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Research

Forgotten forests: expanding potential land use in traditional Hawaiian agroecosystems, and the social-ecological implications

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ABSTRACT. The development of agricultural systems is a fundamental component of social-ecological transformation and a predominant factor influencing social behavior and structuring. However, oversimplification of traditional agricultural production often occurs and limits the understanding of past populations' abilities to mitigate potential risks and enhance food security through effective land management strategies. The social-ecological traits that characterize the Hawaiian Islands provides a unique vantage to explore human ecodynamics over the *longue durée* and assess how these systems can be used to inform current and future land-use strategies, both locally and globally. Using the Hawaiian archipelago as a case study, digitized historical maps depicting a range of crop species and cropping systems were georeferenced to assess previous estimates of land use by early island populations and demonstrate the limitations of narratives constructed from previously modeled extents of land-use activity that rely solely on the preservation of archaeological remnants. The results of our mapped vegetation correspond well with the more intensive forms of agriculture that were included in previous models, but overall indicate that previous models do not fully represent the extent of land use by early island populations, missing vast applications of agroforestry and arboriculture. Based on our findings, we argue that the omission of cultivation systems not associated with physical infrastructure has vastly limited the comprehension of land use by early island populations and driven narratives in social-ecological dynamics that underestimate the extent of agricultural production while inferring sociopolitical outcomes based on the prevailing agricultural dichotomy. To remedy this limitation, we suggest a multimethods approach that integrates diverse data sets for an agricultural model that is more inclusive of all agricultural forms implemented by early Native Hawaiian populations and, therefore, is more representative of the extents of land use by island populations.

Key Words: *agroforestry; arboriculture; Hawaiʻi; land management practices; socioecosystems; traditional agriculture*

INTRODUCTION

The development of agricultural production systems is a fundamental component in social-ecological transformations that has considerable implications for the social structuring and behavior of early populations (Kirch 1994, 2010). Production systems are often presented as an agricultural dichotomy of contrasting systems (e.g., wet vs. dry, collected vs. produced, wild vs. managed; Kennedy 2012). This binary perception overlooks additional forms of cultivation such as arboriculture and agroforestry systems, which were integrated to mitigate risks by increasing total yields and enhancing resilience through diversity. By simplifying agricultural forms, which are a critical contributing factor to social-ecological change, nuanced outcomes may be overlooked or erroneous outcomes may be reached. The archaeological record is an effective tool for assessing the sustainability of land management practices, examining long-term shifts in environmental conditions, and identifying potential risk management strategies employed (Kirch 2005, Fitzhugh et al. 2019, Nesbitt 2020, Rick and Sandweiss 2020). However, the reliance on archaeological remnants to identify and model past land-use activity is often limited by structural preservation, or lack thereof, and may underrepresent land management practices that lack an archaeological footprint.

The use of islands as model systems has proven effective in examining human-ecological relationships to gain insight into environmental modification by humans and the subsequent effects on human societies (Kirch 2007, Rick et al. 2013). Recent research has used a range of techniques to demonstrate agrodiversity in land management practices by early island populations, with an emphasis on arboricultural and agroforestry practices (Kennedy and Clarke 2004, Quintus et al. 2019, Huebert and Allen 2020, Lincoln 2020). Arboreal species and agroforestry were integral components in constructing a highly productive environment, yet are often overlooked as part of the cultivated landscape (Kennedy 2012). In Pacific Island populations generally, and Hawaiʻi specifically, the narrative for social-ecological transformation has predominantly focused on contrasting wetland and dry-field agricultural systems, and narratives of sociopolitical outcomes are derived from this agricultural dichotomy (Kirch 1994, Ladefoged et al. 2009, Kirch 2011). If widespread, the inclusion of arboricultural and agroforestry systems has the potential to augment the production discrepancies between wetland- and dryland-dominated areas, changing the narrative of sociopolitical drivers and interactions between disparate areas.

Hawaiʻi has been employed as a model system of human ecodynamics because of the simultaneous complexity and tractability of its social and ecological systems (Vitousek 1995, 2002, Kirch 2007). The naturally occurring biogeochemical, climate, and topographical gradients that characterize the Hawaiian Islands created various opportunities and constraints for agricultural development (Ladefoged et al. 2009, Lincoln et al. 2018). Early Hawaiian farmers cultivated a broad range of environmentally adapted agricultural systems across the diverse ecology of the archipelago (Handy 1940, Lincoln and Vitousek 2017, Winter et al. 2020). Younger, drier environments characteristically have expansive volcanic plains overlaid by fertile soils that could support an array of rainfed agroecosystems along the large rainfall gradients, including intensive cultivation of

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annual crops, swidden agricultural systems, and various forms of agroforestry (Lincoln et al. 2018). In contrast, geologically older landscapes with higher cumulative rainfall have a more dissected topography and nutrient-depleted soils that primarily supported flooded agriculture in the river valleys, rainfed systems along the valley slopes, and arboricultural systems on the depleted shield surfaces (Kirch 1974).

The broad and highly organized environmental gradients of the Hawaiian Islands, coupled with the fine-tuned agroecological adaptations implemented by Native Hawaiian cultivators, have facilitated the spatial modeling of ancient agricultural distribution. Previous models define environmental thresholds to predict the distribution of flooded wetland, intensive rainfed, and colluvial slope agriculture (Ladefoged et al. 2009, Kurashima and Kirch 2011, Kurashima et al. 2019), which corresponds strongly with the extant archaeological infrastructure (Soong et al. 2023). These models have further been used to extrapolate insight into various social parameters such as population carrying capacity and agricultural labor requirements, with the resulting agricultural surplus considered a key driver in the development of political complexity (Kirch 1984, 1994, 1997, 2010, Ladefoged and Graves 2000, Hommon 2013). Regional variation in these outcomes has driven interpretations of social interactions such as political stability, trade, and conflict (Kirch 1984, 1994, Graves et al. 2011, Kirch 2011, Hommon 2013, Dye 2014, Kagawa-Viviani et al. 2018).

We perceive the previous modeling efforts to be constrained by the archaeological preservation of infrastructural remnants on the landscape; they may therefore be limited in their identification of agricultural forms and their estimated distributions. Collectively, these models have relied on archaeological evidence of early Hawaiian agricultural production systems to identify forms of agricultural systems, parameterize the spatial modeling, and assess its accuracy. As a result, these models omit forms of agriculture that do not require physical infrastructure and are therefore less apparent. These forms include agroforestry and arboriculture, prevalent and often dominant forms of agriculture employed throughout Polynesia (e.g., Yen 1973, 1974, Quintus et al. 2019), which are not associated with the creation of physical infrastructure because the trees themselves are the physical infrastructure. Consequently, models that rely solely on archaeological evidence likely underrepresent the breadth and extent of agroforestry and arboricultural production systems implemented by early island populations (see Konowalik and Nosol 2021).

Here, we aim to understand better the spatial distribution of agroforestry systems by using historical maps that depict traditional agricultural plantings. Mapping efforts conducted between 1819 and 1920 for land surveying purposes across the Hawaiian Islands depict forms of arboriculture and agroforestry, as well as areas of native forest and the more widely documented wetland and dry-field (i.e., rainfed) agricultural systems. Environmental data from mapped depictions of agricultural and forest species were extracted to demonstrate the associated parameters and assess the distribution of agricultural production systems, including agroforestry and arboriculture, in relation to current spatial models of Hawaiian agriculture. While not perfect, these maps provide a cursory understanding of the spatial distribution for areas in which these systems did and did not occur on the landscape. Distribution patterns of the arboricultural and agroforestry systems are discussed, along with their implications for the prevailing narratives regarding social-ecological transformation in Hawaiʻi.

TRADITIONAL HAWAIIAN AGRICULTURE SYSTEMS

A diverse array of cultivation techniques was implemented by early Hawaiian farmers to optimize productivity and overcome environmental constraints in more marginal areas. Wetland systems (*loʻi*), dry-field cultivation, and agroforestry highlight early Hawaiian ingenuity and the adaptation of Polynesian-introduced crops (Handy 1940, Handy et al. 1972, Lincoln and Vitousek 2017, Lincoln et al. 2018). While wetland systems and dry-field cultivation are readily identifiable by the associated landesque capital (Ladefoged et al. 1996, 2003), agroforestry systems lack infrastructural remnants and are consequently less acknowledged in archaeological context (Lincoln et al. 2018, Quintus et al. 2019). Here, we provide a brief overview for each of the predominant forms of Hawaiian agriculture (i.e., wetland, dry field, agroforestry), along with unmanaged forested regions, the environmental landscapes in which they were cultivated, and the primary crops grown in each system.

Flooded wetland cultivation

Wetland agriculture (*loʻi*) focused on the production of *kalo* (taro, *Colocasia esculenta*), a staple root crop, with *maiʻa* (banana, *Musa* spp.), *kō* (sugarcane, *Saccharum officinarum*), and *kī* (ti leaf, *Cordyline fruticosa*) grown along the periphery (Handy et al. 1972). *Loʻi* occur at lower elevations (> 21°C) within river valleys, or across floodplains, in proximity to a flowing water source (i.e., streams, springs, or the water table; Kirch 1977, Earle 1980). Located in geologically older river valleys, nutrients that are necessary for *kalo* production are derived from alluvial and colluvial soils, and sourced mineral and biological nutrients are transported downstream by the current (Palmer et al. 2009). Canals, or *ʻauwai,* were constructed to divert water from flowing rivers into *loʻi* systems to maintain consistent water flow or, in more stagnant water, mounds were formed to elevate *kalo* above water level to prevent rot (Handy et al. 1972).

Distribution patterns for the modeled extents of wetland agriculture reflect these environmental constraints, predominantly occurring in river valleys on geologically older substrates across the Hawaiian Islands (Ladefoged et al. 2009, Kurashima and Kirch 2011). The modeled agricultural extents differ slightly based on their defined parameters for a water source and the irrigable extent, as well as differences in the elevation thresholds.

Fixed-field rainfed systems

In contrast to wetland cultivation, dry-field production systems are primarily dependent on rainfall for moisture. Although there are many forms of rainfed agriculture, here, we specifically refer to "fixed-field" rainfed systems as the vast contiguous systems defined by their common infrastructure of earthen and/or rock walls and mounds. Investment into the intensive rainfed systems occurred where both adequate rainfall and soil fertility occurred (Vitousek et al. 2004, 2014). Because soil fertility evolved primarily as a function of soil age and precipitation, the "sweet spots" for dry-field systems occur in younger, mesic habitats (Ladefoged et al. 2009, 2018). Because these systems extended across vast ecological gradients, their specific function and crop assemblages were somewhat diverse, including several staple tuber crops such as dryland-adapted *kalo,* ʻ*uala* (sweet potato, *Ipomoea batatas*), and ʻ*uhi* (greater yam, *Dioscorea alata;* Lincoln et al. 2018). ʻ*Uala,* a major dryland crop, is characteristically resilient to drought and able to withstand low temperatures (> 18°C) in nutrient-depleted soils (Kagawa-Viviani et al. 2018). Along the embankments (i.e., *kuaiwi*) of these fixed-field systems, tall crops such as *kō, maiʻa,* or *kī* provided structural stability, microhabitat, and mulch, while the cleared fields extending between the walls were used for staple crops of *kalo,* ʻ*uala,* and ʻ*uhi* (Lincoln and Vitousek 2016). The extensive infrastructural footprint of intensive rainfed field systems is distinguished by archaeological remnants across the landscape (e.g., Ladefoged et al. 1996, 2003), which have been used to validate the general accuracy of the spatial models.

Other rainfed systems

In addition to the intensively developed "fixed-field" rainfed systems, archaeological evidence demonstrates that less systematic forms of rainfed agricultural systems were also implemented (e.g., Schilt 1984, Allen and McAnany 1994). These systems ranged broadly from the opportunistic development of microsites in highly marginal habitats, such as very young lava flows (< 4000 yr), to more intensive developments that were restricted from being developed into fixed-field systems due to environmental constraints such as degree of slope, inadequate rainfall, or lack of soil nutrients.

Kurashima and Kirch (2011) identified areas of cultivation on colluvial slopes alongside river valleys and gradual slopes of windward areas, where active erosion rejuvenates the soils to levels of soil fertility that can support intensive rainfed agriculture (Vitousek et al. 2010). However, the variable topography and steep slopes do not allow for the systematic development of infrastructure, and a much more ad-hoc approach is seen in which more diversified infrastructure is used to support a combination of intensive tuber cropping and other crop types such as arboriculture (e.g., *kukui, kī;* Kurashima and Kirch 2011, Morrison et al. 2022).

Agroforestry and arboriculture

The incorporation of tree and shrub species in agroforestry practices is an integral component in the development and sustainability of highly productive agricultural systems (Schoeneberger et al. 2017). In Hawaiʻi, agroforestry systems comprise a variety of native, actively managed species that were fundamental in overcoming land constraints (e.g., slope and vertical cultivation), enhancing soil fertility (e.g., pit cultivation), minimizing environmental disturbance (e.g., erosion, wind breaks), and cultivating additional resources such as medicines, timber, and even famine foods. The application of arboreal species to enhance nutrient acquisition and cycling allowed for the implementation of cultivation in more marginal zones considered unfavorable for dense production of herbaceous crops.

Varying forms of agroforestry were implemented across a range of environmental conditions in the Hawaiian Islands to overcome environmental constraints, increase diversity, and mimic natural systems (Quintus et al. 2019, Lincoln et al. 2023). Vertical cultivation takes advantage of different canopy heights by incorporating a variety of species such as *noni* (Indian mulberry, *Morinda citrifolia*), ʻ*awa* (kava, *Piper methysticum*), *maiʻa* (banana, *Musa* spp.), and ʻ*awapuhi* (ginger, *Zingiber zerumbet*). In coastal regions, salt-tolerant species included *hala* (screwpine, *Pandanus tectorius*), *niu* (coconut, *Cocos nucifera*), *kou* (*Cordia subcordata*), *milo* (Pacific rose wood, *Thespesia populnea*), *hau* (hibiscus, *Hibiscus tiliaceus*), and *noni.* In rocky, less fertile areas or on geologically young soils (< 10,000 yr), *kukui* (candlenut, *Aleurites moluccanus*) and *hau* were cultivated to increase soil fertility due to their rapid growth and decomposition rates, while nutrient-rich slopes with colluvial soils were typically zoned for ʻ*ulu* (breadfruit, *Artocarpus altilis*) cultivation. Because *kou* (*Cordia subcordata*) was actively managed by coastal populations, near households or in home gardens, for a multitude of culturally relevant purposes (e.g., shade, windbreak, boundary markers) and sourced for a variety of materials (e.g., famine food, fuel, medicinal use; see Kirch 1977, Friday and Okano 2006), we classify it here as an arboreal crop species, although it has been shown to be an indigenous species (Burney et al. 2001). Recent work has documented extant trees associated with agroforestry and arboricultural systems (e.g., ʻ*ulu* and *kukui*), suggesting that they closely approximate the traditional footprint of these agricultural forms (Lincoln 2020, Lincoln et al. 2021, *unpublished manuscript*).

Native forests

Native forests were an integral component of the managed landscape that provided a variety of additional resources. Island populations employed various components of indigenous and endemic species for different purposes, including medicinal or ceremonial, a fuel source, to supplement subsistence, or for raw materials such as wood, fibers, or dyes (Abbot 1992, Whistler 2009). Extending across the drier leeward regions, dry forests contained a range of tree and shrub species, including *holei* (*Ochrosia compta*), ʻ*ohai* (*Sesbania tomentosa*), *pua* (*Osmanthus sandwicensis*), and *wiliwili* (*Erythrina sandwicensis*), as well as *alaheʻe* (*Psydrax odorata*), *hinahina* (*Heliotropium anomalum*), and *puakala* (Hawaiian poppy, *Argemone glauca*). Also identified in dry forested regions were species of grass *kalamalo* (*Eragrostis* spp.) and weed ʻ*auhuhu* (*Tephrosia purpurea*). Wet forested regions are located in areas subject to higher rainfall and consist of a variety of tree and shrub species, and the increased rainfall promotes the growth of ferns and vines. Groves of *koa* (*Acacia koa*) are prominent in these regions, along with ʻ*ākala* (*Rubus hawaiensis*), *aku* (*Cyanea* spp.), *kalia* (*Elaeocarpus bifidus*), *māmaki* (Hawaiian nettle, *Pipturus albidus*), *maile* (*Alyxia stellata*), and ʻ*ōhelo* (*Vaccinium reticulatum*), as well as ferns (e.g., *hāpuʻu, Cibotium* spp. and *uluhe, Dicranopteris* spp.), *kihe* (*Xiphopteris saffordii*), *paʻiniu* (*Astelia* spp.), and ʻ*ieʻie* (*Freycinitia arborea*). Several species occupy a range of diverse environments, including ʻ*ōhiʻa* (*Metrosideros polymorpha*), *lama* (*Diospyros sandwicensis*), *māmane* (*Sophora chrysophylla*), and *kōpiko* (*Psychotria hawaiensis*). Although native forests are not depicted by previous models, they are generally indicative of areas not intensively cultivated by island populations.

METHODS

Use of historical maps for depicting agricultural distribution

The analysis was performed using digitized historical maps of the Hawaiian Islands. All Hawaii State Registry Maps (*N* = 3729) and Hawaii Plat Maps (*N* = 1023) were acquired from the digitized state database (http://ags.hawaii.gov/survey/map-search/), in addition to a small number of other historical maps and surveys (*N* = 36) from the Bishop Museum (http://data.bishopmuseum.org/kekahuna). All maps were catalogued according to online availability, survey date, and depiction of vegetation. Of the available maps, those that did not depict agricultural features, were duplicative, contained low-quality data, or could not be georeferenced were excluded from further analysis. The remaining maps were georeferenced into ArcMap 10.6.1 (ESRI, Redlands, California, USA) using fixed landscape features such as natural formations, human-made structures, or traditional political boundaries (*ahupuaʻa;* retrieved from https://geoportal.hawaii.gov/) when appropriate. Historical maps that lacked identifiable markers and could not be accurately georeferenced were eliminated from additional analysis at this stage, resulting in 573 maps used in the final analysis (Fig. 1). The usable maps supported broad coverage of five Hawaiian Islands but with variable coverage, with multiple overlapping maps depicting most locations, and some locations not depicted at all (Fig. 2).

Fig. 1. Flow diagram illustrating the process used to select the historical maps used in the analysis.

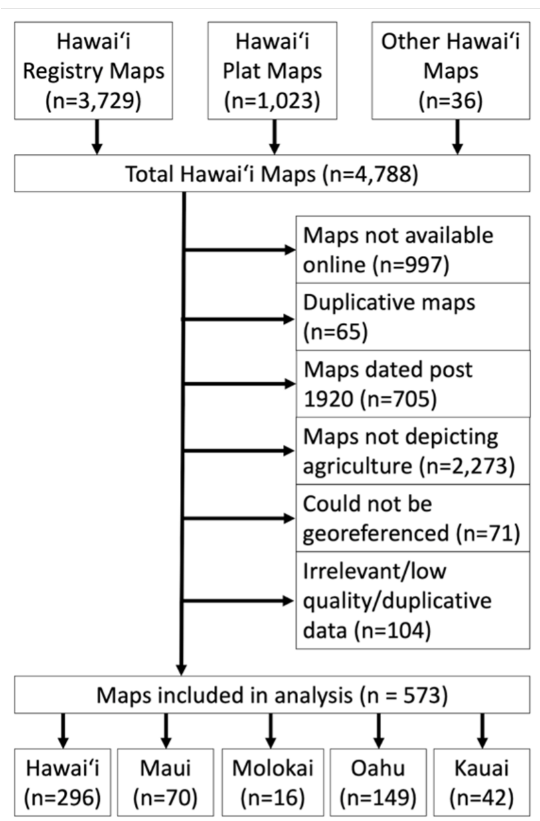
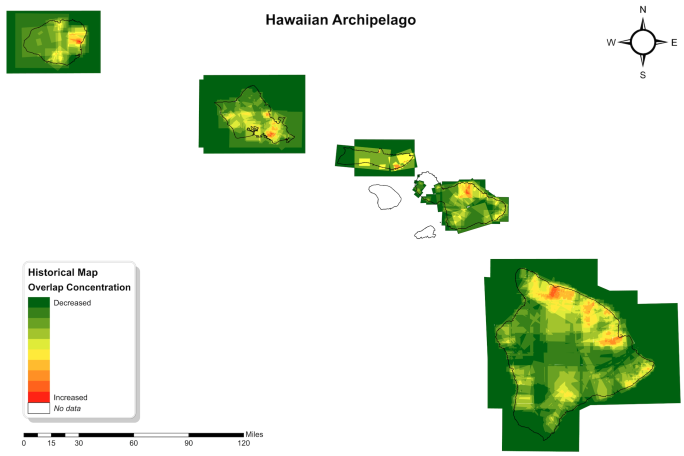


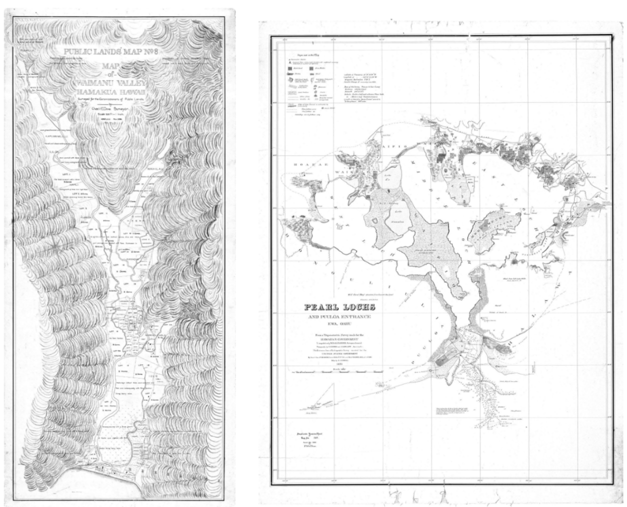
Fig. 2. Concentration of georeferenced historical maps across the Hawaiian Archipelago used for data extraction. The color gradient indicates areas of decreased (green) or increased (red) concentration of historical map overlap. Areas in which no maps were georeferenced and no data were available are also indicated (white).



The depiction of historic vegetation varied slightly between maps and, in many instances, lacked explicit boundaries (Fig. 3). To minimize over- or underrepresenting the environmental extent of any particular form of agriculture, individual points were centered within the written word or marked directly on top of the symbolic imagery. We opted for point-based data because the purpose of this exploratory research was to broadly understand the distribution and patterns of agroforestry and arboriculture in Hawaiian cultivation systems. Because of the variability in both map coverage across the state and how each map depicted agricultural extent, we did not feel confident in conducting quantitative analysis of distributions such as by using a systematic grid and, instead, used the individual points simply to represent areas of agroforestry potential. The point-based data were manually extracted by creating an appropriately classified point for each relevant depiction of agriculture or native forest.

Agricultural classifications were derived from Kirch (1982) and Lincoln and Vitousek (2017), consisting of three main systems of agriculture: swidden or dry-field cultivation, wet or flooded cultivation, and agroforestry or arboriculture. Based on the mapped descriptions and the species indicated, points were classified as either wetland, dry field, arboriculture, or native forest (Table 1). Because our purpose was to expand the scope of production systems beyond the binary wetland and dry field systems, we used a simplified classification system that amalgamates varying forms of arboriculture and agroforestry systems. The categories are intended to demonstrate broader patterns of managed and unmanaged regions across the Hawaiian Islands depicted on historical maps, to extract environmental data of documented locations of vegetation presence, to assess the extent of agroforestry practices across the archipelago, and to demonstrate relationships between managed forms of production.

Fig. 3. Digitized historical maps depicting vegetation from the 19th century. Left: Waimanu Valley, Hamakua district, Hawai'i Island depicting *ohia, kukui, kalo,* ferns, *mai'a,* and *kī* (Dove 1986). Right: Pearl Lochs, Ewa district, O'ahu depicting vegetation drawings of *niu, kalo,* and *mai'a (Lyons 1873).*



Environmental data were extracted using point data generated from the georeferenced maps, along with climate data layers of elevation, annual rainfall, and average annual air temperature obtained from the Hawai'i Evapotranspiration Portal (Giambelluca et al. 2013, 2014). Geological age was obtained from the United States Geological Survey (Sherrod et al. 2007). Summary statistics were generated for the point data. Percentiles of 99 and 1 were used to describe the environmental parameters to clip the extreme outliers, an approach that has been shown to work well with the assessment of extant agroforestry trees in Hawai'i (Lincoln et al. 2021).

Comparison of point data to existing geospatial models

Previously modeled extents of dry-field and wet-flooded cultivation in traditional Hawaiian agriculture by Ladefoged et al. (2009) and Kurashima et al. (2019) were imported, and a spatial intersection was performed to identify the modeled agricultural form associated with each point extracted from the maps. Model identification included three categories: dry field (D), wetland (W), or no agriculture (O). In the case of Kurashima et al. (2019), "colluvial" agriculture was combined into the dry-field category. These three categories were compared against the four categories determined from the mapped points: dry field (D*), wetland (W*), arboriculture (A*), and native forest (O*).

Using classifications derived from the georeferenced maps and the modeled extents of traditional agriculture, we applied confusion matrices to assess the data, using the map-derived data set as the actual condition and the modeled outcome as the predicted condition. Multiple confusion matrices were constructed by dividing data sets into different inclusive and exclusive portions to determine true/false positive/negative outcomes. Four iterations of confusion matrices were run for each

Table 1. Agricultural species depicted on digitized historical maps, including Hawaiian and scientific names, origin (E = endemic, N = native, P = Polynesian introduction, U = Unknown), and the classified form of each identified species.

Crop	Scientific name	Origin	Classification			
			Wetland	Rainfed	Arboriculture	Forest
akala	*Rubus hawaiensis*	E				X
aku	*Cyanea* spp.	E				X
alahee	*Psydrax odorata*	N				X
auhuhu	*Tephrosia purpurea*	N				X
awa	*Piper methysticum*	P			X	
awapuhi	*Zingiber zerumbet*	P	X			
hala	*Pandanus tectorius*	P			X	
hapu'u	*Cibotium* spp.	E				X
hau	*Hibiscus tiliaceus*	U			X	
hinahina	*Heliotropium anomalum*	E				X
holei	*Ochrosia compta*	E				X
ie'ie	*Freycinetia arborea*	N				X
kalamalo	*Eragrostis* spp.	E				X
kalia	*Elaeocarpus bifidus*	E				X
kalo	*Colocasia esculente*	P	X			
kī	*Cordyline fruticosa*	P				
kihe	*Xiphopteris saffordii*	E				X
koa	*Acacia koa*	E				X
kolea	*Myrsine* spp.	E				X
kou	*Cordia subcordata*	N			X	
kukui	*Aleurites moluccana*	P			X	
lama	*Diospyros sandwicensis*	E				X
lauhala	*Pandanus tectorius*	N			X	
lehua	*Metrosideros polymorpha*	E				X
mahoe	*Alectryon* spp.	E				X
mai'a	*Musa* spp.	P			X	
maile	*Alyxia stellata*	N				X
mamaki	*Pipturus albidus*	E				X
mamane	*Sophora chrysophylla*	E				X
niu	*Cocos nucifera*	P			X	
noni	*Morinda citrifolia*	P			X	
ohai	*Sesbania tomentosa*	E				X
ohelo	*Vaccinium reticulatum*	E				X
ohia	*Metrosideros polymorpha*	E				X
opiko	*Psychotria hawaiensis*	E				X
painiu	*Astelia* spp.	E				X
pili	*Heteropogon contortus*	N		X		
pua	*Osmanthus sandwicensis*	E				X
puakala	*Argemone glauca*	E				X
puhala	*Pandanus odorattissimus*	E			X	
uala	*Ipomea batatas*	P		X		
'ulu	*Artocarpus altilis*	P			X	
uluhe	*Dicranopteris* spp.	E				X
wiliwili	*Erythrina sandwicensis*	E				X

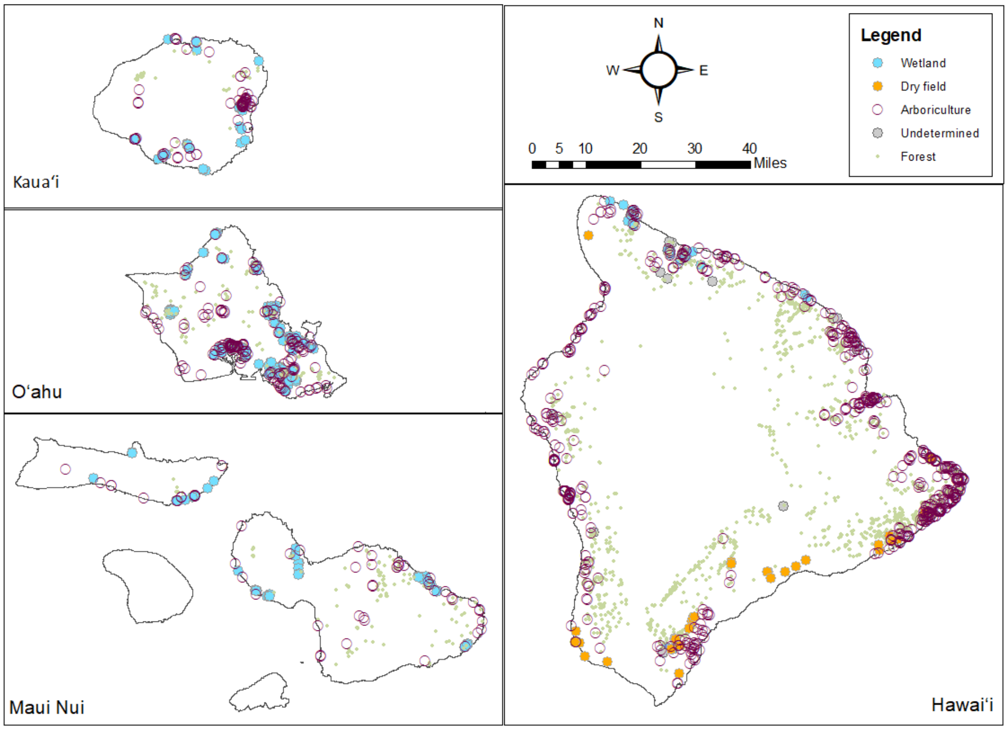
of the two spatial models, in which the following components were matched as true positive (with all other categories considered negatives): W to W* (wetland assessment); D to D* (dryland assessment); W and D to W* and D* (wet and dry assessment); W and D to W*, D*, and A* (all agriculture assessment).

The results from the confusion matrices were used to calculate the accuracy (ACC), which defines the number of correct classifications over the total number of classifications, using Eq (1).

$$ACC = \frac{(TP + TN)}{(TP + FP + TN + FN)} \quad (1)$$

where TP is true positive, TN is true negative, FP is false positive, and FN is false negative.

Fig. 4. Mapped vegetation data points for each of the Hawaiian Islands extracted from georeferenced historical maps depicting different agricultural forms, including wetland, dry field, arboriculture, and native forests.



RESULTS

Overall georeferencing of the maps appeared highly accurate, with good alignment to contemporary geological and political features. Maps varied in their usefulness, but many clearly depicted agricultural forms and associated species. For any given point in the state, a number of overlapping maps depicted the area. In total, 3028 points were extracted from the georeferenced maps and categorized as dry-field agriculture (N = 32), wetland systems (N = 552), arboriculture (N = 838), or native forest (N = 1595).

Point distribution varied across the islands, with visual patterns and clustering apparent (Fig. 4). Data points associated with wetland agriculture show distribution patterns that span the Hawaiian Islands, with their relative occurrence increasing on the older islands of O'ahu and Kaua'i. The dry-field agriculture distribution was limited to the southern coastal area of Hawai'i Island. Arboreal species are broadly distributed across the archipelago and occupy an expansive range of ecological niches within each island environment, indicating overlap with wetland and dry-field niches in some areas.

Analysis of the climatic variables showed differences between the classification types, providing some insights into how the distribution of agroforestry systems may be situated across the landscape relative to the wetland or dry-field systems (Table 2). Distributions of elevation and temperature align with expectations. At one extreme, arboriculture systems extend to sea level and ~23.5°C, aligning with both wetland and dry-field forms. At the other extreme, dry-field and arboriculture reflect similar environmental thresholds (~950 m and ~17°C), which are considerably higher and colder than wetland systems (~400 m and ~21°C).

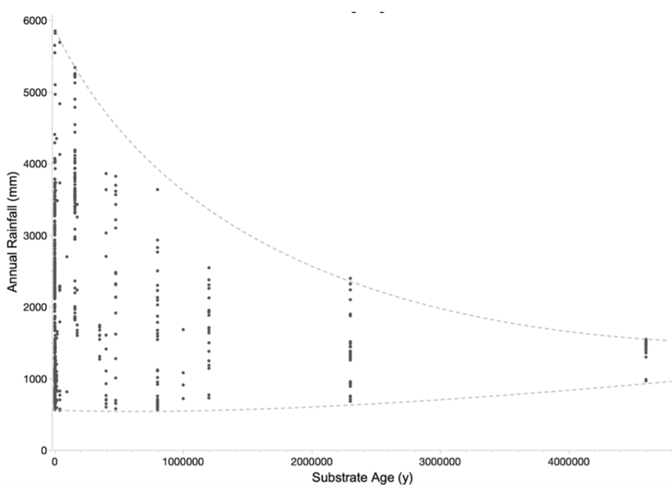
In terms of rainfall and substrate age, which also interact to result in soil fertility, arboriculture extends to both drier and wetter extremes than dry-field systems and on much older substrates. These results align with expectations from ethnohistorical and other accounts but provide some quantification to the ranges. Examining the distribution of rainfall represented by arboriculture sites across the gradient of substrate age, the maximum rainfall values appear to show a clear decline following a log-log relationship (Fig. 5). The product of rainfall and substrate age approximates mineral weathering potential, which strongly affects soil fertility. This decay relationship suggests that there is a lower threshold for soil fertility below which agroforestry may not have been developed.

Assessment of the confusion matrices and accuracy calculations between our point classification and the model classification highlighted some clear patterns. Of the 838 points classified as arboriculture from the historical maps, 697 (83.2%) and 691 (82.5%) fell outside the modeled extents represented by Ladefoged et al. (2009) and Kurashima et al. (2019), respectively. This result suggests that current models of traditional Hawaiian agriculture do not capture the extent of agroforestry. This result is not surprising, as the models were specifically parameterized for intensive rainfed and wetland forms of agriculture. Examining

Table 2. Distribution of environmental parameters of the spatial points defined for each agricultural type, showing the mean and the 99th and 1st percentiles.

Agriculture type	Elevation (m)			Rainfall (mm/yr)			Substrate age (10^3 yr)			Temperature (°C)			Slope (%)		
	P_1	Mean	P_{99}	P_1	Mean	P_{99}	P_1	Mean	P_{99}	P_1	Mean	P_{99}	P_1	Mean	P_{99}
Wetland	1	51	405	334	1551	4269	1	308	2300	20.7	23.1	23.8	0.1	4.7	28.6
Dry field	6	342	930	626	1622	3089	0	14	350	17.1	21.2	23.6	0.8	3.9	14.7
Arboriculture	0	132	979	240	1958	5251	0	396	4600	17.3	22.5	23.9	0.1	4.9	24.7
Native forest	11	724	2043	615	2573	6341	0	376	3800	10.3	18.5	23.2	0.5	7.0	34.6

Fig. 5. Distribution of rainfall across geologic substrate age for the 99th percentile of agroforestry points, with log-log trends of the maximum and minimum values.



the calculations of model accuracy, both models score high on the wetland, dryland, and wet and dry assessments, indicating that the models demonstrate a high degree (> 85%) of true positive and true negative classification for the components of traditional agriculture to which they were directed (Table 3). When mapped points classified as arboriculture are included in the all agriculture assessment, the model accuracies drop by almost 20 points, verifying that the model accuracies are negatively affected by the consideration of agroforestry systems.

DISCUSSION

Previous models have aimed to capture the more intensive forms of wetland and dry-field agriculture based on a preserved archaeological footprint (Ladefoged et al. 2009, Kurashima et al. 2019). The oversimplification of agricultural systems into binary classifications (e.g., wetland/dry-field, collected/produced, wild/managed) minimizes the role of traditional ecological knowledge as well as the potential of early land stewards to overcome environmental constraints (Kennedy 2012). While the intensive wetland and dry-field systems may have accounted for much of the food production, additional production from extensive agroforestry systems would contribute substantially to the yields, resilience, and diversity of agricultural production systems in most Hawaiian environments. Unlike the wetland and dry-field systems that were closely tied to a narrow spectrum in the evolution of soils and

Table 3. Accuracy calculation derived from confusion matrices based on various inclusion levels of the mapped and modeled agricultural forms.

Modeled extents	Wetland assessment	Dry field assessment	Wet and dry assessment	All agriculture assessment
Ladefoged et al. 2009	0.90	0.94	0.85	0.67
Kurashima et al. 2019	0.88	0.90	0.86	0.68

topography across the archipelago, agroforestry systems could be applied to a much broader ecological range and, according to ethnohistorical accounts and modern botanical surveys, were employed extensively across all the islands, in both wet and dry locations (Handy 1940, Quintus et al. 2019, Lincoln et al. 2021, 2023). Using historical maps as an alternative, spatially explicit data source, we verify that previous models largely do not account for the distribution of agroforestry. Given that in most Polynesian Islands, agroforestry was the most extensive form of agriculture (Yen 1974, Maxwell et al. 2016, Quintus et al. 2019, Huebert and Allen 2020), we argue that the inclusion of agroforestry into the consideration of traditional Hawaiian agriculture, and the associated sociopolitical outcomes, is essential for discussions pertaining to the coupled human-environment systems.

The strong agreement between the mapped vegetation points and previously modeled extents of agricultural production systems further validates the extents of wetland and dry-field agricultural forms and demonstrates the validity of the data derived from historical mapping efforts. However, the decline in calculated agreement when agroforestry systems are included suggests that previous models grossly underestimate the extent of land use by early Hawaiian populations. This underestimation may be due to previous model estimates focused primarily on subsistence crops, although agroforestry systems integrate subsistence crop and resource crops, as they were both critical elements of agricultural production (Lincoln and Vitousek 2017, Quintus et al. 2019, Huebert and Allen 2020, Lincoln 2020). Previously modeled agricultural land use by Hawaiian populations was estimated to be ~3–6% (Ladefoged et al. 2009, Kurashima et al. 2019). However, Lincoln et al. (2023) suggest a footprint of landscape modification for agriculture closer to 25%, with the inclusion of agroforestry, arboriculture, and other marginal production systems.

Arboriculture accompanied, or was integrated into, the more intensive forms of wetland and dry-field systems (Kelly 1983, Kirch 1994). Overall patterns in mapped arboriculture closely parallel zones identified by Kirch (1994) for wetland and dry-field agricultural systems across the Hawaiian Islands. Additionally, Kurashima and Kirch (2011) classify colluvial slope cultivation as a mixed-crop rainfed system that incorporates arboriculture (i.e., ʻ*ulu*) and other supplementary crops (e.g., *kī, maiʻa*). These arboreal crops are associated with multiple cropping systems and are not as strictly confined by environmental parameters as wetland or dry-field systems, demonstrating the shortcomings of dichotomous agricultural classifications. Despite the cross-classification of crop species, it is clear that previous models did not fully depict potential land area used for agricultural production.

Only 1% of data points depicted on historical maps are associated with dry-field agriculture, potentially suggesting that these systems were either systematically omitted or were largely absent by the mid-19th century. Dry-field systems required substantial labor to maintain continued production (Kirch 1994, Ladefoged et al. 2009), and rapid abandonment of these high-maintenance cropping systems following European contact appears common. In addition, these areas were targeted for land-use conversion into plantations and pasture lands for multiple reasons (e.g. occurence on more fertile soils, already cleared of trees and forest, European familiarity with similar forms of agriculture). The subsequent conversion of these dry-field zones eliminated infrastructural remnants associated with dry-field systems, resulting in further loss of indication of early Hawaiian production systems (Gon et al. 2018). While potential bias in the selection of mapped features may account for the lack of dry-field systems depicted in historical maps, the extensive documentation of these expansive systems and high agreement between archaeological remnants and geospatial models suggests systematic ommission was likely not the case. Rather, we suggest that the modeled extent of dry-field agriculture and corresponding archaeological remnants (Ladefoged et al. 2009, Kurashima et al. 2019, Soong et al. 2023), coupled with the lack of historically depicted dryland forms of agriculture post-contact, demonstrate that processes of social-ecological transformation are embedded in the cultural landscape. We can use this shift in depicted dry-field systems to argue the lack of historically depicted dry-field agriculture effectively quantifies the decline in, and abandonment of, the once dominant rainfed dry-field systems.

When considered within the context of ethnohistorical accounts and historical documentation, the large population and highly complex sociopolity observed at European contact would not have been sustained by the two predominantly recognized forms of agricultural production (i.e. wetland and dry field). Although wetland systems provided higher yields and decreased risk due to consistency in available resources (e.g., water and nutrients), they were restricted to river valley floors that compose a small proportion of the total land area, particularly in younger substrates. Dry-field systems were more extensive than wetland systems but required more labor inputs and had higher levels of risk due to climate sensitivity and limited growing periods. The environmental extent of arboreal crops encompassed and exceeded the environmental range of wetland and rainfed systems (refer to Table 2). Across the Hawaiian Islands, arboreal species were marked in areas in which wetland and dry-field systems were not considered suitable, being too low in rainfall, too high in elevation, or geologically too young, and thus, unable to support intensive forms of cultivation. The implementation of arboriculture and agroforestry as a risk management strategy to overcome environmental constraints associated with wetland and dry-field production would have increased resource availability and permitted more marginal regions to be inhabited while reducing labor inputs and crop susceptibility to maximize the potential outputs within the limited land area of the archipelago.

The widespread distribution of agroforestry data points demonstrates that agroforestry was implemented across the archipelago and would therefore act to smooth the differences emphasized in the socioeconomic outcomes of the wet-dry dichotomy. Previous anthropological arguments have suggested that the high reliance on wetland systems, with more stable and higher surplus production, on the older island of Kauaʻi allowed for more stable politics, while conversely, the reliance on dry-field production, with more variable and lower surplus production, on the younger island of Hawaiʻi resulted in high political turmoil and the stimulus for warfare (Kirch 2011). Graves et al. (2011) provide a compelling demonstration for differing socioeconomic outcomes (warfare, marriage alliances, number of polities, etc.) between Hawaiʻi and Maui islands, which they largely attribute to potential differences in the environmental structures and associated agricultural systems. However, widespread agroforestry systems as part of these production matrices tempers the variability of dry-field systems and balances the high surplus of wetland systems. Although the agricultural dichotomy of wet vs. dry is often thought to be the leading driver of sociopolitical outcomes in Hawaiʻi, the consideration of agroforestry and arboriculture must be applied to understand better the linkages between environmental structures and sociopolitical outcomes (Graves et al. 2011). It should further be considered that agroforestry systems, in addition to providing additional food resources, were essential for their provisioning of resources that are not provided by dry-field or wetland systems, such as timber, firewood, fiber, and oil, in addition to medicine, dye, and ceremonial necessities. They therefore could not be omitted from wetland-dominated areas, even if the wetland systems alone provided an adequate and stable food supply.

Our results suggest that while the incorporation of archaeological evidence provides an opportunity to assess long-term human ecodynamics, a multiproxy interdisciplinary approach provides a more robust comprehension of environmental constraints and adaptive land management practices. The demonstrated agreement between historically mapped vegetation and remnants of agricultural infrastructure for wetland and dry-field systems supports findings of previous models (Ladefoged et al. 2009, Kurashima et al. 2019) and expands upon previously modeled extents of early agricultural systems to provide additional insight into early island cultivation practices. When coupled with archaeological remnants of agricultural infrastructure, we reduce limitations of modeled agricultural extents with more complete data sets, minimize potential biases, and further enhance the understanding of place-based social-ecological change and the potential factors driving sociopolitical outcomes. This approach can be adapted and applied more broadly in other regions to explore the influential role of agrodiversity in social-ecological development. Because managed forests are not unique to Pacific Islands (e.g., Heckenberger et al. 2007, Erickson 2008, Diemont and Martin 2009, Vallejo-Ramos et al. 2016, Armstrong et al. 2021), these adaptive practices can offer insight into sustainable land use, better food security, and climate-adaptative practices, both locally and globally.

CONCLUSION

A long-standing narrative of socioeconomic disparity is reliant on the agricultural dichotomy and reinforced by limited identification of agricultural infrastructure. Although geospatial models capture intensive forms of agricultural production in areas otherwise lacking agricultural and archaeological remnants, the ommission of a key cropping system underestimates the complexity of traditional ecological knowledge and adaptive practices that were implemented by early societies to support the development of a highly complex sociopolity. Additionally, minimizing the extent of agrodiversity in traditional land-use practices consequently diminishes the resourcefulness and ingenuity of early populations, as well as the enduring impact of European contact on traditional societies. To overcome potential biases and demonstrate shifts in potential land use for traditional societies, we suggest a multimethods approach to refine previously modeled extents and establish a more inclusive model that is representative of the various forms of agricultural systems employed by early Hawaiian farmers. The development of agricultural production systems, from productive coastal and inland zones into more marginal regions, not only attests to the environmental diversity of Polynesian introduced crops, but to the resilience and ingenuity of early Hawaiian farmers. Employing Hawaii as a model system, we can apply the results of this approach to enhance the understanding of social-ecological relationships as well as the sociopolitical dynamics of other early societies.

Author Contributions:

Conceptualization, Data curation, Investigation, Validation, Visualization, Writing - original draft: T. M. L.; Formal analysis, Methodology, Software, Writing - review & editing: T. M. L., N. K. L.; Funding acquisition, Project administration, Resources, Supervision: N. K. L. All authors have read and agreed to the published version of the manuscript.

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Data Availability:

The resources used to obtain the results of this study are available in the public domain. The map database was derived from the State of Hawaii, Department of Accounting and General Services (https://ags.hawaii.gov/survey/map-search/) and the Bishop Museum (http://data.bishopmuseum.org/kekahuna/kekahuna.php?b=about). The spatial files used to georeference maps are available through the Hawaii Statewide GIS Program (https://geoportal.hawaii.gov/). The environmental data were derived from the U.S. Geological Survey Open-File Report (https://pubs.usgs.gov/of/2007/1089/).

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