

## Annals of the Association of American Geographers

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/raag20>

### A Dynamic History of Climate Change and Human Impact on the Environment from Keālia Pond, Maui, Hawaiian Islands

Stephanie Pau<sup>a</sup>, Glen M. MacDonald<sup>b</sup> & Thomas W. Gillespie<sup>b</sup>

<sup>a</sup> National Center for Ecological Analysis and Synthesis (NCEAS)

<sup>b</sup> Department of Geography, University of California, Los Angeles

Available online: 27 Feb 2012

To cite this article: Stephanie Pau, Glen M. MacDonald & Thomas W. Gillespie (2012): A Dynamic History of Climate Change and Human Impact on the Environment from Keālia Pond, Maui, Hawaiian Islands, *Annals of the Association of American Geographers*, DOI:10.1080/00045608.2011.652853

To link to this article: <http://dx.doi.org/10.1080/00045608.2011.652853>



PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.tandfonline.com/page/terms-and-conditions>

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

# A Dynamic History of Climate Change and Human Impact on the Environment from Keālia Pond, Maui, Hawaiian Islands

Stephanie Pau,\* Glen M. MacDonald,<sup>†</sup> and Thomas W. Gillespie<sup>†</sup>

\*National Center for Ecological Analysis and Synthesis (NCEAS)

<sup>†</sup>Department of Geography, University of California, Los Angeles

High-resolution palynological, charcoal, and sedimentological analysis of a sediment core from Keālia Pond, Maui, coupled with archaeological and historical records, provides a detailed chronology of vegetation and climate change since before human arrival. These records provide new evidence for human–environment linkages during the Hawaiian Polynesian period and subsequent European period. Prior to human arrival, the charcoal record indicates that native forests were subject to natural fires. A shift from dry to wet climate conditions marked the beginning of the Medieval Climate Anomaly (MCA) as evidenced by a precipitation reconstruction based on a pollen abundance index. Charcoal increases around AD 840–1140 signal the presence of Polynesians in the Keālia Pond region, but there is no evidence of rapid and extensive forest clearance immediately after Polynesian arrival. The greatest reduction in pollen diversity at Keālia Pond occurred during the European period (post 1778), at which point the pollen record indicates that montane forest taxa declined, native lowland taxa disappeared from the record, and nonnative taxa *Prosopis* and *Batis* made their first appearances. Accounts by early Europeans during the nineteenth and twentieth centuries provide a historical narrative supporting the interpretation that European impacts on vegetation were widespread, whereas in this region of Maui, Polynesian impacts on vegetation appear largely confined to the lowlands. **Key Words:** forest clearance, Hawaiian Islands, lowland dry forests, Medieval Climate Anomaly, Polynesian population growth.

从对毛伊岛Keālia池塘的沉积物岩心的高分辨率孢粉，木炭，和沉积分析，加上考古和历史记录，提供了一个自人类到来之前的植被与气候变化的详细年表。这些记录给在夏威夷的波利尼西亚期间和随后的欧洲期间人类与环境的联系提供了新的证据。在人类到来之前，木炭记录表明，天然森林遭受自然火灾。以花粉丰度指数为基础的降水重建证明，从干燥到潮湿的气候条件的转换，标志着中世纪气候异常（MCA）的开始。在约公元840-1140时期木炭的增加示意了波利尼西亚人在Keālia池塘地区的存在，但是没有证据表明在波利尼西亚抵达后存在立即迅速和广泛的森林砍伐。Keālia池塘最大的花粉多样性的减少发生在欧洲期间（1778后），在这一时期的花粉记录表明，山地森林类群下降，本土低地类群从记录中消失，外来类群牧豆和腌蓼草第一次出现。在十九世纪和二十世纪早期的欧洲人的帐户提供了一个历史叙事，支持欧洲对植被的影响是广泛的这一解释，而在毛伊岛地区，波利尼西亚对植被的影响主要局限于低地。关键词：森林砍伐，夏威夷群岛，低地干燥森林，中世纪气候异常，波利尼西亚的人口增长。

Los análisis palinológico, de carbón vegetal y sedimentológico a alta resolución de un núcleo de sedimento de Keālia Pond, Maui, junto con registros arqueológicos e históricos, permiten derivar una cronología detallada del cambio de vegetación y clima, desde antes de la llegada del hombre. Estos registros suministran nueva evidencia de los vínculos hombre-medio ambiente durante el período hawaiano-polinésico y el subsiguiente período europeo. El registro del carbón vegetal indica que, antes de la llegada del hombre, los bosques nativos estuvieron sujetos a incendios naturales. Un cambio de clima, que pasó de condiciones secas a húmedas, marca el comienzo de la Anomalía Climática Medieval (MCA), como se evidencia por una reconstrucción del cuadro de precipitaciones a base de un índice de abundancia de polen. Los aumentos de carbón vegetal durante el período que se extiende aproximadamente del año 840 hasta el 1140, indican la presencia de polinesios en la región Keālia Pond, pero no hay evidencia de una rápida y extensa eliminación del bosque inmediatamente después de la llegada de aquella gente. La más grande reducción en la diversidad del polen en la región de Keālia Pond ocurrió durante el período europeo (después de 1778, etapa en la cual el registro del polen indica una declinación de las taxa del bosque montano y las taxa nativas de las tierras bajas desaparecen del registro, en tanto que las taxas no nativas *Prosopis* y *Batis* hacen sus primeras apariciones. Los informes de los primeros europeos durante los siglos XIX y XX proveen

una narrativa histórica que apoya la interpretación de que los impactos europeos sobre la vegetación fueron vastos, en tanto que en esta isla de Maui los impactos polinesios sobre la vegetación aparecen confinados en las tierras bajas. *Palabras clave:* desmonte, islas de Hawaïi, bosques secos submontanos, Anomalía Climática Medieval, crecimiento de la población polinesia.

Today, it is unquestioned that the diversity and distribution of plant species on the Hawaiian Islands is highly modified by human impact. The alteration of the landscape began with arrival of the Polynesians by AD 800 (Kirch and McCoy 2007). Many questions remain, however, regarding the magnitude and pattern of landscape change and how environmental factors, including climate variations, might have affected Polynesian societies and land use (Kay 1994; Kirch and Hunt 1997; Nunn 1999, 2007; Stock, Coil, and Kirch 2003; Kirch et al. 2004; Vitousek et al. 2004; Kirch 2007a). Paleocological records of Polynesian impact have been developed from fossil pollen studies, but these records are few—particularly records from low elevation sites—and often represent relatively coarse temporal resolution (Athens, Ward, and Wickler 1992; Athens and Ward 1993; D. A. Burney et al. 1995; Athens 1997; Hotchkiss and Juvik 1999; D. A. Burney et al. 2001; Athens et al. 2002; L. P. Burney and Burney 2003). In addition, historical records from early European explorers and immigrants provide some evidence of the extent of Polynesian impacts on the Hawaiian Islands (e.g., Vancouver 1798) as well as major impacts by Europeans through agricultural cropping practices, livestock grazing, and the introduction of plant and animal species (Cuddihy and Stone 1990; Kay 1994).

Furthermore, Hawai'i is prone to variations in precipitation linked to large-scale changes in Pacific sea surface temperatures (SSTs). These climate variations set the conditions for vegetation growth and change, and thus establish the background of natural variability for understanding human alteration of vegetation. During the Medieval period (AD 800–1300), large-scale changes in the Pacific resulted in extensive aridity in southwestern North America that has been linked to changes in Native American settlement patterns and population sizes in areas such as California and New Mexico (T. L. Jones et al. 1999; Kennett and Kennett 2000; Reed 2004; Benson et al. 2007; MacDonald, Kremenetski, and Hidalgo 2007). How such climatic changes might have affected Polynesians in Hawai'i remains poorly resolved.

In this study we used a high temporal resolution analysis (40–120 year) of fossil pollen, charcoal, and sedimentological properties of a sediment core taken from

Keālia Pond on Maui to provide a detailed record of vegetation and climatic change from a low elevation site that extends throughout the period of Polynesian and European occupation on Hawai'i (Figure 1). Keālia Pond receives intermittent streamflow from watersheds containing lowland dry forests and montane forests. The results of the sediment core analyses were combined with information from previous archaeological studies and historical records to address three outstanding questions:

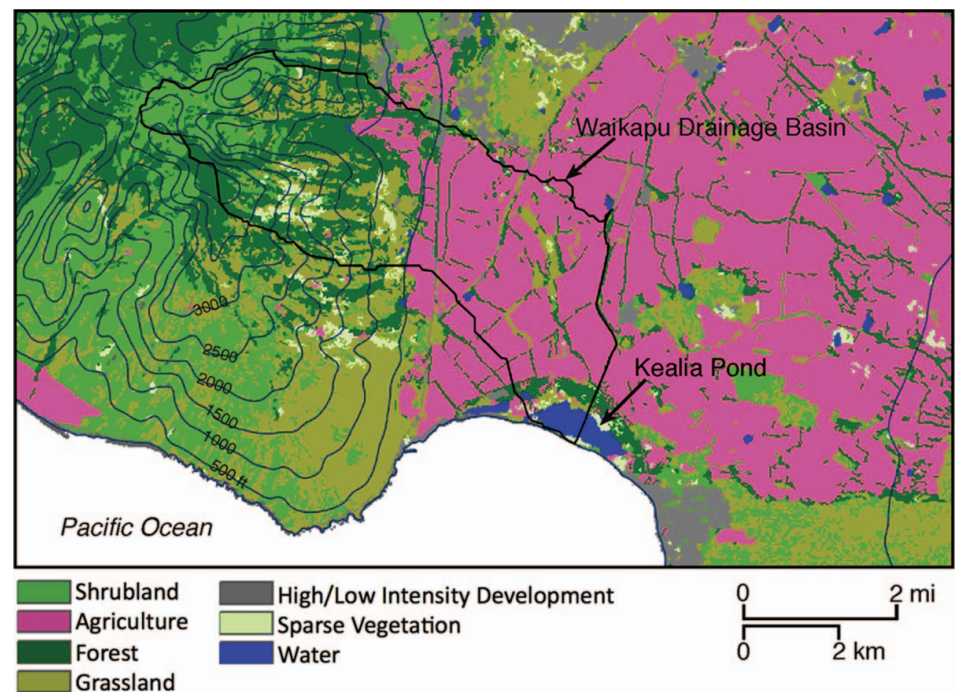
1. What climatic changes set the stage for Polynesian and European settlement and how might such changes have affected people in Hawai'i?
2. Second, what was the temporal pattern and magnitude of Polynesian modification of the forests in the Keālia Pond catchment?
3. How did Polynesian forest modification compare with subsequent European impacts?

This study shows that a shift from dry to wet climate conditions marked the beginning of the Medieval Climate Anomaly (MCA) and that this shift coincided with rapid Polynesian population growth. Contrary to the current understanding of Polynesian impact on Hawai'i, however, in the Keālia Pond record, widespread forest clearance does not immediately follow an increase in fire during the Polynesian period. The greatest reduction in pollen diversity in the Keālia Pond record occurred not during the Polynesian period but during the European period (post-1778), when higher elevation montane forest diversity began to decline as well.

## Climate Change in Hawai'i

The response of the tropical Pacific to climate variability such as the MCA (also known as the Medieval Warm Period) and El Niño-Southern Oscillation (ENSO) is an important analogy for understanding projected future climate change. The Hawaiian Islands in particular are uniquely located in a region of large-scale climate teleconnectivity in the northern tropical Pacific. Nunn (1999, 2000, 2007) has summarized extensive evidence, based primarily on temperature and sea-level change records, showing that significant

**Figure 1.** Map of the Keālia Pond region, which lies primarily within the Waikapu drainage basin (black outline). The surrounding area today encompasses agricultural land, grasslands, shrublands, and forests. Montane forest communities begin between 1,500 and 2,000 ft. elevation (Wagner, Herbst, and Sohmer 1999). Land use types and elevation contours are from the Hawai'i GAP Analysis and Hawaii State GIS program (<http://Hawaii.gov/dbedt/gis/download.htm>). (Color figure available online.)



environmental change occurred in the tropical Pacific around AD 1300 and that this change coincided with major cultural change on many Pacific Island societies. The AD 1300 event is marked by a transition from a warm dry MCA, between AD 750 and 1250, to a cool dry Little Ice Age (LIA; Nunn 2007). The Hawaiian Islands are known to experience very different climate dynamics from the entire Pacific Basin, however, as addressed by Nunn. Indeed, there is considerable evidence from the climate literature that the MCA was associated with decreasing El Niño frequency—which is consistent with the period after AD 1300 experiencing increased El Niño events as Nunn (2007) stated—or a persistent La Niña-like state (e.g., Crowley 2000; Bradley, Hughes, and Diaz 2003; Cobb et al. 2003; Mann et al. 2005). El Niño conditions are known to result in drought in Hawai'i because of weakened tradewinds as well as a strengthened Hadley cell circulation that increases subsidence over the islands (Chu 1995; Chu and Wang 1997; Chu and Chen 2005; Kolivras and Comrie 2007; Pau, Okin, and Gillespie 2010). Therefore, decreasing El Niño frequency should result in a wetter MCA in Hawai'i.

### Current Paleoecological Understanding of Polynesian–Environment Interactions

One of the best examples of human impact on the biodiversity of the Hawaiian Islands was the discov-

ery by paleontologists of numerous previously unknown and now extinct bird species. This discovery has brought the total number of extinct endemic bird species on the Hawaiian Islands to more than 50 percent of the total number of resident bird species, completely altering the previous understanding of diversity on the islands (Olson and James 1982; Christensen and Kirch 1986; Athens et al. 2002). Based on radiocarbon ages of the fossil bones and supporting evidence from the timing of endemic land snail extinctions, these bird extinctions probably occurred during the Polynesian period and have largely been attributed to habitat destruction in native lowland forests.

Since the 1980s, examples such as these have revealed that the Polynesians altered the environment of Hawai'i more severely than had previously been understood. These findings represented a shift in thinking away from the “popular orthodoxy of indigenous peoples in symbiotic ‘harmony’ with nature” (Kirch, cited in Kay 1994, 425). The current paradigm for understanding Polynesian impact on their environment has been a response to past notions of the “noble savage” (Kirch, cited in Kirch and Hunt 1997, 6) and has remained this way for the last two or three decades (see Kirch and Hunt 1997).

Paleoecological and archaeological research have since supplied numerous examples of the severity of Polynesian impact on the Hawaiian environment, often relying on the temporal relationship between charcoal

and native forest pollen decline (Athens, Ward, and Wickler 1992; Athens and Ward 1993; D. A. Burney et al. 1995; Athens 1997; D. A. Burney et al. 2001; Athens et al. 2002; L. P. Burney and Burney 2003). Burning was a primary way that Polynesians altered their environment by clearing native forests with fire for cultivation and repeated burning in slash-and-burn or shifting cultivation (Kirch 1985; Cuddihy and Stone 1990; Kirch, cited in Kay 1994). Burning did not occur everywhere, however. For example, charcoal records from Kaua'i, distributed throughout high and low elevations, provided evidence that fires during the Polynesian period were concentrated in the lowlands, with high-elevation sites relatively undisturbed (L. P. Burney and Burney 2003).

Athens (1997) provided remarkable baseline accounts of the prehuman lowland vegetation and proposed that the lowland vegetation on O'ahu has been entirely altered from its original condition, beginning around AD 800 and lasting until complete lowland deforestation by AD 1400–1500. In particular, *Pritchardia* palm forests, which are now rare in the lowlands, were once widespread with *Dodonaea viscosa* and *Kanaloa kahoolawensis* understory. *K. kahoolawensis*, once common and registering high percentages in pollen records before human arrival, is now extremely rare, existing as only two remaining plants on the island of Kaho'olawe (Lorence and Wood 1994). According to fossil pollen records from O'ahu, lowland forest decline occurred rapidly after Polynesian arrival, and in some records prior to the presence of charcoal, indicating that in addition to fire, other indirect causes such as introduced disease and seed predation by rats might have played a role in the disappearance of native forests (Athens 1997; Athens et al. 2002). Sediment cores from 'Ewa Plain, O'ahu contained evidence of forest decline before the presence of charcoal, but at the same time bones of the Polynesian-introduced rat (*Rattus exulans*) appeared in the record (Athens et al. 2002). The hypothesis linking Polynesian rats to forest decline has received recent attention as an alternate explanation for the precipitous decline of Easter Island's forest (Hunt 2007), but questions regarding the cause of Easter Island's deforestation remain unanswered (Diamond 2007).

D. A. Burney et al. (2001) documented other significant ecological changes to lowland communities using sediment records from a large sinkhole and cave system on the south coast of Kaua'i. In particular, they suggested that plant taxa now known from only higher elevation mesic-wet forests, such as *Zanthoxylum*, *Kokia*, and *Pritchardia*, were once a component of lowland plant

communities. Their study also provided evidence showing the subsequent loss of diversity in other groups, such as native land snails and birds, and the replacement of diverse native communities with an impoverished assemblage of introduced species associated with Polynesian colonization.

Anthropologist Patrick Kirch wrote that “probably 80 percent of all the lands in Hawai'i below 1,500 feet in elevation had been extensively altered by the human inhabitants” (Athens 1997, 249). Archaeologist J. Stephen Athens added to Kirch's suggestion:

While Kirch's figure of 80% may sound rather extraordinary, we now believe the true figure to be closer to 100%, if not quite 100%. This, of course, is amazing. The lowland vegetation of O'ahu was in fact completely altered from its original and pristine condition. And it has been this way since before the time Captain Cook arrived in Hawai'i in A.D. 1778. (Athens 1997, 249–50)

## Study Site

Keālia Pond National Wildlife Refuge is located along the Mā'alaea coastline of south-central shore Maui (Figure 1). A sandy beach barrier forms the southern edge of the coastal lagoon, which is approximately 2.8 km<sup>2</sup> in area when full. It lies primarily within the Waikapu watershed, with streamflow originating in the West Maui Mountains. However, it also receives intermittent flow from the Pohakea watershed in West Maui as well as the Kalialinui and Waiakoa watersheds from the slopes of Haleakala (Athens, Ward, and Tomonari-Tuggle 1996; Hawaii State GIS Program 2010). The current vegetation in the region is primarily *Batis maritima* (pickleweed) with a few isolated individuals of *Prosopis pallida* (kiawe) and *Acacia farnesiana* (klu) along the sand dunes to the south. Large sugarcane fields surround the site to the northwest.

## Methods

### Coring

We extracted a 175-cm-long sediment core from Keālia Pond, Maui, in August 2005 using a Russian corer. The core was wrapped in plastic and aluminum foil, and it was subdivided into 50 cm sections for transport. It was stored at 4°C and subsampled into continuous 1 cm<sup>3</sup> samples for pollen, charcoal, and loss-on-ignition (LOI) analyses. The core was taken from the deepest section of the lagoon in the wider northwest

area (see Figure 1), where the water depth was approximately 1 m, although no formal lake bathymetry was performed. The 175 cm core appeared to recover the full formation, with the last 2 cm ending in coarse black sand—probably volcanic—mixed with small (1–3 mm) white shell fragments.

### Pollen Analysis

We processed 1-cm<sup>3</sup> samples for pollen and pteridophyte spores by using standard procedures following Faegri, Kaland, and Kryzysinski (1989) and MacDonald et al. (1991), with the exception of acetolysis being replaced by a Schultz solution (KClO<sub>3</sub> and HNO<sub>3</sub>). Continuous samples were not always possible to count because of poor pollen preservation as well as low pollen concentration in some samples, but the temporal resolution of the pollen analysis was still relatively high, with the majority of the diagram yielding a resolution between 40 and 120 years. Pollen percentages were based on a pollen sum of at least 200 grains of terrestrial pollen and spores, excluding aquatic types, because fossil pollen concentration in Hawaiian sediment cores is typically too low to achieve higher minimum pollen sums (Athens, Ward, and Tomonari-Tuggle 1996). The average count per level was 220.6 grains. We quantified pollen concentration and accumulation rates (PAR) with the addition of a *Lycopodium* tablet during pollen processing. Taxonomic references include Selling (1946, 1947) and a reference collection at UCLA Geography. The modern pollen vouchers for the reference collection were collected from the Pacific Herbarium (BISH) in July 2006 and from wild vouchers collected in the field from 2005 to 2006.

### Charcoal and LOI Analysis

We analyzed continuous 1 cm<sup>3</sup> samples for charcoal and LOI. Standard LOI procedures were performed following Dean (1974) for estimation of organic and inorganic carbon content expressed as percentage of dry weight of each sample. Charcoal samples were pretreated with 5 percent NaHMP overnight. The sediment was passed through a 250 μm sieve into a 125 μm sieve and the resulting >125 μm fraction was counted on a grided Petri dish under a binocular microscope. Charcoal counts were expressed as concentrations (particles per unit volume) and charcoal accumulation rates (particles per cm<sup>2</sup> year<sup>-1</sup>). Following Long et al. (1998), Charcoal Analysis Programs (CHAPS) was used to interpolate concentrations into pseudo-annual intervals

(interpolated between calendar year before present [cal yr BP] dates) to produce influx values termed CHAR (particles per cm<sup>2</sup> year<sup>-1</sup>) at even aged intervals. Then CHAR values were decomposed into two components: (1) a lower-frequency background component to indicate the rate of charcoal production, charcoal that is not immediately deposited in the sediment, and charcoal from nonlocal fires (fires outside the catchment); and (2) a peaks component representing single fire events within the catchment using a threshold that is a ratio between the influx and the smoothed background component. In this case we chose a 200-year window and a 1.2 peaks threshold.

### Precipitation Reconstruction

To reconstruct precipitation we derived a pollen abundance index (PAI) from Hotchkiss and Juvik (1999) for each pollen type. PAI values (mm) were derived by using the modern precipitation of 102 surface samples from the Island of Hawai'i, where the maximum percentage of that pollen type was found. The precipitation estimate for each 1 cm<sup>3</sup> subsample was an average of PAI values for a pollen assemblage weighted by the pollen percentages (Hotchkiss and Juvik 1999). The PAI of *Pritchardia* was excluded because there is strong evidence that its current distribution is not an accurate indicator of precipitation. In the past certain species in this genus once had a lowland leeward distribution and thus they might be restricted to higher elevation wet forests in the surface samples because of human-driven extirpation (Athens 1997; D. A. Burney et al. 2001; Woodcock and Kalodimos 2005). The precipitation reconstruction based on the PAI is only reliable prior to the Polynesian arrival to Keālia Pond because human impact on vegetation complicates any climatic interpretation.

## Results

### Chronology

Four radiocarbon ages out of seven were used to establish a chronology (Table 1) based on bulk sediment, a charcoal fragment, and *Ruppia maritima* seeds (a submerged brackish water aquatic plant, identified with assistance from the National Tropical Botanical Garden Lāwa'i, Kaua'i). We used an age model that fits a previous Keālia Pond record (Athens, Ward, and Tomonari-Tuggle 1996) based on radiocarbon ages, as well as changes in pollen of *Chenopodium* or *Amaranthus*



**Table 1.** Radiocarbon ages and calibrated ages from CALIB 6.0 for Keālia Pond, Maui (Stuiver and Reimer 1993)

Depth (cm)	Material	$^{14}\text{C}$ age	$1\sigma$ calibration	Calibration type	Lab number
38–39	Bulk	$960 \pm 60$	681–798 cal yr BP	25% $\Delta R$ $110 \pm 80$	TO-12919
56–57*	Bulk	$940 \pm 20$	690–744 cal yr BP	25% $\Delta R$ $110 \pm 80$	UCIAMS-36061
69–70	Bulk	$2,640 \pm 80$	2,495–2,603 cal yr BP	25% $\Delta R$ $110 \pm 80$	TO-12918
93–94*	Bulk	$5,270 \pm 160$	5,722–6,029 cal yr BP	25% $\Delta R$ $110 \pm 80$	TO-12917
111–112*	Ruppia seeds	$3,805 \pm 15$	3,988–4,050 cal yr BP	25% $\Delta R$ $110 \pm 80$	UCIAMS-36062
120–121	Ruppia seeds	$3,540 \pm 60$	3,612–3,733 cal yr BP	25% $\Delta R$ $110 \pm 80$	TO-12916
169–170	Charcoal	$3,930 \pm 50$	4,289–4,437 cal yr BP	Int-04	Beta-216073

Note. Samples with asterisks (\*) were not included in the age model (see Results for discussion of age models and Appendix A for alternative age model, which included all samples except the extreme reversal at 93–94 cm). Cal yr BP = Calendar year before present.

pollen types (referred to as Cheno-Am because their morphologies are indistinguishable but both are herbaceous and represent dry open conditions). Alternatively, an age model that includes all radiocarbon ages, except an extreme reversal in the 93–94 cm sample (regarded as erroneous likely due to a reservoir effect caused by the assimilation of bicarbonate water from inert sources of carbon in the basin), was used for comparison and is examined in the remainder of the Results and Discussion in regard to the primary findings. The alternative age model was derived from a linear regression applied to calibrated radiocarbon ages (cal yr BP = depth (29.128);  $R^2 = 0.89$ ), which did not change the relative relationship between pollen and charcoal but shifted the timing of events earlier and during some periods altered the rate of change (see Appendix A). The most recent age of the  $1\sigma$  calibration was used for calendar years. All dates of events were interpolated; thus, the timing of events will be referred to as circa (c.) dates. The radiocarbon age calibration was done with a 25 percent mixed marine calibration curve (because of high  $^{13}\text{C}/^{12}\text{C}$  ratios) with a  $\Delta R$  value of  $110 \pm 80$  years for all samples except the charcoal sample using Mixed Marine NoHem curve in CALIB 6.0 (following Stuiver and Reimer 1993; Athens, Ward, and Tomonari-Tuggle 1996). Additional diatom results confirmed that Keālia Pond is brackish and thus a marine influence needed to be accounted for in the calibration.

## LOI

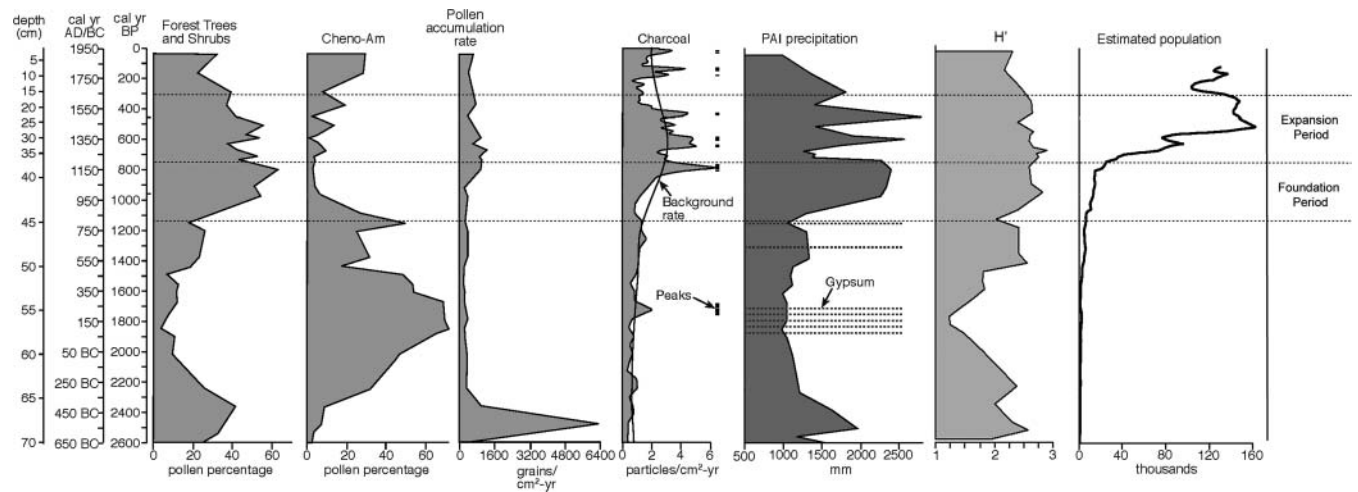
The organic and inorganic carbon content shows a high rate of variability from the bottom of the core until c. 3,000 cal yr BP, at which point the inorganic carbon content drops off abruptly, suggesting that the sand beach barrier impounding the lagoon stabilized around this time (see Appendix B). Between c. 3,000 and 1,100 cal yr BP the high-frequency variability of both the organic and inorganic carbon content declined. Begin-

ning c. 1,100 cal yr BP the organic carbon content shows a slight plateau of elevated levels of about 7 to 8 percent. The large spike in inorganic carbon c. 300 cal yr BP could have been caused by a large storm and surge of marine water carrying beach sands or a concentration of shell fragments.

## Charcoal

Polynesian arrival to the Keālia Pond region is inferred by a large charcoal peak (total influx under the peak =  $268.4 \text{ particles/cm}^2$ ) c. 810 cal yr BP (AD 1140), consistent with archaeological data (Figure 2). The largest charcoal peak in the alternative age model yields an earlier date of c. 1,110 cal yr BP (AD 840; see Appendix A). The charcoal record during this period also shows a general increase in the background rate of charcoal, indicating a mean state of change. Charcoal peaks average 2.57 per century after human arrival. Peaks in the charcoal record represent local fires, which are not present for several hundred years just prior to Polynesian arrival. The previous peak c. 1,760 cal yr BP (AD 190) is most likely too early to be a signal of Polynesian activity (Kirch 1985; Hunt and Holsen 1991; Athens et al. 2002; L. P. Burney and Burney 2003) and is a smaller peak (total influx under the peak =  $129.0 \text{ particles/cm}^2$ ). Fire activity remains high until c. 430 cal yr BP (AD 1520); thus, the major Polynesian period as evidenced by increased fires persists for about 380 years. Following this activity there is a reduction in charcoal levels for about 240 years, between c. 420 and 190 cal yr BP (AD 1530–1760). Fire activity resumes at the top of the core during the European period, but these fires are not as large as previous ones (total influx under largest peak =  $105.4 \text{ particles/cm}^2$ ) or, due to differences in fuel, did not produce as much charcoal.

Prior to human arrival (AD 840–1140), the charcoal record indicates that native forests were subject to natural fires (see Appendix B). From the base of the core



**Figure 2.** Relationship among vegetation change, fire, precipitation variability, and Polynesian cultural history. The precipitation reconstruction is based on a pollen abundance index (PAI) from Hotchkiss and Juvik (1999). A dry period is evident from c. 400 BC to AD 850, followed by a sustained increase in precipitation evident c. AD 950 to 1250. The Shannon–Wiener diversity index ( $H'$ ) for pollen types increases with increases in precipitation, which coincided with rapid archipelago-wide Polynesian population growth rates (modified from Dye and Komori 1992, no data before c. 100 AD) during the Foundation Period in Polynesian cultural history (AD 800–1200; Kirch and McCoy 2007).

to Polynesian arrival, charcoal peaks average 1.86 per century, most likely ignited by volcanic activity or lightning. Although this rate is lower on average compared to the rate observed after human arrival, the first 2,000 years of the record appear to be a period of frequent fires. Between c. 4,500 and 2,700 cal yr BP (2550–750 BC), peaks per century average 2.83, which is slightly higher than during the period of human occupation. Peaks are identified by a threshold ratio of the raw influx (particles/cm<sup>2</sup> year) and background component, however, and the background component (raw influx smoothed to a 500-year moving average) is highest after human arrival. Between c. 2,700 and 810 cal yr BP (750 BC–AD 1140) charcoal peaks average 0.95 per century, and it appears that fires subside.

### Precipitation Reconstruction

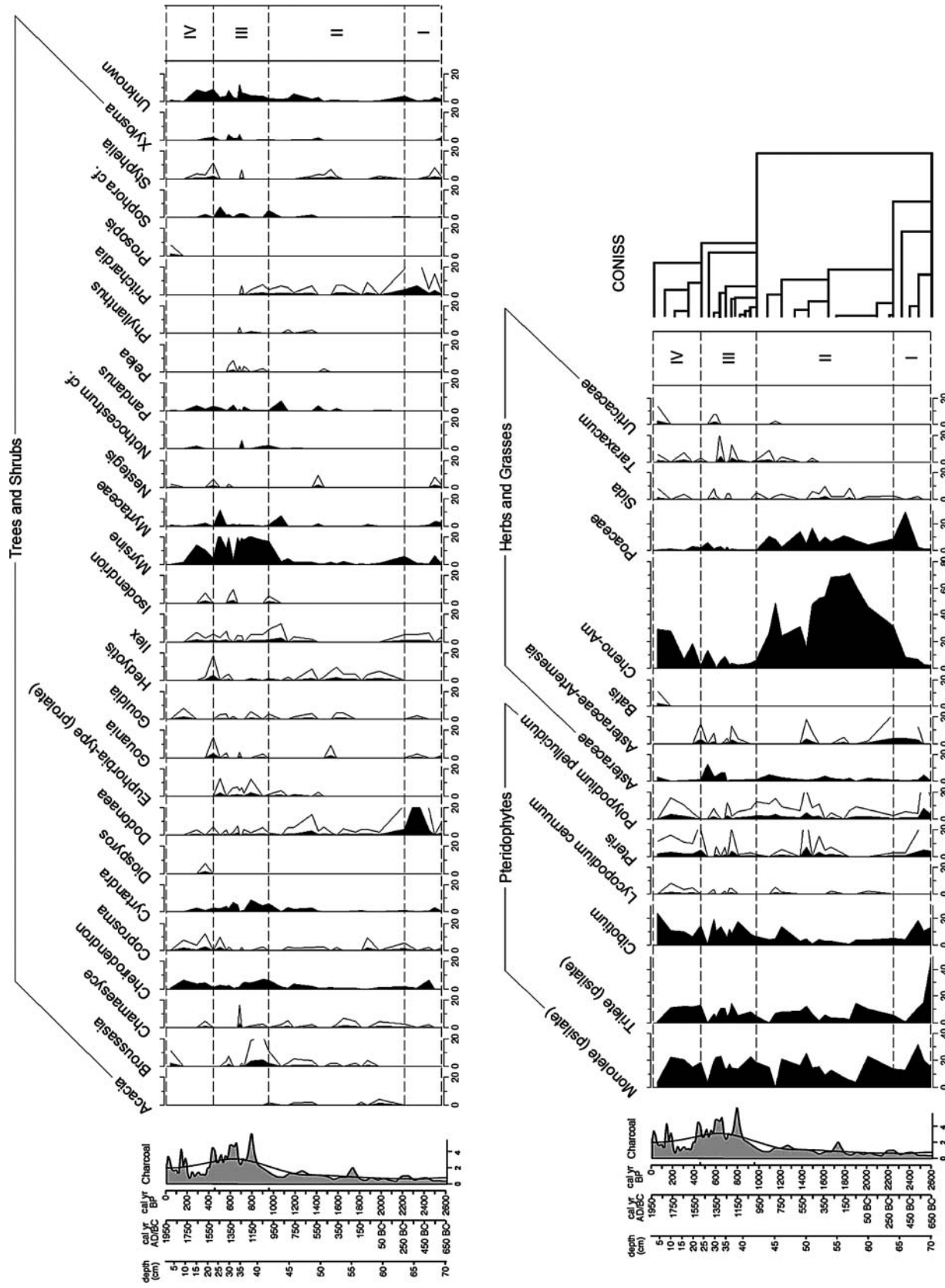
The precipitation reconstruction indicates that precipitation was relatively low until about c. 1,150 cal yr BP (AD 800), after which precipitation rose sharply to a sustained peak lasting until c. 700 cal yr BP (AD 1250; Figure 2). This peak lasted for roughly 300 years, from c. 1,000 to 700 cal yr BP (AD 950–1250), and then became highly variable, most likely because of Polynesian influence on the vegetation; thus, it is not a climate signal. Additionally, gypsum, an evaporite that forms during dry conditions independent of pollen, was present throughout the sediment core until the sharp rise in

precipitation when it ceased to form at the site. The alternative age model results in dry conditions occurring between c. 1,800 and 1,250 cal yr BP (AD 150–700) followed by a shift to wetter climate occurring between c. 1,139 and 994 cal yr BP (AD 811–956).

### Pollen Analysis

Pollen analysis was limited to c. 2,600 cal yr BP (the first 70 cm) because of the apparent time it took for the stabilization of the beach barrier in front of the pond, which limited marine influence (see LOI results). This date is generally consistent with the interpretation by Athens, Ward, and Tomonari-Tuggle (1996) of the date of stabilization. Sixty-nine pollen and spore types were identified in the Keālia Pond pollen record (from c. 2,600 cal yr BP; Figure 3). No individual unknown or indeterminable pollen type exceeded 2 percent, and total unknown or indeterminable pollen types did not exceed 9 percent except for one sample (12 percent unknown or indeterminable). Four pollen zones were identified using a constrained incremental sum of squares cluster analysis. Zone I, c. 2,603 to 2,253 cal yr BP (653–303 BC), the basal portion of the core, begins with a diverse pollen spectra of primarily mesic-wet forest taxa, such as *Cibotium*, *Cheirodendron*, *Cyrtandra*, *Freycinetia arborea*, *Ilex anomala*, *Myrsine*, and *Myrtaceae* (probably *Metrosideros*), but also including dry-mesic taxa such as *Pritchardia* (which could be considered





**Figure 3.** Pollen diagram from Kealia Pond showing major taxa (>3 percent) from 2,600 cal yr BP. Note changes in x axis. Solid black fill shows pollen percentages and black unfilled lines represent an exaggeration of pollen percentages by eight times.

mesic-wet as well) and *Nestegis sandwicensis*. The palynoflora of the latter part of this zone suggests establishment of much drier conditions. The spectra is dominated by high percentages of grass pollen (Poaceae) and the commonly low-elevation shrub taxon *Dodonaea viscosa*—both reaching their highest percentages in this zone at 29 percent and 28 percent, respectively—and more than 4 percent *Artemesia*, whereas many but not all of the forest taxa decline. Zone II, c. 2,253 to 973 cal yr BP (303 BC–AD 977), is characterized by a high percentages of the Cheno-Am pollen type (between 15 and 71 percent), very likely *Chenopodium oahuensis*—an herbaceous species that occurs in open dry habitats—in addition to Poaceae (2–17 percent), also indicative of a dry, open habitat. Distinct gypsum layers throughout Zone II, another indication of dry conditions, match peaks in Cheno-Am percentages. There are several dry-mesic forest taxa present during this period, such as *Acacia koa*, *Chamaesyce*, *Hedyotis*, and *Pritchardia*, but none achieve dominance in the pollen spectra during this zone. Zone III, c. 973 to 451 cal yr BP (AD 977–1499), is the beginning of the Polynesian period. Here the pollen reaches its greatest diversity, dominated by mesic-wet forest taxa but highly dynamic. *Cibotium*, *Broussaisia*, *Cheirodendron*, *Cyrtandra*, c.f. *Euphorbia*, *Gouania*, *Hedyotis* (*Gouldia*-type), *I. anomala*, *Myrsine*, and *Pandanus tectorius* and *Xylosma* (in one interval *Sesbania* reaches 4 percent, assumed to be *S. tomentosa* because the only other species *S. sesban* is naturalized and listed only on Kaua'i and O'ahu; Wagner, Herbst, and Sohmer 1999) increase, whereas Cheno-Am and Poaceae decline. Early during this zone, *A. koa* pollen disappears from the record, and near the end of the zone, *Pelea*, *Phyllanthus distichus*, and *Pritchardia* all disappear from the record as well. Zone IV, c. 451 cal yr BP to present (AD 1499–present), is similar to the previous zone but less diverse. There is a general increase in Cheno-Am pollen, although the short-term pattern is highly variable. Near the very top of Zone IV during the European period, the forest taxa decline, with the exception of *Cibotium* (15–24 percent) and Cheno-Am, with percentages that remain high (28–29 percent).

## Discussion

### Climate Variability and Cultural Change

Over the last 2,500 years that span this record there have been two major climatic events: first the MCA (AD 800–1300), followed by the LIA (AD 1400–1850). The extent of these events and the regional effects in

the tropical Pacific are uncertain, however (Hughes and Diaz 1994; Bradley, Hughes, and Diaz 2003; Cobb et al. 2003; Sachs et al. 2009). Climate dynamics during these events have relevance for understanding future climate change because they elucidate underlying mechanisms for predicting future change. Increased rainfall during the MCA in Hawai'i supports the evidence that climate dynamics during the MCA was consistent with decreasing El Niño frequency or a persistent La Niña-like state (e.g., Crowley 2000; Bradley, Hughes, and Diaz 2003; Cobb et al. 2003; Mann et al. 2005). It is possible that wet conditions evidenced at Keālia Pond might have been regionally isolated and decoupled from broader climate patterns elsewhere on the islands if, for example, an increase in Kona storms or wintertime extratropical cyclones brought heavy rainfall to the leeward side of Maui but not to all of the Hawaiian Islands. The precipitation reconstruction provides evidence of a sustained increase in precipitation during the MCA between c. AD 950 and 1250, after a dry period from c. 400 BC to AD 850. The presence of gypsum during the dry period and an increase in pollen accumulation rates during the MCA provides supporting evidence—independent of pollen—of a shift from dry to wetter conditions during the MCA. The alternative age model results in wetter conditions occurring between c. AD 800 and 950, which is earlier in the MCA period, following a dry interval from c. AD 150 to 700. Forest pollen remains high and large peaks in precipitation, which are more protracted in the alternate age model, are evident until c. AD 1350 (see Appendix A), however. The charcoal record indicates the presence of humans just prior to large and rapid variability in the precipitation reconstruction, most likely the consequence of Polynesian modification of the vegetation through fire because the precipitation is based on pollen percentages. Whereas reductions in native forests are a known consequence of Polynesian modification of the landscape, peaks in forest pollen and the reconstructed precipitation are not likely the result of Polynesian impact. An increase in forest resources during this wet climate interval coincided with rapid Polynesian population growth (Figure 2).

Finally, it should be mentioned that a severe drought was described in the journal of John Whitman in 1806, during a major climate anomaly associated with higher El Niño variability (Stahle et al. 1998; P. D. Jones and Mann 2004; D'Arrigo et al. 2005):

In 1806 these Islands were visited by a severe calamity. I am informed by a respectable American who lived at

that time on the Island of Mowee that no rain fell on that Island from October to April of the succeeding year, consequently almost every thing that could support life was destroyed . . . The natives reduced almost to skeletons were to be seen groping among the rocks eagerly scratching up the soil and seizing with avidity any thing that would administer relief to their famished bodies. The usually abundant streams of water that descend of the mountains were so reduced that to find in any place the amount of a cocoa nut shell of water was a luxury. Great numbers of the natives perished literally of starvation and thirst, even the trees on the mountains assumed a sickly yellow hue, when at last a deep blue cloud was seen hanging on the horizon with a promise of rain the frantic joy of the suffering natives knew no bounds. (Holt 1979, 65–66)

### Pre-Polynesian Vegetation and Vegetation Change during the Polynesian and European Period

This high-resolution record from Keālia Pond reveals a highly dynamic history of changes in the pollen diversity, composition, and vegetation structure. During the roughly 500 years prior to the Polynesian period, background levels of charcoal were low and no large fires appear to have occurred within the watershed, although results indicate there were occasionally large fires early in the record. Prior to the Polynesian period, the Keālia Pond region appears to have been comprised of diverse dry forest taxa dominated by *Pritchardia*, *Dodonaea*, and *Acacia* as well as mesic-wet forest taxa in the nearby montane environments dominated by *Myrsine*, *Cibotium*, *Cyrtandra*, *Cheirodendron*, and *Broussaisia* (in order of decreasing pollen percentages). There was a conspicuous absence of *Kanaloa* in the record, which has been repeatedly documented in fossil pollen records as a complement to *Pritchardia*-*Dodonaea* communities (e.g., Athens 1997). A pollen reference could not be obtained for *Kanaloa*, and confident identifications based on photographs and descriptions could not be made. Many of the unknown or indeterminable pollen types were small tricolporate grains that could likely have been *Kanaloa* (the majority of the rest of the unknown or indeterminable pollen types were pteridophytes).

The presence of Polynesians in the Keālia Pond region is inferred by charcoal peaks c. AD 840 to 1140, which correspond to the Foundation Period (AD 800–1200) in Polynesian cultural history (Kirch and McCoy 2007) and a period of rapid population growth beginning c. AD 1110 (Figure 2; Dye and Komori 1992; for recent review of dating habitation sites in Hawaiian prehistory; see Dye 2009). These dates are consistent with the known history of Polynesian settlement

because initial settlement was primarily confined to windward valleys, whereas dry leeward regions were settled after AD 1200 during the Expansion Period (Kirch 1985, 1994).

In contrast to other charcoal records from O'ahu and Kaua'i (Athens 1997; L. P. Burney and Burney 2003), this record shows that the forests of Maui had been subject to fire prior to human arrival (AD 840–1140); thus the fire activity of Polynesians was not unprecedented here as previously hypothesized for the islands. Throughout much of the Polynesian period, the native forests in the pollen catchment area for the pond appear to be relatively diverse and resilient to fire because high pollen percentages of different forest taxa are present, even when fire activity increased dramatically (and this relationship between charcoal and pollen does not change using different age models; Figure 2). It is possible that increases in charcoal during this time are the result of an increase in available biomass to burn during forest resurgence, but this relationship between forest pollen and charcoal is not consistent during other periods of forest dominance, such as c. 2,400 cal yr BP when there is no correspondingly high influx of charcoal.

The end of intense Polynesian fire activity marked by a sustained decrease in charcoal around c. AD 1520 coincides with similar decreases evident in charcoal stratigraphies from Kaua'i (L. P. Burney and Burney 2003). L. P. Burney and Burney (2003) hypothesized that settlement was too dense by c. AD 1600 for continued burning. Records from O'ahu (Athens 1997) also show a pre-European decline in charcoal, although this occurred earlier (c. AD 1200). Using the alternative age model, this decrease in charcoal at Keālia Pond begins around AD 1350, which falls between findings from previous records. Nonetheless, a drop in fire activity between Polynesian and European settlement is consistently reported. Athens (1997) suggested that this late decline in charcoal signals the complete deforestation of the lowlands resulting in no available biomass to burn.

Only some plants appear to decline during the period of intense Polynesian burning based on the pollen evidence. The diverse dry-mesic-wet forest taxa probably represent a mixed signal from the immediate vicinity of Keālia Pond as well as lower and higher montane forests (above 500 m or 1,640 ft; see Figure 1). There is a clear reduction in the pollen of *Pritchardia* soon after the first charcoal peak, indicating that it was in the immediate vicinity of Keālia Pond. This interpretation is consistent with previous work showing that *Pritchardia* was

once a substantial component of lowland forests and heavily affected by Polynesians (Athens 1997; D. A. Burney et al. 2001; Woodcock and Kalodimos 2005). In addition, *Pelea* and *Phyllanthus* disappear completely from the pollen record around this time, suggesting that they might have once been a component of lowland forest, although their establishment prior to their disappearance is not clear because they occurred in low percentages. Yet other lowland taxa, such as *Diospyros*, *Dodonaea viscosa*, and *Nestegis sandwicensis*, are present during the Polynesian period (disappearing c. AD 1600 or later in the case of *N. sandwicensis*). *Acacia koa* declines about 172 years prior to the first charcoal peak, indicating that causes other than fire—such as seed predation by rats as proposed by Athens et al. (2002) and Hunt (2007)—might be what contributed to its decline. Therefore, extensive lowland forest clearance does not occur until c. AD 1600, well after Polynesian settlement and later than what has been documented on O'ahu (Athens 1997). Using the alternative age model, the timing of this late decline in forest taxa does not change substantially (although the rate of change appears slower).

The late decline of forest taxa occurred when fire activity around Keālia Pond tapered off (Figure 2). An alternative hypothesis to fire as the primary agent for forest decline is that the numerous native lowland bird extinctions dated during the Polynesian period (Olson and James 1982) could have played a role in the degradation of native forest functions, such as pollination and dispersal. The degradation of native forest might have lagged considerably behind the beginning of avifauna extinctions because the loss of native pollinators and dispersers would result in a slow, rather than rapid, decline of forest functions and regeneration. Additionally, the rat predation might have been an alternative cause of forest decline, although it is not clear why rat predation would lag behind Polynesian arrival because the effects of rat predation were documented soon after Polynesian arrival yet before the effects of fire (Athens et al. 2002; Hunt 2007). Long-term aridity could also result in forest decline; however, the precipitation reconstruction in this study is based on pollen, and there is no gypsum present in the sediment core during this period, which would be the only independent indication of aridity.

Almost all forest taxa disappear during the European period (post-1778), and this is when the most severe reduction in pollen diversity occurred, probably representing the decline of montane forests in addition to the lowland regions that were affected during the Polyne-

sian period (Figure 2). *Cibotium* and *Cheirodendron* are the only two taxa that remain above 5 percent and are eventually replaced by high percentages of Cheno-Am, as well as European introductions *Prosopis* and *Batis*. Expanding agricultural production, the introduction of plants and animals, and logging for trade are examples of European changes that radically altered the diversity and distribution of vegetation (Cuddihy and Stone 1990; Cuddihy and Stone, cited in Kay 1994). Sinclair (1885), an early skeptic of the survival of the native flora, noted the rapidity and large extent of change during this time: "Forest fires, animals, and agriculture, have so changed the islands, within the last fifty or sixty years, that one can now travel for miles, in some districts, without finding a single indigenous plant" (Introduction).

An examination of primary accounts by European explorers, botanists, and other visitors during the nineteenth century points specifically to the introduction of grazing animals—most notably cattle—as responsible for the unprecedented accelerated pace and extent of environmental change. Captain George Vancouver was the first to bring cattle to the Hawaiian Islands in February 1793 at Kealakakua Bay, Hawai'i, in the hopes of establishing a breeding population as a gift to the Hawaiians (Vancouver 1798). King Kamehameha I placed a *kapu* (taboo) on the cattle for almost thirty years to allow the population to grow (Kramer 1971; Cuddihy and Stone 1990). Many early Europeans observed this population growth. Whitman, between 1813 and 1815, lamented in his journal that cattle occur in "large drives" (Holt 1979), Macrae (1972) mentioned the presence and great numbers of cattle several times in his diary from 1825, Ellis (1826) remarked on the "immense herds" of cattle, and by 1856 botanist William Hillebrand announced that "of all the destroying influences man brings to bear on nature, cattle is the worst" (Baldwin and Fagerlund 1943, 188). Later, the destruction caused by cattle was referenced by Isabella Bird in 1875, who concluded in *Six Months in the Sandwich Islands* that "The forests, which are essential to the well-being of the islands, are disappearing in some quarters, owing to the attacks of grub, as well as the ravages of cattle" (Bird 1966, 269). In 1853, George Bates, a visitor to Maui, described the region behind Keālia Pond as a cattle pasture (Bates 1854, 309). Kramer (1971) included a chapter on feral cattle in his book and compiled various sources from the late nineteenth and early twentieth centuries to describe the consensus that cattle were severely damaging the forests of Hawai'i, with a few specific mentions of Maui.

During the early twentieth century, the role of cattle in degrading native forests was well known by foresters in Hawai'i, and the first quantitative estimates of forest loss began to be made (see Cuddihy and Stone 1990). Other significant ecological changes during the early twentieth century included the widespread planting of invasive tree species by early foresters. This was done for the purpose of protecting watersheds primarily in the interest of the sugarcane industry (Woodcock 2003).

## Conclusion

The last twenty or thirty years of research has sought to confirm the severity of Polynesian impact on the Hawaiian Islands. Indeed, there is no doubt that the Polynesians altered the native landscape in ecologically significant ways. Yet in the Keālia Pond record, forest clearance does not immediately follow an increase in fire during the Polynesian period. Lowland dry forest taxa such as *Diospyros*, *Dodonaea viscosa*, and *Nestegis sandwicensis* are present throughout much of the Polynesian period (declining c. AD 1600 or later), whereas previous records on O'ahu indicate that by AD 1400 to 1500 the lowlands were completely deforested. The greatest reduction in pollen diversity in the Keālia Pond record occurred not during the Polynesian period but during the European period (post-1778), when higher elevation montane forest diversity began to decline as well. Primary accounts by early Europeans during the eighteenth and nineteenth centuries provide a historical narrative that supports the paleo-evidence that European impacts on vegetation were extensive whereas Polynesian impacts appear largely confined to the lowlands. Furthermore, this record provides strong evidence of a shift from dry to wet climate conditions during the beginning of the MCA in a region where there is currently a lack of high-resolution climate records. This study provides a new understanding of Polynesian impact on the environment, which might not have been as rapid, severe, or widespread as previously concluded, as well as environmental impacts on Polynesian demography and cultural development.

## Acknowledgments

We thank our anonymous reviewers for comments on an earlier version of this article. We also thank the Keālia Pond National Wildlife Refuge, and particularly Glynnis Nakai, for assistance and granting us permission

to do research at Keālia Pond. We thank Clyde Imada and Napua Harbottle at the Bishop Museum for permission to examine herbarium specimens for taxa identification. We thank J. Stephen Athens, Sara Hotchkiss, and Jonathan Price. We also thank James Regetz (National Center for Ecological Analysis and Synthesis) for assistance with the figure in Appendix A. This research was funded by the National Science Foundation (NSF) Grant BCS0455052, UCLA Department of Geography, UCLA Stephen A. Varva Fellowship, NASA Earth System Science Fellowship, and the UCLA Dissertation Year Fellowship. This manuscript was completed while Stephanie Pau was at the Department of Geography, University of California, Los Angeles; revisions were completed while Stephanie Pau was a Postdoctoral Associate at the National Center for Ecological Analysis and Synthesis, a Center funded by NSF (Grant #EF-0553768), the University of California, Santa Barbara, and the State of California.

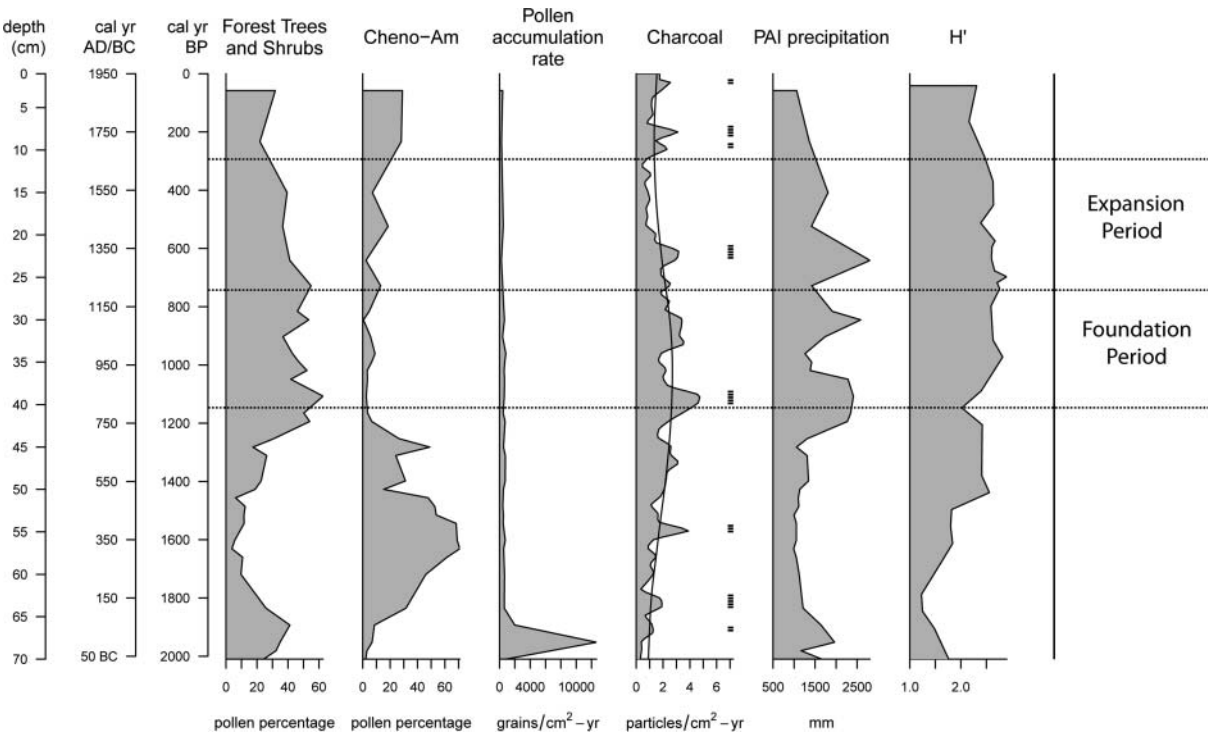
## References

- Athens, J. S. 1997. Hawaiian native lowland vegetation in prehistory. In *Historical ecology in the Pacific Islands*, ed. P. V. Kirch and T. L. Hunt, 248–70. New Haven, CT: Yale University Press.
- Athens, J. S., H. D. Tuggle, J. V. Ward, and D. J. Welch. 2002. Avifaunal extinctions, vegetation change, and Polynesian impacts in prehistoric Hawai'i. *Archaeology in Oceania* 37:57–58.
- Athens, J. S., and J. V. Ward. 1993. Environmental change and prehistoric Polynesian settlement in Hawai'i. *Asian Perspectives* 32:205–23.
- Athens, J. S., J. V. Ward, and M. J. Tomonari-Tuggle. 1996. *Archaeological inventory survey and paleoenvironmental coring for kiosks, boardwalk and parking areas, Keālia Pond National Wildlife Refuge, Kihei, Maui, Hawai'i*. Honolulu, HI: International Archaeological Research Institute.
- Athens, J. S., J. V. Ward, and S. Wickler. 1992. Late Holocene lowland vegetation, O'ahu, Hawai'i. *New Zealand Journal of Archaeology* 14:9–34.
- Baldwin, P. H., and G. O. Fagerlund. 1943. The effect of cattle grazing on koa reproduction in Hawai'i National Park. *Ecology* 24:118–22.
- Bates, G. W. 1854. *Sandwich Island notes by a Haole*. New York: Harper & Brothers.
- Benson, L. V., M. S. Berry, E. A. Jolie, J. D. Spangler, D. W. Stahle, and E. M. Hattori. 2007. Possible impacts of early-11th-, middle-12th-, and late-13th-century droughts on western Native Americans and the Mississippian Cahokians. *Quaternary Science Reviews* 26:336–50.
- Bird, I. L. 1966. *Six months in the Sandwich Islands*. Honolulu: University of Hawai'i Press.
- Bradley, R. S., M. K. Hughes, and H. F. Diaz. 2003. Climate in medieval time. *Science* 302:404–05.

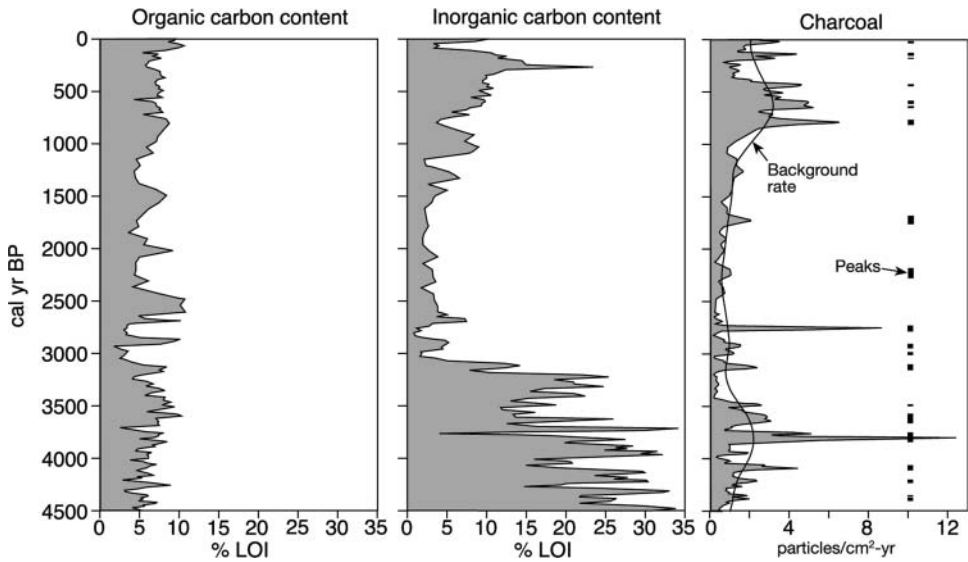
- Burney, D. A., R. V. DeCandido, L. P. Burney, F. N. Kostel-Hughes, T. W. Stafford, Jr., and H. F. James. 1995. A Holocene record of climate change, fire ecology, and human activity from Flat Top Bog, Maui. *Journal of Paleolimnology* 13:209–17.
- Burney, D. A., H. F. James, L. P. Burney, S. L. Olson, W. Kikuchi, W. L. Wagner, M. Burney, et al. 2001. Fossil evidence for a diverse biota from Kauai and its transformation since human arrival. *Ecological Monographs* 71:615–41.
- Burney, L. P., and D. A. Burney. 2003. Charcoal stratigraphies for Kauai and the timing of human arrival. *Pacific Science* 57:211–26.
- Christensen, C. C., and P. V. Kirch. 1986. Nonmarine mollusks and ecological change at Barbers Point, O'ahu, Hawai'i. *Bishop Museum Occasional Papers* 26:52–80.
- Chu, P. S. 1995. Hawai'i rainfall anomalies and El Niño. *Journal of Climate* 8:1697–1703.
- Chu, P. S., and H. Chen. 2005. Interannual and interdecadal rainfall variations in the Hawaiian Islands. *Journal of Climate* 18:4796–4813.
- Chu, P. S., and J. Wang. 1997. Tropical cyclone occurrences in the vicinity of Hawai'i: Are the differences between El Niño and non-El Niño years significant? *Journal of Climate* 10:2683–89.
- Cobb, K. M., C. D. Charles, H. Cheng, and R. L. Edwards. 2003. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature* 424:271–76.
- Crowley, T. J. 2000. Causes of climate change over the past 1000 years. *Science* 289:270–77.
- Cuddihy, L. W., and C. P. Stone. 1990. *Alteration of native Hawaiian vegetation*. Honolulu: Cooperative National Park Resources Studies Unit, University of Hawai'i.
- D'Arrigo, R. A., E. R. Cook, R. J. Wilson, R. Allan, and M. E. Mann. 2005. On the variability of ENSO over the past six centuries. *Geophysical Research Letters* 32:L03711.
- Dean, W. E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *Journal of Sedimentary Research* 44:242–48.
- Diamond, J. 2007. Easter Island revisited. *Science* 317:1692–94.
- Dye, T. 2009. *Traditional Hawaiian surface architecture*. Honolulu: Society for Hawaiian Archaeology.
- Dye, T., and E. Komori. 1992. A pre-censal population history of Hawai'i. *New Zealand Journal of Archaeology* 14:113–28.
- Ellis, W. 1826. *Narrative of a tour through Hawai'i, or Owyhee; with remarks on the history, traditions, manners, customs, and language of the inhabitants of the Sandwich Islands*. London: H. Fisher, Son, and P. Jackson.
- Faegri, K., P. E. Kaland, and K. Kryzwiniski. 1989. *Textbook of pollen analysis by Knut Faegri and Johs. Iversen*. 2nd ed. Chichester, UK: Wiley.
- Hawaii State GIS Program. 2010. <http://Hawaii.gov/dbedt/gis/> (last accessed 2 February 2010).
- Holt, J. D., ed. 1979. *The Hawaiian journal of John B. Whitman 1813–1815: An account of the Sandwich Islands*. Honolulu, HI: Topgallant.
- Hotchkiss, S., and J. O. Juvik. 1999. A Late-Quaternary pollen record from Ka'au Crater, O'ahu, Hawai'i. *Quaternary Research* 52:115–28.
- Hughes, M. K., and H. F. Diaz. 1994. Was there a “Medieval Warm Period,” and if so, where and when? *Climatic Change* 26:109–42.
- Hunt, T. L. 2007. Rethinking Easter Island's ecological catastrophe. *Journal of Archaeological Science* 34:485–502.
- Hunt, T. L., and R. M. Holsen. 1991. An early radiocarbon chronology for the Hawaiian Islands: A preliminary analysis. *Asian Perspectives* 30:147–61.
- Jones, P. D., and M. E. Mann. 2004. Climate over past millennia. *Reviews of Geophysics* 42:RG2002.
- Jones, T. L., G. Brown, L. M. Raab, J. McVicar, G. Spaulding, D. J. Kennett, A. York, and P. L. Walker. 1999. Environmental imperatives reconsidered: Demographic crises in western North America during the Medieval Climatic Anomaly. *Current Anthropology* 40:137–56.
- Kay, A., ed. 1994. *A natural history of the Hawaiian Islands: Selected readings II*. Honolulu: University of Hawai'i Press.
- Kennett, D. J., and J. P. Kennett. 2000. Competitive and cooperative responses to climatic instability in Southern California. *American Antiquity* 65:379–95.
- Kirch, P. V. 1985. *Feathered gods and fishhooks: An introduction to Hawaiian archaeology and prehistory*. Honolulu: University of Hawai'i Press.
- . 1994. *The wet and the dry: Irrigation and agricultural intensification in Polynesia*. Chicago: University of Chicago Press.
- . 2007a. Hawai'i as a model system for human ecodynamics. *American Anthropologist* 109:8–26.
- . 2007b. Paleodemography in Kahikinui, Maui. In *The growth and collapse of Pacific Island societies: Archaeological and demographic perspectives*, ed. P. V. Kirch and J. Rallu, 90–107. Honolulu: University of Hawai'i Press.
- Kirch, P. V., A. S. Hartshorn, O. A. Chadwick, P. M. Vitousek, D. R. Sherrod, J. Coil, L. Holm, and W. D. Sharp. 2004. Environment, agriculture, and settlement patterns in a marginal Polynesian landscape. *Proceedings of the National Academy of Sciences* 101:9936–41.
- Kirch, P. V., and T. L. Hunt, eds. 1997. *Historical ecology in the Pacific Islands: Prehistoric environmental and landscape change*. New Haven, CT: Yale University Press.
- Kirch, P. V., and M. D. McCoy. 2007. Reconfiguring the Hawaiian cultural sequence: Results of re-dating the Halawa dune site (MO-A1–3), Moloka'i Island. *Journal of the Polynesian Society* 116:385–406.
- Kolivas, K. N., and A. C. Comrie. 2007. Regionalization and variability of precipitation in Hawai'i. *Physical Geography* 28:76–96.
- Kramer, R. J. 1971. *Hawaiian land mammals*. Rutland, VT: Charles E. Tuttle.
- Long, C. J., C. Whitlock, P. J. Bartlein, and S. H. Millsaugh. 1998. A 9,000-yr fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forest Research* 28:774–87.
- Lorence, D. H., and K. R. Wood. 1994. *Kanaloa*, a new genus of Fabaceae (Mimosoideae) from Hawaii. *Novon* 4:137–45.
- MacDonald, G. M., K. V. Kremenetski, and H. G. Hidalgo. 2007. Southern California and the perfect drought: Simultaneous prolonged drought in southern California and the Sacramento and Colorado River systems. *Quaternary International* 188:11–23.
- MacDonald, G. M., C. P. S. Larsen, J. M. Szeicz, and K. A. Moser. 1991. The reconstruction of boreal forest fire

- history from lake sediments: A comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Reviews* 10:53–71.
- Macrae, J. 1972. *With Lord Byron at the Sandwich Islands in 1825: Being extracts from the MS diary of James Macrae, Scottish botanist*. Honolulu, HI: Petroglyph Press.
- Mann, M. E., M. A. Cane, S. E. Zebiak, and A. Clement. 2005. Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *Journal of Climate* 18: 447–56.
- Nunn, P. D. 1999. *Environmental change in the Pacific Basin: Chronologies, causes, consequences*. London: Wiley.
- . 2000. Environmental catastrophe in the Pacific Islands around A.D. 1300. *Geoarchaeology* 15:715–40.
- . 2007. *Climate, environment and society in the Pacific during the last millennium*. Amsterdam: Elsevier.
- Olson, S. L., and H. F. James. 1982. Fossil birds from the Hawaiian Islands: Evidence for wholesale extinction by man before Western contact. *Science* 217:633–35.
- Pau, S., G. S. Okin, and T. W. Gillespie. 2010. Asynchronous response of tropical forest leaf phenology to seasonal and El Niño-driven drought. *PLoS ONE* 5: e11325.
- Reed, P. F. 2004. *The Puebloan society of Chaco Canyon*. Westport, CT: Greenwood.
- Sachs, J. P., D. Sachse, R. H. Smittenberg, Z. Zhang, D. S. Battisti, and S. Golubic. 2009. Southward movement of the Pacific intertropical convergence zone AD 1400–1850. *Nature Geoscience* 2:519–24.
- Selling, O. H. 1946. *Studies in Hawaiian pollen statistics: Part I. The spores of the Hawaiian pteridophytes*. Bernice P. Bishop Museum Special Publication 37, Honolulu, HI.
- . 1947. *Studies in Hawaiian pollen statistics: Part II. The pollens of the Hawaiian phanerogams*. Bernice P. Bishop Museum Special Publication 38, Honolulu, HI.
- Sinclair, I. S. 1885. *Indigenous flowers of the Hawaiian Islands*. London: Sampson Low, Marston, Searle, and Rivington.
- Stahle, D. W., R. A. D'Arrigo, P. J. Krusic, M. K. Cleaveland, E. R. Cook, R. J. Allan, J. E. Cole, et al. 1998. Experimental dendroclimatic reconstruction of the Southern Oscillation. *Bulletin of the American Meteorological Society* 79:2137–52.
- Stock, J., J. Coil, and P. V. Kirch. 2003. Paleohydrology of arid southeastern Maui, Hawaiian Islands, and its implications for prehistoric settlement. *Quaternary Research* 59:12–24.
- Stuiver, M., and P. J. Reimer. 1993. Extended 14C data base and revised CALIB 3.0 14C age calibration program. *Radiocarbon* 35:215–30.
- Vancouver, G. 1798. *A voyage of discovery to the North Pacific Ocean 1790–1795*. 3 vols. London: G. G. and J. Robinson.
- Vitousek, P. M., T. N. Ladefoged, P. V. Kirch, A. S. Hartshorn, M. W. Graves, S. C. Hotchkiss, S. Tuljapurkar, and O. A. Chadwick. 2004. Soils, agriculture, and society in precontact Hawai'i. *Science* 304:1665–69.
- Wagner, W. L., D. R. Herbst, and S. H. Sohmer. 1999. *Manual of the flowering plants of Hawai'i*. Honolulu, HI: Bishop Museum Press.
- Woodcock, D. 2003. To restore the watersheds: Early twentieth-century tree planting in Hawai'i. *Annals of the Association of American Geographers* 93:624–35.
- Woodcock, D., and N. Kalodimos. 2005. Tree mold evidence of Loulu palm (*Pritchardia* sp.) forest on the Kona coast, Hawai'i. *Pacific Science* 59:491–98.





**Appendix A.** The alternative age model using all radiocarbon dates except an extreme reversal at 93–94 cm was derived from a linear regression applied to calibrated radiocarbon ages (cal yr BP = depth (29.128);  $R^2 = 0.89$ ).



**Appendix B.** Loss-on-ignition (LOI) estimates of organic (left) and inorganic (middle) carbon content as percentage of dry weight of sediment from Keālia Pond since 4,500 cal yr BP. Charcoal profile (right) showing CHAR values (gray fill; particles/cm² year<sup>-1</sup>), which are interpolated to even-aged ten-year intervals and then decomposed to a background component (black line; 500-year moving average) and peaks component (dashed lines; no units, threshold = 1.3).

*Correspondence:* National Center for Ecological Analysis and Synthesis (NCEAS), 735 State Street, Suite 300, Santa Barbara, CA 93101, e-mail: pau@nceas.ucsb.edu (Pau); Department of Geography, University of California, Los Angeles, 1255 Bunche Hall, Box 951524, Los Angeles, CA 90095–1524, e-mail: macdonal@geog.ucla.edu (MacDonald); tg@geog.ucla.edu (Gillespie).