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Research Article

Ideal distribution models and the tempo of agricultural development in a windward valley of Hawai‘i

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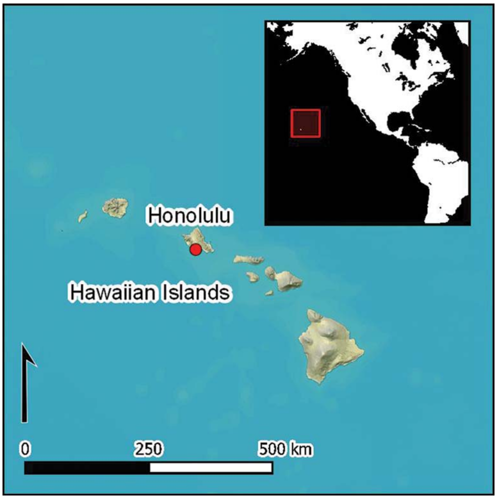

Across the Pacific, agricultural systems have used two main complementary cultivation regimes: irrigated farming of wet environments and rain-fed cropping of drylands. These strategies have different productive potential and labour needs, which has structured their temporal and spatial distributions. Although these approaches have been studied a great deal at a general level, there has been less work on the local use and significance of these strategies. Here, the authors evaluate ideal distribution models of agricultural activities in the Punalu‘u valley on O‘ahu, Hawai‘i, to assess how habitat suitability changed as a result of infrastructural investment and dynamic environmental, social and demographic change. The results are of relevance for contemporary initiatives to revive Indigenous agricultural systems in Hawai‘i and beyond.

Keywords: Pacific Islands, Hawai‘i, Bayesian modelling, agriculture, irrigation, terracing, taro, sweet potato

Introduction

Traditional agricultural systems incorporate multiple crops and cultivation practices adapted to diverse environments. These choices and routines, and their development over time, are intertwined as each one shapes the wider socio-ecological context within which others are practised. The Indigenous agricultural systems of many Pacific Islands, with a primary distinction between wet environments where irrigation is used and dry environments dependent on rainfall, typify this relationship (Barrau 1965; Kirch 1994). This is the case in the Hawaiian archipelago, a region first settled approximately 1000 years ago (Handy *et al.* 1972; Athens *et al.* 2014). Here, distinct variations of this basic agricultural dichotomy can be observed at three spatial scales. At the archipelago scale, irrigated pondfield cultivation (*lo‘i*) was widely established in the northern islands, where erosion has carved well-watered

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valleys; in contrast, extensive rain-fed dryland systems were prevalent in the geologically younger southern islands where soils retained more rock-derived nutrients (Ladefoged *et al.* 2009). At the scale of individual islands, archaeological evidence for irrigation techniques is predominantly found in windward valleys where there is adequate rainfall and permanent streams and rivers (Ladefoged *et al.* 2009). In contrast, evidence for rain-fed systems is typically found on leeward slopes in locations where sufficient rainfall, temperature and soil nutrients create 'sweet-spots' for cultivation (Vitousek *et al.* 2004). These take the form of either expansive, formal field systems extending across moderate to gently sloping terrain (e.g. Ladefoged & Graves 2008) or spatially constrained, less structured complexes on colluvial slopes (e.g. Rieth & Tomonari-Tuggle 2013). Finally, at the scale of individual valleys, archaeological evidence for wetland techniques is found on alluvial plains and terraces, adjacent to streams or located in marshland areas, while dryland techniques are practised on the colluvial slopes formed through the erosion of valley cliffs (Kirch 1977; Kurashima & Kirch 2011).

The predominant crops that were cultivated across the cultural sequence reflect the environmental conditions. Taro (*Colocasia esculenta*, *kalo*) was most productively grown in irrigated fields organised into a system of raised beds or bounded pondfields, though it was also grown in rain-fed settings with sufficient precipitation (Handy *et al.* 1972). In contrast, sweet potato (*Ipomoea batatas*, *'uala*) was the primary crop grown in rain-fed settings. Originally domesticated in South America and introduced to Hawai'i around the fourteenth century AD (Ladefoged *et al.* 2005), the crop filled an environmental niche where taro could not be grown or was less productive. Mixed cropping, including arboriculture, took place across colluvial slopes in windward valleys and the crop roster in each location was likely targeted to local environmental characteristics (Kirch 1977).

In the tenth and eleventh centuries AD, the initial Polynesian inhabitants of Hawai'i settled in the well-watered, east-facing windward valleys of several islands, constructing irrigation infrastructure within the first 200 years of settlement (McElroy 2007; McCoy *et al.* 2013; Athens *et al.* 2014). Robust dating for these irrigated systems is, however, limited (see Dye 2016). Rain-fed, dryland cultivation infrastructure was initially constructed in the fifteenth century (Allen 2004; Ladefoged & Graves 2008; Quintus & Lincoln 2020), as settlement expanded into leeward areas, with further expansion in the seventeenth century and later (Dye 2014). The development of dryland infrastructure in colluvial-slope environments seems to follow a similar chronology to general leeward environments (Morrison *et al.* 2022), though research in colluvial environments is currently limited. Rapid depopulation after European contact at the end of the eighteenth century was followed by the abandonment of most agricultural infrastructure, particularly in areas of dryland cultivation.

Evidence for agricultural systems has played a prominent role in the construction of archaeological narratives about the archipelago (e.g. Kirch 1994, 2010; Hommon 2013). The development of irrigated agriculture has been frequently linked to population growth, leading to settlement expansion into more marginal leeward environments. This, in turn, gave rise to productive variability in divergent environments, setting in motion cycles of intensification and the production of agricultural surpluses. The varying productive capacity of different agricultural practices has been argued to be a cause of warfare, the consolidation of political units, and the growth of 'archaic states' by the eighteenth century (Kirch 2010; Hommon 2013, but see Bayman *et al.* 2021).

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While we have a broad understanding of the temporal development of agricultural techniques at the archipelago scale, robust local-scale chronologies, notably within individual valleys, are limited, for both irrigated and colluvial-slope practices. As these techniques provided the bulk of food production in the northern islands of the archipelago, better data on their development is key to linking agriculture to other themes of Hawaiian history. Furthermore, we expect the incorporation of different agricultural activities to have varied within and between individual valleys, and better understanding of temporal variation of these techniques at the local scale may provide insights into demographic expansion and the growth of social inequality across the islands. Localised chronologies can help us understand not only the date of the initial construction of infrastructure, but also the ongoing tempo of agricultural works across divergent environments, which is largely unknown over the longer cultural sequence. Such gaps in our knowledge limit understanding of changing agricultural habitat suitability and the drivers of those changes. Finally, understanding the development of these systems and their relationships with landscape suitability and labour is an essential prerequisite to reinstating these cropping systems to support contemporary food production.

To this end, this article brings together and compares a suite of radiocarbon dates from two agroecosystems in the windward valley of Punaluʻu on the island of Oʻahu. Using Bayesian models, we highlight temporal relationships between these two systems, which we visualise with tempo plots; we also use ideal distribution models to conceptualise the socio-ecological embeddedness of different production techniques. Through this research, we are better positioned to understand the drivers of changing agricultural habitat suitability in Hawaiʻi, the tempos of agricultural development in divergent environments and the linkages between environment, agriculture, demography and political organisation.

Ideal distributions and Hawaiian agricultural practices

Ideal distribution models, or IDMs, consider the relationship between population density, habitat characteristics and social controls to understand how organisms distribute themselves across space (Fretwell & Lucas 1969). Drawing from a formal body of theory, these models provide testable hypotheses of human subsistence and settlement behaviour in response to environmental and social factors (Prufer *et al.* 2017). The models predict how human settlement may be conditioned by characteristics of habitat suitability, or the potential for a habitat to have a positive impact on the success of an individual (Weitzel & Codding 2020: 2). While IDMs assume that humans will maximise suitability of any particular habitat, suitability is not static (Bliege Bird *et al.* 2020); rather, it is dependent on a range of social and environmental factors that influence the costs and benefits of using particular habitats over time.

We explore these concepts of dynamic habitat suitability around three iterations of IDMs. First, ideal free distribution models assume that when individuals enter a new environment, if their choices are unconstrained, they will use the areas that are most suitable. Suitability is determined by the density and distribution of useful resources given a particular subsistence strategy. In an ideal free distribution, there is negative density dependence, and habitat suitability declines with increasing human population density and the depletion of resources (Fretwell & Lucas 1969). This, in turn, leads to the use of less-suitable habitats. This leads us to the second model iteration: an ideal free distribution with an Allee effect,

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which is positive density dependent in the sense that higher population densities make some habitats more appealing (Allee 1931). This iteration recognises that, in some environments, a dense population may generate opportunities for habitat enhancement by way of agricultural infrastructure and other investments (e.g. anthropogenic soils). Alternatively, larger populations may allow for opportunities to employ more labour-intensive strategies or intensify cropping cycles (Kirch 1994). There is an optimal group size, however, after which increases in population density would result in reduced suitability (Weitzel & Codding 2020). The third model iteration, the ideal despotic distribution, predicts human use of habitats under constrained conditions. These constraints might be physical, such as when infrastructure reduces the potential for subsequent investment, or social, for example, when there are claims of prior possession that limit available resources. In these situations of negative despotism, marginal areas might be used before population density in suitable areas reaches a sustainable maximum. This is because increased territoriality reduces the suitability of seemingly high-ranked habitats (Summers 2005). Under positive despotism, however, leaders may also try to attract individuals into habitats to increase the suitability of that habitat (Bell & Winterhalder 2014). This may be especially useful when some agricultural strategies require large labour forces to be successful. Finally, IDMs are typically discussed in the context of growing population, but depopulation would hypothetically result in the abandonment of lower-ranked habitats but persistent use of high-ranking habitats (Jazwa & Jazwa 2017).

Oceanic islands, and islands more generally, are particularly amenable for the application of IDMs (Kennett *et al.* 2006; Winterhalder *et al.* 2010), due to their bounded nature, varied environments and biotic and agronomic introductions. Differential productive potential provides one measure of environmental suitability in the context of agricultural systems because it is based on environmental characteristics that affect plant growth (e.g. moisture, nutrients, temperature) and the marginal returns of agricultural practices. In this context, irrigated agriculture had the highest marginal returns of the strategies used in Hawai'i, offering opportunities for substantial surplus production, while rain-fed production yielded far less per unit of labour (Kirch 1994). For example, Kurashima & Kirch (2011) estimate yields of 25, 10 and 11 wet metric tons/ha/year for irrigated, intensive dryland and colluvial slope systems, respectively. Additionally, rain-fed agriculture is considered riskier as it is tied to seasonal and interannual fluctuations in precipitation (Allen 2004).

As such, consistent with an ideal free distribution, we would expect pondfield agriculture to have been established shortly after the initial settlement of the valleys. When population growth outpaced the development of pondfield agriculture, we would then expect that intensive rain-fed agriculture developed on the colluvial slopes (perhaps replacing some earlier low-intensity cultivation, such as agroforestry). This might have been because the expansion of pondfields was no longer possible due to physical constraints. In conjunction, and in keeping with an Allee effect, we hypothesise that the suitability of colluvial slope agriculture increased as population size increased given the higher labour requirements per unit of production in the dryland cultivation of Hawai'i. Given the increasing social stratification that arose through the Hawaiian sequence, we also expect that despotism played a role, either positive or negative. If negative despotism occurred, we anticipate the construction of elite architecture in the vicinity of wetland infrastructure to demonstrate control with evidence of territoriality. This is because low-labour but high-yielding strategies are of high value. Wetland

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agricultural yields are also more predictable and more densely distributed, making it a technique worth defending. Such territoriality would be evidenced by the combination of ritual architecture and the end of irrigated pondfield construction. On the other hand, if positive despotism was present, we expect no evidence of constraint in the use of colluvial slopes even though leaders might attempt to control these landscapes. Labour is necessary to increase the productivity of dryland agriculture. While leaders might attempt to control this environment, we hypothesise that they would not want to constrain access to it. Finally, and given the above, we expect that populations abandoned colluvial slope cultivation in the context of population decline. These various expectations are summarised in Figure 1.

Archaeological research in Punaluʻu Valley

Recent research in Punaluʻu Valley on the windward coast of Oʻahu (Figure 2) offers an opportunity to study the chronology of agricultural development in wet and dry environments. Punaluʻu is a deep valley with broad alluvial plains near the coast and alluvial terraces farther inland (Handy *et al.* 1972). These alluvial environments are bounded by colluvial slopes, the product of erosion from the cliffs that lead up to the narrow ridges that define the valley. The data presented here were generated as part of the Punaluʻu Archaeological Field School over three seasons (2018, 2019 and 2021). The field school was created under a partnership between Kamehameha Schools (the landowner), archaeological consultant firm International Archaeological Research Institute, Inc., and the University of Hawaiʻi at Mānoa. Each season provided the opportunity for primarily locally based students to learn about archaeology near home and to increase the pool of archaeologists available to work in Hawaiʻi cultural resource management. The data collected have been shared with the Punaluʻu valley residents and have contributed to improving the land management, including agricultural practices, and archaeological stewardship initiatives of Kamehameha Schools.

Archaeological research in the valley has examined the relationships between Indigenous agricultural systems, demography and social change (Rieth *et al.* 2021; Morrison *et al.* 2022). This has led to the documentation of two formal agricultural systems (Figure 3): a wetland irrigated pondfield complex on an alluvial terrace (Site 50-80-06-2936, Figure 4) and formal dryland fields on the colluvial slopes (Sites 50-80-06-2927 and 50-80-06-7302). The pondfields are positioned atop an alluvial terrace between the south-eastern valley wall and a bend of Punaluʻu Stream. The system is characterised by a set of at least 23 stone-faced terraces with bunded sides enclosing approximately 1.1ha. The formal dryland fields are located on the colluvial slopes at the south-eastern margin of Punaluʻu Valley, near the coast. This system encompasses a variety of architectural elements, including linear mounds that served as land boundaries, cultivation and habitation terraces, enclosures and a large ritual compound (called a *heiau*; Site 50-80-06-0296).

Thirty-three radiocarbon dates and one uranium-thorium date from 22 architectural elements have been obtained from locations across the *lo*ʻ*i* and colluvial slopes (Figure 5). All radiocarbon dates used in this study, including those newly presented, are listed in Table S1 in the online supplementary material (OSM). Bayesian models have been constructed for the colluvial slope environment, building on the models developed by Morrison *et al.* (2022), and for the wetland environment using Oxcal 4.4 (Bronk Ramsey 2009). The

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	Ideal Free Distribution (Growth)	Allee Effect	Ideal Despotic (Negative)	Ideal Despotic (Positive)	Ideal Free Distribution (Depopulation)
Rule	High ranking habitats will be developed ahead of lower ranked habitats.	The suitability of an environment may be improved by an increase in group size.	Territoriality will develop in high ranking habitats, resulting in those habitats being less preferred.	Elite presence will attract a larger population, making a habitat more suitable.	Decreased population will result in abandonment of lower ranked habitats.
Expectation	Irrigated facilities will be developed prior to dryland environments. Over time, dryland settings will be more suitable as irrigation reaches its spatial extent.	The suitability of dryland environments will increase as population size increases. This is due both to the construction of infrastructure and also the potential for cropping cycle intensification.	Territoriality or elite presence will develop surrounding irrigated environments.	Elite presence will be established as a mechanism to attract populations to dryland environments.	Dryland cultivation will be abandoned following historic-era depopulation.
Signature	Dates from irrigated facilities will be earlier.	Exponential or continued growth over time in colluvial slopes.	Construction of ritual architecture followed by reduced agricultural construction in irrigated environments.	Construction of ritual architecture followed by continued or increased agricultural construction.	Absence of agricultural infrastructure dated to the historic period.
Result	Consistent. Colluvial slope development increased following a decrease in the construction of irrigated facilites.	Consistent. Growth of colluvial slope agriculture accelerated with population growth.	Inconsistent. No evidence of territoriality in the pondfield environment.	Consistent. Establishment of elite ritual architecture amongst colluvial slope complexes.	Consistent. Historic-era land use is found in the irrigated facilities but not along the colluvial slopes.

Figure 1. Rules, expectations, signatures and results for agricultural development in Punalu'u derived from ideal distribution models (figure by Seth Quintus).

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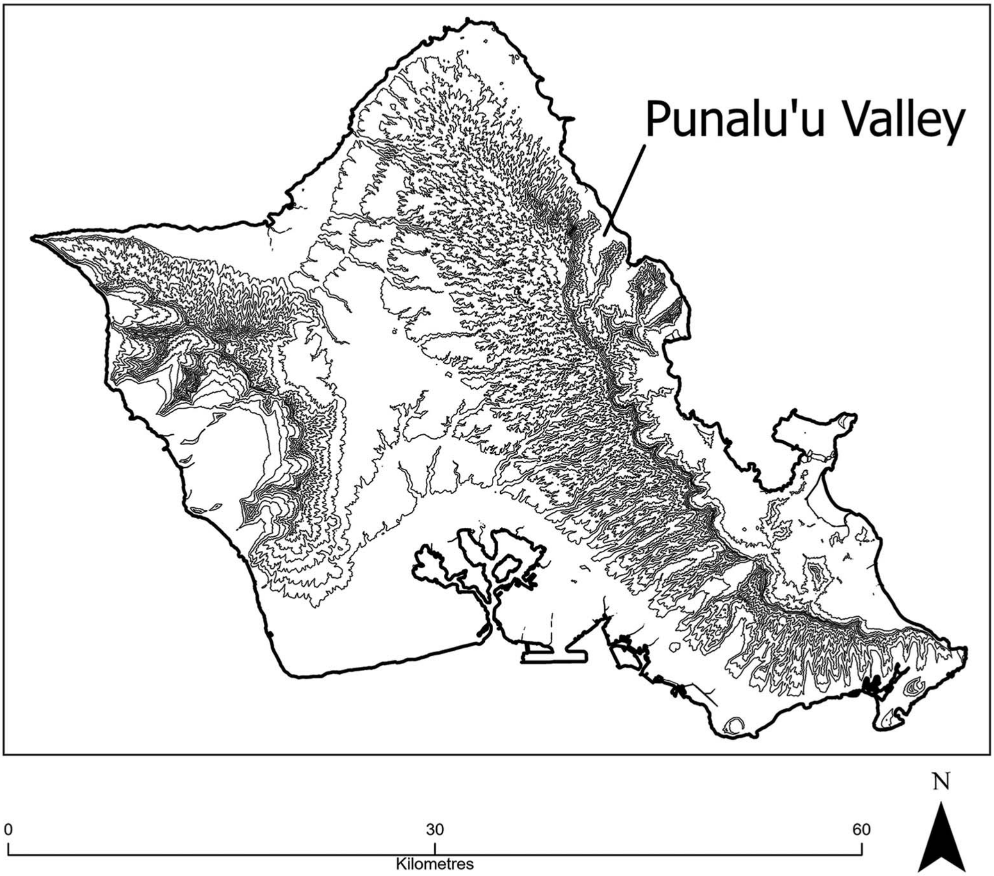

Figure 2. The location of Punaluʻu on Oʻahu. The dark line is the shoreline, while the lighter lines are 100m contours (figure by Seth Quintus).

Bayesian models are designed to estimate the construction of standing or buried architectural elements: terrace retaining walls, enclosure walls or linear mounds and alignments (see OSM). Individual dates are stratigraphically related to these architectural elements and classified as *terminus post quem* (TPQ) or *terminus ante quem* (TAQ) constraints for each depositional context. Modelled dates are presented as 95.4 per cent highest posterior density. Outputs from the Bayesian analysis, in the form of Markov chain Monte Carlo (MCMC) results, are used as the input to construct tempo plots in ArchaeoPhases (Philippe *et al.* 2017).

The nature and tempo of construction in Punaluʻu

Figure 6 shows the modelled ages for built infrastructure. Early evidence of construction within the pondfield system, dating to AD 1228–1336 (95.4%, Trench 1) and AD 1110–1383 (95.4%, Trench 7), is found within alluvial deposits that are characterised as sandy loam with well-rounded and poorly sorted cobbles and pebbles.

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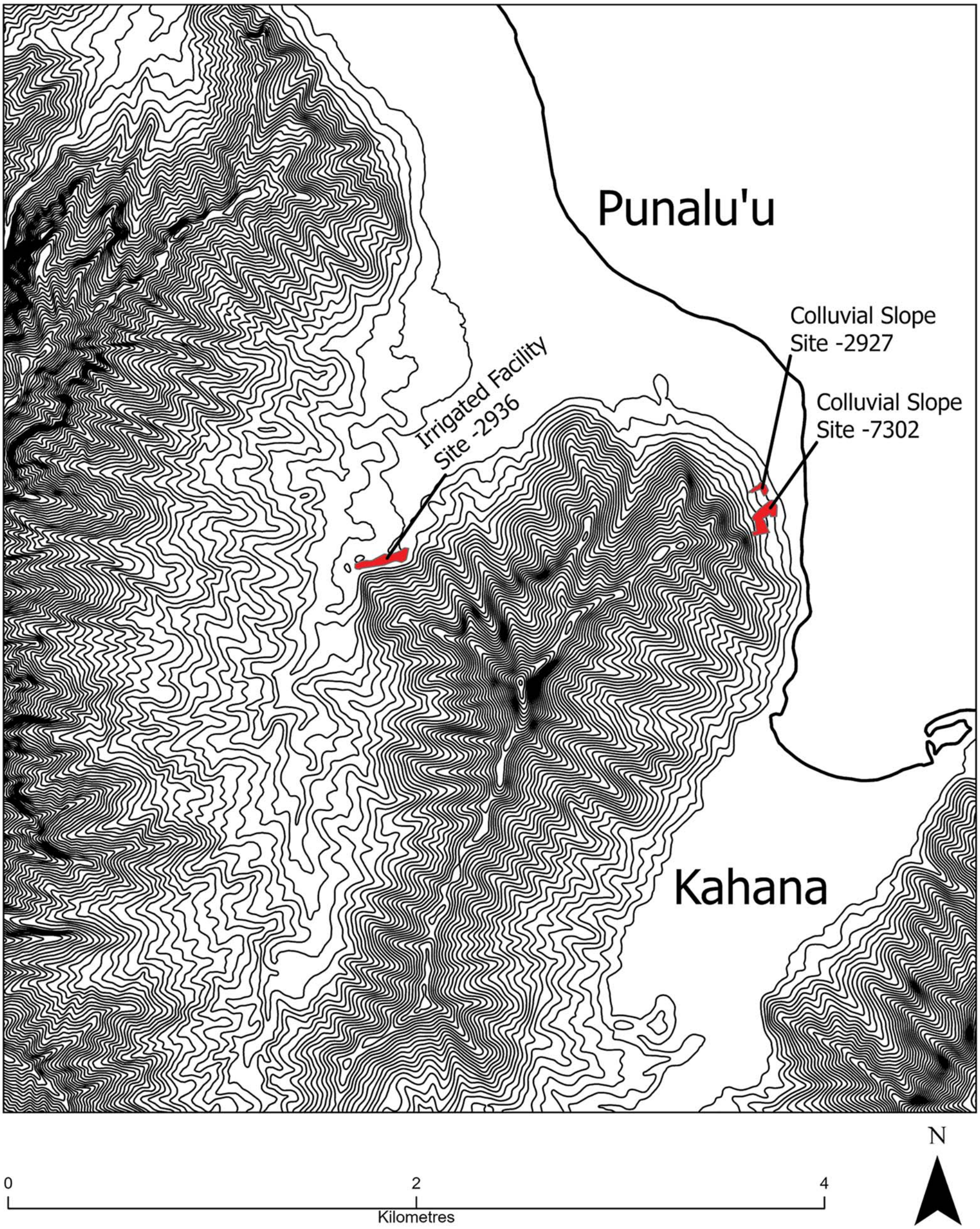

Figure 3. Location of the two agricultural systems in Punalu'u Valley. The dark line is the shoreline and the light lines are 40m contours (figure by Seth Quintus).

This simple architecture comprises single- or double-course stone alignments (Figure 7a). We interpret these features as barrage terraces or checkdams designed to trap fine alluvium in order to create a stable, stream-side landform. Judging by the accumulation of finer sediments above these features (Figure 7b), the terraces successfully trapped sediment carried by natural

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Figure 4. Plan view map of the loʻi *complex with trench locations. The stream is located to the north of the system and the intake ditch is located to the south (figure by Chris Filimoehala).*

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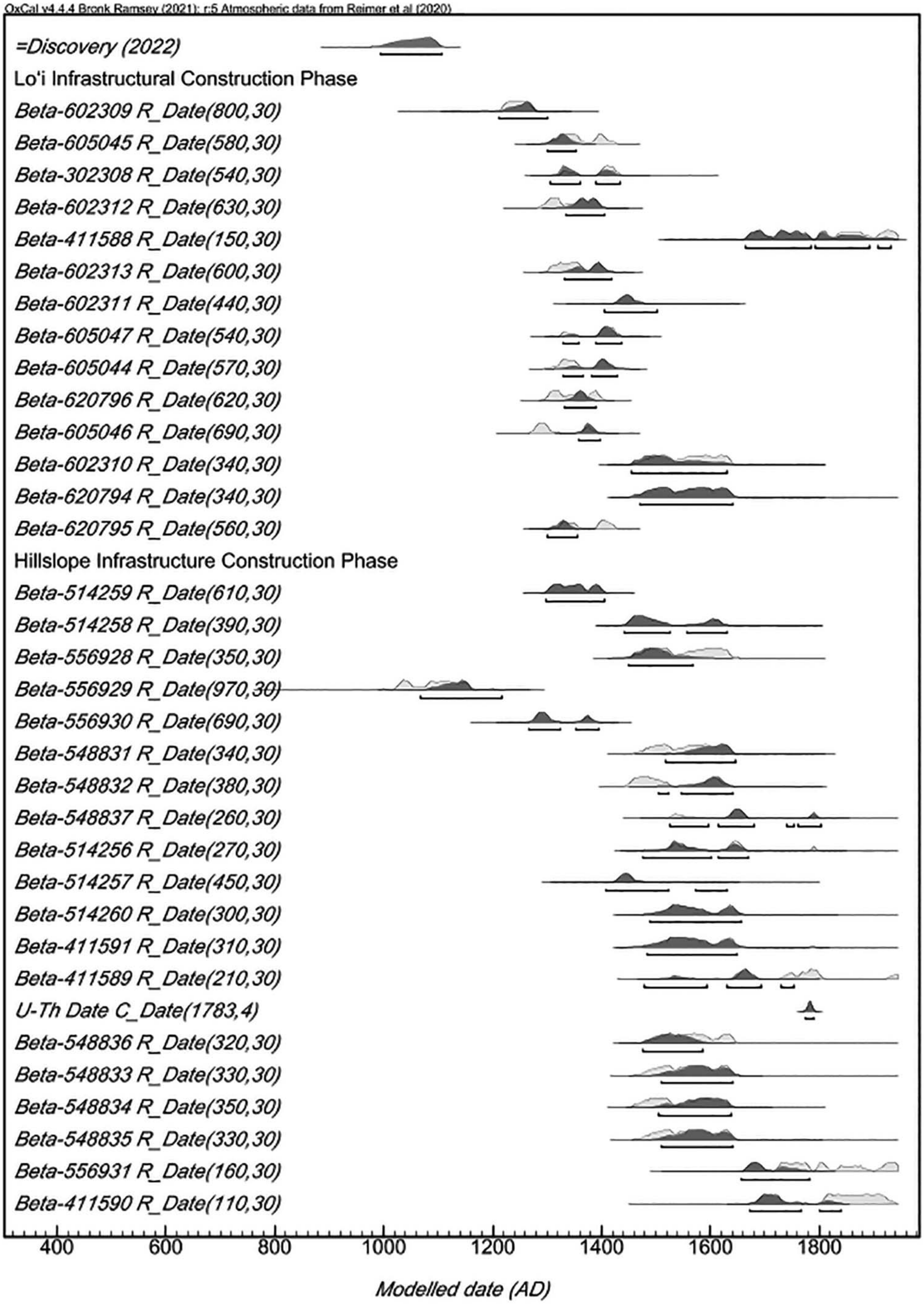

Figure 5. Modelled radiocarbon dates associated with relevant colluvial slope and irrigated infrastructure in Punalu'u (figure by Seth Quintus).

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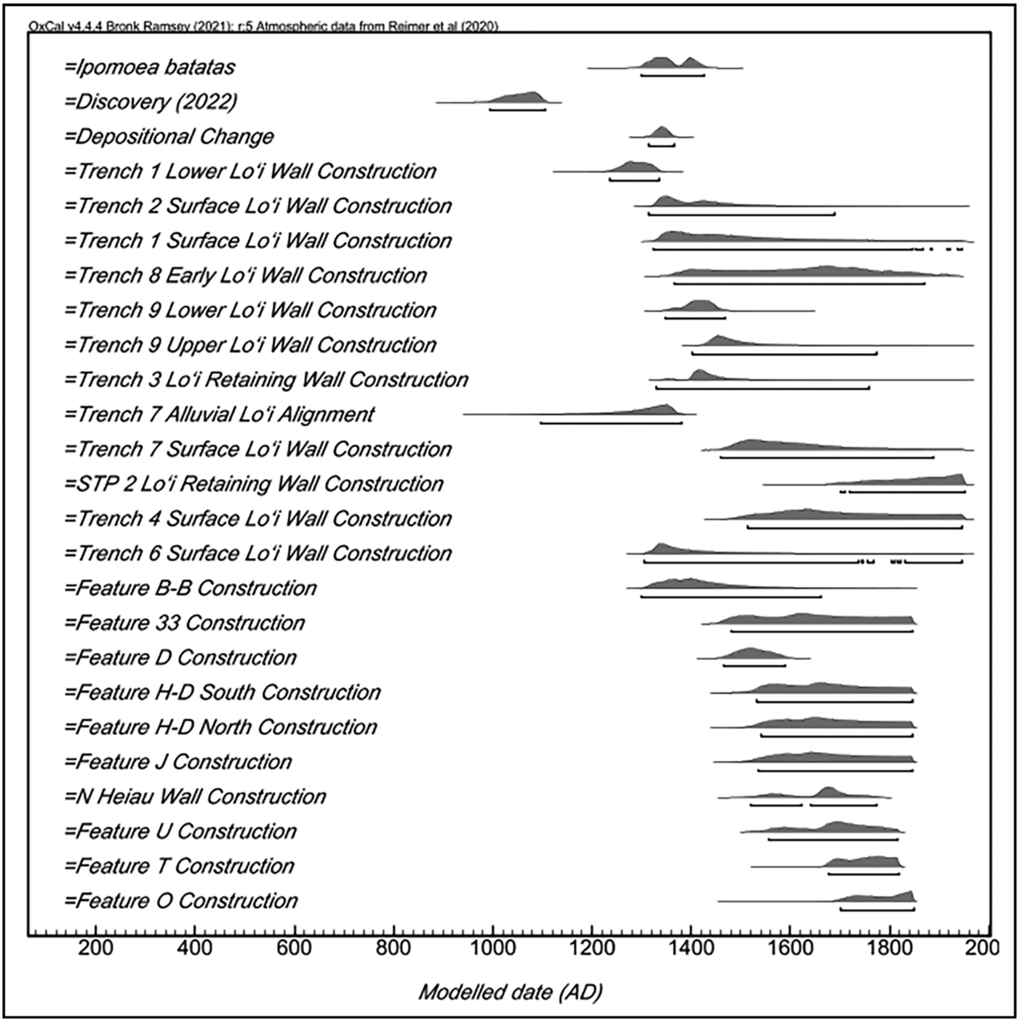

Figure 6. Estimated construction ages for 22 features across the colluvial slopes and irrigated systems (figure by Seth Quintus).

depositional processes such as overbank flooding. Our Bayesian model indicates that the transition from predominantly coarse to fine sediment deposition occurred in *AD 1321–1370* (95.4%). The accumulation of fine sediment laid the foundation for intensive agriculture at the site, and the rate of infrastructure construction accelerated markedly in the fifteenth century (Figures 6 & 8). This infrastructure is more elaborate, most notably earthen terraces with stone-faced retaining walls (Figure 7c). The rate of construction declined in the seventeenth century, presumably because the system continued to produce regular yields; indeed, the consistent presence of charcoal into and beyond the seventeenth century suggests the continued use of the system. Based on the lack of historical land claims recorded for this location, the pondfields were probably abandoned by the mid-nineteenth century due to population decline following Western contact. Historical maps, however, depict the area as being under

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Figure 7. a) Small-scale boulder alignment at the base of Trench 7; note the position of the alignment among smaller alluvial cobbles. b) The relationship between fine and coarse alluvial sediments visible in Trench 6; both walls were built in the upper fine sediments. c) The surface and buried retaining wall of Trench 9; the lower wall was built on top of coarse alluvial deposits (figure by Seth Quintus).

rice cultivation by the latter part of the nineteenth century and into at least the first decade of the twentieth century. By the 1920s, historical maps indicate that taro was again being cultivated but this may have been a short-lived phase.

Excavations on the colluvial slope have revealed single-phase construction sequences, with the potential exception of the ritual compound or *heiau* (Morrison *et al.* 2022). Direct dating of archaeobotanical remains highlights the incorporation of some arboreal elements into the subsistence system by the fifteenth century, including breadfruit (*Artocarpus altilis*, *'ulu*),

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coconut (*Cocos nucifera*, *niu*) and candlenut (*Aleurites moluccana*, *kukui*) (Morrison *et al.* 2022). The building of infrastructure commenced as early as *AD 1302–1659* (95.4%) but the bulk of activity occurred later, from the sixteenth to eighteenth centuries (Figures 6 & 8). Several linear mounds and terrace-retaining walls abut other features, and therefore post-date them, highlighting a process of field segmentation over time. Ladefoged *et al.* (2011) argue that such a process is the archaeological signature of rain-fed intensification, wherein more agricultural labour supported by a higher population was invested in agricultural practices. If this same argument holds for the colluvial slopes, it would highlight the role that population size plays in enhancing the utility of these environments. The tempo plot highlights the continued use of these systems until the nineteenth century. There are no historical records or archaeological evidence for later cultivation of this area. The preservation of this complex relates to its unsuitability for nineteenth- and twentieth-century commercial agriculture in the valley, which often resulted in the wholesale removal of earlier surface structures.

The developmental sequences reconstructed for the alluvial plain and the colluvial slopes can be compared using tempo plots (Figure 8). Initial development of agricultural systems on the alluvial plain at some time prior to the mid-fourteenth century was followed by 200 years of intensive development. Activities on the colluvial slopes at this time were restricted to the planting of introduced tree crops and, by the end of the period, the initial construction of infrastructure. Some form of shifting cultivation prior to the building of infrastructure cannot be ruled out, though there is no direct evidence and little charcoal was found beneath agricultural infrastructure in either the colluvial or irrigated environments. By the sixteenth century, the development of the pondfield system slowed as existing terraces were subdivided and new terraces were added at the margins of the system. The development of infrastructure on the colluvial slopes accelerated in the sixteenth century and continued through to the early nineteenth century.

The evolution of Hawaiian valley agriculture

Our data allow us to assess the expectations and hypotheses set out above (Figure 1). The sequence of development on the alluvial plain and colluvial slopes of Punalu'u meets the expectations derived from an ideal free distribution model where suitability is determined by potential yield per unit effort: initial investment in high-yield irrigated agriculture on the alluvial plain is followed by the development of agricultural infrastructure for lower-yield dryland crops on the colluvial slopes. These sequences indicate a change in the relative suitability of the alluvial plain and colluvial slopes over a period of time.

The suitability of novel habitats for human settlement on islands is largely conditioned by the subsistence techniques and crops introduced from elsewhere. In the case of Hawai'i, Polynesian settlers initially brought crops that were well suited for tropical environments, having been domesticated and selectively propagated in these settings for millennia. It is unsurprising that irrigated agriculture was quickly established as the islands' well-watered environment would have been familiar to the Polynesian settlers and the use of irrigation was known to be the highest-yielding strategy.

The earliest infrastructure appears to have been geared toward stabilising a dynamic environment: the banks or shallow sections of a permanent river. In addition to creating arable

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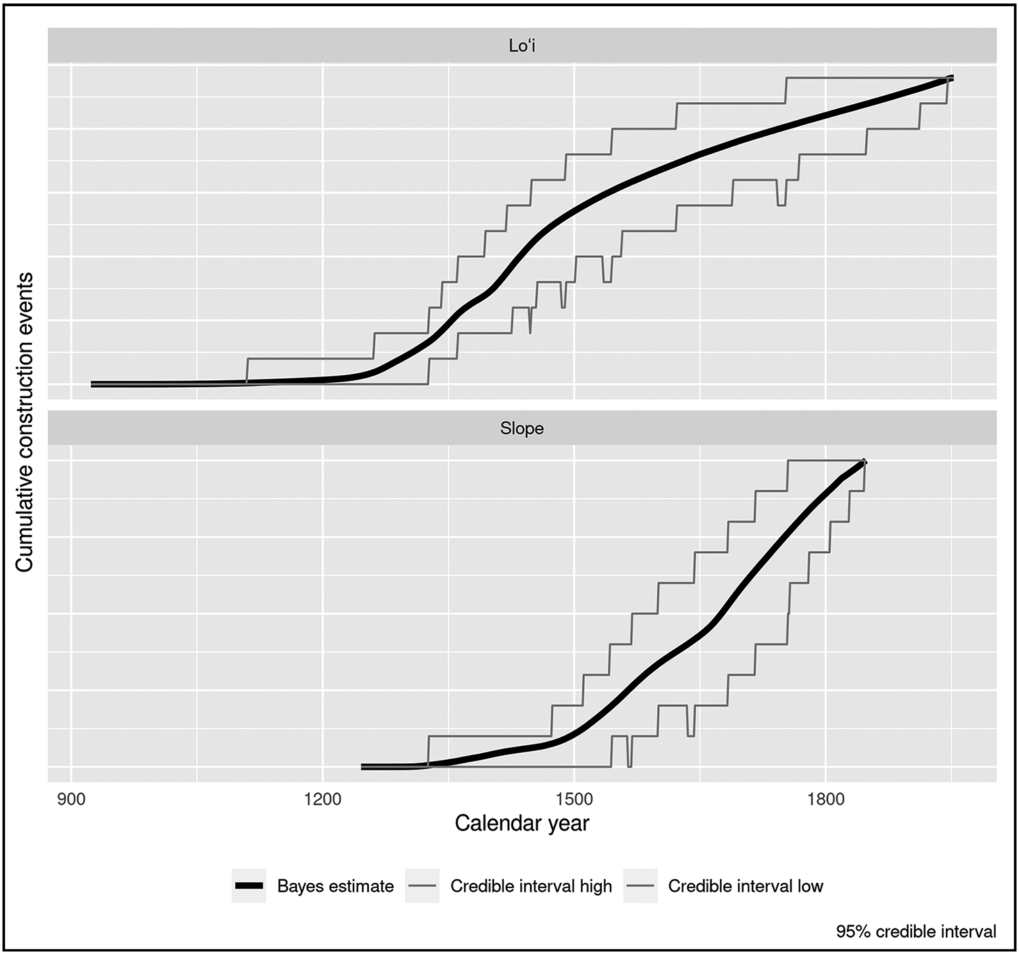

Figure 8. Tempo plot comparing the construction of infrastructure across the lo'i *(top) and colluvial slopes (bottom) (figure by Tom Dye).*

land, the consequence of this infrastructure was the enhancement of the location for later pondfield development and its expansion by the trapping of sediment. We hypothesise that the building of infrastructure initiated a positive feedback loop, wherein the trapping of fine sediments led to increased suitability for cultivation and continued elaboration of the agricultural system. Habitat suitability was enhanced by infrastructure that accumulated fine sediments leading to aggradation (increased height of the landform), which would have reduced the effects of erosive flooding. Such processes are similarly hypothesised for other irrigated environments in the archipelago (Kirch 2002; McCoy *et al.* 2013). It is conceivable that sediment movement was aided by the practice of shifting (or swidden) cultivation elsewhere in the valley, as noted by Spriggs (1997), but we currently lack data to confirm this. The result was productive resilience, at the cost of increased, but generally predictable, maintenance (McCoy *et al.* 2013: 1537). Such processes highlight the role of anthropogenic construction in changing habitat suitability (Bliege Bird *et al.* 2020).

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Agricultural development of the colluvial slope was due, in part, to population growth resulting from expanded production on the valley bottom, as predicted from an ideal free distribution model and as proposed more generally to explain increased investment in rain-fed agriculture across the archipelago (Ladefoged & Graves 2008; Kirch 2010). Rain-fed production requires more labour per land unit, relative to wetland production, to produce a similar yield (Kirch 1994). As such, the suitability of the colluvial slope environment would have increased only as the labour force grew or as the yields from irrigation decreased. In this context, it is notable that the early period of cultivation on the slopes included some tree crops grown with limited infrastructure (Morrison *et al.* 2022). This indicates an initial phase of relatively low-labour-intensity perennial cultivation prior to the institution of more labour-intensive annual cultivation evidenced by field boundaries. As tree crops persisted and the workforce grew, colluvial slopes may have attracted more farmers whose labour enhanced the suitability of the environment through an Allee effect. In conjunction, absolute surplus production would have increased. While the surplus production per worker across colluvial slopes, as modelled by Kurashima & Kirch (2011), is not as high as for pondfields, the absolute surplus produced may have rivalled that of the irrigated facilities if a large enough workforce were available to put the slopes around the entire valley into production. In this regard, we note that the colluvial slopes were developed after power became further consolidated by elites on Oʻahu (Kirch 2010). The growth of polities and elite presence may have enhanced colluvial slope suitability as elites pushed for surplus production to support a growing wealth economy (Dye 2014). On that note, and as predicted above, positive despotism was another factor affecting investments in the system. The construction of a large *heiau* (*AD 1525–1764*) that is physically connected to the agricultural infrastructure (Morrison *et al.* 2022) highlights that elites were interested in the colluvial slope landscape.

These developments occurred in conjunction with the introduction of the sweet potato (McCoy 2006; Morrison *et al.* 2022). Compared with the 1500–2000mm annual rainfall required to grow dryland taro, sweet potato is a more drought-tolerant crop, needing only 500–750mm of rain annually, with approximately 90mm of rain in the month of crop establishment. The near-coastal colluvial slopes of Punaluʻu receive an average of 1500mm of annual rainfall (Giambelluca *et al.* 2013), which would support only the marginal cultivation of taro. The earliest-recorded sweet potato macrobotanical remains in the archipelago probably date to the fourteenth century, but could be as late as the fifteenth century (Ladefoged *et al.* 2005), with our model providing a date of 1300–1426 (see OSM). As noted by Ladefoged & Graves (2000), experimentation with sweet potatoes, including varietal development, was necessary prior to any high-intensity production. Once that knowledge was gained, and while dryland sweet-potato production would still yield far less than wetland taro per unit of labour, the presence of sweet potato made colluvial slopes far more suitable for other uses too. This is consistent with not only increased production but also a risk-aversion strategy (Allen 2004). Diversifying crops, cultivation methods and field locations within Punaluʻu Valley could have reduced the effects of interannual variation. Like geomorphological change, the introduction of new crops speaks to the role of cultural practice in effectively resetting suitability calculations. It was, however, the combination of a larger labour pool made possible by investment in irrigation, the introduction of the sweet potato and changes in social organisation that made colluvial and leeward slopes more attractive for

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agricultural exploitation. The eventual importance of sweet potato cultivation in Punalu'u was the result of the prior development of irrigation in the valley.

Indigenous agricultural practices were abandoned along these colluvial slopes shortly after the arrival of Europeans. In contrast, the use of irrigation persisted through the historical period, including in the Punalu'u valley. This meets another expectation of the ideal free distribution model in a situation of population decline. The reduction in use of colluvial slopes and the increasing suitability of valley lowlands for cultivation was probably also driven by the abolition of traditional tribute demands, the reduced social importance of pigs (fed by crop surpluses), the initiation of a cash economy and the cultivation of rice and other introduced crops.

Ideal distribution models help us better understand the drivers of agricultural change and relationships between agricultural techniques in Punalu'u, despite some inconsistencies in the predictions. A negative despotism model would predict that evidence of territoriality would be found in irrigated environments. There is, however, no such evidence from Punalu'u, where possible markers of elite activities (e.g. the large *heiau*) are located in proximity to colluvial slope systems. This does not imply that negative despotism was absent, as some forms of territoriality do not leave material traces, but it does highlight the potential importance of positive despotism in dryland environments where a large labour force was crucial. Further, as currently constructed, ideal distribution models are less effective at incorporating notions of anthropogenic change. The Allee effect includes some elements of anthropogenic change, but it is most frequently cited in the context of labour and group size rather than transgenerational ecological inheritance (e.g. environment and crops). In Punalu'u, both exchange and engineering altered habitat suitability. As such, the incorporation of these dynamics, along with social and political factors, could further improve the utility of ideal distribution models (Prufer *et al.* 2017; Bliege Bird 2020).

Conclusions

While demography is typically seen to be variable, other factors that affect habitat suitability in ideal distribution models tend to be treated as constants (Weitzel & Codding 2020). Such fixed suitability in any particular environment, however, is rare. The actions of farmers create conditions that shape future opportunities and constraints, through the incorporation of alternative crops, the expansion of arable land or the development of agricultural infrastructure (Quintus & Cochrane 2018). By doing so, as our study illustrates, the relative suitability of environments is modified. Data from Punalu'u highlight an early use of environments conducive to irrigation, with subsequent iterations of land use gradually enhancing the suitability of these agricultural habitats. Infrastructural-based investment in dryland areas were a later development, possibly driven by a combination of population growth, the introduction of a new crop (the sweet potato), risk management efforts and the growth of a large-scale political economy.

The temporal depth of these practices provides important insights into their contemporary revitalisation. Pondfield systems are resilient because, when skilfully managed, they are habitat enhancing. This is not necessarily the case for the rain-fed systems that were developed after the sweet potato was introduced to the islands; farmers mastered its cultivation, and a

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large labour force became available to support the expansion of its cultivation. The rain-fed systems, however, were abandoned shortly after the arrival of Europeans. The differences in how these systems were viewed and used in the past makes an important contribution for ongoing conversations around present-day agricultural revitalisation in the Hawaiʻi archipelago.

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Supplementary material

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