windward Kohala (Figs. 4 and 5). While forests can survive (even thrive) while drawing most of their nutrients from atmospheric deposition (Kennedy et al. 1998, Chadwick et al. 1999), intensive agriculture involves the removal of large quantities of nutrients in harvest and other pathways, and the windward shield surface of the Kohala volcano appears to be too depleted in nutrients to support the precontact Hawaiian system of rain-fed agriculture without additional inputs by cultural or natural processes.

Most of the intensive agriculture in precontact windward Kohala was based on irrigated pondfields in valleys; could erosion and deposition within these valleys supply crops with substantial quantities of

TABLE 2. Soil properties in windward Kohala grouped by valley size and slope position.

Soil property	Small valleys (<50 m deep)		Large valleys (>200 m deep)		
	Slope (N = 17)	Alluvium (N = 15)	Slope (N = 11)	Alluvium (N = 11)	Shield (N = 134)
Base saturation (%)	32.1*** ± 4.3	39.2*** ± 3.2	49.2*** ± 6.8	54.5*** ± 2.8	13.3 ± 0.9
Resin P (mg/kg)	1.5 ± 0.3	12.9* ± 6.7	6.6 ± 1.6	10.9** ± 3.1	5.4 ± 1.4
P remaining (%)	41.5 ± 3.2	44.8 ± 6.9	90.5*** ± 6.8	98.6*** ± 7.5	34.4 ± 2.0
Ca remaining (%)	10.1*** ± 1.6	14.3*** ± 2.8	33.9*** ± 9.1	36.6*** ± 2.8	2.1 ± 0.2

Notes: Soil properties in windward Kohala divided by valley size and slope position. Values are means ± SE, with the number of samples indicated in each column. P and Ca remaining are calculated as described in Table 1. Asterisks next to means indicate significant deviation from values on the shield surface: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

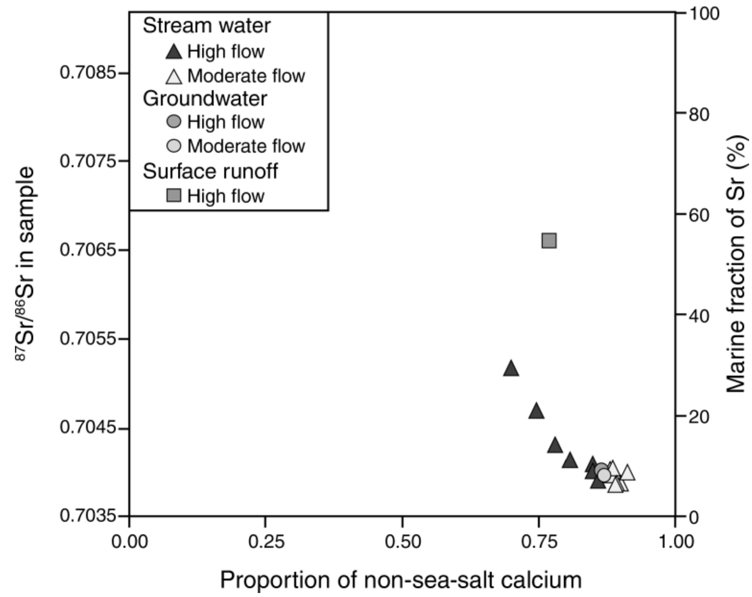

FIG. 6. Strontium isotopic ratios from stream water and non-sea-salt calcium collected during high stream flow (dark triangles) and during moderate flow conditions (light triangles), at several locations in the Waikama watershed, windward Kohala. A groundwater spring was sampled in both flow conditions (high flow, dark circles; moderate flow, lighter circles), and a sample of surface runoff was collected at high flow (square). The right-hand *y*-axis indicates the fraction of Sr derived from marine aerosol, calculated as described in *Methods: Stream water chemical analyses*. Sr isotope ratios are plotted vs. the proportion of non-sea-salt calcium, calculated as described in *Methods: Stream water chemical analyses*; values near 1 indicate Ca derived from rock rather than atmospheric sources.

rock-derived nutrients? Isotopic analyses demonstrate that trees in valleys within native forest in Hawai'i (including Kohala) acquire more rock-derived Sr than those on nearby shield surfaces (Porder et al. 2005), and this "rejuvenation" of the supply of rock-derived nutrients is associated with greater P availability. Similar patterns of enrichment of eroding soils have been observed on volcanic landscapes in Costa Rica (Bern et al. 2005, Porder et al. 2006).

Soils in large (>200 m deep) Pololu Valley were substantially enriched in base saturation and total quantities of P and Ca, to levels comparable to the rain-fed field system on the leeward flank of Kohala volcano. However, resin-P was enriched only marginally in the large valley, and then only in alluvium. The combination of a large pool of total P and small pool of resin P is comparable to the situation in young soils on a substrate age gradient across the Hawaiian archipelago (Crews et al. 1995): the capacity to supply P via weathering is substantial, but most P remains bound up in primary mineral forms that can be weathered but are not immediately available to plants (Vitousek 2004). The alluvial floor of the large valley is effectively a young soil of this sort, even though the lava that makes it up is well over 100 000 years old; most of the alluvium is little-weathered lava transported by gravity and floodwaters from the erosional downcutting of steep valley walls. The thresholds derived from much older leeward soils in Kohala, where resin P is low and little P remains to be weathered in sites wetter than the threshold, may not apply to this situation. Given its nutrient status, it is plausible that intensive rain-fed agriculture could have been practiced on the floor of Pololu Valley, and in fact many of the cultural features there are indicative of rain-fed agriculture rather than irrigated pondfields (Tuggle and Tomonari-Tuggle 1980).

Smaller valleys are not nearly as enriched in total elements or resin P as is Pololu Valley, though they do have higher base saturation than the shield surface (Table 2). The less-fertile soils of the smaller valleys probably derive a larger proportion of their alluvial and colluvial soils from upland soils that have already been weathered and depleted in rock-derived nutrients. We speculate that the levels of enrichment observed in the smaller valleys could have contributed some nutrients to Hawaiian crops there, but that soil fertility in these areas was marginal (at best) as the major support of intensive agriculture on the rain-fed pattern practiced in the leeward field system. We suggest that additional nutrient inputs would have been important to the sustained productivity of these small-valley systems.

A third possible source of nutrients to intensive windward agriculture is irrigation water that has passed through little-weathered rock en route from rain to streams. Isotopic analyses demonstrate that most of the Sr in the stream we analyzed derived from basalt weathering, and ratios of Ca and other elements to Cl suggest that the same is true of Ca (and other nutrient cations; Fig. 6). With some assumptions, we can estimate the quantity of calcium supplied to pondfield taro via irrigation water. Irrigated taro requires a near-continuous flow of water; the "Hawaiian legal requirement" for water supply is 280 000 $L \cdot ha^{-1} \cdot d^{-1}$ (de la Pena 1983), corresponding to almost 10 $m \cdot ha^{-1} \cdot yr^{-1}$. With a concentration of rock-derived Ca of 2 mg/L (typical of moderate flows at low elevation in this stream), irrigation water could supply approximately 200 $kg \cdot ha^{-1} \cdot yr^{-1}$ of Ca to irrigated taro. In contrast, by analogy to weathering rates on a substrate age gradient across the archipelago (Vitousek 2004), we estimate that weathering could supply <3 $kg\ Ca \cdot ha^{-1} \cdot yr^{-1}$ to soils on the windward Kohala shield surface. Equivalent values for P, derived in part from Hawai'i Department of Health water quality sampling of Waikama Stream that yielded a mean total P concentration of 0.018 mg/L at low to moderate flow (State of Hawaii, Department of Health, *unpublished data*), suggest that irrigation water could supply ~2 $kg\ P \cdot ha^{-1} \cdot yr^{-1}$, vs. <0.03 kg $P \cdot ha^{-1} \cdot yr^{-1}$ via weathering. These inputs compare with calculated removals of 15 $kg\ Ca \cdot ha^{-1} \cdot yr^{-1}$ from a low-input taro pondfield in Fiji (Kubuabola et al. 2000), and of 1.4 $kg\ P \cdot ha^{-1} \cdot yr^{-1}$ from low-input dryland agriculture in Hawai'i (Lee et al. 2006). All of these estimates are fairly rough, but they do suggest that irrigation water, not weathering, could represent a source of nutrients in excess of crop requirements in irrigated Polynesian pondfields. Solution inputs may have been a significant source of nutrients to irrigated upland agricultural systems as well, although we have no information on the amount of water they received. The importance of irrigation water as a nutrient source is not unique to Polynesia; Brown et al. (1999) calculated that irrigation water supplied ~300 $kg\ Ca \cdot ha^{-1} \cdot yr^{-1}$ to rice pondfields in Jhikhu Khola, Nepal (Brown et al. 1999).

We conclude that irrigation water effectively brought products of rock weathering to the crops in most or all irrigated systems in windward Kohala. Floodwaters may have served a similar function in the large Pololu Valley, by distributing nutrients from the stream sediments to the alluvial soils where rain-fed agriculture was practiced. Inputs of dissolved or suspended rock-derived nutrients via irrigation could have reduced or eliminated the need for extended fallow periods and/or extensive mulching, and thus helped to sustain intensive agriculture in otherwise nutrient-depleted windward environments. Mulching was practiced in both windward and leeward Kohala; however, its costs in labor and in resource depletion of surrounding lands are believed to have become more difficult to sustain as the scale of agricultural enterprise expanded and the social/cultural complexity of Hawaiian society increased in the centuries before European contact (Kirch 2000).

Implications

Linking modern soil analyses to precontact ecological conditions and societies is challenging, but it offers a unique opportunity to address long-term human and ecosystem sustainability. Typically, studies of sustainable land management focus on low input subsistence-based agricultural systems. However, Hawaiian cultivators maintained large and intensive agricultural systems for centuries, in the face of demonstrably infertile soils in many windward environments. They did so in part because irrigation water brought substantial quantities of nutrients from little-weathered rock deep in the soil to the crops, essentially as an ecosystem service. Looking beyond contemporary techniques of intensification towards sources that access underutilized nutrients within or near agricultural landscapes may help some systems achieve longer-term sustainability to agriculture, with smaller environmental consequences.

Acknowledgments

This research was supported by grants from the Andrew W. Mellon Foundation and by the National Science Foundation (grant BCS-0624346). We thank the State of Hawaii for permission to carry out this research; Parker and Ponoholo Ranches, Surety Kohala Corporation, and New Moon Foundation for access to their lands; Doug Turner for laboratory analyses; Elizabeth Callaway, Heraldo Farrington, Michael Gomes, Christina Hoffman, Sara Hotchkiss, and Sarah Truebe for assistance in the field; and Michael Gomes for sharing his knowledge of the land.

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