Indicators of soil fertility and opportunities for precontact agriculture in Kona, Hawai‘i

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Abstract. The distribution, mode, and intensity of agriculture both influence and are influenced by the natural environment. Soil fertility indicators that correlate with the intensification of dryland agriculture in pre-contact Hawai‘i have been mapped across the Hawaiian archipelago. We investigated these soil fertility indicators and agricultural development in the unique environment of Kona, Hawai‘i, the largest, culturally most significant, and geologically youngest of the dryland field systems in Hawai‘i. Agriculture was intensified systematically on substrates ≥4,000 years old with appropriate climate and fertility in Kona, in keeping with archipelago-wide analyses. In comparison with other dryland agricultural systems in Hawaii, we found that soil fertility indicators used to predict pre-European agricultural intensification are shifted towards lower rainfall on the younger geological substrates of Kona. For example, base saturation reached low levels (<30%) at ~1200 mm/yr rainfall on 1,200 year old substrate and at ~1400 mm/yr on 7,500 year old substrate in Kona, versus ~1800 mm/yr on 150,000 year old substrate on Kohala Volcano. We suggest that this difference reflects a kinetic, rather than an irreversible, limitation to soil fertility in Kona, and we discuss how this difference could have influenced opportunities for agricultural intensification and the distribution of agroecological zones.

Key words: agroecology; dryland agriculture; field systems; Hawaii; indigenous agriculture; Kona; soil development; soil nutrients.

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INTRODUCTION

Archeologists divide Pre-European Hawaiian agriculture into wetland, flood irrigated systems that were restricted to stream valleys and coastal plains of each island and dryland, rainfed systems that covered vast areas of relatively fertile soils on the younger islands (Ladefoged et al. 2003). Each agricultural system entrained its own pattern of social organization (Kirch 1994), and development of the dryland systems in particular led to consolidation of social control by the ruling elites (Kirch 2011). Some intensive dryland systems, such as the well-studied leeward Kohala agricultural area, supported relatively homogeneous agricultural infrastructure and intensive agricultural plantings (Ladefoged et al. 2003, Ladefoged and Graves 2008) whereas others such as the Kona system developed into a highly diverse patchwork characterized by a matrix of agricultural practices overlaid onto a spectrum of lava flows of varying ages.

Research in the Kohala field system has demonstrated that the boundaries of systematic
agricultural intensification consistently aligned with several soil properties—particularly percent base saturation, exchangeable calcium and total and extractable phosphorus—which conversely have been applied as indicators of a soil fertility threshold below which the systematic intensification of agriculture was not pursued (Vitousek et al. 2004). Ladefoged et al. (2009) used this threshold to evaluate the potential distribution of intensive rainfed agricultural systems across the Hawaiian Archipelago and summarized their results in a geospatial model depicting the potential extent of intensified agricultural systems in Hawai‘i. Output of the model correlated spatially with well-documented sites and led to the identification of intensively cultivated areas not previously mapped.

The Ladefoged et al. (2009) model was designed to provide an archipelago-wide perspective on the controls of agricultural intensification rather than a guide to place-based intensification features (e.g., Vitousek et al. 2010). Place-specific controls of soil fertility may alter the predicted extent of agricultural intensification. The Kona district of the Island of Hawai‘i offers an opportunity to evaluate the importance of place-specific controls in an environment with high spatial variability in soil properties, extremely young substrate ages, unique agricultural practices and agroecology, and a large spatial extent of dryland agriculture (Kelly 1983, Allen 2001, 2004). Further, Kona became the cultural and political center of the Island of Hawai‘i late in the precontact period (Kamakau 1961). The farming landscape of Kona thus offers an opportunity to link soils, societies, and agricultural development in a culturally important and highly diverse landscape.

In this paper we develop site-specific characterizations of soil fertility and summarize the archaeological evidence for pre-historic agricultural development in the Kona district. We describe the properties of Kona soils from 0.5–7.5 ky, and discuss them in the context of continuous intensive versus patchy systems of agriculture, which we refer to as “systematic” and “informal” agriculture respectively. For the Kona system, the Ladefoged et al. (2009) model predicted patchy intensification of systematic agriculture due to the exclusion of lava flows <4 ky based on the expectation of inadequate soil thickness. For the purpose of this paper “Kona soils” refers to lava flows of all ages across the landscape of Kona, “young soils” refer to <4 ky flows, and “old soils” will refer to ≥4 ky flows. We utilize this information on soils to ask (1) do soil fertility indicators in Kona follow the same patterns with climate as they do in the intensified Kohala field system, (2) is 4 ky an appropriate age threshold for systematic or intensive agriculture in pre-European Hawai‘i, and (3) what landscape-level patterns of agriculture occur on the different Kona soils?

SITE, CLIMATE, AND LAND-USE HISTORY

Climate, geology, and soils

Kona is situated on the western slopes of Mauna Loa and Hualalai volcanoes with a local weather system controlled by a land-sea breeze cycle that creates a wet environment compared to other leeward areas in the archipelago. Rainfall increases upslope from as little as 600 mm/yr at the coast to as much as ~2000 mm/yr at ~600 m elevation, declining again at higher elevation (Fig. 1A; Giambelluca et al. 2012).

Hualalai and Mauna Loa volcanoes also create a patchwork of overlapping lava flows (Fig. 1B) that range from less than 65 to over 10,000 years old (Trusdell et al. 2006). Hualalai lava has an alkalic composition while Mauna Loa lava is tholeiitic in nature. The two volcanic sources differ importantly in chemical composition, with alkalic sources typically containing much lower concentrations of silica and sodium, but higher concentrations of aluminum and especially phosphorus. Soils in Kona are primarily Histosols and Andisols (NRCS 2010). Histosols are recognized in recent flows where organic matter has accumulated but tephra and lava have not sufficiently weathered to produce the short-range-order minerals that typify Andisols. Most of the nutrient supplying and holding capacity in Histosols comes from organic matter that on very young flows is introduced from nearby vegetated areas and by in situ pioneering plants as the flows become vegetated. With increasing lava flow age, weathering and secondary mineral formation lead to the development of Andisols, which feature both increased surface area provided by clays and relatively abundant nutrients derived from weathering.
Tephra deposits and organic matter settle on top of the lava flows within the voids of the irregular shaped chunks of lava. Over time this process forms a soil layer consisting of mostly unweathered rocks known as clinkers; tephra and organic matter fill in the spaces between the clinkers, and the clinkers weather in place over time. Because tephra is a significant component of Kona soils, soil ages are younger on average than the underlying flow ages. Moreover, the fine and coarse fractions of soils may originate from different sources (Ziegler et al. 2003). Even under the oldest Kona flows, ~12.5 ky, much of the original lava texture can be observed almost unweathered on the underlying bedrock, illustrating the importance of tephra deposition and organic matter accumulation in the development of Kona soils.

**Farming landscape of the Kona field system**

Across the farming landscape and soils, Kona was segregated into four major agroecological zones—the *kula*, *kaluulu*, *apaa*, and *amau* zones—that created distinct bands as one moved upslope (Kelly 1983, Malo 1951). These zones are thought to have existed irrespective of the age of underlying flows, but may have extended further along the coastal-inland continuum depending on substrate type. Crops grown in the different zones are summarized in Table 1. The *kula* is the...
dry coastal plains, described as the farmable areas receiving less than 1000 mm/yr rainfall. The kaluulu was an agroforestry development where understory crops were grown beneath an open canopy primarily of breadfruit; Lincoln and Ladefoged (in press) suggest it was bounded by 1000–1250 mm/yr of rainfall. The apaa, was considered to be the most productive planting zone; it is generalized from historical testimonies as occurring between 1250–2000 mm/yr, but archeological evidence indicates variability in the transition of the apaa to the amau, the final zone of cultivation. This uppermost zone modified the native forest to grow cultivated crops and encourage naturally occurring resource plants within the subcanopy. Historical descriptions broadly place this zone between 600-900 m.

Intensive, systematic agricultural systems can be usefully separated from informal agriculture developments. The former consisted of relatively homogenous infrastructure, short or no fallow period, and little redistribution of resources above the level of an individual field within the system, while the latter vary widely in form and are believed to have depended upon resource concentration. Systematic agriculture in Kona is characterized by a common infrastructure, most importantly long rock walls (kuaiwi) running parallel to the slope that encompassed cleared fields (Escott and Spear 2003). Other common features are cross walls that intersect perpendicularly with the kuaiwi, and rock mounds that occur in the fields between kuaiwi. As defined by the common infrastructure, systematic agriculture is considered to have primarily occurred within the two central agroecological zones—the kaluulu and the apaa—although there are rare examples in areas with favorable conditions where systematic infrastructure extends through the kula to sea level (Escott and Spear 2003).

Informal agricultural techniques are less generalizable, and encompassed a range of techniques, infrastructures and planting densities. We assume that informal farming techniques strove to overcome agricultural limitations that prevented the establishment of systematic agriculture. These limitations may include soil depth, soil moisture, or soil fertility. The methods of informal agriculture therefore concentrated or exploited naturally concentrated soil resources.

### Table 1. Crops grown in the climate defined ethno-agricultural zones of Kona, Hawai‘i.

| Crop                  | Kula | Kaluulu | Apaa | Amau |
|-----------------------|------|---------|------|------|
| Aleurites moluccana (Kukui) | ...  | xx      | x    | x    |
| Artocarpus artis (Ulu)   | ...  | xxx     | xx   | ...  |
| Broussonetia papyfera (Wauke) | x    | xxx     | x    | ...  |
| Calophyllum inophyllum (Kamani) | x    | ...     | ...  | ...  |
| Cocos nucifera (Niu)     | xxx  | ...     | ...  | ...  |
| Colocasia esculenta (Kalo) | ...  | x       | xxx  | x    |
| Cordia subcordata (Kou)  | xx   | ...     | ...  | ...  |
| Cordyline fruticosa (Ki) | ...  | x       | xxx  | x    |
| Curcuma longa (Olena)    | ...  | x       | x    | ...  |
| Dioscorea alata (Uhi)    | ...  | ...     | xx   | xxx  |
| Heteropogon contortus (Pili) | xxx | ... | ... | ... |
| Hibiscus tiliacus (Hau)  | xx   | ...     | ...  | ...  |
| Ipomea batatas (Uala)    | xx   | xxx     | xxx  | ...  |
| Lagenaria sicarica (Ipu) | xx   | x       | ...  | ...  |
| Morinda citrifolia (Noni) | xxx  | ...     | ...  | ...  |
| Musa spp. (Mai)          | xxx  | ...     | xxx  | xxx  |
| Pandanus tectorius (Hala) | xx   | x       | ...  | ...  |
| Piper methysticum (Aua)  | ...  | xx      | xx   | x    |
| Pipturus albus (Manaki)  | ...  | ...     | ...  | ...  |
| Saccharum officinarum (Ko) | ...  | x       | xxx  | x    |
| Schizostachyum glaucifolium (Ohe) | ... | ... | xx | x |
| Syzygium malaccense (Ohia ai) | ... | xx | x | x |
| Tecta leontopetaloides (Pia) | ... | xx | ... | ... |
| Tephrosia purpurea (Auhuah) | xx | ... | ... | ... |
| Thepesis papulnea (Kou)  | xx   | ...     | ...  | ...  |
| Touchardia latifolia (Olona) | ... | ... | ... | xxx |
| Zingiber zerumbet (Awapuhi) | ... | x | x | x |

Note: xxx = prevalent, xx = occasional, x = probable.
increased organic matter in the soils, utilized deep or uniquely rooted plants to increase capture, uptake and storage of nutrients, or enhanced or exploited naturally elevated soil moisture. Informal agricultural techniques left less noticeable archeological remains compared to systematic agriculture, but are documented in all four farming zones in Kona. Informal farming methods can be placed in three general categories: the use of terraces to capture soil and create swale agriculture, the use of composting to create soils in “pocket” or rock mound farming, and the use of tree crops or naturally forested areas to practice agroforestry.

**Sampling and Analyses Methods**

Soil samples were collected along four transects (Fig. 1) representing five lava flow ages selected to encompass a range of rainfall and elevation. The lava flows have been dated to approximately 0.5, 1.2, 2.25, 4, and 7.5 ky (Trusdell et al. 2006). Three samples of approximately 100 g each were taken by trowel from small soil pits within localized depressions every 50 m elevation from just above sea level to 1150 m, and composited. Soil depth was variable, and the lower portion of samples typically contained clinkers (rocks >2 mm) in a matrix of fine soil. Samples were taken to 30 cm with soil extracted from around clinkers; depth to clinker layer and total depth to 30 cm was noted during collection. Sampling locations were recorded on GPS, and climatic data were summarized for each point using GIS layers obtained from the Hawai‘i State GIS Program (www.state.hi.us/dbedt/gis) and the University of Hawai‘i Geography Department (rainfall.geography.hawaii.edu).

All soils were passed through a 2 mm sieve and homogenized. The samples were split into three parts. One subsample was analyzed for pH, total carbon and nitrogen, ammonium and nitrate, and resin extractable phosphorus at Stanford University (following procedures in Soil Survey Laboratory Staff 1992). A KCl extraction was performed with 3 g of field-moist soil and 20 ml of 2 M KCl. Samples were shaken for 2 hours and filtered extract was analyzed with a WestCo SmartChem 200 Discrete Analyzer for ammonium and nitrate. Air-dried soil was mixed with deionized water in a 1:2 ratio, allowed to stabilize over a 30-minute period and measured for pH. Total C and N were analyzed on a Carlo Erba NA1500 Elemental analyzer, using 5 mg of oven-dried soil. Resin extractable phosphate was evaluated after shaking 5 g of air-dried soil in 50 ml of deionized water for 24 hours with mixed cation and anion resin bags; resin bags were eluted in a 0.5M HCl solution and analyzed for phosphate concentration using a WestCo SmartChem 200 Discrete Analyzer. A second subsample was shipped to ALS (Reno, Nevada) for total element analysis using lithium borate fusion and XRF. The loss or accumulation of elements (relative to parent material) was determined using Niobium as an immobile index element, and using average parent elemental concentrations from Mauna Loa and/or Kilauea Volcanoes. Elemental gains or losses relative to parent material were calculated using the equation in Porder et al. (2007). The third subsample was analyzed for exchangeable cations, cation exchange capacity, and base saturation using the ammonium acetate (NH₄OAc) method buffered at pH 7; these analyses were carried out at the University of California, Santa Barbara (following procedures in Soil Survey Laboratory Staff 1992).

In addition to the data from our samples, we made use of data from samples analyzed in Porder et al. (2007). Data was converted to match our sampling protocol (homogenized samples 0–30 cm depth) by applying weighted averages representing thickness of soil horizons analyzed within the surface 30 cm. We also made use of data from Vitousek et al. (2004) and Palmer et al. (2009) for comparisons to the Kohala system; sampling depth in these studies matched our own. Analytical procedures for each data set followed the same protocols applied in this study.

**Results**

Soil properties vary as a function of flow age and of climate, and can interact with other soil properties. We present the results from all samples and analyses in the Supplement. In addition, Tables 2 and 3 summarize soil properties by individual and grouped flow ages using a subset of samples in the rainfall range of 900–1300 mm/yr, where all flows were well repre-
sented with a similar mean rainfall (± 25 mm/yr); these results are discussed in the subsections below. Table 4 utilizes all results to summarize the influence of rainfall as well as soil age and carbon on soil properties. Results from two regressions—one based on rainfall alone, the other incorporating rainfall, soil age, and carbon—are presented to emphasize the influence of rainfall for different soil properties; relevant aspects of these results are highlighted in the subsections below. In the final subsection we summarize the important soil properties used as indicators of Hawaiian agricultural intensification as they vary with rainfall and age (Figs. 2–4).

Table 2. Mean values (with SE in parentheses) of soil properties for individual flow ages using a subset of samples in the rainfall range of 900–1300 mm/yr.

| Soil property | 500 (n = 9) | 1250 (n = 17) | 2250 (n = 15) | 4000 (n = 9) | 7500 (n = 17) | 12,500‡ (n = 4) |
|---------------|------------|---------------|---------------|-------------|--------------|---------------|
| Carbon (%)    | 28.0 (1.4) | 16.9 (2.5)    | 17.7 (1.9)    | 8.0 (1.6)   | 10.9 (0.7)   | ...†          |
| Total nitrogen (%) | 2.18 (0.36) | 0.90 (0.10) | 1.59 (0.10) | 0.76 (0.14) | 1.09 (0.07) | ...           |
| Inorganic nitrogen (µg/g) | 134.3 (50.1) | 83.2 (12.6) | 82.8 (22.8) | 102.6 (23.0) | 108.6 (17.9) | ...           |
| C:N           | 14.5 (1.8) | 17.5 (1.0)    | 10.9 (0.7)    | 10.6 (0.3)  | 9.9 (0.2)    | ...           |
| Ca++ (mEq/100 g) | 39.7 (10.1) | 27.4 (6.1)    | 26.8 (3.4)    | 25.6 (4.5)  | 36.6 (2.2)   | 38.1 (5.1)    |
| K+ (mEq/100 g) | 0.87 (0.24) | 0.69 (0.16)   | 1.00 (0.16)   | 2.64 (0.66) | 1.94 (0.36)  | 1.47 (1.1)    |
| Mg++ (mEq/100 g) | 14.0 (2.3) | 7.2 (0.2)     | 10.1 (1.4)    | 13.6 (2.3)  | 12.9 (1.2)   | 15.7 (1.2)    |
| Na+ (mEq/100 g) | 1.07 (0.19) | 0.80 (0.13)   | 0.56 (0.09)   | 0.46 (0.06) | 0.67 (0.09)  | 0.93 (0.30)   |
| Sum cations (mEq/100 g) | 55.62 (12.17) | 36.03 (7.83) | 38.39 (4.74) | 42.33 (6.60) | 52.02 (2.81) | 56.28 (5.48)  |
| CEC           | 131.5 (14.2) | 93.2 (15.3)   | 89.4 (6.1)    | 81.6 (7.0)  | 85.0 (2.0)   | 56.3 (5.5)    |
| Base saturation (%) | 40.1 (5.2) | 42.5 (5.0)    | 46.3 (5.4)    | 52.1 (7.2)  | 61.0 (2.9)   | 87.7 (11.1)   |
| pH            | 5.00 (0.31) | 4.54 (0.14)   | 4.95 (0.14)   | 5.54 (0.21) | 5.63 (0.12)  | 6.66 (0.73)   |
| Extractable PO4 (µg/g) | 15.6 (6.9) | 29.7 (6.0)    | 17.9 (4.3)    | 44.8 (12.5) | 121.6 (22.6) | ...           |
| P2O5 (%)      | 0.17 (0.03) | 0.12 (0.01)   | 0.24 (0.02)   | 0.25 (0.03) | 0.36 (0.02)  | 0.22 (0.06)   |
| P2O5 remaining (%) | 444.9 (220.7) | 219.1 (15.1) | 234.6 (40.9) | 219.2 (28.7) | 247.5 (14.9) | 138.3 (36.8)  |
| Depth to clinkers (cm) | 8.1 (0.8) | 9.6 (1.2)    | 10.6 (1.5)    | 23.8 (0.9)  | 29.5 (0.2)   | 30.0 (0.0)    |
| Depth to bedrock (cm) | 27.6 (1.2) | 28.5 (0.4)   | 29.3 (0.3)    | 30.0 (0.0)  | 30.0 (0.0)   | 30.0 (0.0)    |

† Data adapted from Porder et al. (2007).
‡ An ellipsis indicates data were not collected.

Table 3. Mean values (with SE in parentheses) of soil properties for grouped flow ages using a subset of samples in the rainfall range of 900–1300 mm/yr.

| Soil property | Young soils (n = 41) | Old soils (n = 30) | All soils (n = 71) |
|---------------|---------------------|--------------------|-------------------|
| Carbon (%)    | 19.2 (1.5)          | 10.0 (0.8)         | 15.9 (1.1)        |
| Total nitrogen (%) | 1.39 (0.11) | 0.99 (0.07) | 1.24 (0.08) |
| Inorganic nitrogen (µg/g) | 92.2 (13.6) | 106.7 (14.0) | 97.4 (10.0) |
| C:N           | 14.4 (0.8)          | 10.1 (0.2)         | 12.9 (0.6)        |
| Ca++ (mEq/100 g) | 29.1 (3.4) | 33.5 (2.1)       | 30.8 (2.3)        |
| K+ (mEq/100 g) | 0.83 (0.10)         | 2.10 (0.31)        | 1.32 (0.15)       |
| Mg++ (mEq/100 g) | 9.4 (1.0)         | 13.3 (1.0)         | 10.9 (0.8)        |
| Na+ (mEq/100 g) | 0.75 (0.08)         | 0.63 (0.07)        | 0.70 (0.05)       |
| Sum cations (mEq/100 g) | 40.05 (4.43) | 49.55 (2.72) | 43.73 (3.00)      |
| CEC           | 98.0 (8.0)          | 81.6 (2.8)         | 91.5 (5.0)        |
| Base saturation (%) | 43.7 (3.1) | 60.6 (3.3)       | 50.3 (2.5)        |
| pH            | 4.78 (0.10)         | 5.69 (0.12)        | 5.13 (0.10)       |
| Extractable PO4 (µg/g) | 22.6 (3.4) | 97.1 (17.5) | 49.5 (8.1) |
| P2O5 (%)      | 0.17 (0.01)         | 0.31 (0.02)        | 0.22 (0.02)       |
| P2O5 remaining (%) | 266.7 (44.4) | 225.4 (15.2) | 251.6 (28.7)      |
| P2O5 loss (%/yr) | −0.11 (0.02) | −0.02 (0.00) | −0.08 (0.02)     |
| Depth to clinkers (cm) | 9.7 (0.8)       | 27.7 (0.7)         | 16.2 (1.2)        |
| Depth to bedrock (cm) | 28.7 (0.3)      | 30.0 (0.0)         | 29.1 (0.2)        |
relevant to our discussion. However due to uncertainties in the parent source of tephra in the region we present this information in Appendix: Figs. A1–A9.

**Carbon and nitrogen**

Organic carbon levels were high in Kona soils, significantly higher in young soils (19.2%) than old soils (10.0%), particularly the youngest flow (0.5 ky). Carbon levels increased significantly but not strongly with increasing rainfall. Total nitrogen (TN) was highly correlated with percent carbon (p < 0.001; r² = 0.82) and that correlation explained most of the variation in multivariate regression. Total inorganic nitrogen (TIN) was represented by the sum of nitrate and ammonium. While old soils had less TN (0.99%) than young soils (1.39%), they had more TIN (107 µg/g dw versus 92 µg/gdw) and a significantly higher proportion of TN existing as TIN (1.08% versus 0.66%). The carbon to nitrogen ratio declined significantly, though not strongly, with flow age (p < 0.001; r² = 0.27).

**Cation exchange capacity (CEC), pH, exchangeable cations, and base saturation**

CEC was dominated by organic exchange capacity, as indicated by the high correlation between CEC and soil carbon (p < 0.001, r² = 0.75). Soils were strongly acid to neutral, with pH values correlated most significantly with flow age (p < 0.001; r² = 0.37). The sum of exchangeable cations (exchangeable calcium, sodium, magnesium, and potassium) was dominated by calcium, which averaged 69% of the total. Individual cations were dominantly correlated with soil carbon, with the exception of potassium that most strongly correlated with soil age. Base saturation negatively correlated with rainfall (p < 0.001; r² = 0.35), with the relationship being much stronger on old flows than young flows.

**Phosphorus**

Resin extractable phosphate ranged from 0-260 µg/g dry soil. Resin phosphorus concentrations were significantly but not strongly correlated to rainfall on individual flows; resin phosphorus most strongly correlated to soil age (p < 0.001; r² = 0.42). Elemental phosphorus concentrations ranged from 0.08-0.49%; using Nb as an index element, P concentrations in soils were enriched relative to the underlying parent material. The uncertain source of tephra makes the level of enrichment difficult to interpret, but samples showed enrichment relative to all potential tephra sources (Mauna Loa, Hualalai, Kilauea). Phosphorus enrichment correlated most strongly with soil carbon.

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Table 4. Correlation coefficient (R value) of soil properties to rainfall, and best model comprised of rainfall, underlying flow age, and percent soil carbon.

| Soil property                  | Young soils | Old soils | All soils | Young soils | Old soils | All soils |
|--------------------------------|-------------|-----------|-----------|-------------|-----------|-----------|
| Rainfall                       |             |           |           |             |           |           |
| Carbon (%)                     | 0.39***     | 0.44**    | 0.36***   | 0.67***     | 0.47      | 0.69***   |
| Total nitrogen (%)             | 0.11**      | 0.37*     | 0.32***   | 0.91***     | 0.97***   | 0.89***   |
| TIN (µg/g)                     | -0.11       | -0.08     | -0.11     | 0.71***     | 0.54*     | 0.63***   |
| C:N                            | 0.07        | -0.63***  | -0.14     | 0.67***     | 0.49*     | 0.64***   |
| Ca2+ (cmol(+)/kg)              | 0.05        | -0.38***  | -0.20*    | 0.75***     | 0.72***   | 0.73***   |
| Mg2+ (cmol(+)/kg)              | 0.17        | -0.46**   | -0.05     | 0.67***     | 0.49      | 0.57***   |
| Na+ (cmol(+)/kg)               | 0.23*       | 0.12      | 0.20      | 0.80***     | 0.65**    | 0.73***   |
| Sum cations (cmol(+)/kg)       | 0.10        | -0.64***  | -0.13     | 0.78***     | 0.75***   | 0.75***   |
| Cation exchange capacity       | 0.50***     | 0.05      | 0.37***   | 0.88***     | 0.71***   | 0.90***   |
| Base saturation (%)            | -0.45***    | -0.79***  | -0.59***  | 0.70***     | 0.83***   | 0.74***   |
| pH                             | -0.07       | -0.47***  | -0.24*    | 0.44**      | 0.60**    | 0.52**    |
| Resin phosphorus (µg/g)        | -0.41***    | -0.57***  | -0.39***  | 0.61***     | 0.69***   | 0.72***   |
| Phosphorus (%)                 | 0.42***     | -0.17     | 0.16      | 0.74***     | 0.51      | 0.79***   |
| Phosphorus remaining (%)       | 0.00        | -0.14     | -0.03     | 0.57***     | 0.71*     | 0.51***   |
| Phosphorus loss (%/yr)         | -0.18       | -0.20     | -0.14     | 0.73***     | 0.82***   | 0.77***   |
| Depth to clinkers (cm)         | 0.12        | 0.27*     | -0.02     | 0.63***     | 0.59***   | 0.89***   |
| Depth to bedrock (cm)          | -0.10       | ...       | -0.34     | 0.60***     | ...       | 0.58***   |

*p < 0.05, **p < 0.01, ***p < 0.001.
Fig. 2. Resin extractable phosphorus and rainfall (top) within Kona by flow age and (bottom) in Kona and Kohala. Elevated resin extractable phosphorus concentrations occur at a lower rainfall for successively younger lava flows within Kona (top), and at lower rainfall in Kona compared to Kohala (bottom).
Soil depth

Depth of the soil was variable, and in some cases difficult to judge due to the uneven layer of clinkers. We recorded the depth of clinker-free soil for each sample, and the depth to bedrock (i.e., the bottom of the clinker layer) in cases where it was reached. In most cases clinkers could be extracted to the full depth of the sample but they comprised vast majority of the volume within the clinker layer. The clinker-free soil was not necessarily devoid of rocks, but was mostly soil. Due to our sampling of local depressions, soil depth overestimates the landscape average depth for each flow age. Soil depth in the clinker-free layer correlated significantly with flow age \( (p < 0.001; r^2 = 0.79) \). Mean depth to the clinker layer was 9.7 cm and 27.7 cm on the young and old flows, respectively; the latter especially is an underestimate because depths >30 cm were recorded as 30 cm.

Elemental concentrations and retention

We used the complete elemental analyses to calculate apparent element retention and mobility, relative to the index element Nb, across the Kona landscape. This approach is useful for calculating weathering in an environment where both mass and volume are subject to loss (via leaching) or gain (via organic matter addition). However, because Kona soils often developed in tephra derived from volcanoes other than those producing the underlying lava flows, we present these data (together with all of our soil measurements) as a supplemental on-line table (Supplement). We used the 1.2 ky flow as the baseline from which to assess the mass loss. All elements show a general trend of depletion over time (with the exception of phosphorus as discussed above). Despite uncertainty in the provenance of soil material, our results are sufficiently robust to demonstrate substantial depletion of Ca, Na, Mg,
and Si in Kona soils relative to parent material, particularly on older flows and in higher-rainfall sites. Using the 1.2 ky baseline, each element (excepting phosphorus) showed a significant (p < 0.001), inverse linear relationship of concentration remaining over time on a log-log scale, indicating an exponential decay of elemental loss rates over time (shown on linear scale in Appendix: Figs. A1–A9).

**Agriculturally important soil properties**

As previous investigations showed, a few soil-fertility related properties appeared particularly important in defining boundaries of intensive cultivation, foremost among them being resin extractable phosphorus, base saturation, and exchangeable calcium. The distributions of these properties in relation to substrate age and rainfall are summarized in Figs. 2–4. These indicators of soil fertility (and Polynesian agricultural intensification) declined with increasing rainfall on all flows; moreover, the decline occurred at lower rainfalls on successively younger lava flows.

Resin extractable phosphorus in Kona soils (Fig. 2A) averaged below 30 μg/g dry soil above 1300 mm/yr of rainfall, with varying levels of enrichment at lower rainfalls. Each successively younger flow increased in resin phosphorus at a lower rainfall than older flows; this trend holds for all flow ages. The decline in soil base saturation with increasing rainfall also occurred at lower rainfall levels on younger flows (Fig. 3). While the flows in Fig. 3 were chosen for illustrative purposes—they are well represented by samples and are graphically distinct—the trend holds for all flows with the exception of the 0.5 ky flow, which had a relatively constant base saturation across the rainfall gradient. The
relationship of exchangeable calcium with rainfall is less compelling in Kona than Kohala (Fig. 4); the oldest Kona flows (7.5 and 12.5 ky) decrease with increasing rainfall, but the young flows displayed no clear pattern of depletion, with high variability in samples across the rainfall gradient. The high variability in exchangeable calcium in the younger soils can be attributed to CEC being dominated by the high levels of organic material rather than mineral sources.

**DISCUSSION**

The moderate but varying rainfall (~600–2000 mm/yr) and young substrates (~0.5–12.5 ky) made pre-Contact agriculture in Kona fundamentally different from other well-studied dryland systems in Hawai‘i. The best-known Kohala system is composed of relatively old and uniform substrate (areas of ~150 ky and ~400 ky), and is embedded within a very large rainfall gradient (~300–3500 mm/yr); rainfall and the leaching of nutrients drive the limits of agriculture in this system (Vitousek et al. 2004). The agricultural system in Kona more closely mirrors the Kahikinui system on Maui; that system encompasses a broad range of substrates (~3–130 ky), but a small and relatively dry rainfall gradient (~400–900 mm/yr); sufficient moisture for mineral weathering and cultivation appears to drive the limits of agriculture in this system (Kirch et al. 2004, 2005, Hartshorn et al. 2006, Giambelluca et al. 2012). Agriculture in Kona developed with higher rainfall than Kahikinui. As we discuss, portions of the Kona system likely were limited by low rates of weathering and retention of mineral nutrients in young flows. The low release and retention of nutrients in Kona may have encouraged the broad application of resource concentrating farming methods.

**Indicators of soil fertility**

In the well-studied Kohala system, the upper (wetter, lower fertility) boundary of intensive pre-contact agriculture is associated with base saturation ~30%, resin extractable phosphorus ~50 µg/g, and exchangeable calcium ~10 cmol(+)/kg (Vitousek et al. 2004; Vitousek et al., in press). In Kona, these soil properties varied with climate in a way similar to Kohala, declining at higher rainfall, particularly on the older soils. However the annual rainfall at which these values are reached is lower in Kona than on the older Kohala substrates, and within Kona it is lower on younger than on older flows (Figs. 2–4). Over a much longer timescale (150–4,000 ky), these transitions occur at lower rainfall on very old sites (Chadwick and Chorover 2001, Vitousek and Chadwick 2013); together with our results, this suggests that the maximum rainfall that experiences high soil fertility increases and then declines with long-term soils development, rather than experiencing a continuous decline, and that the peak occurs relatively early in the process of Hawaiian basalts (>10–150 ky).

The observation that all three soil fertility indicators are shifted towards drier conditions in Kona than Kohala could be explained in several ways. We suggest that the weathering of the coarse substrate of young lava may be constrained by low surface area, and the low soil fertility in moderately wet Kona sites may reflect the kinetics of supply of elements via weathering and their removal via leaching. Low surface area reduces the reaction of minerals with water, but could increase material transport. Variation in particle size and mineralogy are primarily responsible for heterogeneity in weathering rates within a given climate (Reeves and Rothman 2013).

Other potential explanations for this pattern include: (1) Kona may be wetter than reported (or Kohala drier), potentially explained by high fog drip in Kona (Brauman et al. 2010), highly localized variations, or vagaries of mapping; (2) water erosion may be significant on the young lava, leading soils at a given location to reflect uphill, and typically wetter, conditions; (3) higher soil moisture in Kona driven by higher levels of soil organic matter and lower wind intensity may make soils at lower rainfall behave as if it were wetter; or (4) retention of mineral nutrients in Kona may be limited by weakly adsorbing soil complexes that result in higher leaching of nutrients at a given rainfall. The first two points seem unlikely to contribute substantially to the pattern, in that soil fertility parameters are typically lower on young than old soils within Kona, and downhill fluvial transport is likely greater on the fine-grained soils of Kohala than the coarse lava flows of Kona. The third and
fourth points may contribute to the pattern, but not enough to explain the differences between older flows within Kona, where carbon levels do not vary significantly and CEC declines with increasing flow age.

There is evidence of intensified, systematic agricultural occurring above the rainfall levels that our analyses suggest should bound the development of systematic agriculture (for instance Tainter 1991, Burtchard 1996). Our soil transects on old flows traversed areas of agricultural infrastructure that had soil fertility indicators below the established thresholds. Agricultural intensification in areas identified as marginal based on previously determined indicators could occur if the distribution of these indicators reflects a kinetic limitation of weathering rather than a boundary condition; there would be a sustained supply of mineral nutrients in low-fertility sites controlled by kinetic processes, differing from those controlled by irreversible depletion of weatherable soil minerals as seen in Kohala. Our data set suggests that total elemental concentrations in these wetter areas remain higher than levels seen in Kohala, and that Kona soils therefore could provide sustained nutrient fluxes. Unfortunately our data set has relatively few samples in wetter areas of older flows, is uncertain about parent matter concentrations in tephra, and lacks detailed information on the volume of non-fine materials, limiting our ability to draw a confident conclusion. Another possibility is that some areas considered systematic agriculture relied on alternative sources of soil fertility, such as inputs from nearby forests, incorporating fallow periods, or the development of agricultural practices that enhanced local soil fertility. If the latter is the case systematic agriculture in Kona may have required more management and inputs than did other dryland systems in Hawai‘i.

Thresholds of systematic agriculture in Kona

In general, soils in Kona are more fertile the older the underlying lava flow and the lower the rainfall. The old soils in Kona that receive less than ~1400 mm/yr of rain are fertile enough to support the development of systematic agriculture as defined by the soil fertility indicators observed in Kohala. In contrast, the flows <4 ky typically fall below the fertility thresholds that bound the Kohala field system, or exceed those limitations only at rainfalls below ~1000 mm/yr (i.e., the kula zone). The Ladefoged et al. (2009) model assumes inadequate soil development on the young soils as the basis for the restriction of systematic agriculture. The background levels of soil fertility indicators in Kona soils support the 4 ky threshold for the development of intensive pre-contact agricultural systems. The indicators of fertility in the young soils suggest that systematic agriculture was infeasible even where soil depth was sufficient. The low levels of soil fertility are reinforced by the low quantity of soil on the younger flows.

Nevertheless, examples show that a portion of the land within agricultural sites on young flows was made farmable. However we don’t know how densely these microsites occur across the landscape, or the extent of agriculture between favorable microsites. Approximately half the area defined as the Kona Field System consists of young soils and so even a small percentage of usage is a meaningful contribution to the total yield of the region. Further synthesis of the archeological record could better parse out the types and intensities of resource concentrating agriculture on the different flow ages in Kona.

The ethno-agricultural landscape within Kona

The matrix of agricultural opportunities in Kona relative to climate and soil fertility suggests linkages between Hawaiian farmers and their environment in the development of the agricultural landscape. The four general zones of cultivation (moving upslope the kula, kauaiulu, apaa, and amau) can be viewed in terms of the variable fertility between zones (variation with rainfall) and within zones (variation with flow age).

The kula zone, which was too dry to farm in Kohala and Kahikinui (below <750 mm/yr), has adequate rainfall in Kona (in an average year) to crop sweet potato (Kagawa and Vitousek 2012). Moreover, the soils within the kula show relatively high indicators of soil fertility even on the youngest flows, and cropping would likely meet with success wherever adequate soil and moisture could be gathered. The development of sweet potato farming in the kula can be seen in infrastructure that ranges from systematic kuaiwi in select areas on old soils (Hammatt and Clark
1980, Escott and Spear 2003), sparse kuaiwi, terraces and mounds in a wider range of areas on old and young soils (Hammatt and Clark 1980, Schilt 1984, Henry and Wolforth 1998, Escott and Spear 2003, Haun and Henry 2010), dense mounds and swales in more marginal areas on young soils (Schilt 1984, Rechtman et al. 2001, Haun and Henry 2010), to sparse mounds and other informal techniques in the most marginal areas (Rechtman et al. 2001, Escott and Spear 2003). The high indicators of soil fertility and adequate rainfall for cropping suggest that soil depth within the kula may be the most significant constraint to agriculture here.

The soil fertility indicators within the agroforestry plantations of the kaluulu zone remain high on old flows but fall below levels associated with intensification on the young flows. Lincoln and Ladefoged (in press) show that breadfruit remains highly productive on flows as young as 1.2 ky within this zone, and provides yields comparable to sweet potato production on older flows. Systematic agricultural infrastructure occurs on old flows in this zone (Escott and Spear 2003, Tomonari-Tuggle 2006), and evidence for extensive informal techniques occurs on young flows (Henry and Wolforth 1998, Haun and Henry 2010), suggesting that although the breadfruit canopy was continuous the density of understory plantings varied with soil fertility within the plantations. Here the extensive application of an informal agriculture technique (the use of tree crops) may have been facilitated by the close proximity of high and low fertility soils. Young flows in this zone show a higher density of agricultural features in closer proximity to older flows (e.g., Hammatt et al. 1997). The increased nutrient uplift and storage within the kaluulu could facilitate other informal agriculture. Hawaiians often used groves of trees to provide mulch to support pocket agriculture, to plant within the altered environment, or to periodically engage in slash and burn agriculture.

Within the apaa zone the soil fertility indicators are depleted for young flows, and above ~1400 mm/yr even the oldest flows drop below levels thought to have sustained intensification. In accordance with varying soil fertility, some evidence exists for apaa and amau zones of varying width. For example Cordy et al. (1991) find a very narrow apaa zone on a 2.25 ky flow, with systematic infrastructure prevalent from ~550–700 m (~1250–1315 mm/yr) followed by a rapid transition to informal infrastructure extending up to ~900 m; in contrast the systematic infrastructure of the apaa zone on a 4 ky flow in Kealakekua extends from ~375–800 m (~1250–1650 mm/yr), with historical accounts indicating a narrow amau zone extending to ~900 m (Menzies 1920). This scenario would result in “fingers” of forested area extending further downslope on younger flows. These forested patches could enhance fertility on the young flows and botanical material from the forests could potentially augment fertility on nearby old flows.

**CONCLUSION**

The agricultural mosaic of Kona differed from the other farming landscapes in Hawai‘i due to the hospitable climate of Kona and proximity of soils of varying fertilities. Kona offers the opportunity to understand fertility in early soil pedogenesis and couple human engagement with a diverse and productive landscape. The soil properties used as indicators for Hawaiian dryland agricultural intensification appear to be systematically shifted towards a lower rainfall in younger lava flows within Kona and Kohala (0.5–400 ky). We attribute this shift to limitation of soil fertility in Kona soils by the kinetics of release and retention of mineral nutrients in coarse substrates. It is clear that areas of high fertility were used in intensive, systematic ways, that there existed a range of intensities across the fertility gradients, and that informal techniques were applied in areas in which systematic agriculture was constrained. Agroecological zones within the Kona farming landscape roughly align with changing patterns of soil fertility as they relate to rainfall, while localized adaptations of infrastructure and planting density tend to vary more consistently with soil fertility as it relates to lava flow age.

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**SUPPLEMENTAL MATERIAL**

**APPENDIX**

**Aluminum**

![Box plot of aluminum remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.](image)

Fig. A1. Concentration of aluminum remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.

**Calcium**

![Box plot of calcium remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.](image)

Fig. A2. Concentration of calcium remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.
Fig. A3. Concentration of iron remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.

Fig. A4. Concentration of potassium remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.
Fig. A5. Concentration of magnesium remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.

Fig. A6. Concentration of sodium remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.
Fig. A7. Concentration of phosphorus remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.

Fig. A8. Concentration of silicon remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.
Fig. A9. Concentration of titanium remaining (%) by age compared to the average parent material concentrations from Mauna Loa and Kilauea volcanoes.

**SUPPLEMENT**

Soil and site properties along four transects as described in the main text (*Ecological Archives* C005-003-51).