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Agroforestry Distribution and Contributions in Ancient Hawaiian Agriculture

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Abstract

Agriculture is one of the most fundamental ways in which human societies interact with the environment. The form and function of agriculture have important socio-political implications in terms of yields, labor requirements, variability and resilience, and elite control. Hawai'i has been used as a model system for the discussion of coupled human and natural systems, and how the uneven distribution of agricultural opportunities has manifested in the political ecology. However, consideration of agriculture has emphasized forms with physical infrastructure documented through archaeology and have not included arboricultural forms that were extensive among Pacific Islands. We leverage existing, independent data sets to build and validate spatial models of two intensities of arboriculture across the Hawaiian archipelago: Agroforestry and Novel Forest. Model validation demonstrates good accuracy that includes both expected and unexpected sources of errors. Results of the models demonstrate that arboricultural techniques accounted for ~70% of the agricultural potential by area and ~40% of the agricultural potential by yield. Unlike existing agricultural forms modeled, such as flooded wetland terrace cultivation and rainfed field production, which have strong distributional patterns based on the age of the islands, arboricultural potential is well distributed across all the islands. The extent, distribution, and characteristics of arboricultural methods provide important augmentation of the current narrative of production dynamics and distribution, and the political ecology, of pre-contact Hawai'i.

Keywords Arboriculture · Agroforestry · Agroecology · Hawai'i · Indigenous · Novel forest · Traditional ecological knowledge (TEK)

Introduction

The Hawaiian Islands are often highlighted as one of the most ecologically diverse locations in the world, with over two-thirds of the Holdridge life zones constricted within approximately 16,600 km^2 of land (Asner et al., 2005). This ecological diversity is propelled by vast climatic, topographic, and biogeochemical gradients across the islands, which are among the broadest environmental gradients on Earth and are highly spatially organized throughout the archipelago (Vitousek, 1995, 2002). Hawai'i has also been noted as a model system for understanding human societies, due to its relatively short human history, its extreme isolation, and its development into a highly complex state-level polity (Kirch, 2007). The rare combination of Hawai'i's complex yet tractable ecological and socio-political parameters presents an exceptional model system for understanding the development, evolution, and function of socio-ecosystems.

Although Hawai'i's ecological diversity and adaptive radiation of endemic species is widely recognized, the cultural radiation of knowledge and practices, such as the diverse range of adaptive agroecosystems developed by Native Hawaiian cultivators, is less acknowledged (Lincoln & Vitousek, 2017; Lincoln et al., 2018). As early island populations expanded into the diverse ecosystems across the Hawaiian archipelago, a broad range of place-adapted agricultural systems evolved. These systems, in part due to the success of Hawaiian cultivators' ability to efficiently conform cropping selection and intensity to a given landscape,

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supported and sustained large populations (~400–800,000) for several centuries (Kirch, 1982, 2007; Stannard, 1989). The spatial distribution of these systems has been of interest, as the varying agricultural opportunities afforded different social outcomes, such as carrying capacity, social conflict or cooperation, evolution of political complexity, and ecological footprint, among others, thereby manifesting the role of ecology in society and culture (e.g., Dye, 2014; Gon et al., 2018; Graves et al., 2011; Kagawa-Viviani et al., 2018; Kirch, 1982, 1994; Kirch & Zimmerer, 2011; Kurashima et al., 2019; Ladefoged et al., 2009; Vitousek et al., 2004). Understanding the distribution of these systems also has the potential to inform decisions related to modern-day cropping systems and land management strategies.

Prior investigations of Hawaiian agriculture and their spatial extent have largely been defined by archaeological perspectives, resulting in an emphasis on agricultural systems associated with the development of physical infrastructure, such as flooded-terraced (herein wetland) and fixed-field rainfed (herein intensive dryland) systems (Sen, 1959; Widgren & Håkansson, 2016). Spurred by Kirch's (1994) seminal work on the uneven distribution of wetland and dryland agriculture in Pacific Island systems, subsequent geospatial modeling and discussions of traditional Hawaiian agriculture have further emphasized these more intensive forms of agriculture (Kurashima et al., 2019; Ladefoged et al., 2009). From these models, extrapolations have been made regarding labor requirements, yield, and carrying capacity, with the heterogeneous distribution of agricultural types and their associated outcomes playing a key role in discussions of coupled human and natural system dynamics.

While previous models have accurately demonstrated the extent of potential land use associated with physical infrastructure, the most extensive forms of agroecological systems in Polynesia—arboriculture, agroforestry, swidden agricultural systems, and shifting cultivation—tend to lack any significant infrastructural footprint (Quintus et al., 2019). In Hawai‘i, significant population centers that were supported almost entirely by agroforestry cultivation, such as the Puna and Hamākua districts of Hawai'i Island, are not represented in current models of Hawaiian agriculture (Lee & Lincoln, 2023; Lincoln et al., 2018). Despite the prevalence of these arboricultural systems, their original extent is poorly explored and is not well included in the previously described spatial models and parallel discussions. Previous work exploring the traditional arboriculture footprint in the islands shows evidence that remnant economic trees, such as ‘ulu (breadfruit; *Artocarpus altilis*) and kukui (candlenut; *Aleurites moluccanus*) closely preserve the footprint of traditional agroforestry (Lincoln, 2020; Lincoln & Ladefoged, 2014; Lincoln et al., 2021) and, recently, extensive use of nineteenth-century maps has generated a spatially explicit data set of agroforestry cultivation across the Hawaiian archipelago (Lee & Lincoln, 2023).

We know from ethnohistorical sources that arboricultural and agroforestry systems were major components of Hawaiian agroecological systems as a whole, and their extensive nature, range of resource production, and ability to cultivate otherwise unproductive lands make their inclusion in the discussion of Hawaiian agriculture, ecological footprint, and political ecology essential (Handy, 1940; Handy et al., 1972; Meilleur et al., 2004). This builds on global studies of indigenous agricultural systems, both in the past and present, that seek to better recognize the diversity, ecological roles, and long-term development of arboreal-based systems of production (Lentz et al., 2014, 2015; Terrell et al., 2003). We leverage existing data sets and ethnographic sources to develop and assess spatial models of two forms of Hawaiian arboriculture: intensive agroforestry and novel food forests. We discuss the spatial extent and distribution of these systems, as well as how their consideration and inclusion into Hawaiian agroecological models as a whole enhances the existing narrative of human ecology in Hawai‘i.

Methods

Model Development

Although the absence of any physical infrastructural remnants makes the extent of arboriculture and agroforestry systems difficult to delineate, previous work has engaged new tools to explore indicators. Lincoln and Ladefoged's (2014) use of mixed methods to interpret the extent of one agroforestry development suggested that remnant breadfruit trees on the landscape closely approximated the ancient extent of the system. Use of historical and contemporary aerial imagery to assess patterns of kukui canopy in Lincoln et al. (2021) argued that the declining footprint of kukui outlined ancient Native Hawaiian modification of forests. A pilot project by Lincoln (2020) further argued that the distribution of these two common agroforestry species in conjunction with each other demonstrated patterns that aligned with sociopolitical boundaries and shifts in arboricultural intensity known from ethnohistorical records. Collectively, these previous studies have provided both datasets and frameworks from which initial spatial interpolation of traditional arboriculture can be assessed.

Specifically, we developed two spatial models depicting different intensities of arboricultural methods, which we term Novel Forests and Agroforestry (Fig. 1). Although arboricultural and agroforestry systems take on extremely diverse forms across environments and cultures, these broad categories generally distinguish degrees of management intensity (Dagar, 2016; Nair, 1985, 1989). In our classification, Novel Forest systems are indicative of low management inputs with a primarily closed-canopy and

Fig. 1 Examples of Agroforestry (**A**), which is more intensively managed, includes a higher degree of light penetration and a greater proportion of herbaceous plants, and Novel Forest (**B**), which is less intensively managed, consists of a closed canopy and greater proportion of trees

high proportion of trees, likely representing accumulated shifts in native to novel species over long periods of use. Agroforestry represents more intensive and deliberate management of trees and crops to facilitate production, with increased light penetration and proportion of herbaceous crops compared to Novel Forests.

To parameterize the spatial models, we utilized two existing datasets. From Lincoln et al. (2021) we used a spatial dataset of statewide kukui canopy, derived from a semi-automated classification approach to map kukui across the five largest Hawaiian Islands from high-spatial-resolution satellite Worldview-2 imagery, using images collected in 2013 for Kauai, 2014 for Maui, 2016 for Moloka'i, 2016–2017 for Hawai'i Island, and 2017 for O'ahu. The approach started with a supervised classification using three vegetation classes— kukui, other forests, and pasture/grassland— followed by manual correction of the classification errors. The classical maximum likelihood classifier (MLC) method in ENVI (Harris Geospatial Solutions, Inc., Melbourne, FL) was used and intentionally chose two broadly-defined non-kukui vegetation classes so that the automatic classification was overwhelmed by commission errors instead of omission errors. After applying the MLC, classification errors were manually edited in ArcGIS (ESRI, Redlands, CA) to produce the final dataset depicting the distribution of kukui canopy. The second dataset was obtained from Mausio et al. (2020) and consists of 1,200 naturalized breadfruit trees (cv. 'Maoli') that were manually mapped from systematic ground surveys of Hawaiian breadfruit on four islands (Kaua'i, Molokai, O'ahu, and Hawai'i).

Spatial points were used to extract values from environmental geospatial layers for analyses. Spatial environmental layers were acquired from the Hawai'i Rainfall Atlas (Giambelluca et al., 2013), the Hawai'i Evapotranspiration Atlas (Giambelluca et al., 2014), the USGS Geologic Map of the State of Hawai'i (Sherrod et al., 2007, 2021), and the Hawai'i State GIS Database (http:// geoportal.hawaii.gov/). We followed a similar modeling approach to Ladefoged et al. (2009), which accurately predicted the spatial distribution of intensive dryland agricultural systems in Hawai'i prior to European contact, in which environmental constraints are intersected to determine the potential extent of suitable habitat for the development of each agricultural form (Soong et al., 2023).

The distribution of kukui and breadfruit indicator species were used to parameterize the environmental constraints while considering previously published threshold values. Using the point-based locations of the trees, distributions of average annual surface temperature, rainfall, geologic age, and slope were extracted in ArcMap. In regards to both species, the 99.9% quantiles for slope (30.12º), temperature (18.08 ºC), and rainfall (757.55 mm/yr), aligned very well with previously published extents for the Polynesian development of dryland agriculture of 30°, 18 °C, and 750 mm/yr respectively (Kurashima et al., 2019; Ladefoged et al., 2009). Given the close alignment of our data set with these previously established environmental extents, thresholds of 30° slope, 18 °C average annual temperature, and 750 mm/yr rainfall were used as environmental constraints in our models.

Along with environmental constraints, soil fertility was a key factor in describing the extent of agricultural development and agroecological form in Polynesia, as it qualified or disqualified certain agroecological systems from efficient production (Autufuga et al., 2023; Ladefoged et al., 2009; Lincoln et al., 2014; Quintus & Lincoln, 2020; Vitousek et al., 2004, 2010, 2014). Soil fertility, or the capacity of soil to supply nutrients and water to plants, of the volcanic shield surfaces in Hawai'i is largely determined as a function of weathering potential and substrate age (Autufuga et al., 2023; Chadwick et al., 2021; Vitousek et al., 2021). In this case, weathering potential is largely a function of climate-driven water availability. We follow Ladefoged et al. (2009) in applying a Rainfall-Elevation Index (REI) as a function of substrate age to represent potential soil fertility. As observed from previous research on the extent of traditional Hawaiian arboricultural systems (Lincoln, 2020; Lincoln & Ladefoged, 2014; Lincoln et al., 2018, 2021), different forms of agroforestry with varying intensities were constrained by the landscape, aligning with patterns of natural soil parameters, with Agroforestry occurring on more fertile soils and Novel Forests occurring on soils of lower fertility. Correspondingly, two soil fertility thresholds were identified: a lower threshold to represent the development of Novel Forests and a higher threshold to represent more intensive forms of agroforestry. No upper extents to the soil fertility were identified as the transitions were defined by the next, more intensive, form of agriculture (that is, the upper limit to Novel Forests is defined by the lower limit of Agroforestry, and the upper limit of Agroforestry is defined by the lower limit for Intensive Dryland agriculture as defined by Ladefoged et al. (2009)).

The determination of these REI-approximated soil fertility thresholds was done by extrapolating environmental parameter endmembers from breadfruit and kukui distributions mapped from the previously described tree canopy datasets. To determine the minimum REI values required for Novel Forests, the distribution of all trees was used to define a soil fertility floor necessary to support the development of any form of arboriculture. The 99% quantile was used, and lava flow ages with fewer than 3,000 points were excluded from the analysis. To determine the REI cutoffs that defined Agroforestry, the spatially explicit locations of several intensive forms of arboriculture were referenced from ethnohistorical sources. We manually selected the location of points that were known to occur under various forms of agroforestry that are more intensive than simple novel forests, including the *kalu'ulu* breadfruit system of Kona (Lincoln & Ladefoged, 2014), the *pākukui* systems of Hāmākua, Kā'u, and Puna (Lincoln, 2020), the *malu'ulu o lele* breadfruit system of Lāhainā (Meilleur et al., 2004), and the kukui grove *kalanikaula* and breadfruit groves of Hālawa (Handy et al., 1972). Using this manually selected subset of trees, we repeated the previous approach to define threshold values for Agroforestry.

To avoid overfitting the data to individual lava flow ages, biexponential growth and decay equations were used to describe the relationship between the REI and substrate age for the two thresholds (Fig. 2). Model parameters were spatially intersected in ArcMap using a raster calculator that defined the limitations of the four environmental constraints of rainfall (> 750 mm/y), temperature (> 18 °C), slope (< 30°), and REI (with the two identified REI thresholds defined as a function of age). Models were prioritized (Agroforestry > Novel Forest) and intersected with previously developed spatial models for wetland, intensive dryland, colluvial slope agriculture, and marginal dryland (Kurashima et al., 2019; Ladefoged et al., 2009; Lincoln et al., 2023), with all overlapping areas removed from the lower priority models.

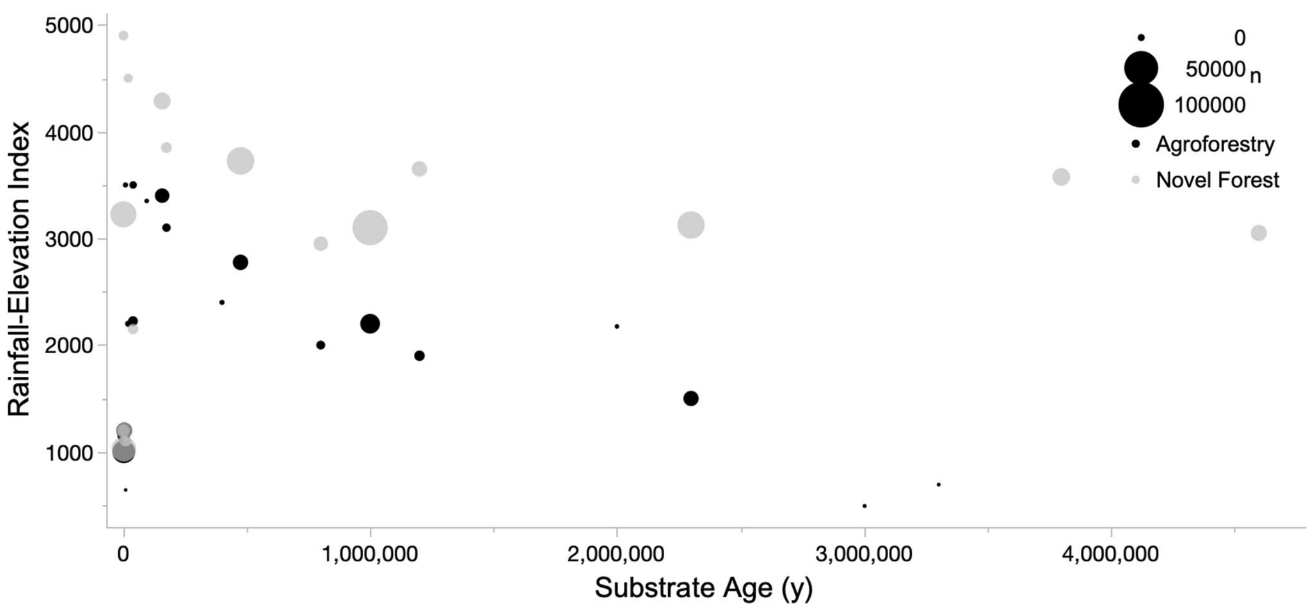


Fig. 2 Cutoff values for the Rainfall-Elevation Index, as a proxy of soil weathering intensity, observed on each substrate age class for the two arboricultural forms classified. Points are sized by the number of tree points on each substrate age

Model Validation

To assess the accuracy of the model, we utilized a dataset independent of the training data recently generated in Lee and Lincoln (2023) that derived spatially explicit points for agroforestry and native forests in Hawai‘i by georeferencing 573 historical nineteenth-century maps. Using this dataset as a model assessment assumes that the nineteenth-century maps, with the time of their creation being much closer in time to existence of these agricultural systems, closely represent the extent of these traditional agriculture systems prior to Western contact. Points from this dataset were uploaded to ArcMap and spatially joined to our model to determine spatial overlap and assess accuracy through a confusion matrix. From the Lee and Lincoln (2023) data set, we define the agroforestry points as actually positive locations and the native forest points as actually negative locations. Our modeled extent of Novel Forest and Agroforestry defines the predicted positive and predicted negative locations. Performance metrics derived from the confusion matrices included the following, where TP is true positive (actually positive = predicted positive), TN is true negative (actual negative = predicted negative), FP is false positive (actual negative = predicted positive), and FN is false negative (actual positive = predicted negative):

Accuracy (ACC), which defines the amount of correct classification (TP and TN) over the total classifications.

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

Sensitivity/Recall Rate/True Positive Rate (TPR), which defines the probability of an accurate positive test.

$$TPR = \frac{TP}{TP + FN} \quad (2)$$

Specificity/True Negative Rate (TNR), which defines the probability of an accurate negative test.

$$TNR = \frac{TN}{TN + FP} \quad (3)$$

The resulting statistics were used to provide statistical insights into the accuracy of our arboriculture model in predicting the extant of traditional Hawaiian arboricultural forms.

Results and Discussion

Model Development and Outcomes

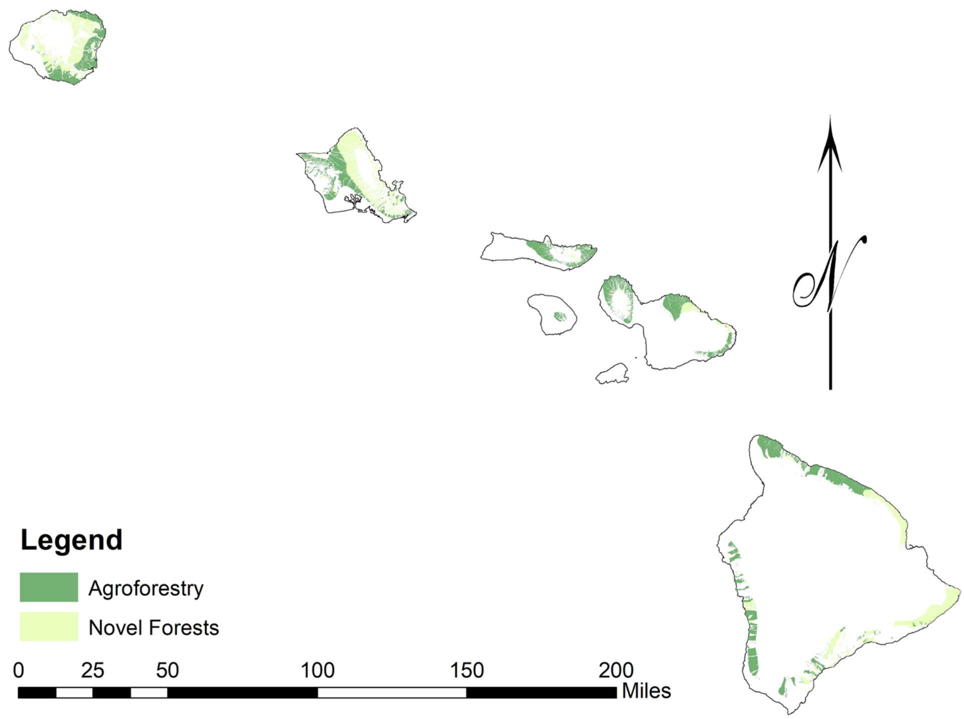
The assessment of remnant botanical distributions as an indicator for Hawaiian arboricultural development showed clear patterns that could be accurately described by biexponential growth and decay functions (Fig. 2). In the youngest flows, up to and including substrates of 20 ky, the REI thresholds increase rapidly, which aligns with previous soil studies that suggest soils up to ~20–40 ky are overcoming kinetic limitations to soil fertility and therefore increasing in fertility over time (Bateman et al., 2019; Chadwick et al., 2021; Lincoln et al., 2014; Vitousek & Chadwick, 2013). Beyond 20 ky, the threshold of weathering intensity follows an exponential decay. The decay appears similar for both Agroforestry and Novel Forests until about 1 My, at which point the limitation for novel forests asymptotes, while the limitation for agroforestry continues to decay, approaching zero by approximately 3.5 My. To match this bimodal pattern observed, biexponential equations were fit to describe the threshold values defining the development of Agroforestry (r^2 0.84; RMSE = 415) and Novel Forest systems (r^2 0.79; RMSE = 687).

The threshold values in REI were combined with environmental constraints (temperature, rainfall, and slope) to generate spatial models of the potential extents of traditional Agroforestry and Novel Forest development (Fig. 3). The resulting models depict substantial areas on most of the islands that are suitable to each of these arboricultural forms, with the exception of the island of Kaho‘olawe that has no potential and the island of Lānai that has minimal potential, both of which are arid islands situated in the rain shadow of Maui. Conversely, these modeled systems dominate the wetter, windward parts of the islands which generally had lower calculated REI values and, therefore, were predicted to have inadequate soil fertility necessary for intensive dryland agriculture. While the modeled distribution of these systems slightly favors the windward (northeast) side of each island, substantial areas of potential also occurred on the leeward sides of each island. The accuracy of the model is supported by the existence of well-known centers of agroforestry from ethnohistorical sources being encapsulated within the modeled extents, including Hāmākua, Kā‘u, and Puna on Hawai‘i Island, Hāna, Waikapu, and Lāhainā on Maui Island, Waimanalo on O‘ahu Island, and Anahola and Wailua on Kauai Island.

Model Validation

The extent and spatial accuracy of these arboricultural systems was assessed by utilizing the data set from Lee and Lincoln (2023), which consisted of points depicting arboriculture (n = 838) and native forest (n = 1,595). A confusion matrix was generated to assess the performance of the models (Table 1; Fig. 4). The validation dataset did not make any distinction between classes of arboriculture, and therefore our two models were validated in total rather than separately. Overall model accuracy was calculated at

Fig. 3 The modeled extent of two different intensities of arboriculture, which we term Agroforestry (more intensive) and Novel Forest (less intensive), across the archipelago of Hawai'i



0.75, while sensitivity (true positive) and specificity (true negative) rates were 0.61 and 0.82, respectively.

We perceived that the false negative values (n = 328), where true agroforestry points were not encompassed by the models, fell into three categories. The first is other agricultural areas, accounting for 144 (44%) of the erroneous points. As defined in the methods, the final extent of modeled agroforestry was determined by subtracting more intensive agricultural forms of wetland, intensive dryland (Ladefoged et al., 2009), and colluvial slopes (Kurashima et al., 2019). Although these areas could have also supported agroforestry development, the assumption applied is that Native Hawaiian cultivators would have opted to employ more intensive cultivation forms where possible. While this is true at a dominant level, it does not preclude the inclusion of agroforestry plantings within the extent of these other systems. In fact, it is documented that trees were often used within these systems, likely performing important functions in dryland systems such as windbreaks, nutrient uplift, creation of microhabitats, and the generation of mulch and wood resources, while in wetland systems they were used for purposes such as to stabilize hillside slopes and provide essential mulch (Handy et al., 1972).

Table 1 Confusion matrix resulting from validation points extracted from historical maps and the modeled extents of arboriculture

		Modeled Extents	
		Agroforestry	None
Validation Points	Arboriculture	510	328
	Native Forest	282	1313

The second major source of false negatives is coastal zones, accounting for 108 (33%) of the points not included in the model. This was an expected source of error. We have previously suggested that coastal agroforestry was employed in areas that were too dry in terms of average annual rainfall but persisted, and in some cases flourished, by accessing the groundwater table as it approached the surface near sea level (Lincoln & Vitousek, 2017; Mausio et al., 2020). However, since no spatial datasets of groundwater depth for Hawai'i exist, this parameter was not considered in the modeling. The final major source of false negatives was model underestimation of arboriculture on young lava flows in east Hawai'i Island, particularly in the Hilo and Puna regions that generally consist of high rainfall (> 2,000 mm/yr) and young lava substrates (< 20 ky). We believe that this may result from the application of the biexponential equation to describe the REI as a function of substrate and rainfall. The sharp peak that occurs at the younger substrate ages is highly sensitive to minute changes in the equation parameters. The equations used to fit the REI function would generate the highest levels of inaccuracies at young substrate ages. Furthermore, while we utilize a specific geologic age from Sherrod et al. (2007, 2021), the substrate ages are determined as a range. So, for example, a flow series assigned an age of 7.5 ky varies from 4 to 11 ky in age, introducing additional error.

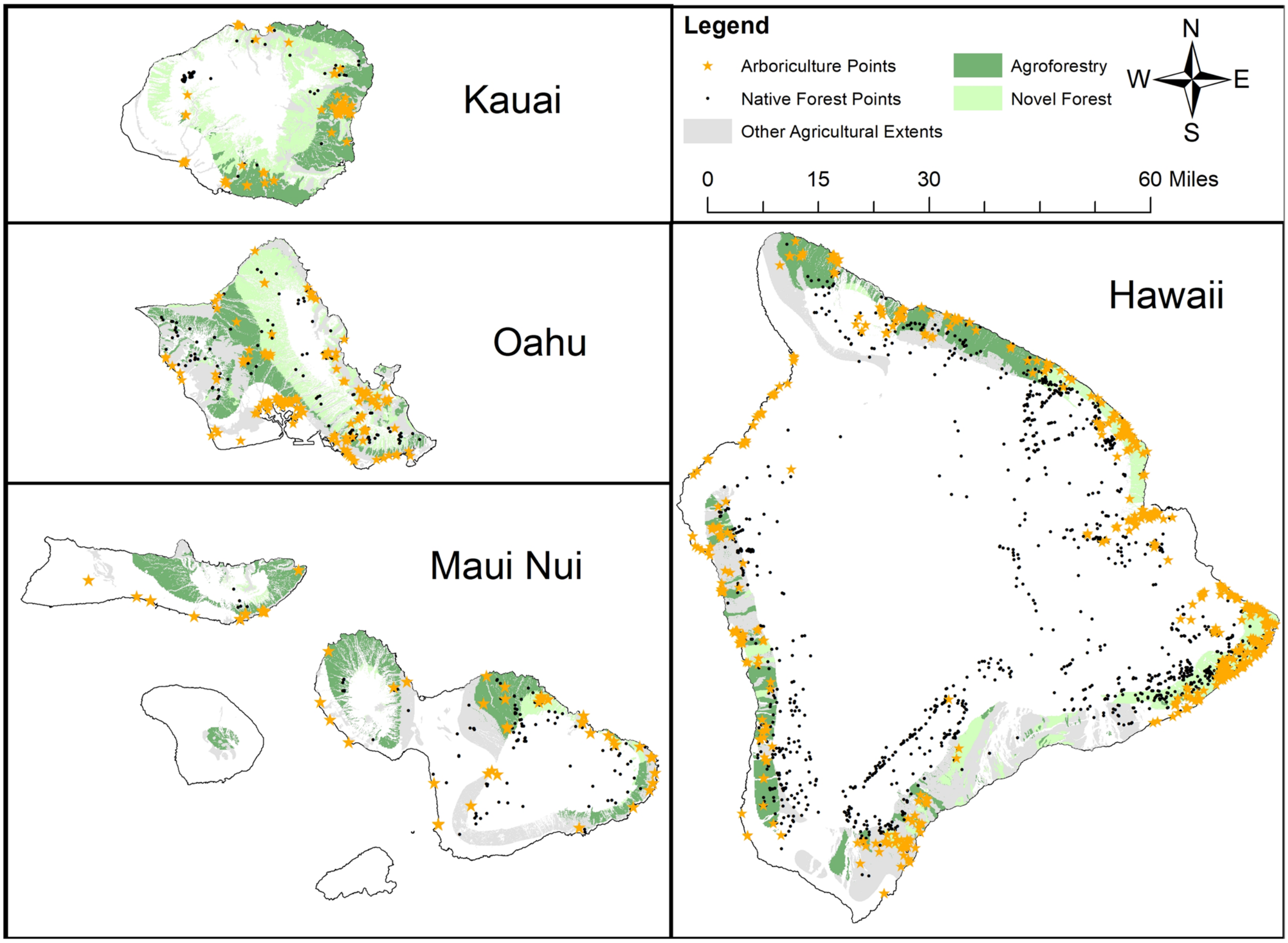


Fig. 4 Depiction of validation points superimposed on the models for Agroforestry and Novel Forest, as well as other agricultural forms depicted in previous spatial models (Kurashima et al., 2019; Ladefoged et al., 2009; Lincoln et al., 2023)

Conversely, false positives (n = 282), that is where true native forest points fell within the modeled extents of arboriculture, were more evenly spread, although they were more prevalent across the upper elevations of the Agroforestry (n = 100) and Novel Forest (n = 182) models. However, despite the majority of false positives occurring in the upper elevations of the models, true positives were often in proximity at similar elevations. Particularly with the Novel Forest model, where native plants and non-native crops were commonly cultivated alongside one another, the interspersion of native and non-native species at various scales of heterogeneity may account for much of this variability. Even in more intensive agricultural developments, ethnographic descriptions suggest that native forest patches were preserved for the cultivation of medicinal and other resource plants (Handy et al., 1972). While these models aim to predict the previous spatial extents of these vast traditional agricultural systems and do so effectively, in truth they depict the areas that could potentially support Agroforestry and Novel Forest development, although this is not to suggest that these areas were developed in totality. It would make sense, due to distance and transportation costs, that less complete alteration of the forests would occur at higher elevations that were located further from the coasts.

Contributions of Agroforestry and Novel Forests

Potential areas that could be developed for Agroforestry and Novel Forests were significant, accounting for ~148,000 ha and ~115,000 ha across the archipelago respectively (Table 2). The distribution of these arboricultural systems is not equivalent across the archipelago but is dependent on Hawai'i's wide variation in ecosystem attributes. In terms of total land area, the percentage of land given over the arboricultural techniques increases across the age gradient of the islands (Table 2). Using previous models of Intensive Dryland, Flooded Wetland, and Colluvial Slope agricultural forms by Kurashima et al. (2019), we can calculate that, as a percentage of potential agricultural extent, Agroforestry and Novel Forests accounted for 38.5% and 30.0% respectively.

Table 2 Arboricultural extent by island in hectares (top) and percentage of each island total area (bottom)

Island	Agroforestry	Novel Forest	Total
Hawaii	52,955	44,700	97,655
Maui Nui	42,480	6,572	49,052
Oahu	25,993	31,328	57,320
Kauai	26,419	32,475	58,894
Hawaii	5.1%	4.3%	9.4%
Maui Nui	13.9%	2.2%	16.1%
Oahu	16.9%	20.3%	37.2%
Kauai	18.2%	22.3%	40.5%

Islands listed as youngest to oldest; Maui, Molokai and Lanai islands are combined into Maui Nui to represent the traditional political division

Table 3 Total potential area (ha), yields (mt), and contribution to production (%) for the three agroecological forms modeled by Kurashima et al. (2019) (Wetland, Intensive Dryland, and Colluvial Slope), and the two forms modeled in this paper (Agroforestry and Novel Forest)

	Hawaii	Maui Nui	Oahu	Kauai	Total
	Total Potential Area				
Wetland	1,434	3,455	8,094	5,824	18,807
Dryland	49,648	11,063	2,902	0	63,613
Colluvial	970	4,410	24,842	8,643	38,865
Agroforestry	52,955	42,480	25,993	26,419	147,847
Novel Forest	44,700	6,572	31,328	32,475	115,074
	Total Potential Production				
Wetland	28,680	69,100	161,880	116,480	376,140
Dryland	446,832	99,567	26,118	0	572,517
Colluvial	8,003	36,383	204,947	71,305	320,636
Agroforestry	357,449	286,740	175,450	178,326	997,966
Novel Forest	60,345	8,872	42,293	43,841	155,350
	% Production Contribution				
Wetland	3.2%	13.8%	26.5%	28.4%	15.5%
Dryland	49.6%	19.9%	4.3%	0.0%	23.6%
Colluvial	0.9%	7.3%	33.6%	17.4%	13.2%
Agroforestry	39.7%	57.3%	28.7%	43.5%	41.2%
Novel Forest	6.7%	1.8%	6.9%	10.7%	6.4%

Such extensive application of arboricultural systems corresponds with other Polynesian Islands in which agroforestry methods were the major, if not the dominant, agricultural system employed by cultivators (Nair, 1989; Quintus et al., 2019; Thaman et al., 2017). If it is assumed that these modeled potential areas for arboricultural production were extensively cultivated by Hawaiian peoples, which our model alignment with ethnographic records would suggest, this greatly changes the prevailing understanding of the Native Hawaiian footprint on the landscape, and the potential habitat altered for economic production would shift from ~6.3% (Kurashima et al., 2019) to > 20.0%.

It is important to note that the spatial modeling here is meant to represent the role and extent of agroforestry at the time of European contact. Agroforestry played various roles over the history of Hawai‘i, occupying different niches at different times. Ancient stories and cosmology in Hawai‘i suggest that early settlements of Hawai‘i relied heavily upon agroforestry methods for food production (Beckwith, 1940; Fornander, 1880; Lincoln & Vitousek, 2017; Malo, 1951), while archaeological studies demonstrate that other areas were slowly converted from native to novel forests over time (Dye & Sholin, 2013). This changing footprint of agroforestry over time should not be overlooked.

Although we define two broad categories of arboriculture—Agroforestry and Novel Forest—it is important to note that the form of agroforestry is highly place-adapted (Quintus et al., 2019; Thaman et al., 2017). Agroforestry practices varied in terms of their occurrence across different islands and atolls, and within each island across the different microhabitats (e.g., Huebert & Allen, 2016; Kirch, 1984; Maxwell et al., 2016; Raynor & Fownes, 1991a, b; Thaman, 1990; Yen, 1996). While detailing these different adaptations is beyond the scope of this paper, it is important to note the diversity of form and practice as it relates to the specifics of each place.

Due to the temporal and spatial variation of cultivation intensity in traditional Polynesian arboricultural systems, the amount of food produced in these systems is not well documented. Previous research estimates on the productivity of these arboricultural systems range from > 1.5 mt/ha (Lincoln, 2020) to > 4 mt/ha at a minimum (Lincoln & Ladefoged, 2014), 5.5 mt/ha (Ragone, 1997), and up to as high as 11 mt/ha (Kirch, 1984). But, given the extensive nature of these systems across the archipelago, even a small contribution of food on a per-area basis would significantly change the prevailing conceptions of agricultural production, distribution, resilience, and variability.

While any extrapolations are subject to numerous assumptions, the exercise is still useful in terms of broadly understanding the potential impacts. We utilize estimations of production and fallow previously applied by Kurashima et al. (2019) for wetland (25 mt/ha, 20% fallow), intensive dryland (10 mt/ha, 10% fallow), and colluvial slope (11 mt/ha, 25% fallow), to which we add estimates for Novel Forest (1.5 mt/ha, 10% fallow) and Agroforestry (9 mt/ha, 25% fallow), to calculate the productive potential for each island by agricultural form (Table 3). The outcomes suggest that for each of the islands, arboriculture accounted for ~40% of the total food production. The relatively consistent contribution of arboriculture across the islands starkly contrasts with the previously modeled agricultural forms, in which clear patterns across the age gradient of the archipelago are apparent. Intensive dryland agriculture, which is reliant on high natural soil fertility, is primarily restricted to younger and mesic landscapes, and therefore clearly declines across the age gradient of the archipelago. In contrast, the development of wetland and colluvial slope agriculture relies on the formation of deep river valleys following long-term erosional processes, which are more prevalent on older landscapes and therefore increase across the archipelago's age gradient. While a slight shift in arboriculture occurs from Agroforestry to Novel Forests as island age increases—due to the progressive exhaustion of soil fertility over time—the overall contribution of arboricultural methods form a core component of traditional food production across the islands. For some islands, arboriculture outproduces the more intensive dryland or wetland systems. In this sense, arboricultural methods would act to dampen the differences between the production systems of young and old islands in Hawai'i, which has been extensively cited as differing between levels of reliance on rainfed vs. irrigated farming systems (e.g., Kirch, 1994; Kirch & Zimmerer, 2011; Kirch et al., 2007).

While much of the literature on agricultural systems has focused solely on food production, it is critical to consider that, in a complex society such as Hawai'i, there are demands for alternative commodities other than food in an agrarian system, such as a substantial need for textiles, lumber, and fuel, in addition to other more minor needs of medicines, dyes, and other materials. Flooded systems, such as those presupposed to dominate the productive capacity of the older islands, are not conducive to a diverse spectrum of economically valuable crops and were utilized almost exclusively to produce food. In these areas, the contributions of arboriculture were especially critical for ensuring that a full complement of productive species were available to allow societies to thrive. Hawaiian ethnohistorical documentation has demonstrated the critical role these systems played in providing alternative commodities while other forms of production were organized to prioritize the cultivation of food crops (Handy et al., 1972; Quintus et al., 2019; Whistler, 2009).

The management of Agroforestry and Novel Forests contrasts with that of more intensive methods (see Allen, 2004; Dye, 2014; Hommon, 2013; Kirch, 2010). The permanent physical infrastructure of the latter systems made them more easily controlled and managed (Allen, 2004; see Erickson, 1995, 2006 for examples outside the Pacific). In comparison, the dispersed nature of arboricultural practices makes these systems less easily managed and overseen, though this varied from place to place with defined zones like the well-documented *kalu'ulu*—a nine square mile band of intensive breadfruit-dominated agroforestry—more entwined in regional political processes (Lincoln & Ladefoged, 2014). Earle and Spriggs (2015) argue convincingly that elites attempt to control bottlenecks in production and distribution. Unlike intensive techniques where labor, land, and water provide those bottlenecks to varying degrees depending on the microenvironment of interest, the dispersed nature of arboricultural techniques and the lack of infrastructure in those systems limit the formation of bottlenecks. Indeed, across Polynesia, while some groves and trees were owned (Firth, 1936; Handy et al., 1972), the use of arboricultural resources in political economies focused on their post-harvest processing and storage that was more labor-intensive and centralized (Allen, 2010; Kirch, 1991). Of note in this regard, fermentation pits enabling the storage of starches, like breadfruit, and, hence, control of arboricultural resources are not reported for Hawai'i beyond a few potential but unconfirmed examples (Langston & Lincoln, 2018).

The productive capacity of arboricultural techniques combined with the extent of these systems implies that communities acquired a substantial component of their food and much of their resources from decentralized systems. The decentralized production of such a large amount of economic goods may seem to weaken opportunities for surplus generation and tribute extraction, but access to these resources by farmers may have been a key concession from elites, whether intentionally or not, that created conditions of well-being and subsequent support of elites. The perception of despotism was a key driver of political usurpation and uprising in Hawai'i (Malo, 1951); access to resources produced in a decentralized manner may have made labor and tribute demands more bearable for commoners and less risky for leaders. Certainly, the diversification of productive techniques and the availability of a broader range of resources is advantageous to both commoners and elites (Allen, 2004). These dynamics are similar to those of *milpa* systems in Mesoamerica where dispersed forest management techniques provided a substantial amount of subsistence and resource goods while more intensive techniques could be exploited and controlled by leaders (Chase & Chase, 1996; Fisher, 2020; Ford & Nigh, 2016; Lucero, 2006). Similarly, leaders were able to control key resources needed for sustained intensive production that both generated wealth and bolstered their ideological control (Lucero, 2002; Scarborough, 1983, 2003). For Hawai'i, the presence and use of arboricultural techniques to support the local subsistence economy make it more likely that intensive techniques and easily extracted resources could be funneled toward the creation of wealth generation (Dye, 2014), which allowed rulers both to compete with other leaders and to legitimize themselves in the eyes of the commoners through elaborate rituals (Kolb, 1999; Valeri, 1985).

The nature of land tenure in Hawai'i is a matter of some recent debate (Dye, 2021). Conventionally, archaeologists and ethnohistorians have argued that shifts in land tenure toward elite ownership and control occurred in the fifteenth century AD and later (Hommon, 2013; Kirch, 2010). While control in an ideological frame is likely, as this is well established in oral records, the practical effects of such ideological control beyond the ability to extract tax and tribute is unclear. Indeed, there is now evidence of place-based practices that are more likely to develop through local practical control and ownership by smallholders with relatively stable access to land (Dye, 2021; Quintus & Lincoln, 2020). The extent and patchwork nature of arboricultural techniques identified herein, besides some well-documented examples like the *kalu'ulu*, are more consistent with practical control of land and resources by smallholders with regular tribute demands by elites.

In LCA (land commission award) records, for instance, individuals frequently make claims to economic trees used for both food and resources away from their more formal systems and claimed parcels (e.g., Kelly, 1983; Maly & Maly, 2005). These claims speak to both the dispersed nature of perceived resource ownership or use rights by commoners, often in novel forests, and their importance to people. For instance, agroforestry cultivation in the Kona region is associated with *lele* (lit. jump or fly) land parcels, in which a single family would have rights to multiple disjointed land parcels that included both intensive dryland plots and agroforestry plots (Kelly, 1983). Data on additional land tenure associated with these forest resources is lacking, though we hypothesize for further testing that the forest may be conceptualized as commons (after Ostrom, 1990), which is documented for other regions of the Pacific (e.g., Raynor & Fownes, 1991b). These forests seem to fit the definition of common pool resources given that membership in a group, notably as members of a corporate decent group associated with an ʻili (Dye, 2021), gives rise to the use of the resource. That these resources could be claimed implies that others could be excluded from their use if they are not members of that group. Further, the land itself is not claimed by the decent group but rather the specific trees, groups of trees, or references to wooded areas are claimed (Maly & Maly, 2005:39–146).

The temporal development of Agroforestry and Novel Forests remains understudied. Allen (2004) argues that the formation of the *kaluʻulu* likely occurred in the fifteenth century AD or later, with the introduction of breadfruit currently understood to be at least by the thirteenth century AD (McCoy et al., 2010). The dating of the introduction of other crops is unclear (Quintus et al., 2019). Other research suggests that at least some stands of economic forests were in place prior to the expansion of more intensive techniques across colluvial slopes in the sixteenth century AD, with increasing additions of breadfruit and kukui dated to at least the fifteenth century AD (Dye & Sholin, 2013; Quintus et al., 2023). This implies that Agroforestry and Novel Forests were part of a protracted process of anthropogenic landscape alteration that began early in the cultural sequence, similar to elsewhere in Polynesia (Huebert & Allen, 2016, 2020). Additional archaeological research tracking novel forest and agroforest development is clearly needed.

Role of Arboriculture in Contemporary Hawaiʻi

Deliberate agroforestry systems are uncommon in Hawaiʻi at the time of this article, with only 347 of the total 7,228 farms in the state indicating that they practice a USDA-defined form of agroforestry (United States, 2019), and a number of identified barriers to the adoption of agroforestry methods existing (Hastings et al., 2021). The most substnatial barrier is economic viability, leaving little incentive for farmers to engage in arboricultural cultivation. Even the most commercially "viable" farming methods in Hawaiʻi are economically tenuous due to the extremely high cost of land and labor, along with the high levels of competition from cheaper tropical countries. Agroforestry methods typically require greater initial investment compared to shorter-term crops, both in terms of up-front capital and investment of time, at least partially accounting for the low adoption rates. Tree crops are the dominant form of crop species in these agroforestry systems, and generally take several years before reaching a threshold in growth in which fruits can be harvested. This delayed return on investment is difficult to tolerate when there is an opportunity cost involved related to the possibility of using other crops and cropping systems. Other barriers to adoption include lack of knowledge and technical assistance, insufficient access to planting material, and short term leases that do not provide security for the long-term investment (Elevitch et al., 2017; Force et al., 2018).

Much of the adoption of agroforestry methods in Hawaiʻi is driven by biocultural restoration efforts (Hastings et al., 2021; Langston & Lincoln, 2018). In these undertakings, traditional values rather than economic values are a core driver in decision making, placing less of a reliance on rapid return on initial investment (Lincoln & Ardoin, 2015, 2016; Morishige et al., 2018). Firmly situated in an epistemology of kinship, Hawaiian cultural views strongly value the outcomes of environmental and ecosystem health, community-based food security, and connection to land and place. Agroforestry cultivation has been demonstrated to conserve ecosystem services by mimicking the ecological nutrient and water cycling of the previous natural ecology, favoring long-term economic viability and sustainability (Winter et al., 2020). This aligns with broader outcomes of agroforestry systems that are recognized to generate a host of non-economic services, including soil health, reduced erosion, carbon sequestration, water conservation and purification, and other "climate-smart" outcomes for agriculture (Altieri & Nicholls, 2017; Muschler, 2016; Singh & Singh, 2017).

Conclusion

Arboricultural methods employed by Native Hawaiian cultivators, as well as those throughout Oceania, have vastly altered their landscape over time. In the case of Hawaiʻi, the consideration of arboriculture to build upon previous models increases the land-based footprint four-fold. However, the methods of alteration, that is, employing vast systems that maintained ecosystem services while simultaneously provisioning key resources necessary to the society, allowed for a high degree of ecological health to be maintained. The legacy of these systems allows us to better understand the composition of contemporary vegetation communities, while their historical presence reminds us of alternative pathways of land management and production outside the Euro-centric concepts of agriculture that have come to dominate the global landscape. The distributions of Agroforestry and Novel Forests on the landscape were well predicted by environmental parameters and were largely a function of soil properties, defined as a function of cumulative weathering potential and climate. The application of agricultural forms that preserve the underlying ecology of a landscape is what we determine to be agroecology – that is, the consideration of the capacity of natural ecological functions and cycles to maximize the productivity of a landscape. Hawaiian cultivators, and indeed many island-based cultures that were forced to maximize the long-term sustainability of a small land base, developed a degree of mastery over these concepts that should be better employed in land-management strategies today.

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Declarations

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