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Synthesis

Constellating cultivation: texturing agroecological legacies with a mixed-methods approach in Hawaiʻi

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ABSTRACT. Indigenous agroecological practices have been identified as sustainable place-based practices supporting community resilience and revitalizing biocultural landscapes in Hawaiʻi. In areas where traditional knowledge and practice have been fractured because of colonial practices, new tools, such as spatial modeling, can aid in understanding the distribution of pre-colonial land use. Currently, spatial models of traditional agriculture do not capture the type of systems that supported populations in the Hilo and Puna districts on Hawaiʻi Island before European arrival in 1778. We utilized a mixed methods approach to address these limitations by considering Kalapana in the Puna District on Hawaiʻi Island as a case study. First, various forms of agriculture within Kalapana were identified and characterized based on written documentation in both English and ʻŌlelo Hawaiʻi. We then reconstructed spatial patterns of the distinct forms of cultivation by incorporating historic maps, archaeological reports, and botanical data from contemporary ground and remote survey data. Finally, we approximated environmental thresholds for agroecological adaptations in the under-studied Kalapana geography. Our findings suggest that the role of cultivated lava and forest systems would have provided substantial contributions necessary for supporting the populations that resided within the Puna district, spanning a time period of pre-European contact onward well into the 20th century. This study highlights the resilience and ingenuity of rural Hawaiian communities that supported themselves within sustainable, place-based practices and actively stewarded their biocultural landscape over time.

Key Words: *agro-ecology; agroforestry; agriculture; biocomplexity; biocultural; historical ecology; Indigenous cultivation; subsistence communities*

INTRODUCTION

The revitalization of Indigenous agricultural systems can promote community and climate resilience, biocultural landscapes, and sustainable food and materials production (Berkes 2021, Winter et al. 2022, Arora et al. 2023, Yeleliere et al. 2023). Recent scholarship centers on the role of Indigenous agroecology in prioritizing ecosystem relationships and supporting the food and land sovereignty of Native peoples (Price et al. 2022). Indigenous forms of agroecological stewardship and management, such as agroforestry, integrated into the environment to establish multi-functional working landscapes that sustained vibrant subsistence economies in Hawaiʻi for centuries before colonization (Kirch 1994, Lincoln and Vitousek 2017). Many of these agroecological systems were disrupted as their caretakers were displaced, engaged in new forms of economy, or land was allocated for new purposes. Rare areas maintained connections between the kuaʻāina (kuaʻāina is "someone who embodied the backbone of the land ... the Native Hawaiians who remained in the rural communities of our islands, took care of the kūpuna or elders, continued to speak Hawaiian, bent their backs and worked and sweated in the taro patches and sweet potato fields, and held that which is precious and sacred in the culture in their care" McGregor 2007:4) and these agroecological systems despite significant changes. The restoration, recognition, and continuation of cultural agroecological systems can help to foster a range of social-ecological benefits, such as increased food sufficiency and resilience, enhanced carbon storage, better sediment retention, and preservation of cultural practices (Brown et al. 2018, Lincoln et al. 2018, Hastings et al. 2020, Winter et al. 2022).

Extensive work has gone into building spatially explicit models of ancestral agriculture in Hawaiʻi. The Hawaiian Islands allow for unparalleled examination of human-environment interactions because of the highly diverse, yet organized, ecosystems (Vitousek 1995) and unique cultural factors (Kirch 2007). These models are relevant because of the extensive erasure of ancient archaeological remains largely by activities of large-scale plantation operations and the severe disruption of Indigenous oral histories (Ladefoged et al. 2009, Lincoln and Ladefoged 2014, Kurashima et al. 2019, Lincoln et al. 2023). These previous bodies of work initially focused on identifying the extent of remnant agroecological footprints. For example, Ladefoged et al. (2009) modeled flooded terrace systems of wetland taro cultivation and "fixed-field" systems of intensive rainfed agriculture across the major Hawaiian Islands. In addition to these, Kurashima et al. (2019) modeled pre-colonial agriculture on colluvial slopes and Lincoln et al. (2023) added other (non-colluvial) agroforestry footprints.

Although the previously documented agroecological systems have been validated at a broad scale (Soong et al. 2023), they ignore the place-specific heterogeneity within the footprints of these large systems. For instance, the large rainfed field systems of the Kona and Kohala regions are depicted as homogeneous in the current spatial models but are known to have applied banded agroecological zones with very different practices occurring (Kelly 1983, Lincoln et al. 2017, Marshall et al. 2017). Similarly, agroforestry, a "spectrum of practices that integrates trees with harvested plants and animals" (Hastings et al. 2020), is generalized in the spatial modeling efforts but traditionally included highly diverse forms including diversified orchards,

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shifting or swidden systems, and novel economic forests (Kalokuokamaile 1922, Handy et al. 1972, Kelly 1983, Lincoln and Ladefoged 2014, Lincoln 2020, McGuire 2022). This heterogeneity was driven by a suite of ecological factors including climate (Lincoln and Ladefoged 2014), soils (Lincoln et al. 2014), and spatial and temporal weather patterns (Lee et al. 2006, Kagawa-Viviani et al. 2018).

Furthermore, the existing geospatial models depict minimal pre-colonial agricultural production in the Puna district, supported by forms of cultivation with lighter archaeological footprints, such as agroforestry systems and "opportunistic" cultivation (Ladefoged et al. 2009, Lincoln et al. 2018, Kurashima et al. 2019, 2023, Lee and Lincoln 2023). However, ethnohistorical sources indicate that the region was a thriving center for the Native Hawaiian populace that employed a diversity of agricultural forms (Handy 1940, Handy et al. 1972).

We integrate ethnohistorical sources, analyses of historical maps, and botanical surveys to reconstruct a textured picture of the pre-colonial Native Hawaiian agroecological forms and their spatial distributions in the Kalapana region of the Puna district. Further, we utilize geospatial methods to explore the distribution of agroecological forms across the environment to understand how the Hawaiian people of Kalapana adapted their specific agricultural practices to the climatic and geologic landscape.

METHODS

Site overview

Our analysis focuses on the *moku* of Puna. *Moku*, generally translated as districts, were politically managed ecoregions (Winter et al. 2018). *Moku* were further divided into *ahupuaʻa*, the smallest political units, that were largely self-sufficient and typically span from the uplands to the nearshore oceans (Gonschor and Beamer 2014, Lincoln et al. 2022). This study includes 12 *ahupuaʻa* from ʻĀ*pua* to *Kēōkea* (west to east) comprising the southern portion of the *moku* of Puna (Fig. 1). Situated down-slope from the active Kīlauea Volcano, lava effusions have created a rugged mosaic of ʻaʻā and pāhoehoe flows (subaerial lava with rough surfaces vs. smooth, undulating lava, respectively) of varying ages and a coastline with large stretches of short coastal cliffs punctuated by boulder and black sand beaches. Upon this geologic mosaic *kīpuka*, "forest islands", ranging up to 3000 years old grow alongside shrublands on younger substrates 100–500 years old (Sherrod et al. 2007, 2021). This region was and remains a place of adaptive management, maintained through a diverse subsistence coast-scape that includes dependence on marine resources, with main villages located in immediate coastal areas. Because of the recurring lava events, the western portion of our study area was claimed by the Hawaiʻi Volcanoes National Park in the early 1900s, at which time the residents were evicted, many of whose descendants continue to reside in the eastern portion of Kalapana today.

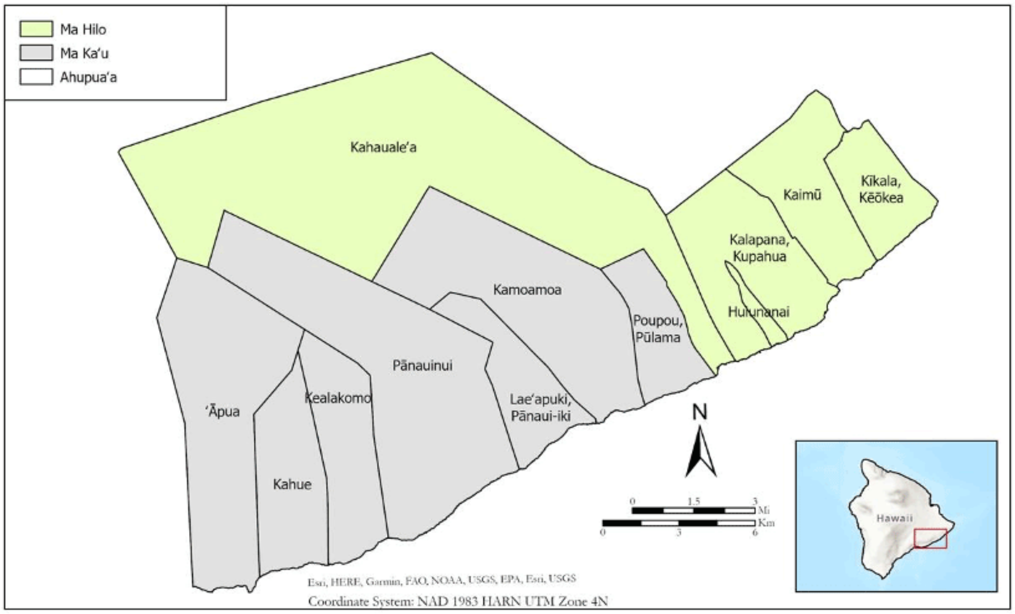
Approach

Our analysis utilized multiple ethnohistorical, survey, and geospatial methods to constellate the agroecological forms and spatial distributions employed by Native Hawaiian residents in the study region from the pre-colonial period through mid-20th century. We first built a qualitative description of pre-colonial cultivation forms through an expansive search of photographic and written depictions of the study region spanning from 1823 to the 1960s. We pursued all the available literature we could identify within our time frame that gave first-hand accounts of agroecological systems in the study region in either English or Hawaiian language (see Appendix 1 1 for a full list of plant species identified). We considered the positionality of written sources, which include *moʻolelo*-based (cultural stories and narratives) interpretation of the eco-historical signatures on the landscape, early descriptions by colonial witnesses, academic and archaeological reports, and the voices of community members (see Appendix 2 for a full list of resources used). Foreign voices (e.g., missionaries, scientists, businessmen), are more widely published in contrast to ʻŌ*iwi* (Native) voices. To minimize interpretive bias, we extracted direct observation data from these records rather than observer-based inferences. Collective descriptions over time were used to define the various forms of agro-ecology implemented.

We then integrated previously published data to construct a spatial database of agroecological forms based on a mixed-methods approach (Table 1). The databases used included (1) historical ethnographies that provided spatial data (locations identified; McGuire 2022), (2) 19th-century historical maps depicting areas of cultivation and indigenous vegetation (Lee and Lincoln 2023), (3) a geoarchaeology database from the State Historic Preservation Division (SHPD) depicting all recorded archaeological investigations (Soong et al. 2023), (4) a current inventory of the coastal cliff vegetative communities (McGuire 2023), and (5) a remote sensing dataset of *kukui* (candlenut, *Aleurites moluccanus*; Lincoln et al. 2021). These five methods are described in the following paragraphs:

- Historical ethnographies were used to extract spatial information on agricultural forms (see Appendix 2). In many cases, specific locations such as settlement names were identified that allowed for precise location. In other cases, slightly less precise but still confident descriptions were presented, such as the *ahupuaʻa* name along with an approximate distance from the coast. Only descriptions that were able to be situated on the landscape with a high degree of confidence were utilized. Diacritics (the ʻokina [ʻ] and kahako [e.g., ā]) were not added in when omitted in the original text cited (for example, the name of Hawaiian newspaper, Ka Nupepa Kuokoa).
- Digitized historical maps of the Hawaiian Islands were analyzed for agricultural form. Hawaiʻi State Registry Maps and Hawaii Plat Maps (http://ags.hawaii.gov/survey/map-search/), and a small number of other historical maps and surveys from the Bishop Museum (http://data.bishopmuseum.org/kekahuna) were assessed for relevance. Of the 4788 maps reviewed, 80 maps were included in this study that (1) were of the study region, (2) depicted agriculture or native vegetation, and (3) were before 1920. From the georeferenced maps, point-based data was manually extracted by creating an appropriately classified point for each relevant depiction of agriculture or native forest identified (see Fig. 2). Classifications were based on the qualitative descriptions identified in the ethnohistory, which align well with Kirch (1982).

Fig. 1. Map depicting the study area in the southwestern portion of the Puna district on Hawaiʻi Island, showing the individual ahupuaʻa names as well as the traditional, but unofficial, bearings of "ma Hilo" and "ma Kaʻū."



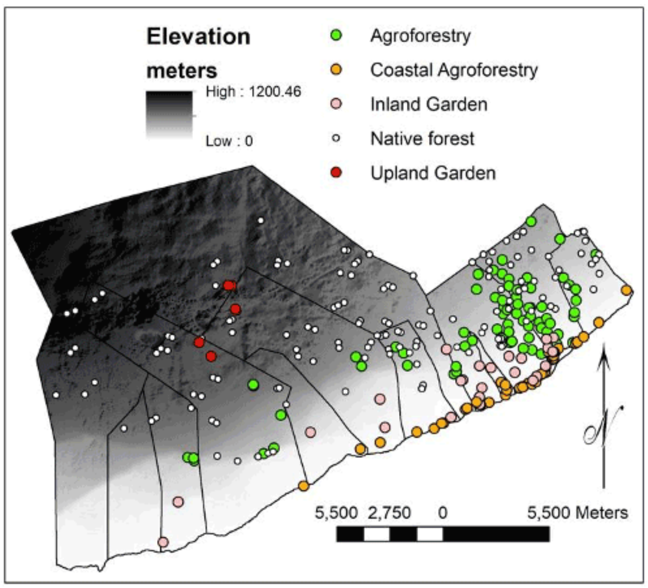
- A geoarchaeology database obtained from the State Historic Preservation Division (SHPD), which consisted of a point-based shapefile of 8561 archaeological sites, was assessed. The geodatabase was accessed through a direct request to SHPD in April 2021 for the explicit purpose of extracting agricultural sites. The records of each archaeological site included an identification of the site's purpose (e.g., "agricultural complex," "possible prehistoric house site"), along with an overview of the site contents (i.e., description, enumeration, and measurements of features). All descriptions for sites within the project area were assessed for relevance.
- A contemporary botanical inventory was referenced for the immediate coastal vegetation community conducted by McGuire (2023). Regularly spaced quadrants were assessed for plant species present and percent cover of each species following a modified Braun-Blanquet abundance scale method (Mueller-Dombois and Ellenberg 1974) for each habitat layer. From this database, locations of Polynesian introduced species were identified. The terrestrial spread of most Polynesian introduced species is slow and considered to be anthropogenic (Chan and Elevitch 2006), therefore large patches of Polynesian canoe plants (e.g., *niu* [*Cocos nucifera*], *milo* [*Thespesia populnea*], *hala* [*Pandanus tectorius*]) were considered to be remnant populations of traditional management.
- Remotely sensed distribution of *kukui* has been used as an indicator of traditional agroforestry and arboriculture (Lincoln et al. 2021). A semi-automatic approach was used to map *kukui* from high spatial resolution satellite Worldview-2 imagery collected in 2016–2017 for Hawaiʻi Island. The approach started with a supervised classification using three vegetation classes, *kukui*, other forests, and pasture/grassland, followed by manual correction. We used the classical maximum likelihood classifier (MLC) method in the ENVI (Harris Geospatial Solutions, Inc., Melbourne, FL) remote sensing software. After applying the MLC, we manually edited them in the ArcGIS software (ERSI, Redlands, CA). To avoid over-representation by large patches of *kukui*, trees were aggregated using the Neighborhood Aggregator function to minimize point clusters within 160 m (0.1 mi).

Point data derived from each of these approaches were used to extract environmental data for spatial modeling of the agroecological zones that were qualitatively identified through ethnohistorical research. Environmental data was obtained from the Hawaiʻi State Geospatial Portal (https://geoportal.hawaii.gov/) and the NRCS Soil Survey Database (https://websoilsurvey.nrcs.usda.gov/app/). Spatial points associated with each agroecological type were used as occurrence data to drive a maximum entropy model (MaxEnt). MaxEnt uses machine learning techniques to allow empirical data to be used to predict the probability of occurrence under spatially explicit conditions and has been used successfully at both regional and local scales (Dudík et al. 2007, Smith et al. 2012). MaxEnt modeling was conducted in R (R Team 2015) using the "dismo" package (Hijmans et al. 2011), with elevation, temperature, rainfall, age, and district as explanatory factors. MaxEnt likelihood (the probability of occurrence of this agroecological system) was defined as a spatial footprint in ArcMap 10.3.1 using the raster calculator (likelihood > 0.1), then converted to polygons and merged. Estimated probabilities of the presence of each agroecological type were delineated using MaxEnt. Subsequent conversion to an exclusive presence-absence model created spatial depictions of the different agroecological zones that overlapped,

Table 1. Multi-method summary table.

Data source	Data assessed	Outcomes
Historic ethnographies	Historic contexts and understandings of the landscape	Place-based definitions of agro-ecological types (“agroforestry,” “coastal agroforestry,” “inland agriculture,” “upland agriculture,” “native forest”) and a place-based determination of the extent of the study area
	Historic plant list and associations for each system type	Context to interpret model outputs
	Qualitative locations of agro-ecological classes	Point data to inform agro-ecological type class distributions (“coastal agroforestry,” “agroforestry,” and “inland and upland agriculture”)
Digitized historic maps	Geo-referenced locations of agro-ecological systems and native forests	Point data of mapped agro-ecological sites (“native forest,” “coastal agroforests,” “agroforests,” “inland agriculture”)
Geo-archaeology database	Agro-ecological footprints	Statewide database did not hold any polygon data for this geography
Contemporary botanical inventory	Percent cover data for immediate coastal vegetation communities (2021)	Point data for “coastal agroforestry,” “agroforestry,” and “inland agriculture” class distributions
Remotely sensed distribution of *kukui* (*Aleurites moluccanus*)	Canopy cover of *kukui*	Point data informs “agroforestry” class distribution

Fig. 2. Depiction of occurrence point data from mixed-method sources for the five agroecological types identified for the study area.



particularly in the low elevations. We employed a simple prioritization to depict the zones as discrete locations, prioritizing systems with a smaller footprint over ones with a larger footprint because of the overlapping nature of their extents (i.e., Coastal Agroforestry > Upland Agriculture > Inland Agriculture > Agroforestry > Native Forests; Fig. 3). Model outcomes were used to construct a textured spatial footprint of the combined agroecological systems for the geography.

RESULTS

Ethnographic descriptions

Eco-cultural history

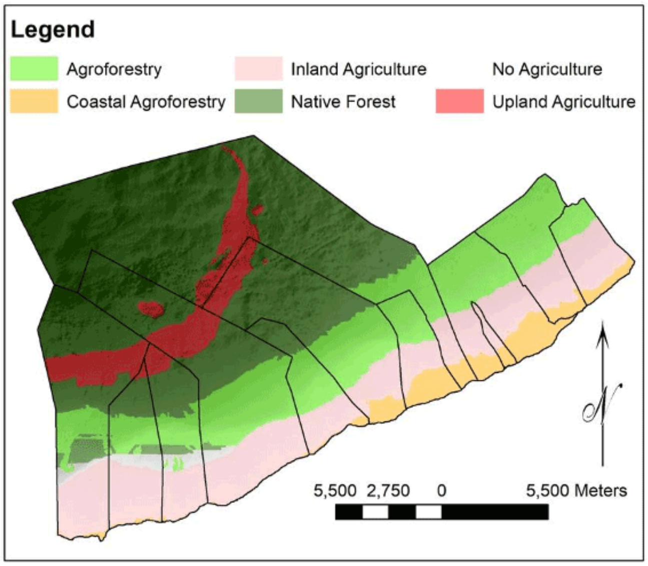
Puna is an ancient region in Hawaiian history. According to legend, the first *niu* brought to Hawaiʻi were introduced along this coast. Historian Martha Beckwith records that “the first time Apua and his brother came from *Kahiki* (a distant land) they did not bring slips of food plants because they expect[ed] to find them growing here ... The first coconuts in Hawaii are planted at Kahaualea and at Kalapana in Puna district” (Beckwith 1970:432). Some of the original grove sites at these locations remain today.

The inhabited regions along the coastline were 1–3 miles wide, with some settlements further inland at 5–10 miles inland (Coan 1882). First-hand traveler accounts highlight Native Hawaiian subsistence practices were dependent on nearshore coastal forests where valued tree species were planted, sweet-potato sewn lava fields in mid-elevational regions, agroforestry developments, upland areas where deeper-soil crops (taro, bananas, and sugar cane) were grown together, and native forests that were an important resource, particularly for the harvest of birds and non-timber forest products. The people who lived in the study area oriented themselves within the geography by westward and eastern directionals (*ma Kaʻū* and *ma Hilo*, respectively) because of differences in the overall landscape and their usage of it (Kauhi and Langlas 1996). In *ma Kaʻū* fresh water was noted as scarce, sourced from upland caves, while *ma Hilo* is remarked to be generally more fertile and watered (Ellis 1895). We utilize this local perspective and classification of the landscape in our subsequent description of the agricultural forms and in the spatial modeling (see Fig. 1).

In 1864, Ka Nupepa Kuokoa published *He mele puali inu wai no Panau* (the song of the drinking waters of Pānau; Kawahine 1864), that tells of the specific rains of Pānau, the pleasant, peaceful, and deep water that sits within the forest, the underwater springs at Punaluʻu that were dove for, and the porous earthen water sources of Kalapana. This piece indicates the intimacy and depth of knowledge held by the people of this coast, from the upland regions (*Nana i ka lai o Paliuli*) to the sea cliffs (*Kawaha na pali o Pulama*). The survival and subsistence of these communities depended on freshwater, lava fields, and forest sites that connected upland and lowland regions. Unique practices and knowledge were necessary to cultivate the young lava flows, which were remarked upon by travelers.

Although substantial populations persisted on these landscapes for several hundred years (Ladefoged et al. 1987), a decline of 90–95% in the Native population started with European contact in 1778 (Stannard 1989). European contact was also accompanied by massive social changes. Introduced plants, animals, and

Fig. 3. Zones of cultivated spaces in the study area were derived using a Maximum Entropy model based on occurrence point data, indicating the general spatial pattern of Native Hawaiian land use.



practices changed components of land usage, while political transformation dramatically changed aspects of land tenure and access, economics, and demographics. Despite these challenges, accounts reflect tremendous resilience and continuity in agroecological practices as well (Langlas and Kūpuna 2016). Accounts from the latter half of the 19th century indicate continued reliance on ancestral groves of culturally important tree species while also incorporating newly introduced species such as mango and coffee into the traditional systems (Rycroft 1890). Cultivation of sweet potato on the mid-elevation sites continued in abundance.

In the first half of the 20th century, Native accounts tell of an era of dramatic shifts in spatial patterns of cultivation and village livelihoods. Major drivers of the changes included *ʻŌiwi* population decline and emigration, the introduction of livestock on the landscape, the increased prevalence of Western economic systems (e.g., labor shifts toward industry rather than cultivation and subsistence livelihoods and increased spending on non-local goods), and the acquisition of large swaths of land by outsiders, including by the National Park that displaced previously inhabited village sites (Ka Hoku o Hawaii 1936, Kauhi and Langlas 1996, Carr and Kekaula 2012, Langlas and Kūpuna 2016). Despite these dramatic changes, components of subsistence-based practices persisted in home gardens, coastal forest remnants, and upland plots in alignment with the spatial practices of ancestors. Although aspects of the traditional systems changed, such as the spatial footprint and the incorporated crops, the form and location of the practices appear to have remained largely intact.

Living in the shadow of Kīlauea, one of the most active volcanoes on Earth, meant living in an ever-evolving landscape. It was recorded by Captain Ed Dutton that "the traditions of the natives declare that no King ever reigned in Puna without seeing large parts of his dominion overflowed" (Dutton 1884:1501). These eruptions have continued into the present day, and in some cases, places recorded to have been cultivated in the past have subsequently been covered by newer lava flows.

Coastal agroforestry

Many accounts recorded and described the cultivated coast forests of the study region, in which "the sea-coast is margined in many places with abundant groves of cocoanut palms and dense thickets of pandanus or screw pine" (Dutton 1884:147) and the "beautiful groves of the cocoa palm, also breadfruit, pandanus, and ohia" flourished (Coan 1882:40). Several valued tree species were cultivated such as *hala* (screwpine), *niu* (coconut), *ʻulu* (breadfruit; *Artocarpus altilis*); *milo* (Portia tree), and *kou* (beach Cordia; *Cordia subcordata*). So much was *hala* a core part of these coastal forests, there is the saying *Puna paiaʻala i ka hala*: Puna hedged with fragrant *hala* (Pukui 1983). Photos of freshwater ponds from the early 1900s highlight a patchwork of *niu* and *hala* groves that existed (Fig. 4), and interviews from the same era demonstrate the continued gathering and processing of *hala* leaves from family-specific *hala* groves (Kauhi and Langlas 1996, McGuire 2022).

Fig. 4. *Niu* (*Cocos nucifera*) and *hala* (*Pandanus tectorius*) groves surrounding fishponds in Kalapana via Baker 1927.

In the *ma Hilo* subregion, through Pānau, Laeʻāpuki, and Kamoamoa *ahupuaʻa*, the nature of the coast was described as "more agreeable" compared to the southern areas (Ellis 1895. Accounts described *kou*, *niu*, and *hala* groves with scattered village sites, and vast coconut groves along the coast, with the stretch between the "fertile" villages of Kalapana and Kaimū consisting of "cocoanut and *hala* groves and ancient breadfruit trees which are now fast disappearing" (Pacific Commercial Advertiser 1892). Kupahuʻa is described as a "well-cultivated country," and Kaimū as bountiful with industriously cultivated fertile soil and abundant fresh (sometimes brackish) water. *Lei* (garland) materials referenced quick access to unspecified flowers, *hala*, and *maile* (*Alyxia stellata*). More *niu* and *kou* groves as well as fields of potatoes were observed and recorded. Moving east of Kaimū, about a mile and a half before reaching Kehena, Ellis observed extensive coconut trees and bananas (*Musa* sp.). The coastal region of *ma Kaʻ*ū was consistently described as more "sterile" (Lyman 1927). Although despite a lack of "means of subsistence in any great variety or abundance," the "desolate" coasts were numerously populated, far more than fertile regions inland, and provided a diversity of food sources (Ellis 1895). Fresh water was noted as scarce, sourced from upland caves.

Inland gardens
Immediately inland of the coastal zone were vast lava plains of various ages. Despite the virtual lack of soil, the land was made to "yield other crops of tropical staples in abundance" that "grows among the rocks in a marvelous way" (Dutton 1884:89). Crops were cultivated in pits, and stone mounds and alignments (Ladefoged et al. 1987). A traveler in 1846 described passing a potato patch in "the broken lava which exceeded anything I had seen. Not a particle of soil was anywhere to be seen, and the holes dug among the stones to receive the potatoes were some of them 6 feet in depth — thus securing a degree of moisture and shelter from the sun — though no more soil than at the surface" (Lyman 1927). *Kalo* (*Colocasia esculenta*) was also commonly grown in this landscape, which "will maintain itself, if only man takes the trouble to stick the *huli* (taro top/shoot) into a cleft of the rock" (Pacific Commercial Advertiser 1892:6).

In the *Ma Hilo* subregion, one practice documented planting in the wet, lowland forests. Cuttings of *kalo* were wrapped in rolls of dry pandanus leaf to keep it moist and provide nourishment in the stony ground. The cuttings were planted under pandanus trees, which were felled and cleared to let in the sun after the crop rooted and put forth the first growth of leaves (Handy 1940). In *Ma Kaʻ*ū, the fern-covered plains between the forest and seacoast in northeast Puna used to be planted in *kalo* and *ʻuala* (*Ipomoea batatas*) with the use of burning to clear grass, shrubs, and ferns in a planting area (Handy 1940). The use of both modified and unmodified planters in the young lava has been documented archaeologically (Ladefoged et al. 1987).

Inland agroforestry
In localities where planting was done along the edges and within the borders of *kukui* forests, crops were planted in mulched pits to make rich humus (Handy et al. 1972, Lincoln 2020). Equally luxuriant was the growth in the fern-forest zone, where tree ferns would be uprooted and crops planted in the holes left. These methods were often used for planting *kalo*, although *ʻuhi* (yams, *Dioscorea alata*) are also reported with the vines scaffolding up the trees. Unique planting regimes have been reported, such as the epiphytic planting of *ʻawa* (*Piper methysticum*) in the crotches of trees (Handy 1940). Puna was the region most famous for *ʻulu* (breadfruit) in all of Hawaiʻi, with extensive plantings of the trees providing a near year-round source of food (Handy et al. 1972, Meilleur et al. 2004). In the early 20th century, traditional sites such as *kukui* groves were adapted to support livestock: "we went there (near Wahaʻula Heiau) to cut *kūkaepuaʻa* grass (*Digitaria setigera*) under the *kukui* groves. That was something for the horse and donkey to eat." (Kauhi and Langlas 1996:99).

Upland gardens
Upland areas were generally wetter and had more developed soils, and deeper-soil crops such as bananas, *k*ō (sugar cane, *Saccharum officinarum*), and *k*ī (ti, *Cordyline fruticose*) were grown together with staples such as *kalo* (Handy et al. 1972, Ellis 1895). There were "extensive upland taro-patches ... between 2,000' and 2,200' elevation" (Wilkes 1845:181), and "plantations ... 5 miles (8 km) inland from the sea" where "plantains, pawpaws, taro, etc. were growing around" (Lyman 1927:19). Of these upland regions, also noted are the "wild strawberries, cape gooseberries, and the ohelo" (Coan 1882). These upland plantings continued into the 20th century (Kauhi and Langlas 1996).

Descriptions of the upland gardens were similar for *Ma Hilo* and *Ma Kaʻ*ū but tended to cluster in the center of the study area. Description of Kahoʻonoho and Walaʻohia at least 2.5 miles into the forested interior as "the two great forest planting areas" document upland agricultural activity in Kahaualeʻa (Handy et al. 1972). Makaiwa *heiau* (temple) and accompanying sites 5 to 6.5 km (3–4 mi) inland, about 400 to 500 m (1200–1500 ft) elevation evidenced cultivation to at least this point (Holmes 1982). Similarly, the Kupahuʻa homesteading area in Kalapana and Kaimū *ahupuaʻa* was 5 to 6.5 km (3–4 mi) inland, quite close to Kahaualeʻa and similar in nature of terrain and vegetation. Similar sites were also observed in upper Pānau and archaeologist Stell Newman describes a field system in Pānau as far inland as 5 miles (Holmes 1982).

Native forests
Above and within the cultivated landscape, native forests provided a myriad of resources. Although the native forests were not part of the agricultural landscape per se, they formed the delineation of the cultivated landscape and provided important resources. In the lower reaches, native areas of smaller trees and shrubs provided important collection grounds for medicinal plants and other resources (Holmes 1982). The native forest regime of upland Kahaualeʻa, with its extensive *ʻ*ō*hia* (*Metrosideros polymorpha*) canopy provided a near ideal habitat for many of the prized birds sought after by bird-catchers and non-timber forest products (Emerson 1895). In these areas, "many canoes are built and transported to the sea, the trees in the vicinity being large and well adapted to this purpose" (Wilkes 1845:181).

Spatial distribution

Point data
Utilizing a mixed-methods approach yielded 291 spatially explicit points of identifiable agricultural forms (Table 2). Despite the different methodological approaches used, data aligned well, and clear patterns were visible in the distribution of the agroecological types identified (Fig. 2). The spatial depiction also demonstrated alignment with the qualitative descriptions of the agroecological zones. Point clusters indicated reasonable separation between agroecological forms.

The distribution of data points corresponded to different environmental parameters, with the various agroecological types having different ranges and mean values of temperature, rainfall, elevation, and geologic age of the substrate (Table 3). Of the environmental parameters, elevation and temperature were highly correlated (r^2 0.997, $p < 0.0001$), while elevation and rainfall were moderately correlated (r^2 0.508, $p < 0.0001$), with temperature declining and rainfall increasing as elevation increased.

Spatial modeling of agroecological zones
As modeled, the cultivable areas and the percentage cultivable area are comparable for the *ma Hilo* and *ma Kaʻ*ū subunits of the study area, although the relative contribution of the different

Table 2. Data sources for spatial points depicting agroecological zones.

Data source	Agroecological zone					
	Coastal agroforestry	Inland agriculture	Agroforestry	Upland agriculture	Native forest	All
Ethnographic	15	19	4	5	--	43
Historical maps	16	5	12	--	142	175
Geoarchaeology	--	--	--	--	--	--
Botanical surveys	14	2	1	--	--	17
Remote sensing	--	--	56	--	--	56
Total	45	26	73	5	142	291

Table 3. Environmental parameters associated with the spatial point data by agroecological classification.

		Agroecological zone				
		Agrofore-stry	Coastal agroforestry	Inland garden	Native forest	Upland garden
Temp (°C)	Min	18.8	23.0	22.0	16.6	17.9
	Mean	21.9	23.3	23.1	20.1	18.0
	Max	23.2	23.3	23.5	23.0	18.2
Rain (mm/yr)	Min	1847	1618	1270	1830	3013
	Mean	2481	2037	2042	2962	3648
	Max	3231	2405	2379	4852	4121
Elevation (masl)	Min	8	1	1	44	760
	Mean	202	9	35	467	776
Substrate age (y)	Min	100	100	100	100	300
	Mean	855	882	351	302	380
	Max	15000	2250	2250	2250	500

agroecological types varies (Table 4). In particular, *ma Ka*ʻū has considerably less Coastal Agroforestry (~25%) and considerably more upland agriculture (~285%) compared to the *ma Hilo* area. This is largely due to the more recent lava cover of *ma Ka*ʻū, which is reflected in the ethnohistoric and botanical survey databases.

Lava-field cultivation of *ʻuala* and *kalo*, upland plots for mixed crops, and coastal and upland agroforests comprised the western Puna systems. We provided a spatial estimate of the pre-colonial agroecological zones. In the *ma Hilo* area, there was considerable overlap in the occurrence points and subsequent spatial models for Coastal Agroforestry, Inland Agriculture, and Agroforestry. The dominant agricultural form we observe in the model interacted and overlapped in their application, taking advantage of micro-sites and utilizing habitat alteration created by agroforestry installations to supply dryland farming within the lava, as suggested within ethnohistoric sources. The spatial depiction of upland agriculture, which was based on a limited number of occurrence points, is likely less accurate than the other models.

Ethnohistoric detailing

In addition to providing insight into the classes or categories of diverse agroecological systems in this geography, the ethnohistoric data offered context not available in the other spatial methods. For example, the account of Emma Kauhi, and her rich telling of the landscape from her early life from 1916 to 1935 from the perspective of *kua*ʻā*ina* (a rural, self-sustaining Native

Table 4. Total area in hectares of each agroforestry type, separated by the local distinction of *Ma Hilo* and *Ma Ka*ʻū.

	Ma Hilo	*Ma Ka*ʻū	Total
Agroforestry	3,860	4,513	8,373
Coastal agroforestry	1,563	391	1,954
Inland agriculture	3,017	4,502	7,519
Native forest	9,260	7,659	16,919
No agriculture	0	493	493
Upland agriculture	715	2,034	2,749
Total cultivation	9,154	11,440	20,595
Total area	18,414	19,592	38,006
% cultivation potential	49.7	58.4	54.2

person), details the rich cultural practices that her family and her ancestors before her used to cultivate their groves and agricultural sites. For example, the gathering and processing of *hala* leaves by the women and children of families from family-specific groves, or the maintenance of traditional agroecological designations such as the upland sites with dryland *kalo*, *k*ō, *mai*ʻ*a* (banana, *Musa* sp.), and onions. This account provides a rarely discussed lens on the subsistence and cultivation landscape: that of a Native child, detailing plants including *nanaku* (bulrush, *Scirpus validus*) that were used to make toy boats, bamboo for kite-making, *kakalaioa* (*Guilandina bounduc*) seeds for marbles, and *w*ā*wae*ʻ*iole* (*Lycopodiella cernua*) for toy hooks. We provide these examples to highlight the depth of relationship and practice to specific agroecological zones, and the distinction known between them from Native voice that is available within ethnohistoric accounts. This depth is lost when only considering spatially derived data. The ethnohistoric accounts are also able to supplement accounts (as highlighted above) of the understory composition of these agroecological sites. Although the historic maps and remotely sensed *kukui* canopies locate cultural forests and agroforests, the assemblages of understory species, where most of the continuous gathering occurs, is hidden. The botanical surveys reveal understory species. For example, McGuire 2023 botanical surveying identified the native species dominated understories of the *kukui* and *niu-milo* groves. However, alone this method does not provide insight into the associated gathering of the understory species such as grasses, *kalo*, and others, and associated cultural practices and lifeways integral to maintaining these sites. Finally, the ethnohistoric methods provide specificity in species that may now be locally extirpated and thus, unable to be documented through the other methods of botanical surveying, remote sensing, or identified explicitly in historic maps. Examples of these in the study area include *kou* (*Cordia subcordata*) groves and mention of *wiliwili* (*Erythrina sandwicensis*; ethnohistories in conversation with McGuire 2023).

DISCUSSION

We present a revised understanding of the agricultural landscape of the pre-colonial western Puna region through spatial reconstructions built using mixed-methods data sources. Our results indicate, from a mixed-methods perspective that the Kalapana geography was a diverse agroecological landscape. We also found five types of agroecolgocial systems being practiced and used in the region including upland and coastal agroforestry systems, inland agriculture, upland agricultural systems, and native forest.

Each of the different agroecological zones, with their different agricultural forms, elevational gradients, and suite of crops, offered different outcomes to the family units. In the case of the Kalapana region, agroforestry offered consistent access to *kukui,* valued for fuel, medicine, and dye while coastal agroforestry afforded fiber, medicine, and food materials within rich, biodiverse systems. Inland agriculture offered accessible production of staple crops (ʻ*ulu* and ʻ*uala*) but little diversity, while upland agriculture offered much more diverse production. Alternatively, the inland agriculture was more susceptible to drought, located in a drier and more variable part of the landscape, while upland agriculture supported more reliable production over time (Lincoln and Vitousek 2017). The varying characteristics and products of the different agroecological zones, accessed by individual extended family groups to each of the zones, and role of cultural practices in reciprocally based landscape use, were critical components to the long-term sustainability and resilience of the society in this challenging environment (Kauhi and Langlas 1996).

The pre-colonial application of place-based and banded agroecological zones across diverse ecosystems is common throughout the Hawaiian archipelago (Lincoln et al. 2022). Each unique environment and cultural community hold a suite of place-based agroecological practices. These agroecological zones relate to the distribution and type of land settlement, which focused on sections of land occupied by extended family units, flexibly organized to steward discrete areas of land (Handy and Pukui 1972, Dye 2021). Spatial models of the agroecological landscape in Hawaiʻi should include models of cultivation that exhibited less dramatic ecosystem alteration such as coastal agroforests and agroforests that do not leave archaeologic signatures. Despite the study area not being depicted as having wetland, intensive rainfed, or agroforestry by Kurashima et al. (2019) or Ladefoged et al. (2009), we demonstrated that a myriad of agricultural forms existed in the region with the methods employed. These findings encourage us to reconsider what “cultivation” means. We reposition this term to refer to sites that were/are actively managed for reciprocal relationships, as has been documented in other Indigenous territories such as Indigenous forests (Armstrong et al. 2021) and clam gardens in the Pacific Northwest (Lepofsky et al. 2021), to name just two.

Our ethnohistoric reconstruction of coastal forest and plains areas evidenced active management in the Puna district for subsistence practices and suggests these ecosystems cannot be understood without considering the cultural curation of these spaces. *Niu*, *milo*, *hala* groves, and the supported forest spaces that they foster, for example, have not yet been fully considered as sites of cultivation. With our results we would like to question models of agriculture, both historical and for future modeling, that discount young lava fields and substrates as sites for agroecological restoration. As we see in this study area, young geologic sites such as young lava fields are in constant cycles of renewal but were used as important sites for the cultivation of food staples such as *niu* and ʻ*uala*. Other sites in Hawaiʻi that have already been modeled for agroecological systems may benefit from texturing of agroecological practices, identified through the ethnohistoric record.

The persistence of these systems over time demonstrates that even in times of great disturbance, whether they be geologic-based, or other clearing-type, there are ʻŌiwi modalities of renewal of care and agroecological relationship (Langlas and Kūpuna 2016). Young lava flows were and are re-soiled and re-vegetated, coastal groves expanded and cleaned, and biodiverse forests and upland agricultural sites actively traversed and managed for reciprocal needs through cultural lifeways. We would like to term this type of care a *kīpuka* agroecological model. In ʻŌlelo Hawaiʻi, *kīpuka* are forest remnants encircled by lava: spaces that are protected and ancestral, islands within a wider sea of change (Pukui and Elbert 1986, McGregor 2007). Similarly, we describe in this paper niche-based patterns of cultivation that were/are highly productive within a fragmented landscape that persist despite being surrounded, impacted, and influenced by lava. In comparison to well-documented Hawaiian agricultural field systems, these practices are relatively more integrative and less intensive in how they alter the landscape. We advocate for future work that considers the spatial extents and productivity of *kīpuka* agroecological style—ancestral and resilient pockets of biocultural refuge—systems across Hawaiʻi and in other Indigenous communities (Tengan and Roy 2020).

We employed mixed methods to get a more accurate understanding of agroecological adaptation. Each of the methods employed, on their own, provides a limited understanding of the agroecological landscape, but collectively the approach allowed us to constellate a place-based cultivation construction for this under-studied geography. For example, the ethnohistoric data highlighted cultivation sites no longer evident within the ecological or archaeological footprint but are sparse and spatially limited, the botanical surveys were widespread but only capture long-lived perennial components, and the historical maps depict all agroecological types but are limited in extent. This analysis sought to explore what agroecological systems were used and where they were applied to understand how Native Hawaiian cultivators adapted to this unique environment and sustained their society.

Detailed agroecological adaptation based on intensive place-based knowledge is not unique to Hawaiʻi, but a common aspect of Indigenous practice globally (Berkes et al. 2000, Menzies 2006, Armstrong et al. 2021). Adaptive management as exemplified by Indigenous communities has been shown to result in multiple benefits, often demonstrating long-term sustainability and resilience of ecosystem function while providing substantial material and cultural outcomes (e.g., Berkes et al. 1994, Toledo 2001, Toledo et al. 2003). Such adaptive management has been documented in marginal habitats, where place-based and fine-tuned knowledge systems are exceptionally necessary for populations to persist and thrive (e.g., Altieri 2002, Altieri and Toledo 2005). The different agroecological bands documented in the study area, add to the collage of agricultural models in Hawaiʻi, demonstrating the adaptive and place-based nature of Hawaiian agroecology. Understanding the role of Indigenous peoples as stewards and shapers of linked agroecological systems provides better insight into the role of Native peoples in ecosystem health and resilience (Armstrong et al. 2021, Lepofsky et al. 2021). The role of cultural practices and lifeways in shaping both Indigenous and non-Indigenous landscapes can only be understood and described fully when considering multiple perspectives and diverse historical records. Future efforts to preserve and revitalize these systems will rely on the fullness and depth of knowledge, not just for where these systems historically existed but for how they were (and in many cases continue to be) sustained.

Author Contributions:

Conceptualization, methodology, writing G.M.; data curation, writing- review and editing, K.K.; methodology, data curation, writing- review and editing, T.M.L.; formal analysis, data curation, revision, N.K.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability:

The data and code that support the findings of this study are available on request from the corresponding author, GM, to ensure ethics of Indigenous data sovereignty for the Native Hawaiian community are maintained within each use. Ethical approval for this research study was granted by University of Hawaiʻi Institutional Review Board protocol no. 2020-00220.

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Appendix 1. Ethnohistoric list of plant species in Kalapana.

Species	Location	Use	Source
‘Auhuhu *Tephrosia purpurea*	Ka‘uluhau pond	fish stunning	Emma Kauhi
‘Awa *Piper methysticum*	Kalapana	ceremonial drink, medicinal	Emma Kauhi
Bamboo *Scizostachyum galucifolium*	Kapa‘ahu	torches, kite sticks	Emma Kauhi
Mai‘a *Musa acuminata*	Poupou Uka	fruit, imu logs	Emma Kauhi
Cabbage *Brassica oleracea*	home gardens	food	Carr & Kekaula
Nīoi *Capsicum fruitescens*	home gardens	food	Carr & Kekaula
Coffee *Coffea arabica*	Kapa‘ahu (behind Uncle Kaipo’s house)	coffee	Emma Kauhi
Eucalyptus *Eucalyptus spp.*	Kapa‘ahu home	medicinal	Emma Kauhi
Green beans *Phaseolus vulgaris*	home gardens	food	Carr & Kekaula
Green pepper *Capsicum annuum*	home gardens	food	Carr & Kekaula
Guava *Psidium guajava*	Poupou Kai	food, imu wood, medicinal	Emma Kauhi, Carr & Kekaula
Ha‘uoi *Verbena littoralis*	Kapa‘ahu home	medicinal	Emma Kauhi
Hau *Hibiscus tiliaceus*	Waha‘ula	wood, cordage, lei	Stone & Pratt
Kākalaioa *Guilandina bounduc*	Kapa‘ahu	seeds used as marbles	Emma Kauhi
Kalo (‘ele‘ele, mana‘ulu, lehua, aipa‘a, manamana varieties) *Coloccasia esculenta*	Poupou Uka, Poupou Kai, Kalapana home gardens, Harry K. Brown Park (cultivated by Elia Kaho‘okaulana)	food	Emma Kauhi
Ko‘oko‘olau *Bidens vernacular*	Kapa‘ahu home	medicinal	Emma Kauhi
Koali‘awa *Ipomoea indica*	Kapa‘ahu home	medicinal	Stone & Pratt
Koli *Desmodium incanum*	Kapa‘ahu home	medicinal (cathartic)	Emma Kauhi
Kou *Cordia subcordata*	Paea house	wood	Emma Kauhi
Kūkaepua‘a grass *Digitaria setigera*	Waha‘ula	livestock feed	Emma Kauhi
Kukui *Aleurties moluccanus*	Waha‘ula	food, dye	Emma Kauhi
Lauhala *Pandanus tectorius*	Kapa‘ahu, Kalapana	weaving, medicinal	Emma Kauhi, Carr & Kekaula, Stone & Pratt
Laukahi *Plantago major*	Kapa‘ahu home	medicinal	Emma Kauhi
Maile *Alyxia stellata*		ceremonial	Emma Kauhi
Maile hohono *Ageratum conyzoides*	Kapa‘ahu	medicinal	Emma Kauhi

Mango *Mangifera indica*	Poupou Kai	fruit, food	Emma Kauhi, Carr & Kekaula
Milo *Thespesia populnea*	Waiʻaʻea, Halape, Keahou	wood	Emma Kauhi
ʻŌhiʻaʻai *Syzygium malaccense*	Poupou Kai	fruit	Emma Kauhi, Carr & Kekaula
Nānaku *Scirpus validus*	Waiaka pond	toys	Emma Kauhi
Naupaka kahakai *Scaevola taccada*	Wahaʻula, ʻĀpua	medicinal	Stone & Pratt 1994
Niu *Cocos nucifera*	Kaʻuluhau beach, Kamoamoa, Wahaʻula, Kamoamoa	food, cordage, shelter	Emma Kauhi, Stone & Pratt
ʻŌhiʻa *Metrosideros polymorpha*	Paea home	imu wood, fishing poles	Emma Kauhi
Onion *Allium fistulosum*	uplands with sugarcane, bananas, & taro	food	Emma Kauhi, Carr & Kekaula
Oranges *Citrus sinensis*	Kapaʻahu home	food	Emma Kauhi
Pineapple *Ananas comosus*	Poupou kai rock crevices	food	Emma Kauhi
Pōpolo *Solanum americanum*	Kapaʻahu home	medicinal	Emma Kauhi
Pumpkin *Curcurbita spp.*	Kapaʻahu	food (mixed with poi)	Emma Kauhi
Ihi *Oxalis debilis*	Kapaʻahu	medicinal	Emma Kauhi
Star apple *Chrysophyllum cainito*	home gardens	food	Carr & Kekaula
Kō *Saccharum officinarum*	Poupou Uka	food	Emma Kauhi
Wāwaeʻiole *Lycopodiella cernua*	Kapaʻahu	toy	Emmau Kauhi
Wiliwili *Eythrina sandwicensis*	Kapaʻahu	NA	Emma Kauhi

Appendix 2. Full list of ethnohistoric sources considered.

Author Name	**Source**	**Year**	**Insight**	**Positionality**
William Ellis	Journal	1823	detailed descriptions of coastal villages and sites of cultivation on his travels	English missionary, botanist, book printer
Titus Coan	Journal	1837, 1840	descriptions of coastal villages on his travels	New England missionary
Barenaba	Ke Kumu Hawaii Newspaper	1838	provides estimates of population numbers within the coastal villages, indicates well-established communities	traveling to share Christian teachings
Chester Lyman	*Around the Horn to the Sandwich Islands & California* travel account	1846	observations of cultivated sites, livestock, and population decline	Yale professor and astronomer, traveling with Titus Coan
Unknown composer	Ka Nupepa Hawaii	1864	song that details intimate relations with coastal and upland regions	composed in ʻŌlelo Hawaiʻi
Captain Clarence Dutton	USGS Report	1882	detailed observations of coastal forests and agricultural sites	American geologist
R.S.S.	Travel account in The Saturday Press	1885	brief description of Pānau	tourist of unknown background
R. Rycroft	Letter to the editor in The Pacific Commercial Advertiser	1890	writes of presence of coffee in the district	American businessman and Puna resident
Anonymous	Travel account in The Pacific Commercial Advertiser	1892	detailed traveler description of forested and agricultural zones	tourist of unknown background
Real estate sale	The Independent	1898	short descriptions of land for sale in Kaunaloa, Ki, and Kalapana	unknown
Ruth Loucks	Mission House Archives	1927	images of coastal forest groves	photos archived are of sites near church sites
Anonymous	Ka Hoku o Hawaii	1936	discusses proposed boundary extension of the National Park eastward	unknown
Marth Beckwith	Recounting of moʻolelo, *Hawaiian Mythology*	1982	legend that the first coconut trees in Hawaiʻi were introduced at Kahaualeʻa and Kalapana	American folklorist and ethnographer, worked extensively in Hawaiʻix
Tommy Holmes	Report for Campbell Estates	1982	eco-historical account that brings together archaeological and oral accounts of Kahaualeʻa	co-founder, Polynesian Voyaging Society, research consultant
Emma Kauhi	*He Moʻolelo no Kapaʻahu*	1996	personal account of life in Kapa'ahu from 1916-1935	Native Hawaiian resident
John R. K. Clark	*Hawaiian Surfing* collection of memories from surfing traditions across Hawaiʻi	2011	memories of coastal trees grown and harvested for surfboard production in the late 1800s to early 1900s	Hawaiʻi surf historian, former lifeguard

Maile Waipa Carr & Nalani Kekaula	Ethnographic account, *Hali'a Aloha o Kalapana*	2012	detailed oral histories of 15 residents of the wider Kalapana area	Native Hawaiian descendants of Kalapana families
Charles Langlas	Ethnographic account: *The People of Kalapana from 1823-2010*	2016	detailed oral histories of 25 elders of the wider Kalapana area	anthropologist and Hawaiian studies scholar