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– ARTICLE –

# Farming the Rock: A biogeochemical perspective on intensive agriculture in Polynesia

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ABSTRACT

In pre-contact Hawai'i, large and intensive rainfed agricultural systems were established only where ongoing weathering of basalt-derived minerals could provide a sustained source of nutrients to crop plants. We demonstrated that the high-elevation, high- rainfall boundary of the Leeward Kohala Field System corresponded to a well-defined threshold in soil fertility, above which soils were acidic and infertile and rock weathering was depleted as a source of biological nutrients. The single most reliable indicator of this boundary was the concentration of exchangeable Ca in soil; rainfed agricultural infrastructure was absent where exchangeable Ca was below ~10 meq/100 g of soil. However, irrigated taro pondfields frequently were developed in windward valleys in soils with <10 meq/100 g exchangeable Ca. In these areas, irrigation water brought a sustained supply of basalt-derived nutrients to pondfields; in effect, rainfed systems brought crops to where basalt was breaking down and supplying nutrients, while irrigation water brought the nutrients resulting from the breakdown of basalt to crops. In contrast to Hawai'i, most of Rapa Nui has soils with <10 meq/100 g exchangeable Ca, but fine-scale erosion and deposition (probably reinforced in some cases by cultural practices) enhanced soil fertility to near this threshold within intensively cultivated rock gardens.

*Keywords*: Hawai'i, Leeward Kohala Field System, Rapa Nui, rock garden, soil fertility

## INTRODUCTION

Pacific islands are valuable models for understanding many aspects of the world, from evolution, ecosystems, and soils to environmental history and human-land interaction (Vitousek 2004; Kirch 2007). In our interdisciplinary research, we (with many others) have sought to integrate biogeochemical analyses of Pacific island ecosystems with studies of the pre-European-contact human societies that drew their sustenance from islands, and in the process influenced island ecosystems profoundly. We focused initially on the dynamics and significance of intensive rainfed agricultural systems in Hawai'i, building upon our understanding of soils (Chadwick *et al.* 2003), ecosystems (Vitousek 2004), and climate history (Hotchkiss & Juvik 1999) to explain why these large and historically significant systems were developed primarily on the younger islands in the Hawaiian Archipelago – and only in reasonably well-defined portions of those islands (Kirch 1994; Ladefoged and Graves 2000).

Initially, we evaluated the supply of biologically essential elements (nutrients) that could have supported sustained growth of Polynesian crops within rainfed field systems. Unlike agricultural systems, forests and other natural systems are conservative in their use of nutrients; they are able to accumulate nutrient inputs over time, and because their nutrient cycles are nearly closed they can maintain high levels of biomass and plant production even where the external supply of nutrients is small. However, agriculture inherently involves removal of the nutrients contained within harvested products – and the more productive and sustained the cropping system and the higher the nutritional quality of the crops produced, the larger the quantity of nutrients removed. Accordingly, a sustained supply of these nutrients, whether through natural processes or cultural inputs, is essential to the maintenance of intensive agricultural systems.

From earlier research on soils and ecosystems – and because Hawaiian ecosystems lend themselves to these

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studies – we had a relatively good understanding of the rates of nutrient supply through natural processes across the environmental matrix of the Hawaiian Archipelago. The main sources of the nutrients we consider here are basalt weathering (the breakdown of volcanically derived minerals that yields elements in soluble and biologically accessible forms); atmospheric deposition of marine aerosol (nutrients that ultimately derive from sea salt, transported to terrestrial systems through the atmosphere); and long-distance transport of continental dust, mostly from Asia. Each of these sources can be characterized by a unique suite of isotopes and element ratios (Kennedy *et al.* 1998; Kurtz *et al.* 2001; Vitousek 2004), and the relative importance of each thereby can be determined. For example, drier portions of Kohala Volcano (<~1800 mm annual rainfall) on the island of Hawai`i derive most of their very substantial nutrient supply from the weathering of volcanic rock, while wetter portions of Kohala (>~2100 mm/yr) receive most of their much lesser supply of nutrients (other than phosphorus) from atmospheric deposition of marine aerosol (Chadwick *et al.* 2003). Phosphorus is relatively immobile, and basalt-derived phosphorus remains important in wet Kohala sites. However, basalt-derived phosphorus is depleted from stable upland soils on the much older island of Kaua'i (Crews *et al.* 1995; Vitousek and Chadwick 2013); there, the main source of the very small input of phosphorus is via long-distance transport of Asian dust, mostly during full-glacial times (Chadwick *et al.* 1999; Vitousek 2004).

We suggested that large, intensive rainfed agricultural systems in pre-contact Hawai'i were established only where basalt weathering could provide a sustained source of nutrient inputs to soils. Basalt weathering essentially disappears as a source of nutrients at a sharp threshold in numerous soil properties (including acidity and the availability of several biological nutrients) at an annual rainfall near 2000 mm/yr on Kohala Volcano (Chadwick *et al.* 2003). We speculated that this threshold constrained the upper-elevation, high-rainfall boundary of the Leeward Kohala Field System. Moreover, because this threshold occurs at progressively lower rainfall on progressively older substrates across the Hawaiian Archipelago (due to the exhaustion of basalt-derived minerals, over hundreds of thousands of years of weathering and solution loss) (Vitousek *et al.* 2004; Vitousek and Chadwick 2013), this threshold also could explain the lack of large rainfed field systems on older islands in the Hawaiian Archipelago.

Here we first summarize our test of this hypothesis on the Leeward Kohala Field System and elsewhere in Hawai'i. Second, we evaluate which measure(s) of soil nutrients predict the boundary of rainfed field systems most reliably. We then explore the potential for erosion to rejuvenate the supply of basalt-derived nutrients and permit rainfed agriculture in particular topographic settings on high rainfall and/or old substrates in Hawai'i. Next, we evaluate the sources of nutrients that supported the other main intensive cropping system in pre-contact Hawaii, irrigated kalo (taro) pondfields. Finally, we apply this perspective to explore the relationship between sources of nutrients and intensive agriculture to rainfed rock garden agricultural systems in landscapes dominated by relatively infertile soils on Rapa Nui.

## METHODS

We collected soils at 200-meter distance intervals along multiple transects within and just above and below the Leeward Kohala Field System (LKFS; Vitousek *et al.* 2004; Kagawa and Vitousek 2012), and at 500-meter intervals at greater distances from the boundary of the system, to near both the leeward and windward coasts of Kohala (Figure 1). Soils were collected as depth-integrated samples from the surface to 30 cm depth. Similar (though less spatially intensive) soil sampling was carried out within and outside the Kona (Hawai'i) Kahikinui (Maui), and Kalaupapa (Moloka'i) Field Systems (Kirch *et al.* 2004; McCoy and Hartshorn 2007; Lincoln *et al.* 2014). Soil samples also were collected along topographic gradients (upland, steep slope, colluvial slope base, alluvial valley floor) in several small valleys in windward Kohala, and in the much larger Pololū Valley in Kohala and Hālawa Valley on Moloka'i (Palmer *et al.* 2009; Vitousek *et al.* 2010). In addition to these surface-to-30-cm samples, soil depth profiles were obtained and analyzed by soil horizon in a few soil pits in most of these areas (Chadwick *et al.* 2003; Hartshorn *et al.* 2006; McCoy and Hartshorn 2007).

Finally, similar samples were collected at closely spaced intervals (from 1 to 5 meters) along transects from rock outcrops on Rapa Nui, across rock gardens at the base of these outcrops, and across non-garden areas between outcrops. Initially, we sampled one transect intensively in the Anamarama region (Figure 2); our sampling started on an outcrop, crossed an adjacent rock garden and then an open tephra-covered area, and terminated in a second rock garden near another outcrop 160 m away. Soils were sampled to a depth of 30 cm every 1–3 meters along this transect in April 2010. In 2011, three additional transects from outcrop through rock garden to non-garden areas were sampled at intervals of 3 to 5 m or more. One of these was in a separate garden in Anamarama; the other two were in separate gardens ca. 320 m apart approximately 1.5 km west of 'Anakena (Figure 2).

Soils were analyzed for a broad suite of properties, including pH, cation exchange capacity, and base saturation; total and exchangeable Ca, Mg, Na, and K; total C and N; resin-extractable and total P; and total Si, Al, Fe, Zr, and Nb pools. These analyses include determinations of biologically available nutrient pools (exchangeable cations, resin P), integrated soil properties related to soil fertility (base saturation, the percentage of cation exchange sites occupied by Ca, Mg, K, and Na), and information more relevant to the formation and long-term dynamics

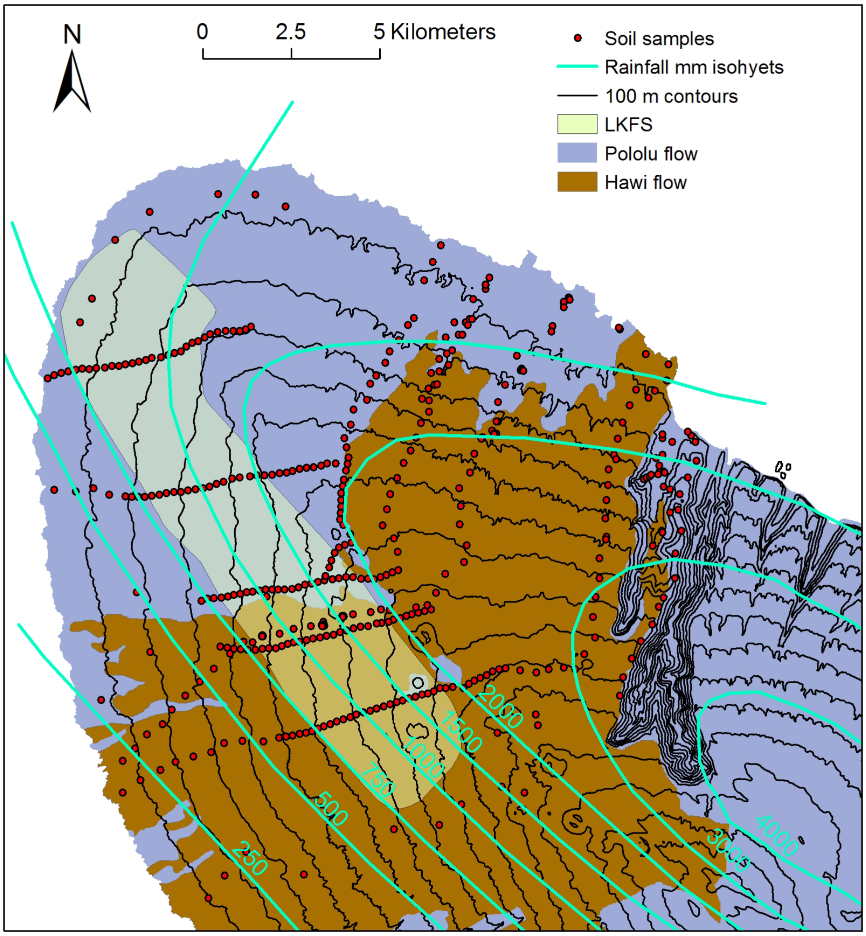

Figure 1. Kohala Volcano, showing the location of the Leeward Kohala Field System (tan shading) and points where soil samples were collected (red dots). The figure also shows elevation contours (black lines), rainfall isohyets (cyan lines), and the distribution of the younger (*ca.* 150,000 year old) Hawi Volcanics (in brown) and older (~400,000 yr old) Pololū Volcanics (in blue). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

of soils (total pools of multiple elements). Measurements were carried out as described in Chadwick *et al.* (2003) and Vitousek *et al.* (2004).

In addition to soil sampling, we evaluated sources of nutrients to irrigated kalo pondfields by collecting streamwater samples at high, moderate, and low flow in Waikama Stream and some of its tributaries, in North Kohala, Hawai'i. Waikama is a relatively small stream and valley that supported pre-contact kalo pondfields in its lower reaches. Water samples were analyzed for Ca, Mg, K, Na, Si, and other elements by plasma emission spectroscopy; for the anions chloride, sulfate, nitrate, and phosphate by ion exchange chromatography, and for the ratio of the isotopes $^{87}$Sr and $^{86}$Sr by mass spectrometry (Palmer *et al.* 2009). Strontium isotope ratios are useful because Sr cycles similarly to the biological nutrients calcium and magnesium, and because the $^{87}$Sr/$^{86}$Sr ratio differs substantially and systematically depending on whether its source is atmospheric deposition of marine aerosol or weathering of Hawaiian basalt (Kennedy *et al.* 1998).

## RESULTS

### *Soil nutrients within intensive rainfed field systems.*

We anticipated that the upper-elevation, high-rainfall boundary of rainfed field systems in Hawai'i (e.g., Figure 1) would correspond to the threshold in soil properties described by Chadwick *et al.* (2003). In fact, we found substantial enrichment in the availability of biological nutrients (illustrated here by exchangeable Ca) within the LKFS in comparison to adjacent areas with both higher and lower rainfall (Figure 3). The higher-rainfall boundary indeed corresponds closely to the threshold; moreover, both the threshold and the boundary of the LKFS occur at lower rainfall on older Pololū volcanic substrate within Kohala, in comparison with younger, richer Hawi substrate (Figure 1). The LKFS occupies an environmental space where rainfall is high enough to support intensive agriculture, but not so high that the cumulative weathering/leaching of nutrients has depleted soil fertility. Moreover, within

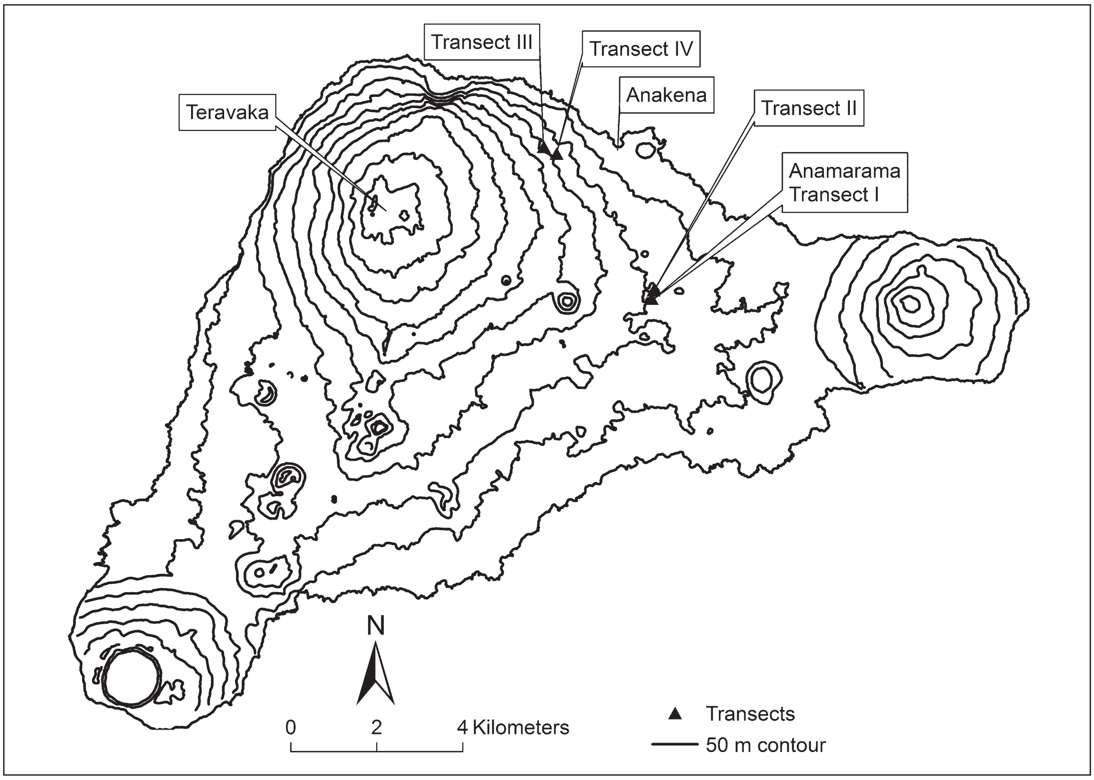

Figure 2. The island of Rapa Nui, with geographical place names and soil transect locations.

this zone the fertility of surface soils has been enriched by tens of thousands of years of biological uplift of nutrients (Jobaggy and Jackson 2001, 2004; Porder and Chadwick 2009); this uplift was carried out by forests that in effect pumped nutrients from deep in the soil profile to the surface in the tens of thousands of years prior to human arrival (Chadwick *et al.* 2007; Meyer *et al.* 2007; Vitousek and Chadwick 2013). In areas drier than the LKFS, lower productivity has meant less enrichment of surface soils, and/or a thin enriched layer has been lost to wind erosion; in areas wetter than the LKFS, the loss of nutrients via weathering and leaching has overwhelmed the effects of biological uplift.

Less intensive sampling in Hawaiian rainfed field systems in Kona, Kahikinui, and Kalaupapa yielded similar results – Hawaiian cultivators intensified rainfed systems in 'sweet spots' with sufficient rainfall and enhanced soil fertility (Kirch *et al.* 2004; McCoy and Hartshorn 2007; Lincoln et al. 2014). Similar sampling along rainfall gradients on much older substrates on the islands of Kauai and Molokai found much lower soil fertility at rainfall comparable to the LKFS (Figure 3), reflecting the cumulative influence of many more millennia of basalt weathering and leaching (Vitousek *et al.* 2010; Vitousek and Chadwick 2013). These gradients on older substrates supported no upland environments both wet enough and fertile enough to match the areas farmed within the LKFS, and no intensive rainfed field systems occurred in these areas. Ladefoged *et al.* (2009) formalized this association between climate, substrate age, and soil fertility into a GIS model predicting the potential distribution of rainfed field systems across the Hawaiian Archipelago.

*Soil properties that predict field system boundaries.*

Multiple measures of nutrient availability and other soil properties co-vary across the threshold that bounds the high-rainfall margin of rainfed field systems (Chadwick *et al.* 2003). Our earlier analyses used base saturation, resin-extractable P, and the P remaining from the original parent material to characterize that boundary (Vitousek *et al.* 2004). Here, we use results from seven transects with closely-spaced samples (~200 m distance) that crossed the high-rainfall, low-fertility boundary of the LKFS (Figure 1) to identify which soil properties are most reliably associated with that boundary. We used the average value of soil properties in the samples just below and just above the field system boundary to represent the value of each soil measure at the boundary of the LKFS. We evaluated the reliability of each predictor by analyzing its coefficient of variation (standard deviation divided by the mean, multiplied by 100) across all seven transects. In addition to analyzing all seven transects, we also used the five 'best' transects, leaving out the southernmost and northernmost transect. The boundary of the LKFS at the southernmost (highest elevation) transect could be shaped in part by

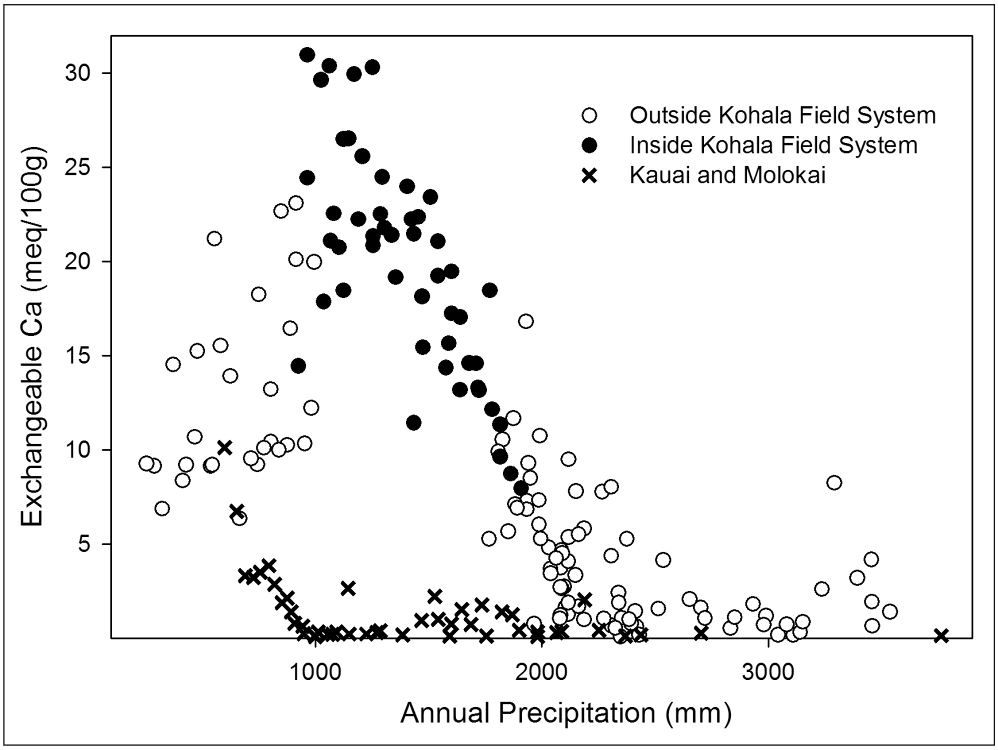

Figure 3. Concentrations of exchangeable calcium along rainfall gradients on Kohala Volcano on the island of Hawai'i, near Hālawa Valley on the island of Moloka'i, and from Mānā Ridge to the Alaka'i Swamp on the Island of Kaua'i. Solid dots represent samples collected within the Leeward Kohala Field System, hollow dots represent samples collected from upland slope positions outside the Leeward Kohala Field System, and X represents samples from upland positions on Moloka'i and Kaua'i. From information in Vitousek *et al.* (2010) and Vitousek & Chadwick (2013).

temperatures too cool for Polynesian crops (in addition to soil fertility) (Kagawa and Vitousek 2012), and the boundary at the northernmost transect is difficult to determine with confidence due to the overprint of more recent plantation agriculture.

Results of this analysis are summarized in Table 1. Exchangeable calcium at the field system boundary had the lowest coefficient of variation, 20% across all seven transects, and only 13% across the 'best' five transects. Base saturation was next for the seven transects (28%), while soil pH was the second most reliable predictor for the five 'best' transects (15%). Where exchangeable calcium was greater than 10.2 meq/100 g (and rainfall was sufficient), Hawaiian cultivators invested in the agricultural infrastructure of a field system; where it was less than this value, they did not do so. This result does not establish that calcium supply per se constrained rainfed Hawaiian field systems, but exchangeable calcium levels predict the boundary of this field system more reliably than do our other measures of soil properties.

### *Erosion and valley-side rainfed agriculture.*

Erosion could increase weathering by removing nutrient-depleted soil, thereby exposing little-weathered material near the surface. This effect has been shown to enhance nutrient supply to natural forests on steep slopes and alluvial substrates in Hawaii and elsewhere (Vitousek *et al.* 2003; Porder *et al.* 2005, 2006). We evaluated whether this enhancement could suffice to support sustained rainfed agriculture within valleys by analyzing upland, slope, and alluvial soils in and adjacent to several small (<30 m depth) and one large valley (Pololū, >200 m depth) in windward North Kohala (Palmer *et al.* 2009), and in and adjacent to the large Hālawa Valley (>200 m depth) on the much older Island of Moloka'i (Vitousek et al. 2010). Soils in the small Kohala valleys were enriched in exchangeable calcium relative to adjacent upland soils; however, at 6.3 meq/100 g their average concentrations were below those at the upper-rainfall, low-fertility boundary of the LKFS (Table 2). In contrast, exchangeable calcium in lower-slope and alluvial averaged 14.3 and 13.9 meq/100 g in the large Pololū and Hālawa Valleys (Table 2), above the threshold value of 10.2 associated with the boundary of the LKFS.

We concluded that erosion could rejuvenate nutrient supply via basalt weathering sufficiently to support intensive agriculture in large but not small valleys (Palmer et al. 2009). Moreover, because older islands like Moloka'i are subsiding much more slowly than the geologically young island of Hawai'i (Moore and Clague 1992), the morphol-

Table 1. *Soil properties at the high-elevation, high-rainfall boundary of the Leeward Kohala Field System. The location of the boundary was derived from field observations (Ladefoged & Graves 2000) and from a LiDAR analysis of the field system (Ladefoged* et al. *2012). Values are means for all seven transects that crossed the boundary, or means for the five central transects for which the boundary was most clearly defined and most clearly related to soil properties (see text); coefficients of variation are means divided by standard deviations, and so provide a measure of the reliability of each soil property in indicating the boundary.*

| | **All Seven Transects** | | **Five 'Best' Transects** | |
|---|---|---|---|---|
| **Soil Property** | Value at Boundary | Coefficient of Variation (%) | Value at Boundary | Coefficient of Variation (%) |
| Exchangeable Ca (meq/100g) | 10.20 | 20 | 10.20 | 13 |
| Base Saturation (%) | 28.30 | 28 | 29.50 | 30 |
| Soil pH | 5.69 | 31 | 5.68 | 15 |
| P Remaining (%) | 99.00 | 40 | 102.00 | 42 |
| Resin Extractable P (mg/kg) | 57.00 | 46 | 50.00 | 39 |

Table 2. *Exchangeable calcium (meq/100g) in a range of landscape positions on Kohala Volcano, island of Hawai'i, and East Moloka'i. Values are means, with standard errors in parentheses. Soils in valleys were collected in both lower-slope and alluvial substrates, which are combined here; small valleys in windward Kohala are less than 30 meters deep, while large valleys (Pololū on Hawai'i, Hālawa on Moloka'i) are more than 200 m deep. From data in Palmer* et al. *(2009) and Vitousek* et al. *(2010).*

| **Landscape Position** | **Island of Hawai'i** | **Island of Moloka'i** |
|---|---|---|
| Leeward Kohala Field System | 19.6 (0.83) | |
| Windward Upland | 3.8 (0.37) | 2.0 (0.56) |
| Small Valley | 6.3 (1.40) | |
| Large Valley | 14.3 (1.40) | 13.9 (1.20) |

ogy of Hālawa Valley and other large valleys on older islands supports a larger fraction of lower-slope colluvial landforms than occurs in large valleys on the island of Hawai'i (Vitousek *et al.* 2010). Kurashima and Kirch (2011) modeled the potential contribution of these lower-slope rainfed systems to overall food production on the island of Moloka'i, and showed that they could have represented the majority of intensive cropland (by area) on the island and could have contributed more than a third of the yields produced by intensive cropping systems (including irrigated kalo). These lower-slope systems thereby could have enhanced the variety and productive potential of agricultural systems on Moloka'i and likely other older islands, in situations where the greater yields, lower labor requirements, and lower vulnerability of irrigated agriculture already conferred considerable advantages (Kirch 1994; Ladefoged *et al.* 2009).

### *Sources of nutrients for irrigated kalo.*

Hawaiian cultivators developed irrigated pondfields wherever there was a reliable supply of fresh water that could be diverted to relatively flat areas (typically alluvial or colluvial landforms) (Ladefoged *et al.* 2009). Many of these areas were on the windward side of older islands in the Hawaiian Archipelago – in areas where nutrient availability in upland soils is below the threshold associated with rainfed field systems. How did these irrigated systems obtain the nutrients required to sustain long-term intensive agriculture? We identified two ways such systems could obtain sufficient nutrients for sustained intensive agriculture – through a rejuvenation of basalt weathering caused by erosion, or through the delivery of nutrients in irrigation water. As discussed in the previous section, erosion may supply sufficient nutrients in at least some large deep valleys; however, this process alone appears insufficient to provide enough nutrients for sustained intensive agriculture in smaller valleys (at least in North Kohala), where many pondfields were located (McCoy and Graves 2012).

We explored the potential influence of nutrient supply via irrigation water by analyzing stream chemistry in the lower reaches of Waikama Stream, in North Kohala. Most of the chloride in streams is derived from the deposition of marine aerosol, which also contains calcium at a well-defined ratio to chloride. By analyzing the calcium:chloride ratio in streamwater, we could determine how much calcium has been added to water as it passes through soils and rocks en route to streams. We found that more than 90% of the calcium in streamwater was derived from sources other than marine aerosol; most of this enrichment must have been due to weathering of basalt along the flowpath from the surface to the stream. Further, analyses of Sr isotopes demonstrated that most of the strontium (a close chemical relative of calcium) in this stream also was derived from basalt weathering. Using the Hawaiian Legal Standard for the quantity of irrigation water (de la Pena 1983), we calculated that streamwater (as the source of irrigation water) could supply more than enough calcium (and phosphorus and other nutrients) to meet the requirements of each crop (Palmer et al. 2009).

Broader analyses of streamwater chemistry suggest that irrigation was the predominant source of calcium to irrigated crops in large as well as small valleys. Also, it likely represented an essential source of nutrients to irrigated upland areas with infertile soils, where intensive agriculture developed late in the pre-contact era (McCoy *et al.* 2011). We conclude that while rainfed field systems represented situations in which crops were planted where basalt was weathering and supplying nutrients to crops *in situ*, irrigated kalo represented a case where flowing water brought the products of basalt weathering to the crops.

### *Extension to Rapa Nui.*

Like Hawai'i, Rapa Nui is constructed from oceanic basalt (Haase *et al.* 1997), with most of its surface within the age range of Kohala Volcano (0.78–0.11 Mya) (Vezolli and Acocella 2009). Also, its agricultural economy was based on rainfed farming of most of the same crop plants (sweet potato, taro, yam, banana, sugarcane) as in Hawai'i. However, both previous soil sampling by Louwagie et al. (2006) and our more recent sampling across Rapa Nui (Ladefoged *et al.* 2005, 2010; unpublished data) has demonstrated that with the exception of the lowest elevations and the northwest side of Terevaka Volcano (Figure 2), most Rapa Nui soils are relatively infertile; they are depleted in nutrients, and their properties are similar to those of Kohala soils that occur at higher rainfall than the boundary of the LKFS.

How could Rapa Nui society develop intensive, surplus-producing agricultural systems within these soil fertility constraints? Intensively cultivated 'rock gardens' are widespread on Rapa Nui (Wozniak 1999, 2001, 2003; Stevenson *et al.* 2006; Stevenson and Haoa 2008; Ladefoged *et al.* 2013), even in areas where most of the soils are highly infertile. Much of the ground surface within these gardens is covered by coarse, little-weathered rocks and small boulders, and some of the gardens have finer rocks worked into the soil. The soils within gardens have been churned by cultivators and contain abundant charcoal and obsidian tools. Rapa Nui rock gardens frequently occur at the base of steep slopes, adjacent to younger a'a lava flows, or near rock outcrops in tephra-blanketed landscapes, all locations where erosional processes could enrich soils in basalt-derived nutrients. In addition, some Rapa Nui rock gardens show evidence for cultural enhancement, where prehistoric cultivators pried and chipped rocks off outcrops and added them to the soil surface or worked them into the soil profile. In light of documented nutrient constraints and cultural manipulations, do these rock gardens have soils that are sufficiently enriched (relative to the thresholds we observed in Hawaii – Table 1) to sustain intensive rainfed agriculture?

We evaluated the fine-scale spatial distribution of basalt-derived soil nutrients in and near one class of Rapa Nui rock gardens by sampling and analyzing soils along continuous transects originating from rock outcrops, passing through adjacent rock gardens, and then extending out into the tephra-blanketed landscape away from the gardens. On the intensively sampled transect at Anamarama, we found concentrations of exchangeable Ca to be low on the outcrop, to rise to levels comparable to the low-fertility threshold of the LKFS in both rock gardens, and to be significantly lower in the tephra-blanketed landscape between the rock gardens (Figure 4). Resin P concentrations also are enhanced in rock garden areas – though concentrations in the tephra-blanketed non-garden areas away from the rock outcrop also are relatively high. Base saturation and soil pH are low everywhere along this transect, below the values at the low-fertility threshold of the LKFS.

Results from the three additional transects that were sampled less intensively in 2011 are not as straightforward as those from the intensively sampled transect. Rock garden soils had higher concentrations of exchangeable calcium than tephra-covered non-garden areas in the two transects in the northeast of the island, but in the second transect in Anamarama the exchangeable calcium levels were higher outside of the gardens than they were in the gardens. In these three 2011 transects, mean concentrations of exchangeable Ca in the rock gardens were not as high as 10 meq/100 g – the threshold value in the LKFS (Figure 5). Other measures of soil fertility (resin P, base saturation, soil pH) performed no better than did exchangeable Ca in delineating these gardened areas.

Overall, in three out of four cases the Rapanui were exploiting and probably helping to create areas of higher soil nutrients in rock gardens than occurred in areas 20 to 30 m away, but the nutrient levels within 3 out of 4 gardens were lower than the 10 meq/100 g threshold observed in Hawai'i. There is some evidence here and elsewhere (Chadwick *et al.* in prep) that like Hawaiians, Rapa Nui cultivators were farming the rock – they were intensifying cultivation where basalt weathering provided a continuing supply of nutrients. In these Rapa Nui rock gardens, a combination of natural processes (particularly fine-scale erosion) and possibly cultural activity (covering the surface with little-weathered rocks) gave crops access to basalt-derived nutrients. It is striking that while Hawaiian cultivators intensified agriculture on naturally high-fertility upland soils over continuous areas of more than 60 km$^2$ (60,000,000 m$^2$), Rapa Nui cultivators intensified production on much less fertile rock gardens, generally over areas of <3000 m$^2$.

## DISCUSSION

Hawaiian cultivators intensified agriculture where they had access to an ongoing supply of relatively large quantities of nutrients from basalt weathering. Intensive rain-

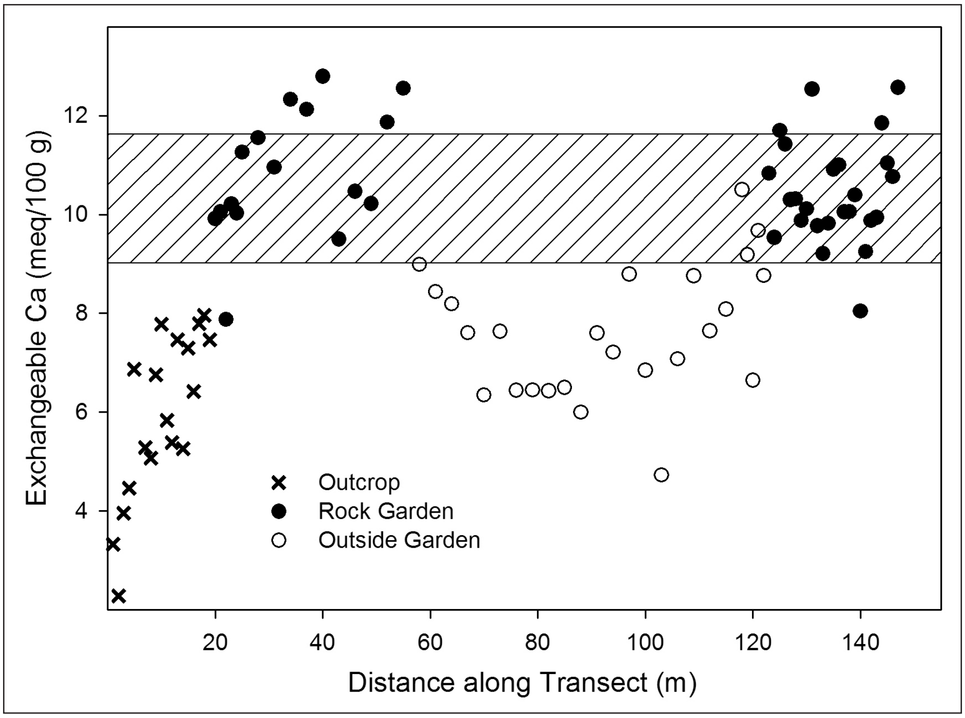

Figure 4. Exchangeable calcium concentrations in Rapa Nui soils collected along an intensively sampled transect from a rock outcrop (×), into a rock garden at the base of the outcrop (solid dots), then into a tephra-covered area with few surface rocks between outcrops (hollow dots), and finally into a second rock garden at the base of a second outcrop. The shaded box represents the mean exchangeable calcium concentration (plus or minus one standard deviation) at the high-rainfall, low-fertility boundary of the Leeward Kohala Field System in Hawaii (Table 1).

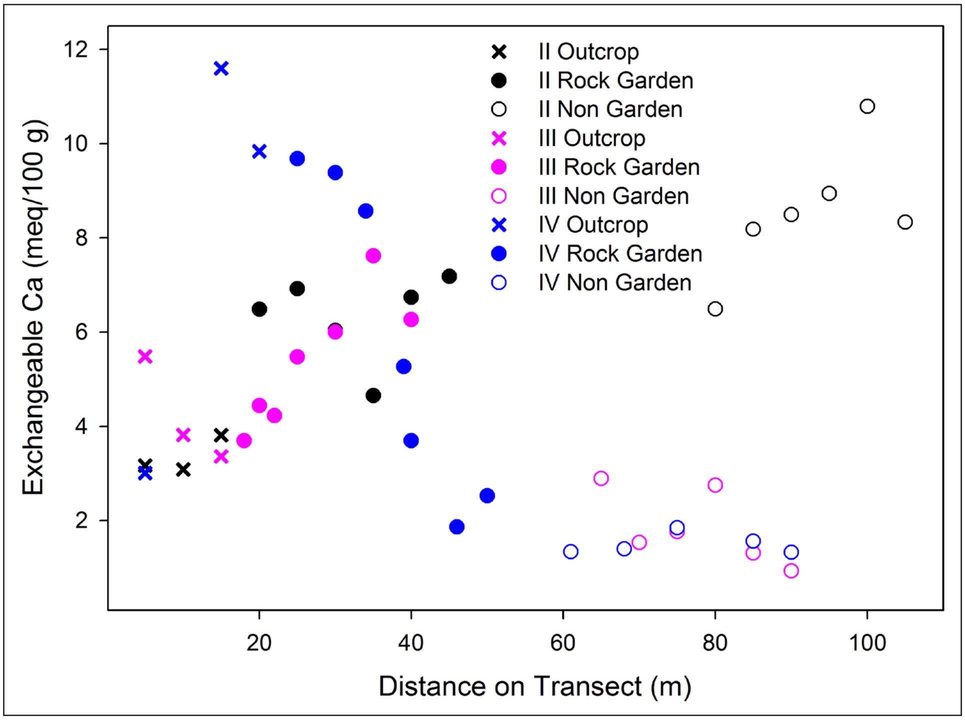

Figure 5. Exchangeable calcium concentrations (meq/100g) along three less-intensively sampled transects (in comparison to that in Figure 4) on Rapa Nui. All three transects began on rock outcrops (×), ran into rock gardens (solid dots), and ended in tephra-covered areas relatively distant from rock outcrops (hollow dots). Colors represent the individual transects. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

fed systems were developed and substantial agricultural infrastructure was constructed in 'sweet spots' of sufficient rainfall and high soil fertility on leeward slopes of younger islands (Vitousek *et al.* 2004; Ladefoged *et al.* 2009). Upland surfaces were either too dry or too infertile to support intensive rainfed agricultural systems on older islands in the archipelago, but erosion and deposition created relatively rich soils with ongoing supply of nutrients by basalt weathering in the lower slopes of large valleys, and much smaller rainfed agricultural systems were developed in these areas (Vitousek *et al.* 2010; Kurashima and Kirch 2011). Irrigated pondfield systems in these large valleys could draw upon erosion as a source of nutrients, and pondfield systems in both large and small valleys also could draw upon products of basalt weathering transported to fields dissolved in irrigation water. In Rapa Nui, there is evidence that intensive cultivation in rock gardens made use of topographically and culturally driven 'micro sweet spots' where basalt weathering could supply crop requirements (Figure 4).

The soil sampling and analysis that we employed to identify these patterns of nutrient supply – and the context provided by soil sampling on older substrates – also contributes to defining and understanding fundamental soil properties and processes. This sampling was guided initially by our hypothesis that the high-rainfall, low-fertility boundary of intensive rainfed systems like the LKFS was constrained by a threshold in soil fertility that Chadwick *et al.* (2003) had identified. Our results supported that hypothesis – and they further revealed additional soil thresholds along rainfall gradients, one of which occurs in the region of the lower elevation, low rainfall boundary of the LKFS (Vitousek & Chadwick 2013). This high-resolution soil sampling (Figure 1) also established the existence of 'soil process domains' in the region between thresholds. Here, the LKFS and other large rainfed field systems occupied all of a soil process domain characterized by element inputs via rock weathering and biological uplift of those (Vitousek and Chadwick 2013). While the research described here was interdisciplinary in conception and execution, focused on understanding constraints to intensive agriculture in pre-contact Hawai'i, it also yielded fundamental and original disciplinary perspectives on soils and ecosystems.

The central importance of 'farming the rock' in a soil domain characterized by basalt weathering and biological uplift of nutrients applies to large, intensive rainfed agricultural systems but not to all pre-contact agricultural systems. Hawaiians and other Polynesian cultivators made use of a wide range of rainfed agricultural practices, many of which were based on concentrating nutrients in space or time (Lincoln *et al.* 2014). For example, cultivators brought mulch from surrounding areas into pits within young lava flows (Handy *et al.* 1972) – thereby subsidizing agricultural production by concentrating resources in space. These systems could be sustained as long as mulch could be obtained from the surroundings – but they used a smaller fraction of the land surface than did intensive systems. Shifting cultivation also was widely practiced in Hawai'i and elsewhere, sometimes with the use of cultural plants like kukui (*Aleurites moluccana* (L.) Willd.) in the 'fallow' phase (Handy *et al.* 1972); in these systems fallow vegetation accumulates nutrients over time from dilute sources (rainfall, low levels of weathering, dust deposition), and those nutrients are released by clearing and burning in preparation for a short cultivation phase. This practice concentrates resources in time; it too can be sustained as long as the fallow portion of the cycle is sufficiently long, and it too used a far smaller fraction of the land surface to produce food crops in any given year than did intensive systems.

## CONCLUSIONS

We suggest that the ability to draw upon nutrients derived from the weathering of primary minerals in rocks and soils is an essential feature of intensive and sustained Polynesian agricultural systems. Weathering supplied nutrients for different reasons and by different pathways to agricultural systems as diverse as irrigated kalo pondfields, rainfed dryland systems in the younger islands of the Hawaiian archipelago, valley-side rainfed systems in Hawai'i, and rock gardens in Rapa Nui. Further, we suggest that differences in access to nutrients supplied by weathering may have influenced human-land interactions in Polynesia. As we illustrate here, areas of soil with substantial ongoing inputs of nutrients via basalt weathering are much smaller in area and are marginal in soil fertility (Figs. 3, 4, 5) in Rapa Nui as compared to Hawai'i – suggesting that Rapa Nui soils had less capacity to produce a substantial and ongoing food surplus. It would be interesting – and it might prove rewarding – to apply a similar soil fertility-based perspective across a wide range of Pacific Island societies.

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