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Assessing spatial models of Hawaiian agroecological extents

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ABSTRACT

The Hawaiian Islands have been employed as a model system to reconstruct agroecological extents of traditional Polynesian agricultural production systems. However, the reliability of previously modeled agricultural extents is unknown due to limitations in empirical evidence to assess accuracy. Utilizing a geospatial database of 8,561 archaeological sites compiled by the Hawaiʻi State Historic Preservation Department (SHPD), this research assessed the accuracy and reliability of three spatial models that estimate the extents of traditional Hawaiian agricultural systems. The results of the model sensitivity assessment indicate the three geospatial models capture the spatial patterns and relative extents of intensive agricultural systems with substantial infrastructure, while additional work is needed to assess reliability of modeled agricultural systems with more indefinite infrastructure.

1 Introduction

The biophysical properties observed across the Hawaiian archipelago provide a broad range of natural ecosystems that yield varying degrees of biological productivity (Asner et al., 2005; Vitousek, 1995). Early inhabitants of the Hawaiian Islands utilized these traits to engineer a productive landscape that supported a substantial population while functioning with low ecological impact (Gon III et al., 2018; Kirch, 2007; Stannard, 1989; Winter et al., 2020). Polynesian introduced crops and subsistence practices were integrated into the diverse island ecology to establish a variety of locally-adapted production systems, which included irrigated wetland pondfields, rainfed dryland systems, colluvial slope systems, agroforestry, arboriculture, animal husbandry, and aquaculture, among others (Handy, 1940; Handy et al., 1972; Lincoln et al., 2018; Lincoln & Vitousek, 2017; Quintus et al., 2019). The form and function of these agricultural systems varied according to the range of island environments in relation to substrate age and structure, soil fertility, water availability, climate, and topography (Kirch, 1977; Kirch et al., 2005; Ladefoged et al., 2009; Lincoln et al., 2018; Vitousek et al., 2004).

The Hawaiian archipelago has been utilized as a model system in archaeological research to examine processes of landscape and socio-political transformations due to its relatively recent occupation by Polynesian voyagers, the spatially organized climate and geologic age gradients, and highly predictable secondary factors of soil fertility and topography within and between the islands (Kirch, 2007; Vitousek, 1995). Island formation from hot spot activity and subsequent erosion are reflected in island topography and the geologic sequence across the archipelago. The geologically older islands of Kauaʻi and Oʻahu have endured extensive physical weathering processes that have eroded shield volcanoes down to relatively small, low-lying islands with numerous alluvial valleys. Whereas the geologically younger islands of Hawaiʻi and Maui have been subject to less erosional forces and, therefore, exhibit a lesser eroded topography. Substantial spatial variation in rainfall, and therefore weathering and erosional intensity, is generated by consistent tradewinds that result in a wet-windward and dry-leeward side of each island. The cumulative effects of rainfall—a function of both annual rainfall and geological age—result in an uneven distribution of factors that affect agricultural opportunities. Rainfall leaches soil nutrients, which is a major factor in the distribution of dryland field systems (Vitousek et al., 2004), and forms surface streams and alluvial valley that are essential for flooded pondfield systems (Kirch, 1977). Interactive effects, such as the colluvial regeneration of soil nutrients (Vitousek et al., 2010), fluvial-driven nutrient dynamics

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(Palmer et al., 2009), and rainfall effects on nutrient inputs (Stewart et al., 2001) provide further texture to the changing landscapes over the course of island evolution.

The forms and functions represented by Hawaiian agriculture offers insight into the nature of coupled human and environmental interactions, with spatial models offering a quantitative approach (DiNapoli & Morrison, 2017; Kagawa-Viviani et al., 2018; Kurashima et al., 2019; Kurashima & Kirch, 2011; Ladefoged et al., 2009; Lee et al., 2006; Lincoln et al., 2023; Lincoln & Ladefoged, 2014). The broad yet organized gradients of climatic and geologic drivers allow for the spatial modeling of the distribution of various agricultural archetypes in traditional Hawai'i, which is necessary due to the extensive erasure of ancient archaeological remains that has occurred particularly through the activities of the large-scale plantations in the historic era. The purpose of these specific models was to reconstruct land use activity and the anthropological implications these results incur on our current understanding of socioecological transformations. The patterns represented by these spatial models drive considerable anthropological extrapolation, from direct impacts relating to the labor requirements and yield surplus of agriculture, to secondary outcomes such as the carrying capacity of the population and the political stability of the regions (e.g., Ladefoged et al., 2008). Models can provide insight into previously employed localized land-use strategies, sustainability of these systems, and effectiveness of these systems to increase production, while maintaining ecosystem services. As such, the spatial extents have also been leveraged for understanding agroecological processes and practices in an environmental context (e.g., Lincoln, 2020) and are promoted in considering contemporary policy and zoning (e.g. Kurashima et al., 2019).

The development of spatial models has tended to rely on a few well-documented examples of each agricultural archetypes, with validation often limited to a couple of intact systems or qualitative alignment to ethnohistorical descriptions. This suggests that current spatial models operate with relatively unknown degrees of accuracy and completeness. Despite the unknown accuracy, these models have played an important role in developing and supporting anthropological narratives.

To provide a more extensive assessment of the validity of existing models, we applied an archaeological geospatial database compiled by the Hawaiʻi State Historical Preservation Division (SHPD) to conduct model validation for existing projections of traditional Hawaiian agricultural extents. First, we recreated models predicting the spatial extent of wetland (i.e., pondfield, *loʻi*), intensive rainfed (i.e., fixed field, dryland), and colluvial slope cultivation. We then classified 8,561 unique archaeological sites in the SHPD database to generate point data of the agricultural forms and utilized the resulting data sets to explore alignment of the spatial models and the SHPD geodatabase. Following the statistical assessments of the absolute and relative performance of the various models, we explored some of the patterns observed within and between the models and highlight key areas where the models fail, where they perform well, and where modeling limitations (e.g., spatial resolution) create errors. We use several spatial examples to drive a discussion of potential future applications in this area.

2. Background to agricultural forms

Spatial models depicting the extent of traditional Hawaiian agriculture systems reflect distinctions in island environments and agriculture production systems, such as irrigated pondfields, intensive rainfed, and colluvial slope systems. These models have contributed to the anthropological argument that socioeconomic differences associated with these agricultural systems drove inter-group interactions towards conflict or cooperation, within and across the four major island kingdoms (Dye, 2014; Graves et al., 2011; Hommon, 2013; Kagawa-Viviani et al., 2018; Kirch, 1994, 2010, 2012; Kirch & Zimmerer, 2011). Differences in labor inputs, crop yields, variability, and resilience of the agricultural forms influence social outcomes (i.e., economical, religious, and political), while the distribution of these systems is argued to have influenced interactions between localities. For instance, in a time of drought, rainfed systems would fail whereas wetland systems were more resilient, necessitating interaction between regions that could be positive (e.g., trade) or negative (e.g., warfare). Less discussed is the different dominant food sources associated with the agricultural forms and environments, which may also manifest in cultural divergences such as dominant local deities, timing of agricultural milestones, food preparations, and *mo'olelo* (cultural stories) and *ʻōlelo nōʻeau* (wise sayings).

While we recognize other forms of production were implemented in early Hawaiian production systems (e.g., agroforestry, home gardens, etc.) (*see* Lincoln et al., 2018; Lincoln & Vitousek, 2017), we focus on intensive forms of agriculture depicted in previous model extents. Here we briefly describe the form and function of each system as well as the modeling parameters used to predict these systems.

2.1. Wetland agriculture

Wetland agriculture primarily consists of irrigated pondfields (*loʻi*) predominantly used for the cultivation of *kalo* (taro; *Colocasia esculenta*), with additional herbaceous perennial crops planted within and around the system (Lincoln & Vitousek, 2017). *Loʻi* systems are constructed by digging up the earth to create a depression, by removing large rocks within the given area and forging them into the walls of the system, while compacting the soil to reduce water permeability (Kirch, 1977). The sources of irrigation for wetland agriculture systems were fed by continual freshwater streamflow from riverbeds (*kahawai*), and or submarine groundwater discharge/springs (*punawai*) (Ziegler, 2002). This hydrodynamic engineering is noted as the *ʻauwai* system, by taking advantage of local stream flow to feed the system (water avaialbility is dependent on rain abundance) (Ladefoged et al., 2009). *ʻAuwai* are forged by compacting the earth to channel waterflow into the *loʻi* system induced by gravity, excess water is returned back into the river bed through the *ʻauwai* system (Lincoln & Vitousek, 2017; Ziegler 2002). Although there are exceptions, *loʻi* were primarily constructed in alluvial soils within river valleys, where an abundant source of fertile soil with poor drainage (primarily Inceptisols) occurs (Deenik & McClellan, 2007; Vitousek et al., 2010). *Loʻi* systems took on a range of forms, from simple barrage dams to elaborately engineered systems of terraces (Kirch, 1977) with soil nutrients being primarily replenished by the transport of rock-derived nutrients via irrigation water (Palmer et al., 2009). In some cases, aquaculture was also employed in wetland agriculture, where naturalized fresh to brakish water fish and shellfish species were raised within *loʻi* kalo systems (Keala et al., 2007).

Spatial modeling of the extent of wetland cultivation was conducted by Ladefoged et al. (2009), Kurashima et al. (2019), and Lincoln et al. (2023). All took similar approaches in defining threshold limitations to elevation/temperature, slope, and soil types differing only slightly in the specifics (Table 1). However, the models deviate substantially in their assessments of water source and irrigation potential. Ladefoged et al. (2009) established their own metric by evaluating individual stream potential to gravity feed water from one cell to the next (10×10 m) within a 500 m buffer from a river source. Kurashima et al. (2019) utilized only perennial streams, applying a 350 m buffer with the assumption that water could be sufficiently spread to this distance and limited primarily by soil type. Lincoln et al. (2023) takes a similar approach, but is more lenient in also utilizing intermittent streams and applying a 500 m buffer.

2.2. Intensive rainfed agriculture

Intensive rainfed agriculture utilized the dense construction of linear embankments (*kuaiwi*), mounds, and cleared fields to cultivate a range of crops with an emphasis on staple tubers, such as *kalo* and *ʻuala* (sweet potatoes; *Ipomea batatas*). Different planting regimes were based on either spatial delineation or temporal delineation of rainfall (Kagawa-

Table 1
Decription of spatial model parameters used to generate predicted extents of the agricultral forms.

Intensive Rainfed Field Systems	Rainfall	Temperature or Elevation	Slope	Soil Type	Soil Fertility
Ladefoged et al. 2009	≥750 mm/y*	≤900 masl	any	>4,000 years	Categorically defined limitation of Rainfall-Elevation by classes of Substrate Age
Kurashima et al. 2019	≥750 mm/y; ≤ 1,600 mm/y	≤885 masl	≤12°	>4,000 years	Categorically defined limitation of Rainfall-Elevation by classes of Substrate Age
Lincoln et al. 2023	≥100 mm/m	≥18 °C	≤12°	>4,000 years	Equationally defined limitation of Rainfall-Elevation by Substrate Age
Colluvial Slope Rainfed Agriculture	**Rainfall**	**Temperature or Elevation**	**Slope**	**Soil Type**	
Kurashima et al. 2019	≥750 mm/y	≤885 masl	≤30°	Alluvium, colluvial, stony colluvial, and Kawaihapai from the NRCS soil survey; Alluvium and older alluvium from the USGS geologic map	
Lincoln et al. 2023	≥100 mm/m	≥18 °C	≤30°	Alluvium, colluvial, stony colluvial, and Kawaihapai from the NRCS soil survey; Alluvium and older alluvium from the USGS geologic map	
Irrigated Pondfield Developments	**Water Source**	**Temperature or Elevation**	**Slope**	**Soil Type**	**Irrigable Extent**
Ladefoged et al. 2009	Rivers ≥ 1 km length above 1500 mm isohyet; if extend to < 3000 mm isohyet then extended to 5 km below 2000 mm isohyet	≤300 masl	≤10°	17 categories of geomorphic descriptions in the Soil Survey Geographic (SSURGO) database); primarily alluvial soils	Elevational difference between each 10 × 10 m cell to represent potential gravity flow; ≤500 m from stream
Kurashima et al. 2019	Streams classified as perennial	≤415 masl	≤10°	Alluvium, colluvial, stony colluvial, and Kawaihapai from the NRCS soil survey; Alluvium from the USGS geologic map	≤ 350 m buffer from stream
Lincoln et al. 2023	Streams classified as perennial or intermittent	≥21 °C	≤10°	Alluvium, colluvial, stony colluvial, and Kawaihapai from the NRCS soil survey; Alluvium from the USGS geologic map	≤ 500 m buffer from stream

* The model from Ladefoged et al. (2009) utilizes a previous version of the Hawaiʻi State Rainfall Map generated by Giambelluca et al. (1986).

Viviani et al., 2018; Lincoln & Ladefoged, 2014; Marshall et al., 2017). Rainfed systems occurred on younger substrates where moderate rainfall can promote weathering of primary minerals but also limit nutrient leaching from the upper soil horizons (Deenik & McClellan, 2007; Ladefoged et al., 2018; Vitousek et al., 2004). The furthest extents of these field systems are observed with *ʻuala* cultivation, which can withstand colder temperatures and lower, more sporadic rainfall compared to *kalo* (Kagawa-Viviani et al., 2018; Ladefoged et al., 2009).

Intensive rainfed systems were modeled using similar approaches, with some variability between datasets (Table 1). Initial modeling by Ladefoged et al. (2009) was specific to intensive, fixed-field agriculture systems with parameters based on thresholds for annual rainfall, slope, and elevation as a proxy for temperature, along with age-specific thresholds in weathering potential using the introduced rainfall-elevation index (REI). Models established by Kurashima et al. (2019) differed slightly in adding a maximum annual rainfall, using an updated statewide precipitation data layer, and applying a modified elevational threshold. Lincoln et al. (2023) differed in their direct use of temperature instead of elevational proxy, the application of a continuous equation rather than categorical treatment of the REI, and, most significantly, specifying a minimum monthly rainfall threshold rather than an annual one.

2.3. Colluvial slope agriculture

Colluvial slope systems appear similar to intensive rainfed systems, employing wall and mound structures alongside cleared fields for agricultural development. Unlike rainfed systems, colluvial agriculture can occupy a greater range in mean annual rainfall and occurs along actively eroding slopes that surround river valleys which generate nutrient-rich soils, in contrast to the intact shield surfaces that are depleted of mineral nutrients under high rainfall (Vitousek et al., 2010).

In modeling these systems, Kurashima et al. (2019), built on the earlier work of Kurashima and Kirch (2011), defined limitations of colluvial-type soils, adequate slope and rainfall, along with elevation as a proxy for temperature (Table 1). The environmental parameters defined by Lincoln et al. (2023) differ only in their use of temperature rather than elevation, and the application of a more lenient low-end rainfall threshold.

3. Methods

3.1. Predictive geospatial models

Geospatial models predicting the extent of wetland, intensive rainfed, and colluvial rainfed Hawaiian agriculture were reconstructed based on the environmental parameters outlined in Table 1. Modeled extents were received directly from Ladefoged et al. (2009), Kurashima et al. (2019), and Lincoln et al. (2023). For analytical purposes, the modeled extents for colluvial slope cultivation and intensive rainfed systems were analyzed both individually and as a combined extent to represent rainfed agriculture broadly. This is because the infrastructural developments of rainfed agriculture are not easily distinguished, regardless of if they occur on colluvial slopes or volcanic shield surfaces. For analysis, the islands of Maui, Molokai, Lanai, and Kahoʻolawe are grouped together as Maui Nui. This is to represent the extent of the “kingdom” that existed at the time of European contact.

3.2. Hawaii State Historic Preservation Department archaeological geodatabase

A point-based shapefile of 8,561 archaeological sites was utilized to evaluate the validity of previous spatial models. Data was collected from Archaeological Inventory Surveys (AIS) and other archaeological reports/studies digitized by the Hawaii State Historic Preservation Department (SHPD) Archaeology Division. The geodatabase was accessed through direct request to SHPD in April 2021 for the explicit purpose of extracting agricultural sites. The records of each archaeological site included an identification of the site's purpose (e.g., "agricultural complex", "possible prehistoric house site"), along with an overview of the site contents (i.e., description, enumeration and measurements of features). Sites were selected from this digitized geospatial database by conducting a keyword search for agricultural-related forms described in each site summary of the AIS reports and categorized, and individually reviewed by the authors to determine the classification (see Table 2).

Site categorization was based on site descriptions and archaeological features documented in the archaeology reports. Keyword searches were used to initially sort each record into a most likely category, and then all records, both those sorted by keyworks and not, were individually reviewed and placed in one of five categories: Wetland; Intensive Rainfed Field Systems; Undistinguished Rainfed; Mixed; and Unidentifiable (Table 2). Wetland Agriculture included descriptions of irrigated terraces or the traditional canals (*ʻauwai*) that fed them. Rainfed infrastructure included field walls and mounds, and was distinguished as being either an "Intensive Field System," which was limited to descriptions that explicitly referenced field systems or systematic field walls, or "Undistinguished Rainfed," which included points that were clearly identified as being rainfed agriculture but lacked sufficient descriptions to classify it as an intensive field system. Sites that contained features consistent with both wetland and rainfed systems were categorized as "Mixed Agriculture", while sites that were identified as agriculture but without any descriptions or structures that could be used to identify the agricultural form further were classified as "Unidentifiable Agriculture.".

3.3. Model validation

Archaeological point data were spatially joined to the geospatial models depicting traditional Hawaiian agricultural forms, along with environmental and social layers, to examine the overall accuracy of the models in predicting total agricultural extent. Points that fell within modeled agricultural extents were considered true positives (TP), while points that fell outside of modeled extents were considered false negatives (FN). From this, the model recall rate, also known as the true positive rate (TPR), which defines the probability of an accurate positive test, was calculated as:

$$TPR = \frac{TP}{TP + FN}$$

4. Results and discussion

4.1. Model comparison

The extents of the three different rainfed models and two different wetland models are illustrated (Fig. 1). Overall, similar patterning in modeled agricultural extents is reflected within and between the islands. All models indicate a relationship between predicted agriculture extent and island age, with wetland systems exhibiting an increased proportion of agricultural area on geologically older islands (e.g., Kauaʻi, Oʻahu) for each model, while rainfed systems cover more land area across younger islands (e.g., Hawaiʻi Island, Maui Nui). The total extent of each production system varies, often substantially, between the models (Table 3). For instance, the total hectares of rainfed systems for the Lincoln et al. (2023) model are more than twice the coverage of the Ladefoged (2009) and Kurashima et al. (2019) models, driven by the application of a monthly, as opposed to total annual, rainfall threshold. Differences between the Ladefoged (2009) and Kurashima et al. (2019) wetland models are likely the result of differences in determining water sources, potential for gravity feed, and soil types. Such discrepancies in the agricultural extents depicted between the three modeling efforts demonstrates the need to improve validation approaches in order to assess modeled parameters and increase the modeled accuracy of traditional Hawaiian agriculture extents that have been a substantial driver of anthropological discussion.

4.2. Geoarchaeology point analysis

According to our classification of the SHPD's archaeological records, a total of 1,659 traditional Hawaiian agricultural sites were identified based on their site descriptions and structural attributes (*see* Table 2). For most points, unambiguous classification into a clear agricultural form was possible, but 396 points could only be identified as "agriculture" without any form attached to it and were, therefore, excluded from further analysis. Points were well distributed across the islands, with spatial patterns aligning with expected distributions, with a few notable outliers (Fig. 2). In particular, point spatial distribution for the predominant forms of agriculture align with patterns from previous ethnohistorical and conceptual work (Handy, 1940; Handy et al., 1972; Kurashima et al., 2019; Ladefoged et al., 2009; Lincoln et al., 2018). Corresponding to results of previously modeled agricultural extents, there is a greater propensity of wetland agriculture to occur on older, wetter locations and rainfed agriculture to occur on the younger, drier locations. Like the modeled extents, there is a very clear pattern of agricultural forms along the age gradient of the islands, in which the form of agriculture shifts from a dominance of rainfed to wetland as the islands age (Fig. 3).

The distribution of points does not depict the full extent of agricultural systems in Hawaiʻi prior to European contact. Site documentation

Table 2
Different forms of agriculture identified in SHPD geospatial archaeological database with descriptions and keywords used to identify each.

Broad Agricultural Form	Classification	Description	Keywords
Wetland Agriculture (*n* = 266)	Wetland	flooded terraces, canals, or barrage dams	auwai, irrigated, pondfield(s), pond field(s), loi, lo'i, taro terrace(s)
Rainfed Agriculture (*n* = 946)	Intensive Field Systems (*n = 427)*	rainfed agriculture that included systematic field walls and mounds	field system, kuaiwi
	Undistinguished Rainfed (*n* = 519)	rainfed agriculture that was unidentifiable as formal or informal due to inadequate feature detail	dryland, rainfed, stone mound(s), linear mound(s), terrace(s)
Mixed Agriculture (*n* = 51)	Mixed	agriculture that contained elements of both wetland and rainfed agriculture	n/a
Unidentifyable Agriculture (*n* = 396)	Agriculture	agriculture that was unidentifiable in its form	agriculture, agricultural, ag

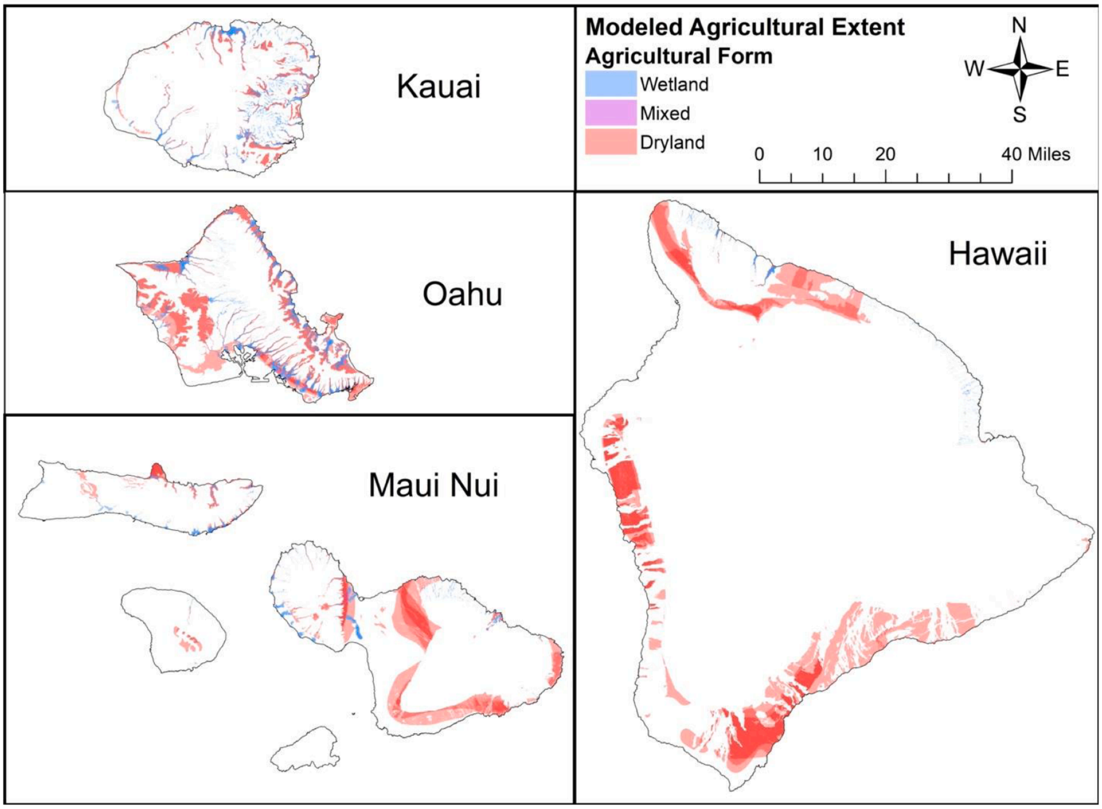

Fig. 1. Extent of environmental conditions suitable for wetland (blue), rainfed (red) agriculture production or both (purple) based on previously established model parameters. Saturated colors represent areas of spatial overlap between models.

Table 3
Modeled extents of the predictive spatial models in hectares.

		Hawaii	Maui Nui	Oahu	Kauai	Total
Wetland	Ladefoged et al. (2009)	1,434	3,455	8,382	5,825	19,097
	Kurashima et al. (2019)	592	2,206	6,907	3,917	13,622
	Lincoln et al. (2023)	1,434	3,455	8,094	5,824	18,807
Rainfed	Ladefoged et al. (2009)	55,600	14,698	3,425	0	73,724
(Shield, Colluvial)		*(55,600, n/a)*	*(14,698, n/a)*	*(3,425, n/a)*	*(0, n/a)*	(73,724, n/a)
	Kurashima et al. (2019)	34,306	15,054	25,566	7,281	82,207
		(33,612, 694)	*(10,809, 4,245)*	*(2,182, 23,384)*	*(0, 7,281)*	(46,603, 35,604)
	Lincoln et al. (2023)	87,489	34,004	36,190	10,064	167,747
		(86,461, 1028)	*(26,785, 7,218)*	*(4,848, 31,342)*	*(348, 9,716)*	(118,442, 49,304)

prior to the 1970s is minimal and took place in some areas following extensive landscape modifications as a consequence of land privatization and construction of modern infrastructure. The archaeological reports used to identify agricultural infrastructure were predominately Archaeological Inventory Surveys (AIS), which are often mandated with certain building permits or requests for land zoning changes. As such, areas that have been subject to substantial development are overrepresented in the sampling. While we recognize the potential for documentation bias to be represented in the spatial distribution of points, we emphasize the importance of mapped data points in identifying areas that were previously subject to cultivation, as indicated by the presence of wetland infrastructure, as well as both "Intensive Field Systems" and "Undistinguished" rainfed agricultural infrastructure. Previous agricultural models were limited by the number of archaeological sites that were used to validate the extent of each production system and the data derived from SHPD geodatabase expands the archeological database previously used to validate modeled extents of each production system. Thus, by expanding upon the number of agricultural sites, the results of this research offers better parameterization that can be utilized for future modeling. However, it is important to note that a formal assessment of the uncertainty associated with the SHPD geoarchaeological database was beyond the scope of this project. As discussed throughout the results, there are likely multiple sources of geolocational error embedded into the database caused by both human and instrumental elements. As such, the broad patterns that emerge from validation may be of greater value than the specific assessments in terms of understanding the usefulness of the spatial models. That is, the value of the dataset may not be in fine-tuning the existing models, but rather in identifying if there are substantial omissions in the current models.

4.3. Point intersection with models

Using the spatial overlap between the SHPD geospatial points and the geospatial models of traditional Hawaiian agricultural forms, we calculated the recall rates for wetland agriculture, rainfed agriculture, and for all agricultural forms (Table 4). Overall, the recall rates were low for each of the three agricultural models. The three wetland models were extremely low (0.23 to 0.30), while rainfed models were determined to be moderate ($<$0.60). When assessed using only "Intensive Field System" sites, the recall rates of the models are markedly improved across

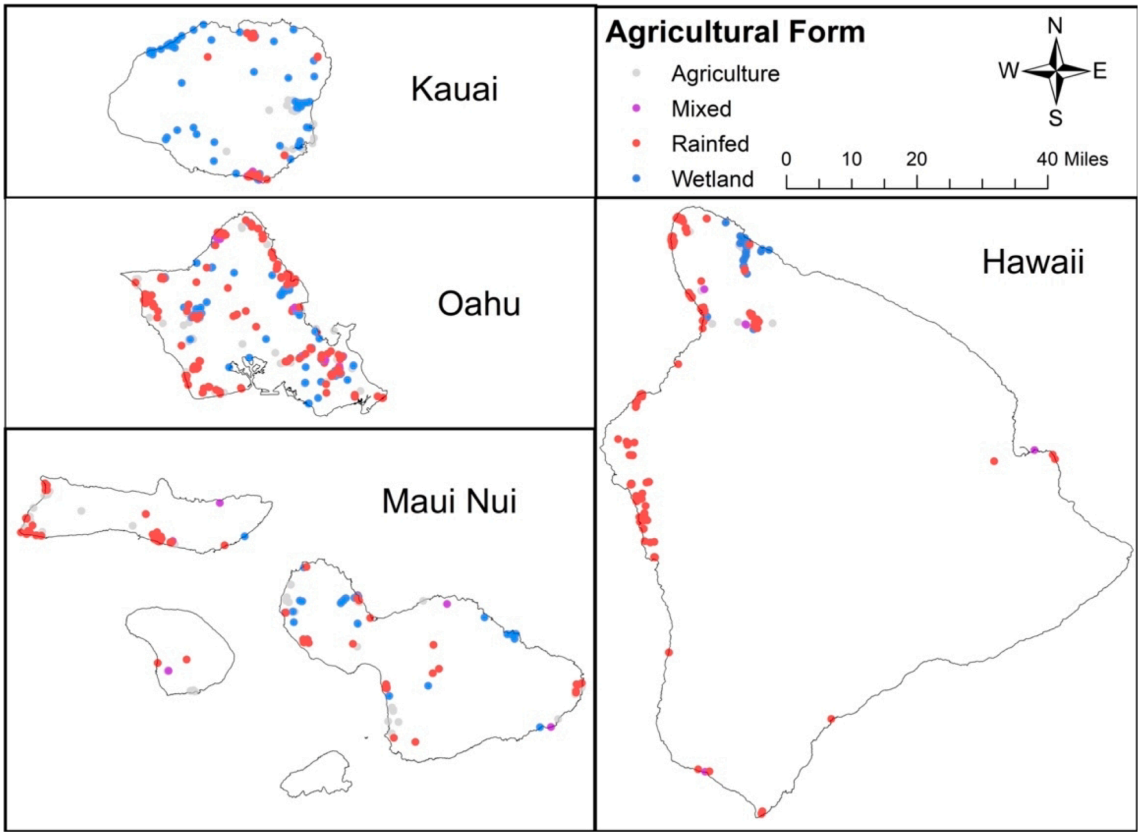

Fig. 2. Distribution of classified agricultural points from SHPD geospatial archaeological database.

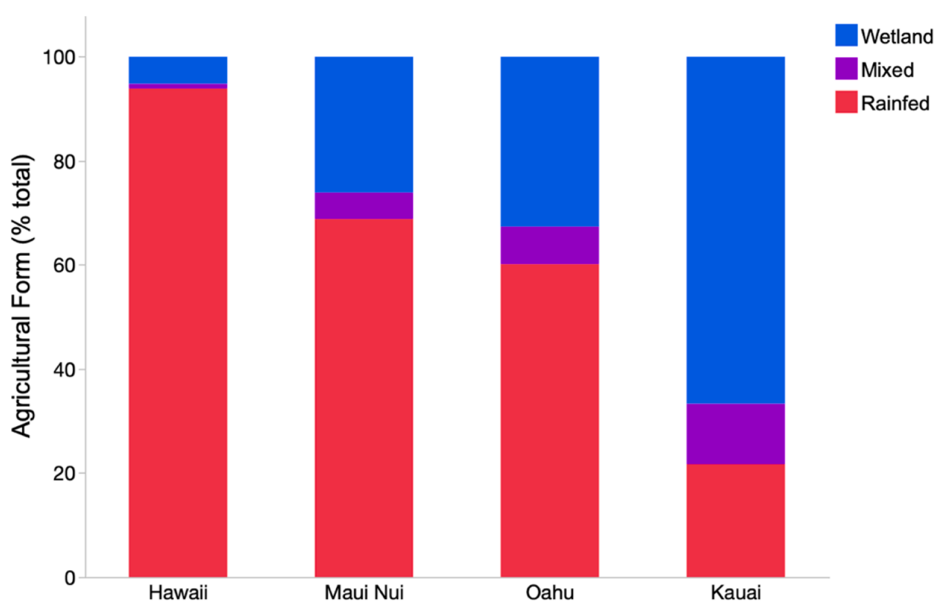

Fig. 3. The percentage occurrence of each indefinable agricultural form across the archipelago, demonstrating the consistent and substantial patterning of rainfed to wetland agricultural form across the island age gradient.

the three models (0.70 to 0.85). When all forms of agriculture are considered as a single class, including the "Unidentifiable Agriculture" the calculated true positive rates suggest substantial variation, with true positive rates of 0.35 – 0.58.

Although the model validation produced relatively poor recall values, suggesting that there are substantial shortcomings to these models, we argue the model accuracies are likely much higher than suggested by this analysis. Here we examine several factors that may have contributed to the low model recall values for each agricultural form, including alignment of overall distribution patterns, the high propensity of near misses, the specificity of agricultural form, as well as potential model or classification errors.

The wetland models demonstrated very low recall rates despite alignment of distribution patterns between archaeological points and

Table 4
Model sensitivity for the three predictive spatial models of traditional Hawaiian wetland and rainfed agriculture assessed using a geoarchaeological database.

	Ladefoged et al (2009)	Kurashima et al (2019)	Lincoln et al. (2023)
Rainfed	0.40	0.50	0.59
Formal only	0.70	0.82	0.85
Wetland	0.30	0.23	0.29
Total Agriculture	0.35	0.47	0.58

the modeled extents. However, if we examine the point-model alignments at an enlarged scale, a high propensity of near-misses (i.e., false negatives) is more apparent as archaeology points closely border the modeled extents of wetland agriculture (Fig. 4). As wetland agriculture is the best recognized form of traditional Hawaiian agriculture and the language utilized in the reports for these wetland systems is unambiguous, we believe our classification error of the SHPD geodatabase associated with wetland agriculture to be very low and we attribute discrepancies between SHPD geodatabase points and modeled extents to likely be an artifact of spatial resolution and geolocational error (see McCoy, 2017, 2020). We suspect the spatial resolution used for both models (10 m), in which areas of high topographical relief may inadvertently be excluded from the modeling process, is a substantial contributing factor. Geospatial errors in the SHPD database may also be driven by island topography with geolocational error occurring in deep valleys and heavily vegetated areas. Geolocational error could additionally be a consequence of defining site areas as single points, leading to an inaccurate representation of the agriculture location. This is particularly relevant in the "mixed" agricultural classification, in which aspects of both wetland and dryland agriculture are described in the same archaeology report. We speculate these reports likely cover a moderate to large area that encompasses both wetland agriculture and nearby dryland agriculture, yet represent the "site" by a single point, leading to inaccuracies as to the precise location of the agricultural features (see McCoy, 2020). The spatial analysis demonstrates that 47% and 57% of the false positive wetland points (archaeological "Wetland" points that fall outside of the wetland models) associated with the two wetland models occur on the neighboring colluvial slopes very close (<100 m) to modeled wetland extents. However, we are left wondering where the error lies. In model validation, the real world patterns need to be very well understood so that the failures of the model results can be clearly linked to the model parameterization. In this case, there is likely too much uncertainty in the archaeological data to determine if it is the model parameterization or the uncertainty of the "real" world data that is the problem. A deeper dive into each individual report that make up the geoarchaeological database might allow for an assessment of each points' spatial accuracy and improvement of the validation dataset.

The model recall for the total category of rainfed agriculture are moderate, with values of 0.4, 0.5, and 0.59 for the three models, and represent several broad areas of dryland agriculture that were not captured by the models. We perceive that the spatial distribution of false positive rainfed points fall into three distinct categories: (1) near-misses, (2) arid, coastal areas, and (3) a few clustered inland occurrences. The near misses (as can be observed in Fig. 4) could be a function of slight model error resulting from parameter threshold specifications, discrepancies with model inputs (e.g., errors in the rainfall map, which itself is a modeled extrapolation), or a consequence of spatial resolution as suggested for wetland modeled errors.

Arid, coastal areas reflect multiple developments of coastal dryland agriculture in regions classified as "too dry" by model inputs, such as in the far west of Molokai and the southwest of Oʻahu. We believe these areas may have potential for dryland cultivation due to the groundwater table (*see* Nunn et al., 2007). Closer to sea level, the freshwater lens approaches the ground surface, thereby increasing soil moisture or generating surface water through springs and seepage. We argue that

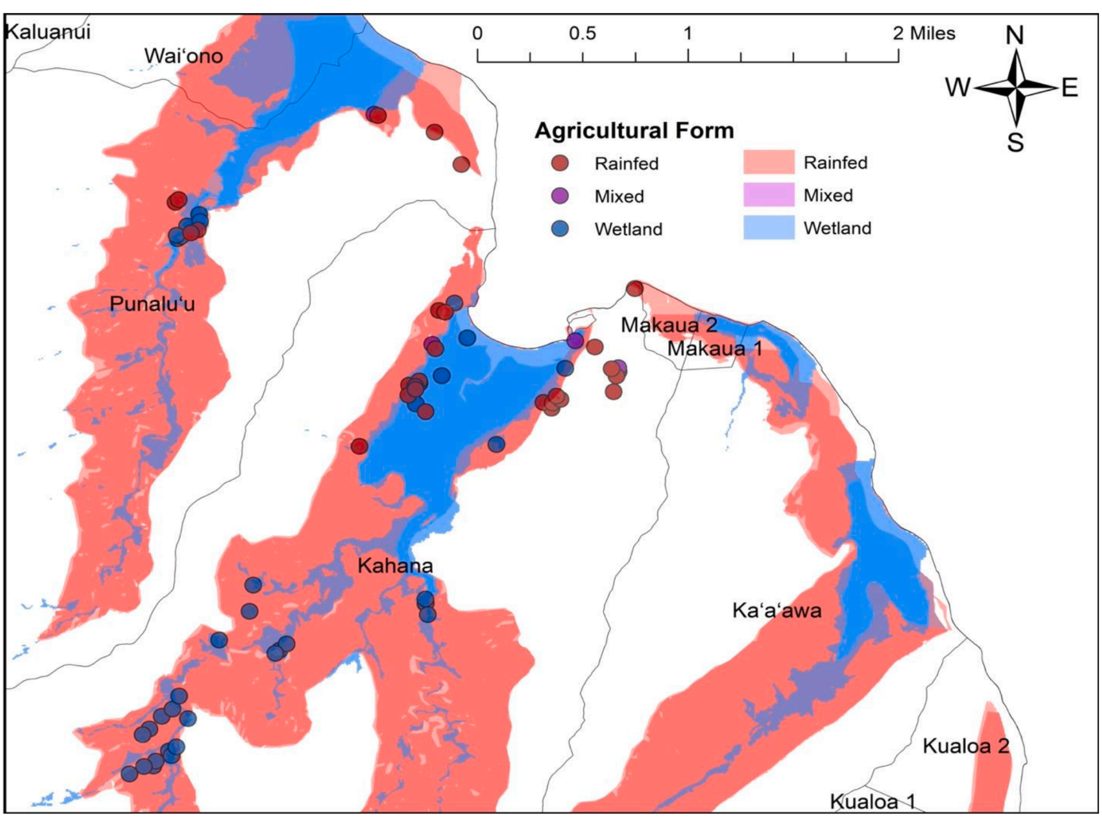

Fig. 4. Close up of windward Oʻahu valleys with the modeled agricultural extents and the classified validation points, demonstrating the high number of "near misses" for both wetland and rainfed agricultural form.

subterranean and surface water supply permits the development of dryland agriculture in these areas through active human agency, uplift of moisture through trees and other deep-rooted plants, or simply an adequate increase in soil moisture to support cultivation of crops. Additional research, along with spatial datasets of the subterranean ground table, could support the consideration of this dryland agricultural parameter.

The inland occurrences for rainfed agriculture that were not captured in the models may have different drivers. A substantial dryland development in the southern region of Kaua'i was omitted from modeled rainfed extents based on inadequate soil fertility related to the substrate age. However, this late-stage eruption series is poorly dated and represented by a very broad age range (0.15 to 3.85 million years). The younger portions of the flow series are likely, in reality, of adequate soil properties to support intensive Hawaiian rainfed agriculture, but the geological data is not resolved in the spatial data sets use to drive the modeling efforts. There are a few dryland occurrences, most notably in the *ahupua'a* (traditional land division encompassing a range of ecological resources; Gonschor & Beamer, 2014; Lincoln et al., 2022) of Honouliuli on O'ahu, and Kamiloloa and Makakupa'ia on Molokai, that are unclear as to the model shortcomings. Given that these clusters of points result from multiple archaeological reports representing different sites, the likelihood of misclassification as the source of error is low, and further work needs to be done in order to understand these substantial omissions from the modeling of traditional Hawaiian rainfed agriculture.

Lastly, we would be remiss to not acknowledge the representation bias in both the geospatial models and the archaeological record, which neglect other forms of agriculture fundamental for sustaining precontact populations. Existing models currently limit their parameters to encompass "Intensive Field System" only. When the models are assessed considering only archaeological points clearly identified as "Intensive Field System", strong recall rates were calculated as 0.7, 0.82, and 0.85 for the three spatial models. As the dryland models were specifically built to represent the intensive fixed field systems, these recall rates suggests that the models encompass the extent of these systems quite well. However, our analysis demonstrates that when considering a broader suite of rainfed agriculture, the models begin to underestimate the extent indicated by the archaeological extent. This is further supported by the consideration of all agricultural extents and archaeological points, in which even the most inclusive model demonstrates a recall rate of < 0.6. Ultimately, we suggest that while the models may perform well in terms of the specific agricultural niches that they target, they are omitting substantial areas dedicated to other agricultural forms based on other agroecological opportunities and constraints. It is therefore difficult to know how real the sociopolitical extrapolations generated from the patterns and distributions of these models are when they only capture on the order of half the agricultural points represented in the archaeological record used in this examination. Although the models are aimed at the most "intensive" forms of agriculture, with the assumption that these agricultural forms provided the bulk of the food, the role of other, presumably less-intensive, forms of agriculture cannot be ignored. Consideration of the whole suite of agricultural production has the potential to contribute to production, mitigate variation and risk within the local production systems, and ultimately shift the prevailing narrative of the unequal distribution of agricultural opportunities driving interactions between localities.

Although less dominant forms of agricultural production are not as widely acknowledged in discussions of agricultural extents for traditional Hawaiian agroecology, these systems play a critical role in land-use practices, enhancing cultivable land areas, and contributing to potential island carrying capacity. Additional forms of agriculture implemented by early Hawaiian farmers that are present in the archaeological record, but omitted from spatial models and this analysis, include aquaculture and non-plant (i.e., salt-production, animal husbandry) systems (*see* Lincoln et al., 2018). Lincoln (2020) also demonstrates that vast agroforestry areas existed but are neither represented in the models nor in the archaeological validation dataset (e.g., east coast of Hawai'i Island), though ethnohistorical sources, such as 18th century maps, provide clear spatial documentation of such systems (Lee and Lincoln, in review). The lack of recorded agroforestry systems is a common bias in archaeological documentation of agriculture systems (see Millerstrom & Coil, 2008). Although agroforestry is a widespread form of agriculture across Polynesian Islands (Huebert & Allen, 2016, 2020; Lepofsky, 1994; Quintus et al., 2019), it is not generally associated with any physical infrastructure and, therefore, is not typically recorded through archaeological investigations. Further exploration of less formal cultivation methods implemented by early Hawaiian populations, could not only provide additional insight into extents of early Hawaiian land-use practices, but could aid in establishing newly modeled extents of traditional Hawaiian agricultural production systems and address potential geospatial errors identified by this research.

5. Conclusion

Our validation assessment of various geospatial models depicting traditional Hawaiian agricultural extent suggests that, despite relatively low specificity rates, the models do a fair job at capturing the spatial patterns and relative extents of ancient Hawaiian wetland and intensive field system agriculture, although improvements can be made. However, it is clear that the current models, while capturing the forms of agriculture they are aimed at, are omitting substantial extent and forms of agricultural production employed in traditional Hawai'i. There are some key parameters governing traditional Hawaiian agriculture that are not currently incorporated into the models, such as the lowland/coastal dryland agricultural forms that were likely powered by groundwater and/or surface water emergence that should be considered in future modeling efforts. There is also a persistent lack of agroforestry representation in agriculture models, which is known to have been a substantial agricultural component in Hawai'i and throughout some Polynesia islands. Expanding model parameters to be more inclusive of the range of systems employed by early Hawaiian farmers may drastically change the anthropological interpretations of the socioeconomic distribution of wealth economy in ancient Hawai'i. Overall, geospatial models depicting extents of traditional Hawaiian agriculture have evolved over time to reflect improvements with more recent applications becoming increasingly accurate and representative of the footprint of Hawaiian agriculture at the time of European contact.

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CRediT authorship contribution statement

Kohlby VH Soong: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Noa Kekuewa Lincoln:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing – review & editing. **Tiffany M Lee:** Formal analysis, Validation, Writing – review & editing. **Thegn N Ladefoged:** Methodology, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data. Requests for the archaeological geospatial dataset should be made directly to the Hawai'i State Historic Preservation Division.

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