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Irrigated taro (*Colocasia esculenta*) farming in North Kohala, Hawai‘i: sedimentology and soil nutrient analyses

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ABSTRACT

How did traditional farming transform the natural environment in the Hawaiian Islands? This question is one that has largely been addressed for rainfed farming of crops like sweet potato (*Ipomoea batatas*), but evidence is lacking for irrigated farming of the critical staple crop taro (*Colocasia esculenta*). We describe the results of soil nutrient and sedimentological analyses of deeply-stratified pondfield deposits representing a 600-year-long record of irrigated taro farming in the North Kohala District, Hawai‘i Island. Soil is categorized by particle size to determine modes of transport and deposition, and concurrent soil nutrient analyses were conducted to infer shifts in the source of sediments and changes associated with taro harvesting. The advent of farming is clearly detectable in sedimentology, the presence of charcoal found within sediments, and soil chemistry. However, diminished nutrient concentrations can be attributed largely to deposition of a mixture of upstream sediments. Overall, there is no clear evidence for nutrient draw-down by taro harvesting, but we cannot yet rule it out as a factor. This study demonstrates the inherent difficulty of correlating changes in soil nutrients evident in irrigated pondfields with the long term history of soil nutrient cycling.

1. Introduction

Taro (*Colocasia esculenta*) was vital in the establishment of successful human settlements on the islands of Oceania (see Addison, 2008 for a recent review). In the Hawaiian Islands, irrigated taro farming, which occurred on each major island, is thought to have been particularly important because it was relatively easy to produce a reliable taro surplus when compared with non-irrigated staple crops, such as sweet potato (*Ipomoea batatas*) and taro farming appears to have promoted stable political systems (Kirch, 1985, 1994, 1997, 2011; Kurashima and Kirch, 2011; Ladefoged et al., 2009). The best evidence for this can be seen when one compares oral histories of the western islands of Kaua‘i and O‘ahu, where production was dominated by irrigated taro, to the eastern islands of Maui and Hawai‘i, where sweet potato was far more ubiquitous. The latter (eastern islands) appear to have taken far longer to consolidate, had internal politics that were more unstable than their neighbors, and it was in this part of the archipelago that we see the rise of the cult of the war god Ku.

The role of irrigated agriculture in the development of Hawaiian social complexity has been considered by a number of anthropologists (Allen, 1991; Earle, 1978, 2012; Kirch, 1984, 2011; Sahlins, 1958). Earle (1978) concluded that labor requirements of building and maintaining irrigation infrastructure at the scale it occurred in Hawai‘i did not require administrative managers, contra Wittfogel's (1957) widely cited ‘hydraulic hypothesis.’ Nonetheless, the considerable surplus production that could have been realized relative to energy investment would have made it attractive for elites who might take advantage of the bottleneck created by the management of production (Earle, 2012; Kirch, 2011; McCoy and Graves, 2010, 2012).

Recent research on sweet potato farming has examined the relationship between traditional farming and key soil nutrients (Hartshorn et al., 2006; Kirch et al., 2004, 2005; Ladefoged and Graves 2011; Vitousek et al., 2004). These studies have leveraged the ability to compare non-farmed, or less intensively farmed, soils

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under infrastructure (windbreak field walls), to soils within plots that show clear contextual evidence for having been farmed, to document change over time. For example, spatial analyses of dry land agricultural plots have not only shown soil nutrient loss due to wind erosion but also matching increases in nutrients with soil redeposition in downwind fields (McCoy and Hartshorn, 2007).

Irrigated systems are part of dynamic environments and thus are far less straightforward to characterize in terms of environmental impacts. Nonetheless, Palmer et al. (2009) have begun to tease apart how nutrient cycling operated in irrigated contexts in the North Kohala District, Hawai‘i Island. They examined three general categories of soils – alluvial and slope soils within valleys and shield soils on the land between valleys – and note that steep-slope erosion provided additional nutrients to soils in the form of little-weathered rock, with natural soil rejuvenation having had greatest effect on alluvial soils. The authors further identify irrigation water as a vector for nutrients as streams carry agriculturally significant concentrations of rock-derived nutrients. Indeed, stream water would have been able to supply soluble nutrients in more than adequate quantities to support taro agriculture.

But, while valley bottom irrigated plots, or pondfields, should have provided an abundance of nutrients through soil erosion and soluble nutrients in irrigation water, how these gardens operated over time remains largely untested. This leaves open the possibility that our present model, which assumes irrigated farming provided a steady, low cost output for the surplus wealth economy, may be incorrect. The lack of such work to date is due in part to the inherent difficulty in recovering a continuous sequence of irrigated farming. In an early comprehensive archaeological study of the extensive irrigated fields of Halawa Valley, Moloka‘i Island, Kirch (1975: 176) outlined some of the major reasons why early irrigation has such low archaeological visibility:

> “First, such water control may have involved only a minimal degree of environmental alteration, utilizing naturally swampy or low laying areas. Second, since population size was probably small, the areal extent of such wet cultivation would have been limited. Third, the earliest systems would have had the longest time span for obliteration, both through natural processes (stream erosion, etc.) and by subsequent construction and environmental manipulation on a major scale for the later pondfield complexes.”

Nonetheless, new fieldwork has shown that a concerted program of excavation can yield general patterns in the expansion and intensification of irrigated farming as marked by the construction and rebuilding of pondfield complexes (McElroy, 2007, 2012).

In this study, we build on recent research on irrigated farming on the windward coast of North Kohala, Hawai‘i Island to determine the long term environmental impacts of taro farming. The study area is home to irrigated field complexes within small valleys documented through intensive survey and remote sensing (McCoy et al., 2011), as well as fields on ridge lands between valleys irrigated by diverting water out of valleys (McCoy and Graves, 2010). The results presented here have relevance not only for understanding the agricultural trajectory of Hawai‘i but also for how we study sustainability in the development of the political economies of societies worldwide.

2. Background

2.1. Windward North Kohala, Hawai‘i Island

Our overall study area includes the easternmost drainages on the windward slopes of the Kohala Mountains, Hawai‘i Island (Fig. 1). This network feeds into Hapu‘u, Kapanaia (also Kapana on modern maps), Keokea, and Neue Bays. Each of these watersheds, or small valleys, were farmed in much the same fashion as narrow sections of larger valleys, such as the well described upland Anahulu Valley on O’ahu Island (Spriggs and Kirch, 1992). The Halawa Gulch is a small valley made up of two major branches (West, East) and the valley’s main branches converge at around 124 masl to create a single Halawa Stream.

There are several key climatic and environmental factors that created opportunities and constraints for farmers: rainfall, surface water, soils, and temperature. The size and orientation of the Kohala Mountains in relation to the predominant northeastern tradewinds create classic wet, windward conditions with annual rainfall among the highest on Hawai‘i Island with most rain in the winter months. Rainfall at the headwaters of streams receive around 2500–3000 mm of rain annually.

In their recent summary of irrigated farming in the Hawaiian Islands, Ladefoged et al. (2009: 2376) point out that ideal temperatures for growing taro are most likely to occur in regions below 300 m above sea level. Most of the fields described here are within this range, however there are a significant number found above 300 masl where temperature could have impacted yield.

The geologic age of the parent material of volcanic soils has been identified as an important variable considered by farmers in Hawai‘i. Soils in the study area are derived from relatively young volcanics, the Hawi series (120–260 kya) and the older Pololu series (260–500 kya), which is more likely to have been naturally depleted of rock-derived nutrients (Fig. 2). Younger series soils can also be unfit for rainfed agriculture due to nutrient depletion from dramatically high rainfall, as is the case with Hawi soils in the higher elevation range of the North Kohala Field System (Vitousek et al., 2004). In windward Kohala, this same process has left younger Hawi series soils even more depleted of nutrients than older Pololu series soils (Palmer et al., 2009). In geomorphologically active environments, however, soils can be rejuvenated by colluvial deposition of less weathered sediments (Vitousek et al., 2003).

The overall picture of the environmental setting in windward Kohala is one that is favorable for irrigated taro farming. Therefore, for this study, our null hypothesis is that irrigated soils had sufficient introduced nutrients, dissolved in irrigation water as well as by deposition of sediments through erosion, to replace nutrients lost through taro harvesting.

2.2. Previous archaeology

The history of archaeology in North Kohala District begins with a turn of the century survey of ritual sites by J.F.G. Stokes of the Bishop Museum (Stokes, 1991). This was followed in the 1960s and 1970s by a series of University of Hawai‘i, Mānoa archaeological field schools in western (leeward) North Kohala at Lapakahi (Newman, 1970; Tuggle and Griffin, 1973) and eastern (windward) North Kohala in Pololu Valley (Tuggle and Tomonari-Tuggle, 1980). Unlike Stokes, later researchers recorded the full range of different types of sites encountered in their study areas. The leeward half of the district has received a great deal of attention by academic researchers and cultural resource management projects compared with windward Kohala (Ladefoged and Graves, 2000, 2008; Ladefoged et al., 1996, 1998, 2003; Vitousek et al., 2004; see McCoy and Graves, 2007: Fig. 5 for a summary of research across the district). Significant work in the windward area includes a regional historical and archaeological overview completed by Tomonari-Tuggle (1988) as well as several other surveys (Cordy et al., 2005; Erkelens and Athens, 1994; Tomonari-Tuggle, 1988; Wolforth, 2003).

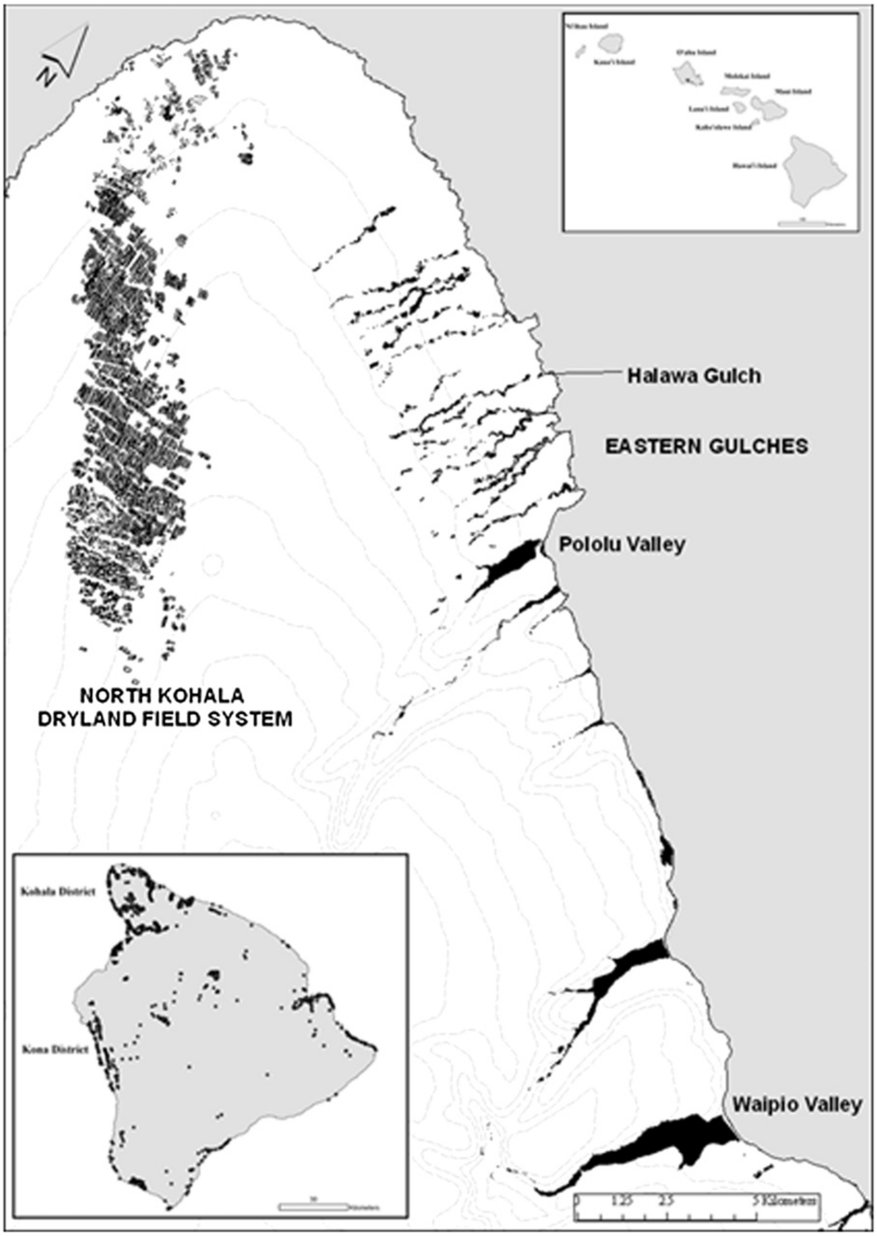

Fig. 1. Distribution of agricultural fields, North Kohala District, Hawai‘i Island.

The archaeological landscape of North Kohala is one of the best preserved in the Hawaiian Islands and as the home of Kamehameha the Great, Kohala holds a unique place in the early history of the Hawaiian Kingdom and includes a variety of sites associated with the regent himself. In the years following the establishment of the kingdom, Kohala once again rose to prominence as a central place in the cultivation, processing, and export of sugar (see Schweitzer and Gomes, 2003). This historical process changed the landscape dramatically, but there are still many locations where evidence of pre-European contact life remains well-preserved.

2.3. *Hawai‘i Archaeological Research Project*

This paper describes archaeological excavations conducted in 2007–2009 as part of the Hawai‘i Archaeological Research Project (HARP) (McCoy and Graves, 2007, 2008, 2010, 2012; McCoy et al., 2010). The research goals of this project centered on describing and explaining the region’s unique social history by examining long-term changes in traditional taro agriculture, while our educational goals centred on training students in the methods of archaeological fieldwork through participating in an active research program. As we outline below, the majority of features we have encountered and recorded in these small valleys were likely used for irrigated agriculture. However, the techniques employed to farm these locations are remarkable for their variety, the density of garden plots, and engineering (McCoy and Graves, 2012).

In describing agricultural architecture we use the term *feature* to denote a single structure. Features are mostly found in clusters of contiguous, related structures called here *complexes*. When a new complex was encountered on our survey it was given a designation according to the territory (*ahupua‘a*) and a number assigned in the order in which it was recorded. For example, HLW-1 is the first complex recorded within Halawa Ahupua‘a (see McCoy and Graves (2007) Appendix III for a list of *ahupua‘a* name

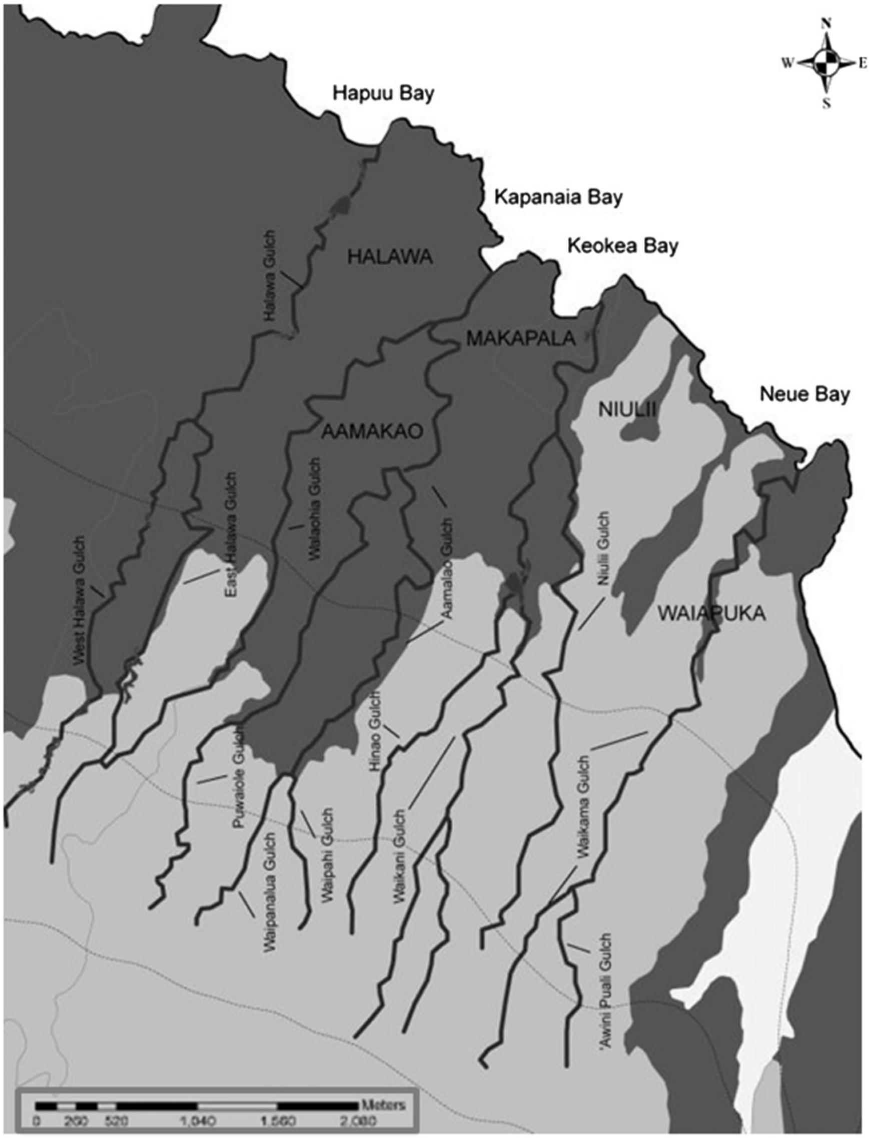

Fig. 2. Small valleys and soil types, Windward North Kohala.

codes used in the project). Individual features are given letters, such as HLW-1A, HLW-1B, and so on. In the case of terraces – that is, architecture with two-to-three free-standing retaining walls creating a flat surface – a feature designation refers to both the retaining wall and the deposits behind it. Terrace complexes were lettered starting at the uppermost tier. Irrigated terraces, or pondfields, are referred to in Hawaiian as *lo'i* and irrigation ditches as *'auwai*.

3. Methods

3.1. Archaeological mapping and geophysical survey

Reconnaissance survey of irrigated fields in Halawa Gulch showed 11–12 ha of fields and we intensively mapped 32 complexes representing about 5 ha (Fig. 3). The intact complex closest to the coast, HLW-29, included a large set of terraces east of Halawa Stream as well as several terraces and a broad flat area on the stream's west bank (Fig. 4). A small geophysical survey was conducted in the flat downslope area where no architecture was evident on the surface to determine if there were further buried stone retaining walls. Resistivity results, shown in Fig. 4, indicated a linear feature at roughly the location we presumed a final, lower terrace of the complex would be located; an interpretation confirmed by subsequent excavations.

3.2. Excavation of pondfield deposits and soil sampling

Excavations of the west bank features of HLW-29 exposed deeply buried pondfield deposits. Three excavations are of particular importance here. Test Unit 6 (TU 6) is a 5 × 1 m trench within feature HLW-29L that exposed the deeply-stratified sequence of construction and deposition described here in terms of sedimentation and soil nutrients. Test Unit 2 (TU 2) is a 1 m long extension of that same trench where garden soils adjacent to the lower retaining wall were exposed. Finally, Trench 2 was excavated into the same lower tier gardened soils represented in TU 2 and exposed a buried, informal retaining wall, or bund, on the downslope edge initially indicated on our geophysical survey. This entirely buried lowest tier in the west bank of HLW-29 was not given a feature

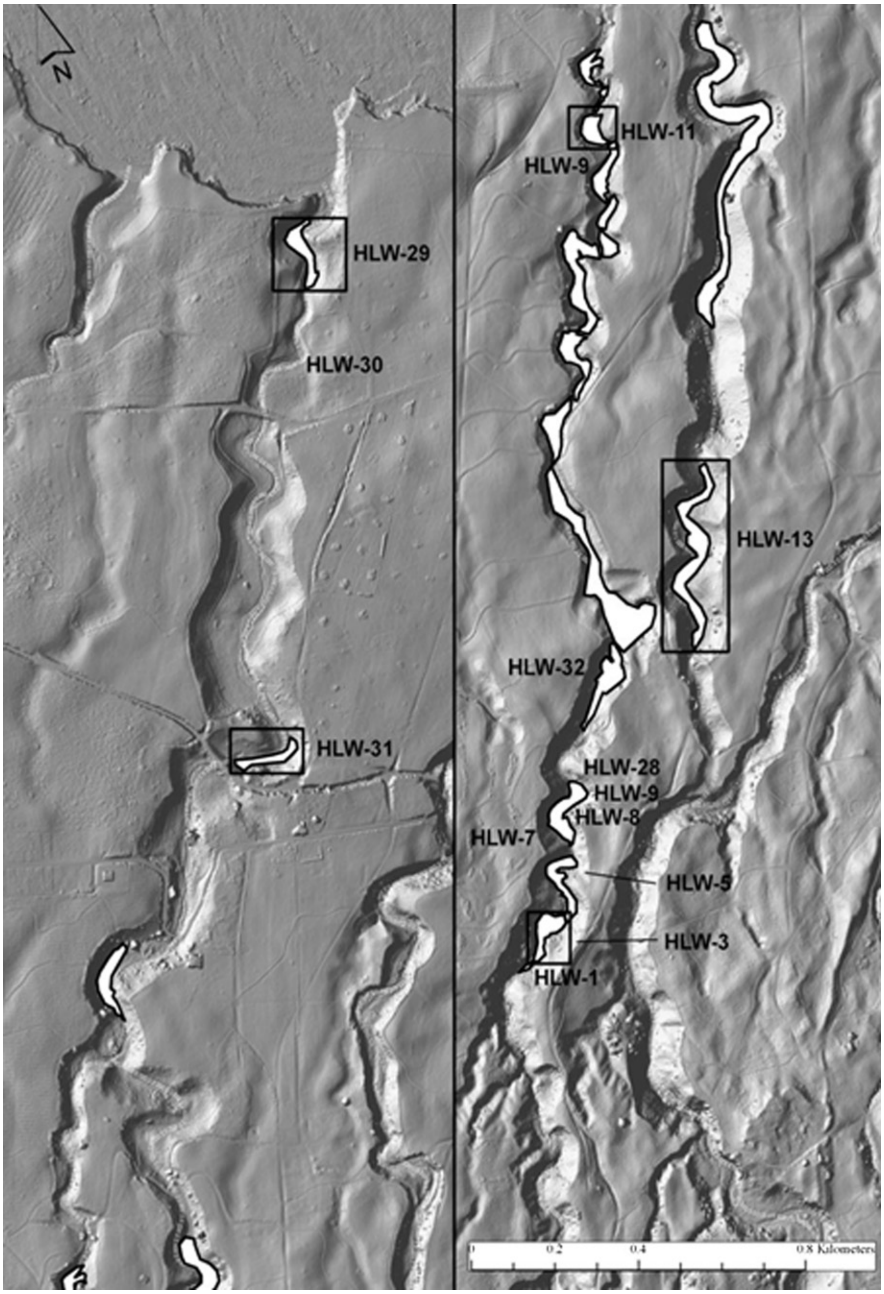

Fig. 3. Locations of irrigated field systems in Halawa Gulch, Windward North Kohala. Boxes around irrigation complexes indicate intensively studied fields (see McCoy and Graves, 2012).

designation letter since it was not evident at the time the complex was originally surveyed.

After the completion of excavation, bulk samples for soil chemical and sedimentological analyses were collected from the east profile of TU 6. Two liters of soil were taken from each identified layer, and a continuous column sample was also taken in 10 cm intervals down the extent of the profile, resulting in eight layer samples (identified as Ly I–VIII) and twenty-six column samples (identified as CS-1, CS-2, CS-3, etc.). Samples were collected in their entirety, with the single exception that rare inclusions larger than 6 cm in diameter were noted, but left in the field. Where possible, charcoal samples for dating were collected *in situ* out of the profile, or derived from flotation from key locations in the sequence. In addition, charcoal was collected from under the exterior retaining wall of HLW-29L as well as from under the retaining bund of the lower tier terrace.

3.3. Laboratory methods

All soil samples were air dried in the field and then split for analyses in several laboratories. Chemical analyses were conducted at University of California, Santa Barbara and processed in accordance with methods laid out in Vitousek et al. (2004, see supplemental materials). Analyses determining available or extractable ions, including Base Saturation (BS), Cation Exchange Capacity (CEC), and concentrations of ferric oxides were performed. These measures are appropriate for assessing current characteristics and nutrient availability of the soils sampled. Total concentrations of Ca,

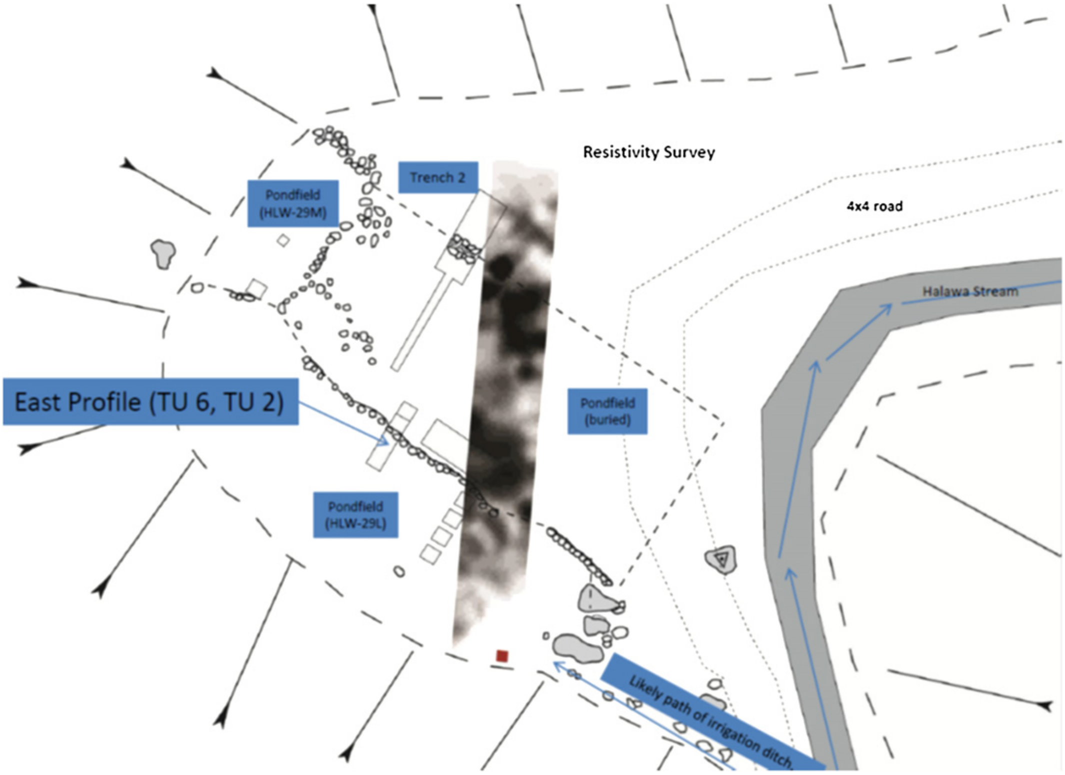

Fig. 4. Complex HLW-29 (west bank) showing location of geophysical survey and excavations.

Mg, P, K, and Nb were obtained through X-ray fluorescence spectrometry of samples fused with lithium borate (ALS Chemex, Sparks, Nevada, USA).

Samples set aside for sedimentological analysis were sent to University of California, Berkeley laboratories, oven-dried at 100C for 24–48 h, and further divided. A 100 g aliquot sub-sample of these was sent to Soil & Plant (S&P) Laboratories (San Jose, California, USA) for particle size analysis. Sand and gravel fractions were determined through sieving and silt/clay fraction by the hydrometer method.

Charcoal samples were identified to taxa by G. Murakami (International Archaeological Research Institute, Inc., Honolulu, USA) and those of short-lived or Polynesian introduced taxa were submitted to Beta-Analytic and National Ocean Sciences AMS Facility for AMS radiocarbon dating.

4. Results

Results are presented in three parts. First, we give an overview of the site's depositional and construction history. For this we use standard archaeological interpretations of soil descriptions and radiocarbon dates to characterize several stages in the use of this garden (pre-agriculture, early and late agriculture use). Second, we use sediment particle size to assess depositional dynamics within the terrace over time. Finally, we present major trends in key soil nutrients (P, K, Ca and Mg) as they relate to the long-term history of farming.

4.1. Pondfield depositional and construction history

The history of construction, farming, and soil deposition represented here is best visualized by working back and forth between *construction phases* – defined as discrete building episodes in the pondfield's retaining wall – and corresponding stratigraphic *layers* retained behind the wall. When actively farmed, the area behind the wall would have been flooded by slow moving water and planted to a depth of perhaps +50 cm below the ground surface, which would have been located slightly lower than the top of the retaining wall at any given time. With each new course of stone that raised the elevation of the downslope retaining wall, the elevation

Table 1
Radiocarbon dates from site 50-10-02-26086, irrigated terrace complex, HLW-29L.

Context	Taxa (weight, g)	Project identification	Charcoal identification	AMS lab identification	Conventional age	$^{13}C/^{12}C$ (‰)	2 sigma calibration
Ly V	*Artocarpus altilis* (<0.01)	HARP-2008-23B	0809-26	OS-72163	690 ± 35 BP	−25.27	1261 (64.7%) 1319; 13(30.7%) 1391
Under Stage 1 retaining wall base	cf. *Wikstroemia* sp. (0.01)	HARP-2009-2	0926-2	Beta-263862	670 ± 40 BP	−23.5	1268 (51.5%) 1329; 1341 (43.9%) 1395
Under retaining bund base	cf. *Pteridophyta* (0.24)	HARP-2009-1	0926-5	Beta-263861	650 ± 40 BP	−25.3	1278 (95.4%) 1398
Ly V	cf. *Pteridophyta* (0.01)	HARP-2008-23A	0809-25	OS-72162	555 ± 30 BP	−23.77	1310 (45.0%) 1360; 1386 (50.4%) 1431
Ly IV	*Hibiscus tiliaceus* (0.02)	HARP-2008-22A	0809-23	OS-72082	430 ± 35 BP	−24.9	1417 (88.4%) 1517; 1595 (7.0%) 1619
Ly IV–Ly III interface	Not identified (0.04)	HARP-2008-17	0908-16	OS-72079	230 ± 30 BP	−28.66	1530 (0.8%) 1538; 1635 (44.4%) 1684; 1736 (39.0%) 1805; 1935 (11.2%) 1955

Table 2
Summary of relative construction phases, soil layers, samples representing those layers in analysis, and radiocarbon dates.

Construction phase	Layer	Era	Depth (cmbd)	Soil sample no.	^{14}C
3c	I	Historic (1795-present)	15–45	1, 2, 3	
3b	II	Proto-Historic (1650–1795)	45–65	4 & 5	
3b	III	Proto-Historic (1650–1795)	65–85	6 & 7	230 BP
3a	IV	Late Expansion (1400–1650)	85–120	8 & Ly IV	430 BP
2b	V	Early Expansion (1200–1400)	95–165	9 to 15	555 BP; 690 BP
2a	VI	Early Expansion (1200–1400)	165–195	16, 17, 18	
1	VII	Early Expansion (1200–1400)	195–235	19 to 22	670 BP; 650 BP
–	VIII	Pre-Agriculture	235–275	23 to 26	

of the planting surface would rise as new deposits accumulated. This continued until older deposits were eventually buried below the active planting zone leaving behind a record of the soils from earlier in the life of the pondfield. Naturally, accumulated deposits could have been removed from the sequence either by purposeful digging out of pondfields during fallow periods, or by accidental failure of the retaining wall leading to mass erosion; but, this appears to have been rare and we note only one case where it appears erosion was so severe that we see punctuated re-deposition of accumulated deposits.

The charcoal recovered from the pondfield deposits we infer represents anthropogenic burning at some location upslope (Tables 1 and 2). Therefore absolute dates can be said to pre-date the point in time at which the deposits containing dated charcoal went out of the dynamic planting zone, giving us a series of *terminus post quem* dates that can be coordinated with the serial sequence of construction phases evident in the architecture and matching retained soil layers. Where possible, we specify when specific construction phases likely occurred in the cultural periods defined for the Hawaiian Islands (Kirch, 1985; Kirch and McCoy, 2007).

Standard archaeological field observation of deposits (color, texture, and inclusions) allowed us to divide deposits uncovered in TU 6 (HLW-29L) into eight discrete layers, which can be correlated to a retaining wall construction history consisting of three stages (Fig. 5). These construction stages are marked by three major re-orientations of the wall which involved moving new courses of stone back toward the slope. The result created a stair-step pattern in profile (see McCoy and Graves, 2008 for a detailed discussion). The lowest deposits, found in Layer VIII, are likely located below the earliest planting zone given their depth below the upper course of the Stage 1 retaining wall stones. Moreover, the lack of charcoal in these deposits, *in situ* or in flotation samples, and the different composition of the soil, all point to a pre-agriculture or natural deposit. As we note below, the presence of these pre-agricultural deposits gives us an excellent baseline for assessing changes associated with human activity.

In the earliest planting layer preserved (Stage 1 and Layer VII) we observed a general change in color, from grayish brown, to brown or reddish brown, likely a result of the accumulation of iron oxides often associated with irrigated taro agriculture (Kirch, 1977; Spriggs, 1981). We discuss the underlying natural soils and these earliest pondfield deposits together below as the pondfield's "Lower Soils." AMS radiocarbon dates from under the main retaining wall and below the lower tier's stone bund exposed following geophysical survey are roughly contemporaneous and likely correspond to clearing events circa AD 1260–1400 (Table 1). In the lowest agricultural soils with charcoal identifiable to taxa (Layer V), we recovered breadfruit charcoal also dated to this period (McCoy et al., 2010). Overall, it is likely farming in Lower Halawa began at least by the early fourteenth century AD making these irrigated pondfields the earliest documented in the eastern half of the Hawaiian archipelago.

The next major stage in the construction of the pondfield (Stage 2 and Layers VI and V), designated here as the start of the "Upper Soils," dates to the Late Expansion Period (AD 1400–1650). Unlike the previous stage, banded oxidation lenses characteristic of pondfield agriculture began to be preserved. This is only unusual in that we would expect that, in gradually accumulating deposits, these soil features would become mixed by later planting.

The last major stage of development dates to the Proto-Historic Period (AD 1650–1795) onwards through the Historic Period (AD

Fig. 5. East profile of HLW-29L showing major construction stages and soil sample locations.

Table 3
Summary of soil layers. Textural descriptions correspond to results of soil texture field test.

Layer	Primary color name	Primary HVC	Mottling color name	Mottling HVC	Depth (cmbd)
I	Very dark grayish brown	10YR 3/2	n/a	n/a	15–30
II	Dark grayish brown	10YR 4/2	Strong brown	7.5YR 5/6	40–55
III	Dark grayish brown	10YR 4/2	n/a	n/a	70–80
IV	Dark grayish brown	10YR 4/2	Yellowish red	5YR 4/6	100–120
V	Brown	10YR 4/3	n/a	n/a	130–150
VI	Very dark grayish brown	10YR 3/2	n/a	n/a	165–180
VII	Very dark grayish brown	10YR 3/2	n/a	n/a	200–220
VIII	Very dark grayish brown	10YR 3/2	n/a	n/a	240–260

1795–1900). This stage includes three construction phases designated 3a, 3b, and 3c based on subtle changes in the uppermost section of the retaining wall in the same general orientation but stepped back closer to the slope. In deposits corresponding to stage 3a, there appears to have been the removal or erosion of sediments marked by a sharp, wavy transition between Layers V and IV. If the deposits found in the excavation of Layer III in TU 2 within the pondfield correspond to the 'missing' Layer V deposits, then their position at the base of 3a retaining stones suggests this was an accidental failure of the retaining wall at some point in the third stage. A similar but much more minor example of this kind of failure is illustrated in the uppermost deposits associated with stage 3c. The top course of stone, preserved in other portions of the feature, is missing here, and we find that the uppermost deposits within the terrace have eroded after cultivation was abandoned. This slow erosion is a natural part of dry laid, stacked masonry architecture. The Layer V–IV soil transition is markedly different from the gradual slope that has developed on the abandoned upper surfaces. This reinforces the idea this earlier re-deposition was not simply a result of temporary abandonment, or the failure of a few retaining stones, but a major, high energy event that effectively wiped out the retaining wall.

4.2. Trends in depositional dynamics

The depositional history of the HLW-29L pondfield terrace is informed as much by the construction of terrace walls as by the introduction of particulate material into the system (Tables 3 and 4). Particle size data provide insights into mode of sediment transport and sediment source. Layer VIII, the sample of a pre-agricultural soil, is consistent with local sediments, which would have formed in the alluvium of the lower valley slope immediately surrounding the feature. This deposit is distinguished from the rest by its somewhat elevated sand content (42.4%) and classification as a clay loam, whereas the remaining layers were classified as clay soils. In the seven upper layers, the total sand content of sediments was relatively stable, at approximately 35% of the total.

The distribution of sand particles among the three size classes present (*very coarse*, *coarse*, and *medium-to-very-fine*) varies from layer to layer (Fig. 6). To simplify this, we have classified sands as either *well-sorted*, where the deposit is dominated over 75% by particles from one size class (i.e., sorted in to one category; leaving less than 25% other sands), or, alternatively, as *moderately sorted*.

Sands from the naturally deposited Layer VIII are moderately sorted with the highest proportion of larger sized material (coarse sands), suggesting a high-energy environment capable of carrying larger material. In Layer VII, the earliest agricultural layer, we see slightly less coarse sand and more medium-to-very-fine sand, precisely what we'd expect when water is being impounded and slow moving water carries only finer lighter sands. In Layers VI and V these finer sands dominate the deposits.

In Layers IV and III, we see increases in the proportion of coarser sands and therefore more moderately sorted sands. This shift indicates a period of higher-energy transport, which is followed in Layers II and I by a return to low-energy transport dynamics that characterized the early (Layers VII–V) part of the sequence. Hence, we can interpret the events associated with the deposition of Layers IV and III as a disturbance to a system of low-energy transport. Given that this high energy anomaly comes immediately after the apparent failure of the retaining wall, it may be that the infrastructure, as it was reconstructed, moved water through at a slightly faster rate, or that some local alluvial soils were relocated to the pondfield as a part of the rebuild.

4.3. Soil nutrients

To assess how soil nutrients were impacted over the course of the sequence we examined the raw values for key elements (Fig. 7), ratios of P, K, Ca, and Mg to Nb (Fig. 8), and the remaining % P and % Ca (Fig. 9; Table 5); factors well understood for the study area (Palmer et al., 2009). For the first measure, we looked at the raw values of P_2O_5, K_2O, MgO, and CaO from the portion of the stratigraphic section where other indicators suggest the transition to agriculture. The results show a distinct drop across the board, but these alone are a poor measure of the long term record of soil nutrient cycling.

Next, we compared average values for cations P, K, Mg, Ca ratioed to Nb, which is less mobile, to determine what this apparent

Table 4
Soil textural classes based on particle size analysis.

Layer	Sampling depth	Very coarse sand (1–2 mm)	Coarse sand (0.5–1 mm)	Med. To very fine sand (0.05–0.5 mm)	Silt (0.002-0.05 mm)	Clay (0–0.002 mm)	USDA soil classification
I	15–45	2.4	4.8	28.2	14	50.4	Clay
II	45–65	1.7	1.9	31.9	17.9	46.4	Clay
III	65–85	6.4	8.3	20.7	21.1	43.4	Clay
IV	85–95	4.9	6.4	24.1	20.1	44.3	Clay
V	95–165	3.4	4	28	18.1	46.3	Clay
VI	165–195	3.8	4	27.6	20.1	44.4	Clay
VII	195–235	4.8	11.2	19.4	17.2	47.4	Clay
VIII	235–275	8	14.1	20.3	21.2	36.4	Clay loam

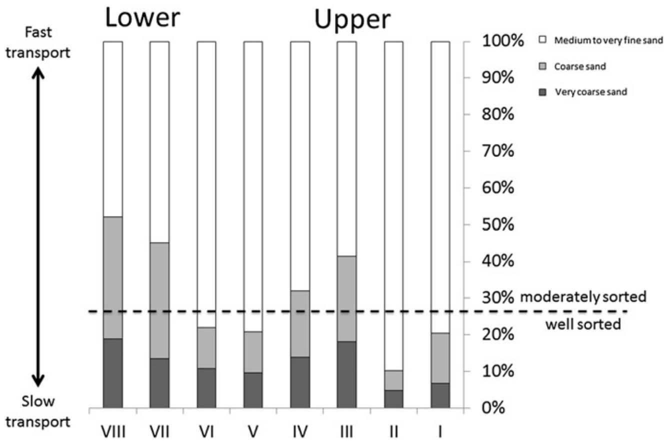

Fig. 6. Size classification of sands by layer. The "lower" soils include pre-agriculture (Ly VIII) and early agriculture (Ly VII). Note that sands more than 25% sands larger than medium size that those layers are classified as 'moderately-sorted' in comparison with those that are comprised of 'well-sorted' sands with more than 75% the smallest size category; a sign of a less energetic transportation environment (i.e., slow irrigation water).

downward trend looks like over time. In Fig. 8 we do see lower Mg:Nb and Ca:Nb over time, but P:Nb and K:Nb do not vary significantly.

For our final measure, we compare average % P and Ca remaining in small valley alluvial, slope, and shield soils (Palmer et al., 2009), with layers in HLW-29. Hawi substrate calculations provide results within the expected range of values, which is consistent with a high contribution from upslope Hawi soils. More importantly, we find that the pre-agriculture and earliest agriculture layers are most similar to alluvial soils (Fig. 9). Upper soils fall generally within the range for slope soils. This finding is consistent with analyses described above and suggests that soils within the pondfield are not terribly different from the upstream environment from which they derived.

5. Discussion

For this study, the null hypothesis was that irrigated farming had no significant impact on soils nutrients. In order to test this hypothesis, we compared pre-agricultural soil (Layer VIII) to agricultural deposits (Layers VII through I), paralleling studies from leeward Kohala where nutrient depletion in agricultural soils was detected (Kirch et al., 2005; Hartshorn et al., 2006; Meyer et al. 2007; Vitousek et al., 2004). The additive nature of the pondfield deposits, wherein agricultural layers are composed entirely of introduced sediments, means we must consider both changes in sediment source and nutrient drawdown due to farming as potential factors that influenced nutrient levels. Because it is possible to link variation in the soils to the local environment from which they were derived, we are able to be reasonably confident that the lowest layers were deposited as alluvial soils with eroded slope soils comprising the majority of the gardened deposits positioned above the pre-agricultural soils.

When examining key soil nutrients for signs of impacts from harvests we have equivocal results; P and K concentrations are stable suggesting little influence of harvesting drawdown, but Ca and Mg vary over time. The best current study of modern taro impacts on Ca and Mg, based on experimental gardens in Fiji, suggest we should expect that on average of 15 kg/ha/year of Ca and 6 kg/ha/year of Mg will have been removed (Kubuabola et al., 2000). Therefore, it remains possible that harvesting is responsible for the pattern shown here, however given the similarity of values found within different types of soils (alluvium, slope), the

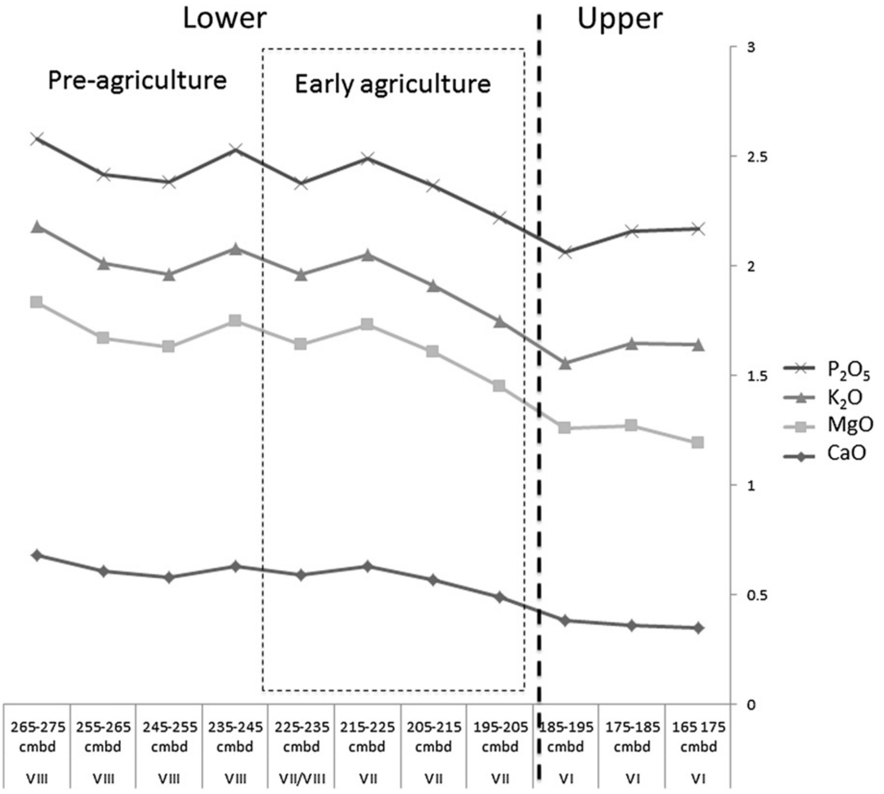

Fig. 7. Raw values (wt%) for key elements. Note the decrease after the onset of agriculture within the lower layer soils.

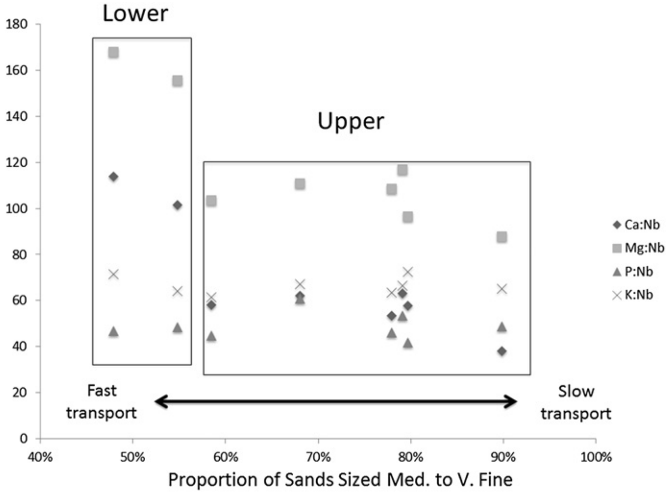

Fig. 8. Ratio of P, K, Ca, and Mg to the less mobile element Nb. Note sharp drop in Ca and Mg from lower to upper layers; the drop in P and K in raw data is unlikely to reflect history of nutrient cycling. Further, changes in nutrients are only grossly correlated with transport speed.

major change seen here is probably due to the erosion of new slope soils in to the pondfield over time.

In sum, we have failed to reject the null hypothesis. The construction of the pondfield certainly changed the depositional environment, allowing for the influx and accumulation of sediments primarily derived from valley slopes. But, we found no clear evidence that these same soils show signs of having been artificially depleted of nutrients by farming and the harvesting of taro. It is of course possible that removal of plant material did have a minor influence that we have been unable to detect due to the nature of the depositional environment. Further, early farmers may have enjoyed slightly better growing conditions as they had within the pondfield alluvial as opposed to slope soils, but this remains to be investigated.

When it comes to irrigated farming, it is important to remember that the distinction between land degradation and enhancement can be blurry (Blaikic and Brookfield, 1987), as highlighted by cases when upland clearing (Spriggs, 1985, 1997; Vitousek et al., 2010) and landslips (Kirch and Yen, 1982) on Pacific Islands cause redeposition that in effect extend the amount of prime farm land in valley bottoms. In the case presented here, soil deposition does not appear to have increased the total available irrigable land in this narrow valley, but does appear to have presented farmers with a constant engineering challenge. As the pondfield collected more and more sediment, the retaining wall was realigned and increased in height. Effort to maintain the system is also evident in repairs made after a major failure of the retaining wall. But, over the long term, these were minor and wholly predictable repairs.

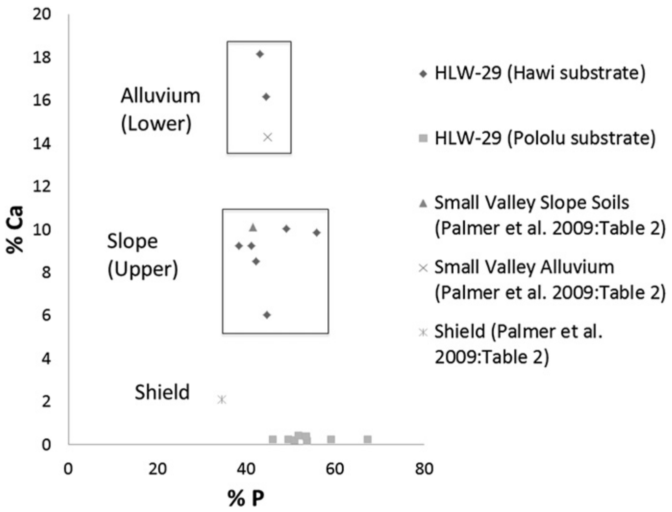

Fig. 9. Source of lower and upper layer soils. Here we show %Ca and %P remaining for alluvial, slope, and shield soils. Lower layers are most similar to alluvium, as we would expect for early deposits with a large component from local sediment. Upper layers are similar to slope soils. We suggest that the shift to from *in situ* alluvium to slope soils deposited within the pondfield explains change in soil nutrients.

Table 5
P and Ca remaining in Lower Halawa Gulch. Calculated using the method described in Palmer et al. (2009), assuming a Pololu and Hawi substrate. We note that the calculations based on Hawi are a better match to the expected both in terms of the values and in what type of soils were eroding from upstream.

Pololu substrate:	I	II	III	IV	V	VI	VII	VIII
%P remaining	46.1	53.7	49.6	67.3	59.1	50.9	53.5	51.8
%Ca remaining	0.21	0.14	0.21	0.23	0.23	0.20	0.37	0.42
Hawi substrate:	I	II	III	IV	V	VI	VII	VIII
%P remaining	38.29	44.60	41.19	55.86	49.01	42.24	44.42	42.97
%Ca remaining	9.23	6.05	9.26	9.87	10.04	8.53	16.17	18.15

What does all this tell us about the role of irrigated taro agriculture in the development of Hawaiian polities? To the degree that these results represent larger valley farming, they confirm that taro likely provided a remarkably sustainable, low investment, high return crop ideal for creating a surplus that could have been dispatched in the pursuit of political power (Earle, 2012; Kirch, 2011). It is easy to imagine that environmental degradation and significantly increased maintenance costs could have acted as counter forces to dampen efforts to push for greater production. The apparent absence of these costs may indeed have contributed to the increased scale of the political economy over time.

6. Conclusions

The analysis of a continuous sequence of irrigated agricultural development stretching from the Early Expansion Period through to the Historic Period suggests that taro farming in Hawai‘i shows no clear signs of *in situ* nutrient depletion due to harvest drawdown and that changes in soil nutrients are best explained as a consequence of soil erosion. The diminished concentrations of Ca and Mg observed in the sequence presented here can be attributed chiefly to the influx of lower nutrients in sediments derived from upslope; although we cannot completely eliminate the possibility that harvesting drawdown was a factor. Future research on how farming impacted similar pondfield systems should carefully consider the influence of sediment source in impacting the observed results.

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