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The potential of indigenous agricultural food production under climate change in Hawai'i

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The value of land-use strategies that increase food production while conserving biodiversity is widely recognized. Many indigenous agroecosystems are productive, adaptive and ecologically principled, but are largely overlooked by planning in terms of their potential to meet current and future food needs. We developed spatial distribution models of indigenous agroecosystems in Hawai'i to identify their potential past distribution, productive and carrying capacities, and future potential under current land-use and mild-to-severe future climate scenarios. Our results suggest that Hawai'i's traditional agroecosystems could have had production levels comparable to consumption today. Carrying capacity estimates support hypotheses of large pre-colonial Hawaiian populations (>800,000). Urban development has reduced (−13%) traditional agroecosystems but 71% remain agriculturally zoned. Projected effects of three future climate scenarios vary from no change in potential production to decreases of 19% in the driest and warmest end-of-century scenario. This study highlights the food-producing potential of indigenous agriculture even under land-use and climate changes, and the value of their restoration into the future.

The expansion and intensification of agriculture is recognized as one of the most substantial drivers of environmental change[1], and with global population expected to reach 9.7 billion by 2050, agricultural production is expected to increase to meet the world's consumption demands[2]. Competing demands for food, fibre and fuel and the urban populace will continue to increase[3]. Climate change is expected to decrease agricultural production and have negative effects on the other three components of food security: access, use and price stability[4]. Management alternatives that can reconcile agricultural production with the maintenance and enhancement of biodiversity and ecosystem services in human-dominated landscapes now and into the future, are critical.

There have been increasing calls for maintaining and restoring production systems designed with ecological principles, including biodiverse indigenous agroecosystems[5]. Indigenous agroecosystems are usually diverse at the farm and landscape levels, often protect natural areas such as patches of forests and streams[6], and can host similar species richness to adjacent forest reserves[7]. They are by nature dynamic and adaptive[8,9]; thus, their restoration involves drawing on indigenous knowledge and principles to develop systems appropriate to today's social and environmental context. Because of their social and ecological design, indigenous agricultural systems are able to retain their function and productivity following disturbance by withstanding damage and/or rapidly recovering[10]. As a result, recent research has begun to assess the conservation and restoration potential of indigenous agricultural systems as tools to improve community and landscape resilience in the face of climate change[11].

To assess the potential for restoration of indigenous agricultural systems, an understanding of the extent and productive capacity of these systems today and into the future is needed. We use a case study of Hawai'i to develop spatial distribution models of three main pre-colonial agroecosystems and address the following questions: (1) Where did indigenous agricultural systems occur in Hawai'i? (2) What was the productive and carrying capacity of these systems? (3) What is their future potential in the context of land-use and climate change? We discuss how our models align with ethnohistoric and archaeological evidence, as well as how this analysis can contribute to the future of Hawai'i's food production, agricultural policies and environmental conservation.

Hawai'i, as one of the most isolated group of islands in the world, provides a critical site to address these questions. It is an archipelago where competing issues of development, food production and biodiversity conservation, and the added pressure of climate change, are especially pressing. Hawai'i has exceptionally high rates of food importation (87%)[12], while 41% of its agricultural lands are unfarmed[13]. There is enormous economic and political pressure to convert state-zoned agricultural areas to urban use[14]. Much of Hawai'i's unused agricultural land is dominated by invasive species, which pose a significant threat to the archipelago's unique flora, 90% of which are endemic[15]. The majority of Hawai'i's agricultural products (that is, seed corn, coffee, macadamia nuts) are exported, failing to contribute to the state's food self-sufficiency targets[14,16]. Hawai'i is also home to a movement of indigenous resurgence, where community-based revitalization projects centred on traditional Kānaka Maoli (Indigenous Hawaiian) food production systems have been expanding over the past several decades[17,18].

Indigenous Hawaiian agriculture can be classified into three broad systems, intensive lo'i and dryland agriculture and extensive rainfed systems, with colluvial agriculture representing one of the most widespread and common extensive rainfed systems (see Supplementary Notes and Supplementary Table 1). Lo'i (irrigated pondfield agriculture) was an intensive irrigated cropping system based on taro (*Colocasia esculenta*; in Hawaiian kalo), the dominant cultigen in traditional Hawai'i, and supplemented by other crops[19]. Intensive rainfed dryland systems were based on sweet potato (*Ipomoea batatas*; 'uala), with secondary crops including dryland taro, yam (*Dioscorea* spp.; 'uhi) and sugarcane (*Saccharum officinarum*; kō), and other crops[19] (see Supplementary Notes). Colluvial agriculture, previously termed 'colluvial slope agriculture'[20], was a rainfed, extensive cropping system that occurred in the fertile lower-elevation slopes of deep valleys and often tended towards an agroforestry system, including a vast mix of annual

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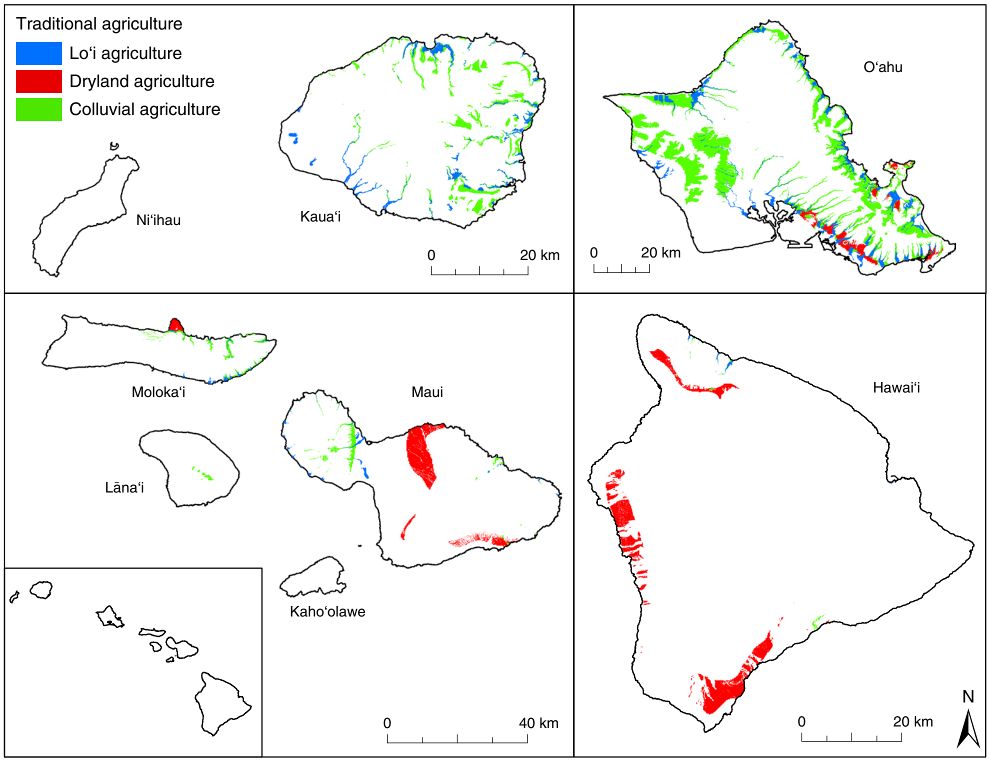

Fig. 1 | Modelled spatial distribution of pre-colonial indigenous agriculture systems across the Hawaiian Islands. Pre-colonial (before 1777) spatial extent of lo'i, colluvial agriculture and dryland agriculture on seven Hawaiian Islands, Hawai'i, Maui, Kaho'olawe, Lāna'i, Moloka'i, O'ahu and Kaua'i, based on spatial modelling.

and perennial root, tuber, shrub and tree crops that were used for food, medicine, ritual, clothing, tools and building[20]. Beyond their main crops, these indigenous agroecosystems involved cultivation and maintenance of native plant species and forest patches[19,21], an approach employed in the restoration of some of these systems today[22]. Though there were other important extensive traditional agricultural systems in Hawai'i that included a broad range of agro-ecological techniques and were often regionally specific[17,19,23], we did not include those in our archipelago-wide analysis. Previous research[20,23,24] has provided important advances on the past spatial distribution of some traditional Hawaiian agricultural systems, yet colluvial agriculture has yet to be modelled across the islands. Despite recognition that climate change is likely to negatively affect agriculture across the archipelago[25], there have been very few studies on[26], and almost no policy attention to, the projected impacts of climate change on agriculture in Hawai'i. We provide the first analysis of the food production potential for indigenous agriculture under land-use and climate change.

To understand where traditional agricultural lands existed in the past and where these systems are possible now and into the future, we created geospatial models using a variety of current environmental and climatic data to identify and illustrate the distribution of lo'i, dryland and colluvial agriculture systems on seven of the eight major islands across the Hawaiian archipelago (Hawai'i, Maui, Kaho'olawe, Lāna'i, Moloka'i, O'ahu and Kaua'i). In terms of past distribution, we focus on the time period immediately before Captain Cook's arrival in 1777. The model projections were compared with multiple archaeological and ethnohistoric datasets[19,27–32]. We estimated the food production potential at this time period using the modelled indigenous agricultural areas to calculate the annual wet weight production (mt yr^{-1}) of the three systems. We assessed the current production potential of indigenous Hawaiian agricultural land, by identifying constraints of current urban development by overlaying the modelled distribution of agricultural systems with existing developed areas (http://gapanalysis.usgs.gov/, based on 2001 imagery). To understand the potential distribution of these systems given past land-cover change and future potential climate shifts, we intersected currently undeveloped potential indigenous agricultural areas identified by the models with the state's land-use zoning data (http://planning.Hawaii.gov/gis/), as well as modelled all three cropping systems under three end-of-century climate scenarios (A1B, representative concentration pathway (RCP) 4.5 and RCP8.5) that represent a wide, but not exhaustive, set of plausible futures for Hawai'i.

Results

Location and distribution of indigenous agricultural lands. Our modelled potential distribution of the three agricultural systems under current climate is assumed to represent the potential pre-colonial spatial extent of these systems at the time immediately before Cook's arrival in 1777. The model of the spatial extent of lo'i, dryland and colluvial agriculture identified a total 100,789 hectares (ha) across the islands that could support indigenous agriculture (Fig. 1). Of the total acreage of potential indigenous agricultural lands, about 12.7% (12,824 ha) is lo'i agriculture, 52.7% (53,058 ha) dryland agriculture and 34.6% (34,907 ha) colluvial agriculture (Fig. 2).

Spatial accuracy of indigenous agriculture distribution models. Our results are highly consistent with the ethnographic and archaeological evidence that exists about indigenous Hawaiian agricultural systems[19,27–32]. A systematic evaluation of model accuracy based on ethnohistoric data[19] yielded an 80% match of selected lo'i, dryland and colluvial agriculture suitable modelled areas with ethnohistorically documented systems (Supplementary Methods). Our model identifies the major known indigenous agroecosystems in Hawai'i, such as Hanalei, Kaua'i; four Maui valleys termed 'Nā Wai 'Ehā',

Table 1 | Estimated theoretical carrying capacity by agricultural system

Agricultural system	Production (mt)	Energy yielded (kcal mt^{-1})	Estimated carrying capacity (people yr^{-1})	Percent of the carrying capacity
Lo'i	256,480	1,450 (ref. [80])	3 39,631	27.8
Dryland	477,522	1,280 (ref. [83])	558,199	45.7
Colluvial agriculture	287,982	1,230 (ref. [84])	323,488	26.5
Total	1,021,985		1,221,138	

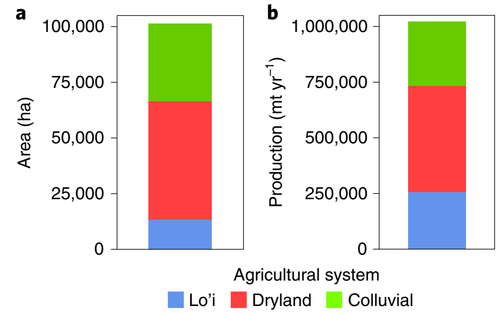

Fig. 2 | Estimated area and production of pre-colonial indigenous agriculture systems in Hawai'i. a,b, Estimated area (ha; **a**) and estimated production (mt yr^{-1}; **b**) of Hawai'i's three pre-colonial indigenous agricultural systems.

known for their traditional lo'i systems and litigation over water rights; and the three main dryland field systems of Hawai'i Island, Kohala, Kona and Ka'ū, two of which have been studied extensively in the archaeological literature[33,34]. There is little information available for colluvial agricultural systems in the archaeological record as it was an extensive system that did not necessarily require permanent improvements and has not been explored as intensively as the other systems; however, our model results are consistent with available archaeological and ethnohistoric information (for example, Supplementary Figs. 1 and 2).

The main discrepancy between our results and the archaeological and ethnohistoric record is that our model did not identify the full extent of the past traditional dryland systems in leeward Maui and Waimea on Hawai'i Island. One explanation could be that current rainfall does not reflect the historical precipitation in the leeward Maui and leeward Kohala areas[35]. Although rainfall has decreased across the entire Hawaiian archipelago over the past century, the precipitation declines are most apparent in climate data for the leeward Maui and Kohala regions. These areas have long cattle-ranching histories, where forests and dryland field systems were converted into large pasture lands early in the 1800s, and where ranching persists today. Given that Hawai'i's native forests may have large cloud water interception[36], deforestation may have led to less water capture over time. The coupled climate and environmental changes likely altered the moisture regime to such a degree that the area's indigenous agroecosystems cannot exist there under current conditions. Another contributing factor could be the mismatch between the older precipitation data used to develop the rainfall elevation index (REI) soil fertility parameter in previous studies[20,24], and the updated precipitation data used throughout the model.

Potential productive capacity of indigenous agricultural lands. Our results suggest that indigenous agricultural systems in Hawai'i could have produced a total of >1.02 million metric tons (mt) of food per year, with lo'i contributing about 25%, dryland providing 47% and colluvial agriculture supplying 28% of the total production (Fig. 2 and Supplementary Table 3). Based on our estimates, this annual production could have yielded about 1.34 billion kilocalories annually, which could support a theoretical maximum population of over 1.2 million people per year, with dryland systems supporting the majority of the population, 46%, lo'i providing for 28% and colluvial systems 26% of the total carrying capacity (Table 1). This estimate does not take into account incidental uses of the food produced such as food spoilage, variability in production due to season, extreme weather events, food for ho'okupu (tribute or tax), food that is used to feed animals and other socio-cultural issues. However, these losses are likely at least compensated for in our calculations as our estimate also does not consider protein and fat calories from fishing, intensive aquaculture (fishponds) and livestock (pig, chicken), which accounted for about 22% of the traditional Hawaiian diet[37], nor food production from home gardens and other extensive systems, which also contributed substantially to the traditional Hawaiian diet[38]. Furthermore, the already large contributions from dryland agriculture production may be underestimated, as recent experiments from a restored pre-colonial dryland system documented yields of up to four times the values utilized in the model[39]. While there are multiple reasons why actual pre-colonial population numbers could be lower than this carrying capacity, it nevertheless provides an estimate of a theoretical maximum.

Constraints of urban development and climate change on indigenous agriculture. Land conversion to urban development has reduced the potential spatial extent of indigenous agricultural systems by 13%, including 8% of the dryland, 12% of colluvial and 24% of lo'i systems (Fig. 3). This reduction decreases potential food production by 13% to 887,552 mt yr^{-1}.

In terms of the potential indigenous agricultural areas that have not yet been developed, the majority (71%) are currently in the 'agriculture' zone across all lo'i, dryland and colluvial agriculture areas (Fig. 3). Over 90% of all the non-developed potential dryland agricultural area, 63% of the lo'i area and 43% of the colluvial agricultural area falls within the agricultural zone. The calculated production of the potential indigenous agricultural lands that are currently zoned 'agriculture' is 629,012 mt yr^{-1}, or 71% of the total productive capacity calculated for all the potential non-developed indigenous agricultural lands. About 20% of the potential indigenous agricultural lands fall into the 'conservation' designation, while about 8% is zoned for future urban development and <1% is designated as 'rural'.

Our models show that the three different future climate projections (under end-of-century A1B, RCP4.5 and RCP8.5 scenarios) have varying effects on the three indigenous agricultural systems (Fig. 3). The A1B-based projections showed very slight acreage changes from the current modelled agricultural distribution, with small increases in lo'i areas and small decreases in dryland agriculture and colluvial agriculture area. The modelled agriculture distribution based on RCP4.5 and RCP8.5 climate scenarios both showed slight increases in the amount of lo'i areas; however, these small increases are unlikely given the consequent decreases in stream flow due to projected substantial drying across the state. The areas that could support dryland and colluvial agricultural systems decrease under the RCP4.5- and RCP8.5-based modelled agriculture distribution. The RCP4.5-based modelled agriculture distribution indicated 18% less dryland areas than current modelled agriculture distribution and 29% less colluvial agricultural areas. The RCP8.5-based modelled agriculture distribution predicts an 18% decrease in dryland areas and a 40% reduction in areas that could support

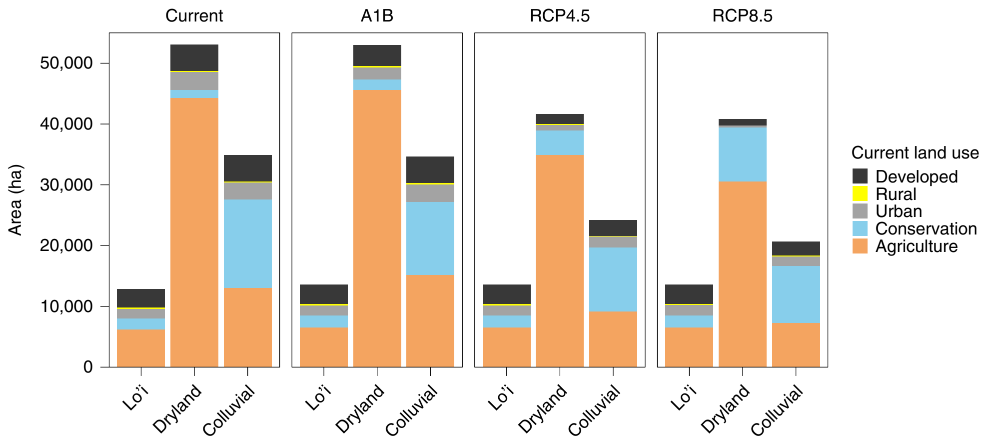

Fig. 3 | Area and land use of potential indigenous Hawaiian agricultural areas under climate scenarios. Area (ha) and current land use of potential indigenous Hawaiian agricultural areas predicted under current and three climate change scenarios: A1B, RCP4.5 and RCP8.5.

colluvial agriculture. The proportion of potential indigenous agricultural areas in each of the land-use designations under the three future climate projections remains fairly similar to the current proportions for the conservation, agriculture and urban zones, with the exception that the drier projections (RCP4.5 and RCP8.5) show slight increases in the proportion of area zoned 'conservation', especially for areas suitable for colluvial agriculture.

The future modelled distributions indicated a 0.18% increase, 16% decrease and 19% decrease in food production from the current modelled agriculture distribution under the A1B, RCP4.5 and RCP8.5 projections, respectively. There was moderate spatial agreement (44% overall) between the three climate change projections and the areas currently shown to have potential for indigenous agriculture (Fig. 4), especially for the lo'i model. About 90% of current lo'i areas, 20% of current dryland areas and 57% of current areas for colluvial agriculture have potential for cultivation under the current and three future climate projections, indicating indigenous agricultural areas that could be especially resilient to a range of climate changes. These areas are concentrated mainly on the windward sides of all the islands, with only a few leeward zones identified.

Discussion

Our research provides a new understanding of the food production contribution of indigenous Hawaiian agriculture now and into the future, highlighting the relevance of restoring indigenous agricultural systems today.

Historical spatial extent and production of indigenous agricultural systems. Although past research focused on determining the historical production of Hawaiian intensive agricultural systems (lo'i and dryland agriculture)[24], our results highlight the important role that that extensive cropping systems (colluvial agriculture), played in the past and can play in the future. Our models identified 100,789 ha with potential for pre-colonial agriculture, over 7,000 ha more than previously identified[24], with colluvial agriculture accounting for over one-third of the total acreage and potentially supporting over one-fourth of the pre-colonial population. Colluvial agriculture was widespread across Hawai'i and could have covered about 22,000 ha more than lo'i systems. Our spatial estimate of intensive indigenous agriculture is about 29% less than past estimates (92,726 ha)[24], likely because we used (1) updated rainfall and temperature layers in our models, which restricted the suitable areas, and (2) a narrower distance from perennial streams in our lo'i model (350 m buffer instead of 500 m) to better capture the cultivated area around streams. Furthermore, the discrepancy between the dryland model and known extent of dryland archaeological features, potentially due to today's drier climates, suggests our values may be underestimating the traditional indigenous agriculture extent.

Our results suggest that the amount of food that could have been produced traditionally is comparable to the amount of food that Hawai'i consumes today, albeit different types. Our models indicate that historically, Kānaka Maoli could have produced a maximum of about 1.02 million mt of food annually, using 100,789 cultivatable hectares, which does not include protein from animals both on land and sea. In contrast, the current agricultural system in Hawai'i encompasses about 369,583 ha of active agricultural lands (both cropland and pasture), yet only 151,700 mt of local food is produced annually, just 13% of all food consumed[40]. This illustrates the efficiency of indigenous agricultural systems, in line with other analyses indicating higher production per unit area on traditional farms compared with conventional agriculture[41]. Along with changes in agriculture, Hawai'i's population demographics and its food preferences have also changed drastically. Nonetheless, given the flexibility of indigenous agroecosystems, ecologically and socially relevant non-traditional crops have been, and could continue to be integrated into these systems to address consumer demand and economic considerations. This is especially true for the colluvial agriculture system. That is, the utilization of former indigenous agricultural lands could provide an approach to produce more local food crops that are culturally appropriate for consumers today. Finally, our analysis compares traditional production potential with modern consumption demands, not modern production potential. In terms of modern production potential, the high cost of labour in Hawai'i is a reason current local food production is so low and therefore is a consideration that needs to be addressed in efforts to increase production. In this sense, colluvial agricultural systems could offer another advantage in that they are typically less labour intensive than conventional agriculture.

Potential traditional carrying capacity. There has been longstanding debate on the population of Kānaka Maoli at the time of Western contact, with numbers ranging from 242,000 to 800,000 (refs. [42–44]). By using a spatial distribution model approach, our study provides a new source of information that can provide insight on the debate. While our intention is not to estimate actual pre-colonial population numbers, our analysis corroborates previous estimates[43] that Hawai'i's environment could have supported 800,000 Kānaka Maoli at the time of Western contact and that the depopulation of

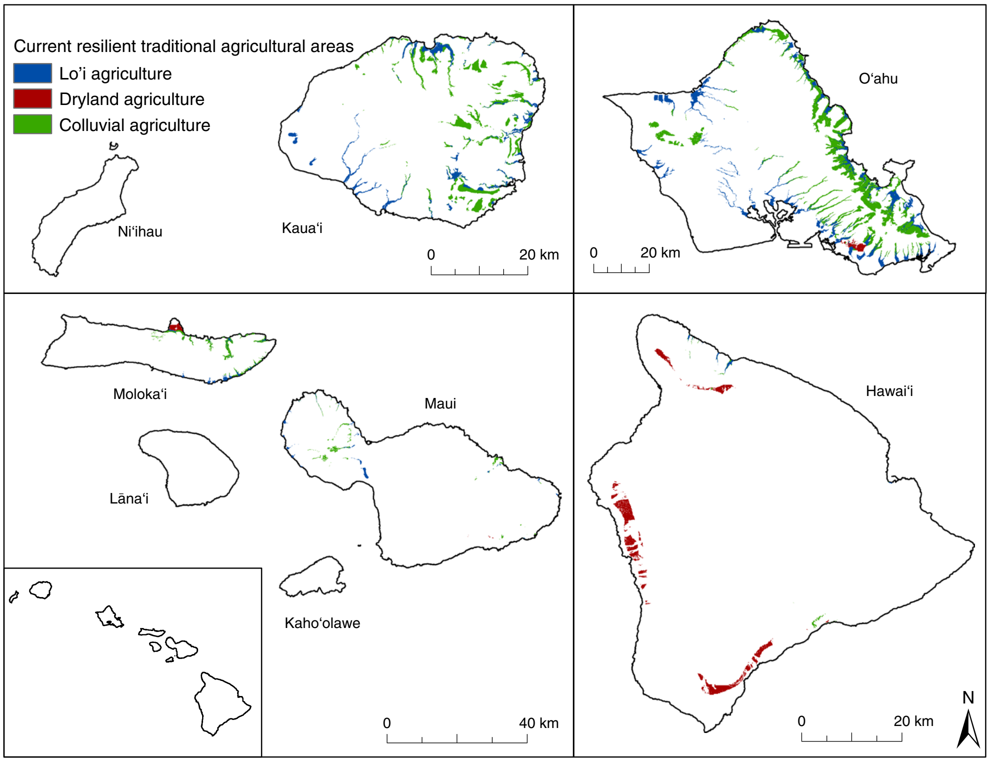

Fig. 4 | Resilient indigenous agriculture areas across the Hawaiian islands. Areas suitable for indigenous Hawaiian agriculture under current climate conditions and under all three future climate scenarios, A1B, RCP4.5 and RCP8.5, representing areas that are especially resilient to a range of future climate changes.

indigenous Hawaiians after the introduction of Western diseases was likely on the order of 90%, similar to the decimation experienced by other indigenous communities (ref. [43], p. 46–48). These results point to the sophistication of the indigenous Hawaiian agricultural system; with food production systems on 6% of Hawai'i's land area, our data support the idea that Kānaka Maoli could have supported a potential population equalling 86% of Hawai'i's populace today[45].

Potential for indigenous agricultural systems today and into the future. Clearly, indigenous agroecosystems in Hawai'i had the capacity to produce large amounts of food, but what is their potential today given that the archipelago is vastly urbanized? Our results showed that only 13% of potential indigenous agricultural areas can no longer be farmed because they are currently covered by roads or other permanent structures. Although the majority of the remaining non-developed potential indigenous agricultural lands are currently zoned as 'agriculture', many of these areas are still threatened by land conversion and development. In Hawai'i, agricultural lands have been rezoned for decades, with agriculturally zoned land reduced by over 11,700 ha statewide since 1969[46]. Because of rising land values and gentrification around urban centres[14,47], this pattern of loss will likely continue.

The state of Hawai'i, like many municipalities and states across the globe, aims to increase its food self-sufficency, with a target of 30% of its food produced locally by 2020[16]. Given that increasing temperatures and changes in precipitation are already occurring locally[25] and globally[4] and are expected to continue, plans to meet food self-sufficiency goals must consider how climate change will affect agricultural viability. Our study provides the first attempt to identify spatial shifts of agricultural systems under climate change in the Pacific, determining resilient areas for protection and restoration. It should be noted that economically feasible areas would be a subset of these climatologically suitable lands.

Our model results showed agricultural systems remaining relatively stable under the A1B-based modelled agriculture distribution, and decreasing in acreage and production under the RCP4.5- and RCP8.5-based distributions, illustrating the importance of using multiple downscaled climate scenarios in future spatial distribution modelling. The three future climate projections indicated 65–75% of the non-developed predicted indigenous Hawaiian agroecosystems are in the agriculture zone, meaning that even under changing climate conditions, most of these areas could be restored without land-use restrictions. The drier climate projections (RCP4.5 and RCP8.5) indicated losses in acreages of colluvial and dryland agricultural lands, and increases in the proportion of these areas in the conservation zone, pointing to the need to consider the integration of Hawaiian agroecosystems in conservation areas under warming conditions. Indigenous agroecosystems incorporate native species and could adapt to drier climates by utilizing drought-tolerant native species. Integrating indigenous agricultural systems into conservation areas of lower concern, especially those at risk to invasive species spread, could help restore native biodiversity, produce food in a changing climate, and mitigate some of the shifts of colluvial systems due to a drying climate.

One factor not considered in our projections of future traditional agriculture potential is possible CO_2-fertilization effects. However, besides the general lack of data to test these effects in traditional systems, CO_2-enrichment effects in natural settings have in many cases not been as large as earlier lab-based results, based on free-air concentration experiments. Additionally, CO_2 fertilization has led to unexpected effects in biodiverse settings (such as traditional agroecosystems) where enrichment effects are modulated by plant community interactions[48].

There was a large overlap among modelled distributions under current and future climate scenarios considered, suggesting lo'i and colluvial agroforesty systems could be resilient to a wide range of future climate shifts. With interest in indigenous agriculture

Table 2 | Temperature and precipitation changes predicted by three climate change scenarios for Hawai'i

Climate change scenario	Mean annual temperature change (°C)	Mean annual precipitation change (mm yr^{-1})	Defining characteristics
A1B	+2.4	+239	Predicts particularly wet windward areas
RCP4.5	+1.7	−213	Predicts >30 % decrease in mean annual precipitation in some leeward areas
RCP8.5	+3.3	−323	Predicts >30 % decrease in mean annual precipitation in some leeward areas

restoration growing across Hawai'i, these models can significantly aid in site selection and planning in these priority areas for restoration. Given the many possible trajectories of change in climate between now and 2100, after early and mid-century climate projections are developed for Hawai'i, secular trajectories of change in agricultural suitability would be especially useful for land-use planning. While our work describes the potential for the main modes of traditional Hawaiian agriculture under current and future climate scenarios at a course landscape level, we recognize there are other factors that may influence the degree of local suitability of areas to any of these cropping systems. Traditional agricultural potential may vary according to seasonal and shorter-term climatic variability[49] and future analysis of traditional systems' response to seasonal variability and extreme events would further refine the resilience of these cropping systems. Hybrid systems that include modern agricultural practices (such as fertilizer inputs) may improve the potential outcomes of such traditional cropping systems. Future field-based studies should explore these novel options that may improve yields and allow for the inclusion of newer crops that meet current demand.

With analyses of global climate change impacts pointing to widespread negative effects on agricultural production and food security[4], there is a need to understand local-level outcomes. Increased shipping and food costs under a changing climate around the world will heighten the necessity of resilient, locally produced food and community-based solutions everywhere, especially in isolated regions such as the Pacific. A growing middle class (expected to be two-thirds of the world's population by 2030[50], with a heightened interest in natural food products, will increase trends in consumer demand for food produced in environmentally conscious and culturally grounded ways. Our research suggests that there is an opportunity to look to the restoration of indigenous agricultural systems as one tool to increase local food production, and given that these systems support high levels of biodiversity[7,9,51], they could play a role in the conservation of increasingly threatened native species. In addition, for indigenous communities around the world, the restoration of indigenous food systems goes far beyond food security, providing opportunities for strengthening identity, social ties, knowledge transmission and well-being, inseparable from indigenous food[52]. All of these can strengthen social resilience to climate change[5]. In an era of vast land-use and climate changes affecting both the ecological and social foundations of agriculture, our study demonstrates the potential contributions of indigenous agricultural systems for future food production.

Methods

Location and distribution of indigenous agricultural lands. Polynesian voyagers arrived to Hawai'i around 1000–1200 AD[53–55], with a suite of cultigens including root, tuber and tree crops. Kānaka Maoli subsequently developed vast agricultural systems that existed with high levels of biodiversity[56], and helped to sustain large populations, with pre-colonial population estimates ranging from 130,000 to 800,000 (refs. [42–44]). To determine where the three indigenous agricultural systems existed in the past and where they are possible now and into the future, we created geospatial models of lo'i, dryland and colluvial agricultural systems across the Hawaiian Islands. We modified procedures originally developed by Ladefoged et al.[24] to model lo'i and dryland agriculture and by Kurashima and Kirch[20] to model colluvial agriculture. Our methods and source data differ in various ways from the previous models as described below. One difference is we included seven of the eight Hawaiian Islands in our study, excluding only the island of Ni'ihau due to the lack of rainfall data for the island. Environmental and climatic raster and shapefile data were obtained from the Hawai'i Department of Planning GIS database (http://planning.Hawaii.gov/gis/), the US Geological Survey (USGS) (http://pubs.usgs.gov/of/2007/1089/ and https://viewer.nationalmap.gov/datasets/) the US Department of Agriculture's National Resource Conservation Service (NRCS) (http://soildatamart.nrcs.usda.gov/), and the Rainfall and Climate Atlases of Hawai'i[57,58]. Model parameters were based on information from the literature on climatic requirements and limitations for the main cultigens for each agricultural system. Models were built using the raster and rgdal packages in R statistical software[59], and projection accuracy was assessed by comparing projected current distributions against known ethnohistorical and archaeological datasets[19,27–32,38] (see Supplementary Methods and Supplementary Figs. 1–3).

Lo'i agriculture. Kānaka Maoli engineered lo'i in alluvial plains in valleys with sufficient stream resources at lower elevations because taro cannot withstand cold temperatures. They built complex irrigation ditches to extract (and return) water from permanent streams[19,60,61] and closely controlled water flow and circulation within the fields to control stagnation, temperature and prevent disease[62]. To identify areas suitable for lo'i systems, we used stream data from the Hawai'i Statewide GIS programme (http://www.state.hi.us/dbedt/gis/index.html), to select and buffer perennial streams by 350 m based on the notion that water can be spread 350 m from a permanent stream at quantities that would support lo'i agriculture. Lo'i are constructed in valley bottoms on alluvial soils, and, to some extent, on lower colluvial slopes[20]. We selected 'alluvium', which includes geologically recent alluvial deposits mainly from the Holocene and Pleistocene from the USGS digital geologic map (http://pubs.usgs.gov/of/2007/1089/), as well as colluvial soils, including the 'Kawaihapai' series[63], 'stony colluvial land' and 'stony colluvial land'[64] from the NRCS soil survey. If these soils are close enough to a water source, they would have suffcent nutrients to support intensive irrigated taro agriculture. Lo'i are often constantly flooded with water, so the areas they occupy must be flat, or only gently sloping. We used a National Elevation Dataset (NED) at 10 × 10 m resolution (https://viewer.nationalmap.gov/datasets/), to select areas with a slope from flat to 10° (refs. [65,66]).

Latitude ranges only 3° in the main Hawaiian Islands, and temperature differences across the landscape are mainly driven by elevation differences. In Hawai'i, there is a fairly constant relationship between increasing elevation and decreasing temperature, called a lapse rate[67]. The temperature dataset was derived using monthly minimum and maximum temperature[58]. We calculated the lapse rate by looking at the correlation between mean annual temperature and elevation (NED) spatial datasets from across the state. Up to about 2,000 m elevation, the lapse rate is fairly constant at about a decrease in 6.4 °C per 1,000 m (temperature (°C) = 23.67 − 0.006405 × elevation (m)). Using Hawai'i's average sea-level temperature ~23.7 °C, we used the lapse rate to find the elevational proxies for temperature. Irrigated taro requires average temperatures above 21 °C (ref. [68]), correlating to elevations from sea level to 415 m in Hawai'i. Using the 10-m-resolution elevation layer from the NED, we selected areas in this elevation range.

Dryland agriculture. Intensive dryland agricultural systems existed on the leeward sides of the geologically younger islands, where rock-derived nutrients have not yet been leached from the soil[34,69]. To define areas suitable for intensive dryland agriculture, we used layers based on slope, elevation, rainfall, substrate age and distance from coast. Dryland field systems were developed on gradually sloping young, and less eroded shield surfaces[29,69]. We used the USGS NED to constrain the slope in the dryland model to areas less than 12° (ref. [20]).

We followed Ladefoged et al.[24], using a combination of variables to determine areas with suitable soil fertility for dryland cultivation. We set an upper limit for elevation. Intensive dryland systems are primarily based on sweet potato, and secondary crops (see Supplementary Notes and Supplementary Table 1) that can withstand cooler temperatures than wetland taro. Intensive sweet potato cultivation can occur in temperatures 18 °C or higher[70], which correlates to 885 m above sea level using the lapse rate. We selected all areas up to 885 m using the NED. Second, we considered rainfall limits, which traditionally constrained dryland agriculture cultivation. Intensive production of sweet potato requires at least 750 mm of precipitation annually[71], but rainfall above 1,600 mm yr^{-1} can cause large declines in nutrient levels for its growth[72]. We included areas that receive an average of 750 mm yr^{-1} to 1,600 mm yr^{-1} rainfall using monthly precipitation data[57]. Third, we considered substrate age. Most primary minerals and rock-derived nutrients are leached from the soil by around 20,000 yr, and most rock-derived phosphorous is leached by 4 Myr in Hawai'i[69,73]. Non-nutrient depleted, young volcanic substrates are fertile enough to adequately support an intensive dryland system[29]. Ladefoged et al.[24] determined that sites younger than 4,000 yr old do not have adequate soil development to support intensive dryland agriculture, while soils older than 700,000 yr were nutrient deficient. Using the USGS geologic map[74], we selected substrates between 4,000 and 700,000 yr old.

Interactions among elevation, rainfall and substrate age determine an area's soil fertility and field system development. Much attention has been paid to the understanding of soil nutrient thresholds in Hawaiian soils. There is a sharp drop in base saturation and pH in young substrates (~150,000 yr old) in Kohala, Hawai'i Island above 2,000 mm yr^{-1} of rainfall. This precipitation and nutrient limitation boundary correlates to the physical upper boundary of this intensive dryland field system, suggesting that Kānaka Maoli cultivated a 'sweet spot' of soils that combined benefits of rainfall and nutrients[34,69,75]. As substrate age increases, these soil nutrient level thresholds occur at lower rainfall[75,76]. To parameterize these interactions, we utilized the REI developed by Ladefoged et al.[24] in which the areas within the elevation, rainfall and substrate age limitations stated above, were further analysed (Supplementary Table 2). A REI was calculated for each 10 m × 10 m pixel, and if they were less than the threshold specific to the substrate's geologic age, they were included in the model. Based on field observations, the geologic age of two areas were adjusted, Kalaupapa was assigned 175,000–299,999 not 500,000 yr old, and Pololū was determined to be 350,000 yr old not 475,000 (T. N. Ladefoged, personal communication). The REI was originally developed using previous rainfall data[77]; here we use the updated rainfall layers used throughout our models.

Because saltwater spray can negatively affect sweet potato production and growth[78], we buffered and extracted the 'coast' shapefile (http://planning.Hawaii.gov/gis/) from the modelled area suitable for dryland cultivation.

Colluvial agriculture. Mixed cropping colluvial agriculture systems occured in the lower colluvial slopes on geologically older islands. The soil fertility and gradual slope toporgraphy of these areas allowed for colluvial cultivation. To identify areas suitable for colluvial agriculture, we included soil, slope, rainfall and temperature (elevation) constraints.

Colluvial agricultural systems were developed on nutrient-rich alluvial and colluvial soils. We used the same methods for selecting the soils for the lo'i model, but also included the areas identified as 'older alluvium'[74], which includes alluvial and colluvial soils deposited in earlier in the Pleistocene and Pliocene. Colluvial agriculture could occur in slopes up to 30°. Archaeological features consistent with colluvial cultivation found in Hālawa, Moloka'i correspond with these assumptions[20]. We used the USGS NED to select areas between 0 and 30° slope across Hawai'i. Using the USGS NED, we defined the elevation boundaries for colluvial cultivation, between sea level and 885 m, because higher elevations can affect crop growth and production[70].

Colluvial agricultural systems need at least 750 mm of rainfall annually for production. There is no upper threshold of rainfall for this system, as some of these crops, specifically banana (*Musa sp.* hybrids), kava (*Piper methysticum*), ti (*Cordyline fruticosa*) and olonā (*Touchardia latifolia*), can grow and even thrive under very high levels of rainfall. Using rainfall data[57], we included areas that had an average annual rainfall above 750 mm. After the colluvial agricultural areas were defined by intersecting the above layers, we excluded all areas that could support lo'i agriculture, under the assumption that Kānaka Maoli would favour lo'i production where available.

Productive potential and carrying capacity of indigenous agricultural lands. To estimate the food production potential in the past, we used the modelled indigenous agricultural areas to calculate the annual wet weight production (mt yr^{-1}) of the three systems. We utilized per hectare production estimates and fallow information of lo'i, dryland and colluvial systems from anthropological studies within Hawai'i and the Pacific[71,79–82] (Supplementary Table 3), representative of pre-colonial Hawaiian agroecosystems. Lo'i systems produce about 25 mt ha^{-1} annually in wet weight[81,82], and we assume that 20% of the total lo'i area was in fallow[79]. We estimate dryland systems yielded about 10 mt ha^{-1} (refs. [71,79,80]). Based on previous studies[20,71], we assume that 10% of the area was fallow although emerging studies incorporating seasonality of these systems have found that fallow rates may have been higher[49]. We estimate that colluvial agricultural systems produced around 11 mt ha^{-1} annually, based on production estimates from colluvial agriculture zones in Nuku, Futuna Island (ref. [79], p. 179–183, Table 11), while about 25% of the system was fallow[20].

To provide evidence for various pre-colonial population estimates, we approximated the population that could have been supported by food produced by the three agricultural systems by calculating the caloric production of each system, assuming a conservative 3,000 cal day^{-1} diet (Table 1). For lo'i, taro has a relatively high caloric content of 145 cal per 100 g (ref. [80]). We assume sweet potato has about 128 cal per 100 g (ref. [83]) for the dryland system, and for the colluvial system, we use a caloric content estimate from a mixed system (breadfruit, taro, giant taro, yams and banana) of 123 cal per 100 g (ref. [84]).

Future potential of indigenous agricultural lands. To assess the current and future production potential of indigenous Hawaiian agricultural land, we first identified constraints of current urban development by overlaying the modelled distribution of agricultural systems with existing developed areas. We selected the 'high-intensity developed' and 'low-intensity developed' land-cover class from the USGS National Gap Analysis Program (http://gapanalysis.usgs.gov/), which determines land cover through a remote-sensing analysis of Landsat satellite imagery from 1999 to 2004. In R, we overlaid the developed layer on the modelled distributions, calculating the overlapping areas, which represent formerly suitable agricultural lands that will not revert back to productive agricultural lands in the foreseeable future. To understand the current potential of undeveloped land in terms of zoning, we intersected all undeveloped areas identified as potential agricultural areas with the state's land-use zoning data (http://planning.Hawaii.gov/gis/).

To assess how climate change is expected to affect the spatial extent of indigenous Hawaiian agricultural lands, we modelled all three cropping systems under different end-of-century climate scenarios. We used three regionally downscaled mean annual rainfall and temperature projections recently developed for Hawai'i: two statistically downscaled projections for two RCP scenarios (RCP4.5 and RCP8.5)[4], and a dynamically downscaled projection for the *Special Report on Emission Scenarios* (SRES) A1B scenario[85]. These climate projections are not to be considered as forecasts of future climate, but instead as a small subset of scenarios that describe a range of plausible futures possible by the end of the century. Our approach to consider uncertainty of our future projections was to include the widest set of projections available for the region. We used all available regional projections designed and validated locally to ensure projections are reflecting plausible scenarios at the island scale. The testing and validation of regional climate projections were included in work describing those projections that show that the underlying models have adequate skill in reproducing current regional climate at a mean annual scale. There were other generic downscaling datasets commonly used elsewhere (for example, WorldClim) that have not been properly validated at local scales, and thus not considered in our analyses. Unfortunately not all regional climate projections (and variables) available had spatially explicit estimates of uncertainty, which made estimates of uncertainty resulting from individual climate projections challenging. Nevertheless, we did take several steps to ensure limitations and uncertainties of the underlying climate projections did not reduce the utility of our agricultural models. First, our projections are focused far into the future (end-of-century), helping us to get a clearer signal of projected change above natural seasonal and interannual variability. Second, we used long periods (20–30 yr) of current and modelled data to avoid having projections reflect this short-term variability. Lastly, our models are based on annual averages that are less likely influenced by models lack of skill in reproducing shorter-term climatic variability.

Downscaled A1B scenario projections. The A1B dynamic downscaled projections are based on an ensemble of 20 Coupled Model Intercomparison Project phase 3 (CMIP3) models, with end-of-century projections for 2080–2099. To determine future mean annual rainfall and mean annual temperature values for Hawai'i, we employed current climate data in combination with dynamically downscaled climate projections. We used projections from the Hawaiian Regional Climate Model (HRCM), which was dynamically downscaled from the Weather Research and Forecasting model (WRF) V3.3 based on the SRES A1B[86] (see Supplementary Methods). To obtain the projected change in rainfall and temperature between present (1990–2010) and end-of-century (2080–2100) conditions, we subtracted HRCM future projections for mean annual rainfall and temperature from HRCM current projections (that is, deltas). These delta values were then added to current actual annual rainfall and temperature values[57,58]. The new projections show general increases in temperature across the archipelago (an average of 2.4 °C increase), and also indicate that warming is slightly more pronounced in leeward areas and much greater at higher elevations. In terms of precipitation, the downscaled A1B projections show increased rainfall in wet areas (especially in windward East Maui and Hawai'i island), and no change/slight decreases in rainfall in dry areas. Across the state, the A1B predicts a mean increase from current rainfall of about 239 mm of rainfall annually (Table 2).

Downscaled RCP4.5 and RCP8.5 scenario projections. To determine end-of-century mean annual rainfall and temperature values for Hawai'i, we followed a similar process described above using statistical downscaled models for Hawai'i derived from the global CMIP5 model, based on RCP4.5 and RCP8.5 scenarios[87]. Since the original statistically downscaled projections did not include mean annual temperature, we also included the recently developed analogous temperature projections available at http://www.atmos.albany.edu/facstaff/timm/temp_maps_hi_cmip5_V1_1.zip. These statistical downscaled projections are based on an ensemble of 32 CMIP5 models, with end-of-century projections for 2070–2099 (see Supplementary Methods).

Despite a mismatch between these statistical and dynamic downscaled projections in underlying general circulation models and temporal span, we consider these projections as representative of the range of climates possible by end-of-century in Hawai'i (see comparisons of scenarios in Table 2). Furthermore, there is no consensus on the relative superiority of these statistical and dynamic downscaling projections and their underlying general circulation models for

Hawai'i, so including all available future climate projections was necessary to represent underlying uncertainties.

In the models under the climate scenarios, we used the same soil, slope, substrate age, coast and soil fertility analysis layers as these physical parameters are not expected to change considerably by 2100. Elevation limits were adjusted using future temperature layers. We then identified the constraints of current urban development and land-use zoning using the methods above.

Under all three climate change scenarios, the elevation range where lo'i and colluvial agriculture can occur increased substantially from the ranges determined by current climate, sea level to 415 m and 885 m, respectively (Supplementary Table 4). Through taro and sweet potato have upper temperature limits for growth, 27 °C (NRCS, 2003) and 33 °C (ref. [88]), respectively, none of the future climate scenarios indicate mean annual temperatures above these thresholds. Using elevation as a proxy, we bounded taro growth based on air surface temperature; yet we recognize that taro growth is also influenced by water temperatures within the lo'i, which is mainly controlled by stream temperature, lo'i structure, evaporation and water flow into the lo'i[62]. Stream temperature is influenced by a complex combination of many drivers, including water volume as surface flow or groundwater discharge from precipitation, geographic qualities such as topography and lithology, atmospheric conditions such as surface temperature, relative humidity or windspeed, and physical characteristics of a stream (riparian vegetation, channel width, substrate)[89]. Though changes in rainfall and temperature are likely to affect stream temperature and flow, and hence lo'i cultivation, how these climate variables will influence those stream characteristics in Hawai'i is not completely known. For instance, in drier areas, rainfall is a major driver of stream flow, and decreased rainfall in these areas could lead to decreases in the number perennial streams. In contrast, in wetter areas, stream flow is dominated by groundwater discharge and dependent on favourable geologic conditions[90], so predicting which non-perennial streams will become perennial is more complex. Our future lo'i model uses the same buffered perennial stream layer from the current model because information on the predicted effects of climate change on stream temperatures is not available to model these complex interactions.

Data availability

The data and R scripts that support the findings of this study, as well as the resulting data layers are available at the University of Hawai'i data repository: https://scholarspace.manoa.hawaii.edu/handle/10125/60445.

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Author contributions
N.K. conceptualized the study, N.K., T.T. and L.F. designed the study, N.K. performed all of the analyses and L.F. assisted in editing R code analyses. N.K. formulated results and discussion. N.K. prepared the draft manuscript, N.K., T.T. and L.K. reviewed and edited the manuscript.

Competing interests
The authors declare no competing interests.

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