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The role of indigenous practices in expanding waterbird habitat in the face of rising seas

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ABSTRACT

In Hawai'i, as is the case globally, sea level rise threatens the availability of suitable habitat for waterbirds and other coastal species. This study examines Hawaiian wetland agro-ecosystems (*lo'i*) as social-ecological systems that may meet human needs while expanding nesting habitat of endangered waterbirds, if restored under an Indigenous Resource Management paradigm. We applied spatial analysis to project: (1) the area of existing waterbird habitat likely lost to sea level rise by the end of the century (2100); and (2) the area of waterbird habitat potentially gained through restoration of *lo'i* systems. Results show that, if *lo'i* offer similar or equivalent habitat value to Hawaiian waterbirds as conventionally managed wetlands, the restoration of *lo'i* would not only compensate for projected losses of wetland habitat due to sea level rise, but substantially contribute toward the recovery of endangered waterbirds that are currently habitat-limited. This study demonstrates capacity for contemporary Indigenous land management to address conservation and food-security needs in the Hawaiian Islands, as well as challenges of multi-objective land use and habitat restoration for endangered wetland-dependent fauna. This research further contributes toward a growing number of studies suggesting that Indigenous practices based on social-ecological frameworks offer potential to achieve sustainability and biodiversity goals simultaneously.

1. Introduction

Conventional conservation practices often separate people from landscapes by limiting their presence in protected areas because they assume that minimal human interaction is optimal for recovery of endangered species (Berkes, 2009; Plumwood, 2012). This exclusionary process creates a fortress-conservation strategy that separates people from nature (Hummel et al., 2019). A lack of community and stakeholder involvement, however, is often considered a major reason for the failure of conservation projects (Rodríguez et al., 2007). While anthropogenic changes to landscapes can lead to undesired ecological regime shifts (Folke et al., 2004), human-modified landscapes can provide habitat for some species (Price et al., 2011). Borrowing from the holistic views of Indigenous systems, Berkes and Folke (1998) suggested that society and nature are inevitably interdependent and should be viewed as integrated social (human) and ecological (biophysical) subsystems. Thus, conservation practices based on social-ecological frameworks may lead to more successful outcomes than exclusionary conservation practices, as they encompass working landscapes and the people in them (Berkes, 2004). Recognition is growing that Indigenous systems applications are essential for meeting global conservation targets (Donald et al., 2019;

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Townsend et al., 2020), as the social-ecological framework of these systems increases resilience following disturbance (Altieri and Nicholls, 2017).

This approach is particularly critical in regions that have both a large number of threatened species and growing human populations with an increasing need for sustainable food production. The Hawaiian archipelago hosts a higher percentage of threatened and endangered species than many other regions of the world (Czech et al., 2000). Many of these species are endemic, found nowhere else in the world (DeMartini and Friedlander, 2004), and they face a complex suite of threats, necessitating large-scale, holistic and multi-objective management solutions (Price and Toonen, 2017). Anthropogenic threats, such as climate change and invasive species (Vorsino et al., 2014), are likely to cause substantial losses of native species, along with associated ecosystem services and their intrinsic value to humans (Sato et al., 2018). Among the most vulnerable species are Hawaiian endemic avifauna. Approximately 55 % of birds that colonized the Hawaiian Islands were waterbirds. Six native waterbirds remain on the main Hawaiian Islands today. They are the ʻ*auku*ʻ*u* (Black-crowned Night-Heron, *Nycticorax nycticorax hoactli*), *koloa* (Hawaiian Duck, *Anas wyvilliana*), ʻ*alae ke*ʻ*oke*ʻ*o* (Hawaiian Coot, *Fulica alai*), ʻ*alae* ʻ*ula* (Hawaiian Gallinule, *Gallinula galeata sandvicensis*), ʻ*ae*ʻ*o* (Hawaiian Stilt, *Himantopus mexicanus knudseni*), and *nēnē* (Hawaiian Goose, *Branta sandvicensis*), hereafter referred to by their Hawaiian names. Five of the remaining six native waterbirds are threatened with extinction (Table 1).

A return to Indigenous agro-ecology, a sustainable approach to meeting human needs within the context of existing ecosystem function (Winter et al., 2020a), may simultaneously achieve conservation and sustainability goals (Ahmed et al., 2013). Indigenous agro-ecosystems are usually diverse at the farm and landscape levels, and often protect surrounding natural areas such as forests (Dawson et al., 2013). Further, they can host similar species richness to adjacent forest reserves (Bhagwat et al., 2008). Some agro-ecosystems, such as those embedded within Indigenous Resource Management (IRM) systems, create shifting landscape mosaics that increase food production while maintaining high levels of biodiversity (Berkes, 2018). This process is critical, as Hawaiʻi imports roughly 87 % of its food, while the majority of agricultural products grown locally (i.e. coffee and macadamia nuts) are exported, making Hawaiʻi vulnerable to natural disasters or global events that disrupt shipments of food supplies (Loke and Leung, 2013). Increasing food self-sufficiency in Hawaiʻi would not only increase food security, but would also diversify and boost the local economy, reduce the carbon footprint associated with shipping, promote healthier lifestyles, and decrease the risk of introducing harmful pests (Loke and Leung, 2013).

Indigenous agro-ecology can also provide habitat for endangered species. For example, Ticktin et al. (2018) found that fifty-eight percent of Indigenous coastal agro-forests in Fiji provide habitat for at least one species threatened with extinction. Like many other islands in the Pacific, the Hawaiian Islands have a long history of resilience through application of social-ecological principles to manage agro-ecosystems (Winter et al., 2018a). Where currently used, those practices provide ecosystem services while preserving ancestral connections (Kikiloi et al., 2017). Following the arrival of Polynesian voyagers to Hawaiʻi no later than 1200 AD (Kirch, 2011), Indigenous Hawaiians developed complex systems of relationships with their surroundings. They greatly expanded wetland habitats by converting lowland forests and alluvial plains into flooded-fields (*lo*ʻ*i*) for agro-ecology to cultivate taro (*Colocasia esulenta*), waterbirds, fish, and invertebrates (Winter et al., 2018b). This practice was enhanced across the greater tropical Pacific by late Holocene sea level fall (Kane et al., 2017). The most recent estimates of the extent of the expansion of wetlands for use in *lo*ʻ*i* cultivation suggested that ~12,824 ha of *lo*ʻ*i* likely existed before European arrival (Kurashima et al., 2019). Hawaiians managed *lo*ʻ*i* as a keystone component of Hawaiian social-ecological systems (Winter et al. 2018a), viewing the social and ecological components that make up an ecosystem as interconnected, supporting both humans and nature (Handy and Pukui, 1972).

In Hawaiʻi, Indigenous wetland agro-ecosystems are heterogeneous both temporally and spatially. A patchwork of fields in different phases of cultivation (Winter et al., 2018a), along with the inclusion of secondary crops along field borders (Kurashima and Kirch, 2011) and *ʻauwai* (irrigation ditches and canals), create habitat mosaics that support a diversity of wetland organisms (Winter et al., 2020a), including endangered native waterbirds (Greer, 2005) and their prey species (Gutscher-Chutz, 2011). This patchwork is similar to the irrigation of rice terraces, practiced by Indigenous Hani peoples of Yuanyang, China (Jiao et al., 2012), and to the Indigenous management of Japanese paddy fields, or *satoyama* (Katoh et al., 2009), which create heterogenous habitats for a wide range of organisms. Furthermore, contemporary Indigenous management of *lo*ʻ*i* often includes actions analogous to endangered species management in protected areas, such as control of invasive plants and predators (Greer, 2005). Given these practices, it is not surprising that the hatching success of ʻ*ae*ʻ*o* and ʻ*alae* ʻ*ula* reported in *lo*ʻ*i* (Greer, 2005; Gee, 2007) is consistent with that reported in protected areas (van Rees et al., 2018; Harmon et al., 2020a; Price, 2020). This field research is consistent with paleological, archaeological, and historical evidence suggesting that Hawaiian waterbird populations were at their apex under IRM systems in the pre-colonial period, when *lo*ʻ*i* systems expanded natural wetlands and increased available habitat (Burney et al., 2001; Burney and Kikuchi, 2006; Winter et al., 2018a). Despite the expansion that occurred following human arrival, wetlands today have a lower extent than they did before human arrival (van Rees and Reed, 2014).

Over the last two centuries, a collapse in native waterbird populations was precipitated by a decline in Hawaiian social-ecological systems, the subsequent decline in wetlands, and an increase in waterfowl hunting with novel hunting tools and

Table 1
Conservation status of six native Hawaiian waterbirds categorized by the U.S. Fish and Wildlife Service (USFWS) and the International Union for Conservation of Nature (IUCN).

Species	USFWS Status	IUCN Red List Status
ʻaukuʻu - Black-crowned Night-Heron (*Nycticorax nycticorax hoactli*)	Not Listed	Least Concern*
koloa - Hawaiian Duck (*Anas wyvilliana*)	Endangered	Endangered
ʻalae keʻokeʻo - Hawaiian Coot (*Fulica alai*)	Endangered	Vulnerable
ʻalae ʻula - Hawaiian Gallinule (*Gallinula galeata sandvicensis*)	Endangered	Least Concern*
ʻaeʻo - Hawaiian Stilt (*Himantopus mexicanus knudseni*)	Endangered	Least Concern*
nēnē - Hawaiian Goose (*Branta sandvicensis*)	Threatened	Vulnerable

* Subspecies are not given IUCN listings independent of their overall species populations.

practices (Kameʻeleihiwa, 1992). The introduction of new diseases beginning in the late 18th century drastically decreased the Native Hawaiian human population (Stannard, 1991). The result was a decline in the productivity, diversity, and size of human managed socio-ecological systems, including wetland systems. Further, the structure and function of Hawaiʻi's wetlands were altered by the influence of continental-based intensive mono-culture commercial agriculture, cattle ranching, and natural resource management practices introduced by European missionaries and settlers in the 19th century (Winter et al., 2018b). Alongside these changes, thousands of plant and animal species, such as mangroves, continental grasses, and predatory mammals, were intentionally and unintentionally introduced to the Hawaiian Islands, altering nutrient cycles, hydrology, ecosystem dynamics (Veitch and Clout, 2002), and the associated potential to support nesting waterbirds. Thus, restoration of Indigenous social-ecological systems may be critical to thriving human and waterbird populations.

Like many endangered species, Hawaiian waterbirds are conservation-reliant, meaning that they are at risk from threats so persistent that they require continuous management (Reed et al., 2012). In particular, invasive grasses render potential nesting habitat unsuitable without persistent human intervention (Veitch and Clout, 2002), and control of invasive predators during the nesting season is critical to reproductive success (Underwood et al., 2014; Harmon et al., 2020a). Sea level rise resulting from climate change threatens coastal habitat, including important nesting habitat, and further exacerbates conservation challenges (Kane et al., 2014; van Rees and Reed, 2018). The social-ecological nature of Indigenous wetland agro-ecosystems allows these systems to retain their function and productivity following disturbance, potentially increasing their resilience to environmental variability (Winter et al., 2018b). As such, they may serve as refugia for native species as sea level rise encroaches on existing wetlands (Czech and Parsons, 2002). Restoration and management of Indigenous Hawaiian agro-ecosystems, coupled with predator and invasive vegetation control, may offer a sustainable landscape-level solution for expanding conservation of these species beyond state and federally managed protected areas.

Although studies have quantified projected losses due to sea level rise for wetlands in specific locations within the Hawaiian Islands (Kane et al., 2014; van Rees and Reed, 2018), until now, no estimates were available for all wetlands and waterbird habitats across all of the Hawaiian Islands. As Hawaiian waterbirds are habitat-limited (Reed et al., 1998; VanderWerf, 2012; van Rees et al., 2020), estimates of predicted wetland gains and losses at island and regional levels are critical for conservation planning. Further, with the equatorial Pacific projected to reach values of sea-level rise 10–20 % above the global mean of 0.54−0.71 meters (Slangen et al., 2014), expanding habitat for Hawaiian waterbirds is critical for the long-term persistence of these species. In addition to preserving Hawaiian cultural practices, building social cohesion in communities, and providing resilient local food production, contemporary restoration of *loʻi* may have potential to increase suitable habitat for Hawaiʻi's endangered waterbirds, as all of the at-risk waterbird species frequently use *loʻi* for foraging and nesting. Furthermore, restoring *loʻi*, and other forms of Indigenous agro-ecology in Hawaiʻi, would align with the United Nations Sustainable Development Goals to support local farmers, promote and sustain economic growth, mitigate effects of climate change, and sustainably manage biodivesity. Restoration of Indigenous agro-ecology is also in line with the United Nations Declaration on Indigenous Rights, which defines the individual and collective rights of Indigenous peoples, including their rights to cultural expression and to maintain and strengthen their own institutions, cultures, and traditions. This study therefore addresses the following research questions. First, what is the extent of waterbird nesting habitat in Hawaiʻi likely to be lost due to sea level rise by the year 2100? Second, what is the potential gain in waterbird nesting habitat in Hawaiʻi through restoration of *loʻi*?

2. Methods

2.1. Waterbird habitat

This study focused on analyzing suitable nesting habitat for three endangered waterbirds: the *ʻaeʻo*, *ʻalae keʻokeʻo,* and *ʻalae ʻula* (hereafter referred to as "Hawaiian waterbirds"). These waterbirds nest in similar elevations and are the most threatened on the main Hawaiian Islands (VanderWerf, 2012). The U.S. Fish and Wildlife Service (USFWS) National Wetlands Inventory provided the extent of wetland habitat, which includes existing *loʻi* and other wetland agro-ecosystems, and surface water for the state of Hawaiʻi. We only considered wetlands that were suitable for waterbird nesting, as many habitats may be suitable for foraging but not necessarily nesting. We considered suitable nesting habitat (hereafter referred to as "potential waterbird nesting habitat") as estuarine or freshwater emergent wetlands at or below 400 m elevation, as this would represent potential habitat for at least one of the three species (VanderWerf, 2012). As such, we removed wetlands not fitting these criteria from the analyses. We considered these areas as potential habitat, as we were unable to confirm whether all areas have ongoing invasive vegetation control, which is necessary for successful waterbird nesting (VanderWerf, 2012). As salinity under future conditions has an extremely high degree of uncertainty due to complex dynamics regarding ground permeability, precipitation, underground water recharge, and freshwater springs, we were unable to discriminate among areas that would be more or less suitable under future conditions for particular species. Instead, we considered likely suitable nesting habitat for at least one of the three focal species. Importantly, all three species considered in this study have been observed nesting in *loʻi* (Greer, 2005; Harmon et al., 2020b). Nesting success in *loʻi* varies based on management practices and habitat characteristics (Greer, 2005; Gee, 2007). This variation is similar to that observed across conventionally managed wetlands. The choice of management practices employed by land managers, however, was beyond the scope of this modeling study. We assumed potential as consistent among locations, as the study intended to model future nesting habitat, rather than the effects of particular management practices or habitat characteristics.

2.2. Projections of sea level rise

We used sea level rise projections produced by Anderson et al. (2018), as these are currently the most robust for the state of Hawaiʻi. The Pacific Islands Ocean Observing System (PacIOOS, 2019) provided the shapefiles for sea level rise inundation for the islands of Kauaʻi, Oʻahu, Maui, Lānaʻi, Molokaʻi, and Hawaiʻi. Anderson et al. (2018) mapped groundwater and marine inundation at 98 cm of global mean sea level rise, corresponding to the upper limit of the likely range (83rd percentile) as set forth in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), Representative Concentration Pathway 8.5 (RCP 8.5). Projections of sea level rise for the islands of Kauaʻi, Oʻahu and Maui accounted for passive flooding, annual high wave flooding, and coastal erosion. For the islands of Lānaʻi, Molokaʻi, and Hawaiʻi, sea level rise projections only accounted for passive flooding due to the lack of historical shoreline data needed to model annual high wave flooding and coastal erosion (Anderson et al., 2018).

2.3. Loʻi *projections*

For the end of the century, we obtained potential distributions of *loʻi* for the State of Hawaiʻi from Kurashima et al. (2019). Models assumed that landscape was suitable for *loʻi* if it was characterized by alluvial or colluvial soils, a slope of 10° or less, a temperature above 21 °C with 415 m elevation and under as a proxy, and located within 350 m of a perennial stream (see data sources in Kurashima et al., 2019). We utilized their models of *loʻi* distribution under the RCP8.5 scenario, which included future rainfall and mean temperature projections. The previous study, however, did not account for future sea level rise or the potential irrigation of *loʻi* from groundwater. We note that Kurashima et al. (2019) highlighted a possible over-simplification of the *loʻi* distribution under climate change. Over-simplification may occur due to the lack of data on the complex and unpredictable interactions between changes in rainfall and air temperature with stream temperature and flow.

2.4. Spatial analysis

We determined the loss of potential waterbird nesting habitat by identifying wetland areas that would be inundated by marine and/or groundwater by the year 2100. We assumed that these areas of marine or groundwater inundation would create unsuitable nesting habitat for waterbirds, as all three waterbirds generally nest on the ground or use vegetation mats to nest in open water (VanderWerf, 2012). We conducted all analyses in ArcGIS Pro 2.3.3.

In this study, the RCP8.5 potential *loʻi* restoration layer from Kurashima et al. (2019) was updated to account for sea level rise. Because most *loʻi* crops cannot tolerate brackish water, we assumed that areas projected for inundation by marine water would be unsuitable for future *loʻi*. Therefore, regions suitable for future *loʻi* only included areas that were not affected by sea level rise or inundated only by groundwater. We defined potentially gained waterbird nesting habitat as existing wetlands projected for inundation by groundwater, that were also suitable for *loʻi* restoration, as well as potentially restored *loʻi* regions that previously were not wetland habitat. We assumed that the draining of freshwater via *hoʻi wai* (drainage ditches carrying water out of *loʻi*) would alleviate flooding from groundwater inundation and create suitable nesting habitat for waterbirds. As all three waterbird species have different salt tolerances, the *ʻaeʻo* with the greatest and the *ʻalaeʻula* having the least, the possibility exists for sea level rise to create new saline wetlands that are unsuitable for *loʻi* cultivation but suitable for waterbird nesting under sufficient management practices. Mapping these areas, however, was not within the scope of this study.

3. Results

Results showed that ~6816 ha of potential Hawaiian waterbird nesting habitat currently exist across the Hawaiian Islands (Table 2). With a one-meter rise in sea level by the year 2100, this area may decrease across the Hawaiian Islands by an estimated 1847 ha (27 %) due to marine water inundation, representing 5–69 % of the potential nesting habitat on each island (Fig. 1–2, Table 2). Further, groundwater may inundate ~136 ha (2%) of potential waterbird nesting habitat across the Hawaiian Islands by the year 2100. This inundation would remove an additional 1–9 % of potential nesting habitat on each island (Fig.1–2, Table 2). Possible gains in areas suitable for *loʻi* by the end of the century were shown to be 13,622 ha. Accounting for sea level rise, however, we estimated 11,698 ha of land across the Hawaiian Islands may be suitable for *loʻi*, and thus waterbird nesting habitat. This area is comparable to historical estimates (before 1778) under Hawaiian IRM practices (Kurashima et al., 2019). Of the area suitable for *loʻi* restoration, we estimated 21 ha as existing wetland habitat projected for inundation by groundwater and 11,677 ha to be new potential waterbird nesting habitat not previously in wetlands (Table 2).

4. Discussion

Although previous studies have examined potential effects of sea level rise on Hawaiian waterbird habitat, these studies focused on a subset of wetlands (Kane et al., 2014) and on a single waterbird species (van Rees and Reed, 2018). van Rees and Reed (2018) estimated that ~8% of *ʻalae ʻula* habitat on Oʻahu may be lost due to marine water inundation by the year 2100, which is considerably lower than the estimate from this study of 30 % for the same island. This variation may be due to differences in the data for sea level rise used as inputs to the two studies, as well as the scope of species and area considered. van Rees and Reed (2018) used projections for sea level rise provided by the National Oceanic and Atmospheric Administration (NOAA), which only take into account passive flooding. The projections for sea level rise employed in this study (provided by the Pacific Islands Ocean Observing System) are an improvement over NOAA's methods, as they also consider annual high wave flooding and coastal erosion for some islands (Anderson et al., 2018). Furthermore, the previous study aimed to quantify the impact of habitat losses on population viability of a single species on one island, using known and documented locations, including ~430 ha of *ʻalae ʻula* habitat on Oʻahu (van Rees and Reed, 2018). As such, they also determined the value of the habitat projected as lost due to sea level rise in regard to use of the habitat by *ʻalae ʻula*.

In modeling potential waterbird habitat, this study did not examine species-specific effects. Thus, we included ~1363 ha of existing potential habitat on Oʻahu that was assumed suitable for at least one of three waterbird species (VanderWerf, 2012). Our analyses did include some of the same wetlands used in van Rees and Reed (2018), however, providing insight into the most beneficial areas for *ʻalae ʻula,* if restored as *loʻi.* van Rees and Reed (2018) identified Hāmākua Marsh within the Kawainui-Hāmākua Marsh Complex (Fig. 2a-b) as highly valuable *ʻalae ʻula* habitat, for example, but this study found it is likely to be inundated by the end of the century. We found that much of the surrounding area, including Kawainui Marsh, may be suitable for *loʻi* restoration and

Table 2
Estimates across the State of Hawaiʻi and for individual islands of (1) existing potential waterbird nesting habitat ("potential waterbird nesting habitat"), (2) projected area of potential waterbird nesting habitat lost to marine water inundation ("marine inundation") and groundwater inundation ("groundwater inundation"), and (3) projected area of potentially gained waterbird nesting habitat ("gained waterbird nesting habitat") through restoration of *loʻi*.

	Kauaʻi	Oʻahu	Maui	Molokaʻi	Lānaʻi	Big Island
Potential waterbird nesting habitat (ha)	4228	1363	292	607	< 1	326
Marine inundation (ha)	966	354	91	419	0	17
Groundwater inundation (ha)	48	52	25	3	0	8
Gained waterbird nesting habitat (ha)	2903	6105	809	1224	229	428

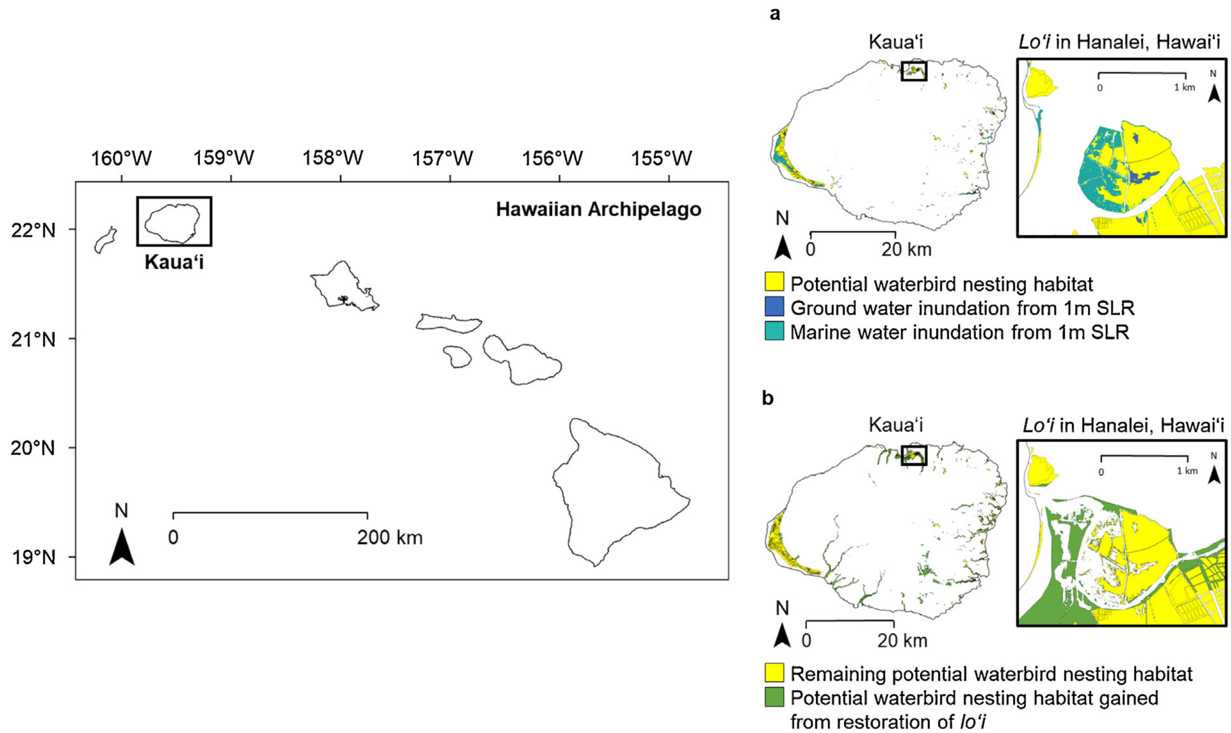

Fig. 1. Projected losses and gains of potential Hawaiian waterbird nesting habitat on the island of Kauaʻi. (a) Projected marine water and groundwater inundation of potential Hawaiian waterbird nesting habitat. (b) Projected gains of potential Hawaiian waterbird nesting habitat through the restoration of loʻi by the year 2100 in currently existing *loʻi* in Hanalei, Hawaiʻi.

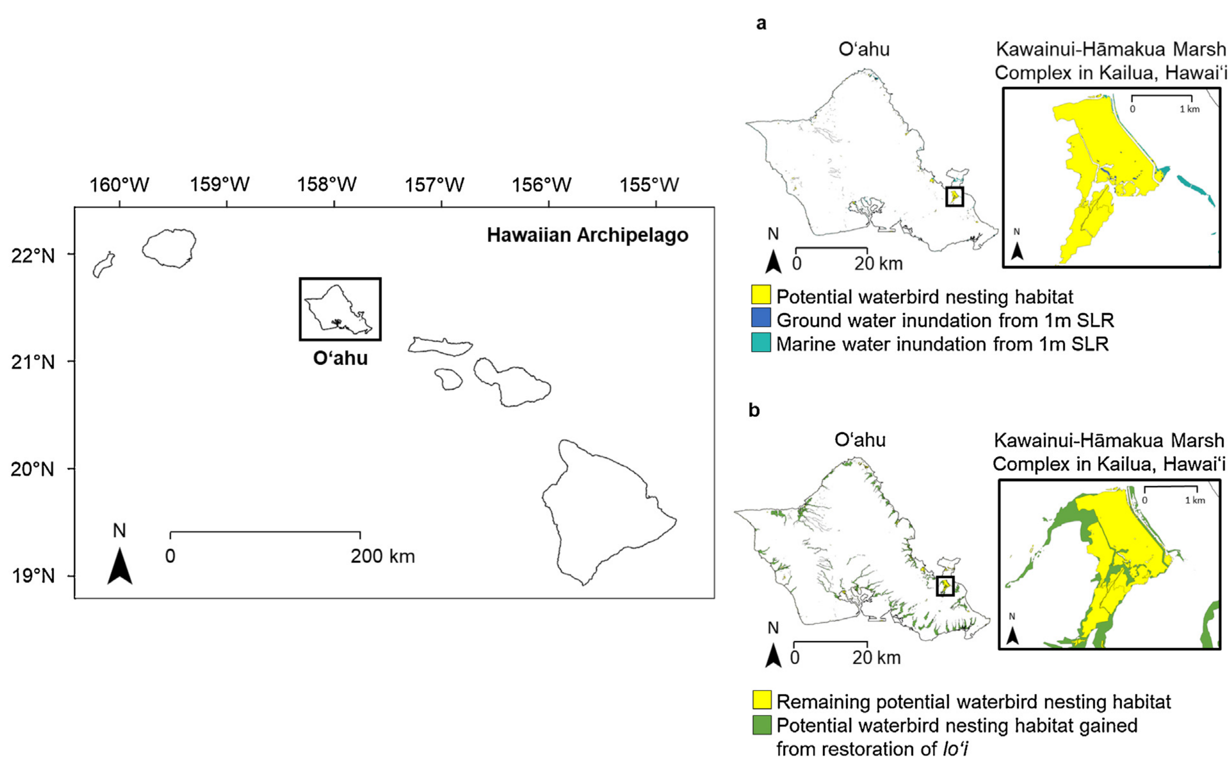

Fig. 2. Projected losses and gains of potential Hawaiian waterbird nesting habitat on the island of Oʻahu. (a) Projected marine water and groundwater inundation of potential Hawaiian waterbird nesting habitat. (b) Projected gains of potential Hawaiian waterbird nesting habitat through the restoration of *loʻi* by the year 2100 in Kawainui Marsh in Kailua, Hawaiʻi.

thus would compensate for loss of *'alae 'ula* habitat. As estimating the percent of loss in relation to gross area of habitat is most valuable if the value of the habitat is known, more studies of Hawaiian waterbirds in *lo'i* are crtical for determining which areas have the highest potential for waterbird recovery.

As Hawaiian waterbirds are habitat limited, loss of wetland habitat due to sea level rise will require acquisition or creation of new waterbird habitat in order to achieve recovery goals for waterbird populations into the future. Creating and managing conventional protected areas is costly (James, 2001; Bruner et al., 2004), and the cost will continue to increase as anthropogenic threats impact more species. One of the biggest resource costs in protected areas is vegetation management. Removal of invasive vegetation is essential to *lo'i* cultivation, and thus working with farmers to increase managed habitat areas could be a realistic and economical solution. As a first archipelago-wide examination of the likely losses of potential Hawaiian waterbird nesting habitat, this study suggests that restoring just a fifth of the *lo'i* systems identified can more than compensate for the loss of existing nesting habitat projected for loss due to sea level rise. Thus, an urgent need exists for field studies of waterbirds in restored *lo'i,* to elucidate co-existence practices that allow waterbird populations to once again thrive alongside human populations. Conservation planning should include protections for these spaces from continuing urban development (Kurashima et al., 2019). Furthermore, some areas may already be developed or utilized for other forms of agriculture (Kurashima et al., 2019), highlighting the importance of engaging landowners and other stakeholders in decisions regarding *lo'i* restoration. Restoring *lo'i* adjacent to urban areas may have added benefits, such as opportunities for increased community-based resource management with local and Indigenous communities, which increases bio-cultural stewardship and cultivates sustainability ethics (McMillen et al., 2020). Additionally, conservation payments to farmers could supplement farm income, as living wages are one of the biggest obstacles to agriculture in Hawai'i.

While protected areas can mitigate threats to biodiversity, such as the conversion of habitat (Carranza et al., 2014), protected areas alone are unlikely to meet global biodiversity goals (Pringle, 2017). Additionally, at least 40 % of protected areas worldwide are on lands of Indigenous Peoples (Garnett et al., 2018). Many of these lands continue to be managed under IRM practices, and thus hold most of the world's remaining biodiversity (United Nations, 2019). Land stewarded by Indigenous Peoples has potential to achieve conservation of biodiversity through management practices in which conservation is not necessarily the primary objective but is inherently an outcome (Donald et al., 2019), typically because they create landscapes with increased habitat heterogeneity (Berkes, 2018). Further, inclusion of Indigenous perspectives can increase the value and success of conservation initiaives (Ward-Fear et al., 2019). In Hawai'i, for example, integrating IRM with conventional practices has led to sustainable management of ecosystem services (Kikiloi et al., 2017; Kurashima et al., 2018; Winter et al., 2020b), with direct benefits to native species (Poepoe et al., 2005; Friedlander et al., 2013), including an increased ability of Indigenous communities to remain connected to their ancestral places. While the importance of incorporating Indigenous knowledge and practices into conservation initiatives is often recognized, in practice, addressing the needs and values across multiple knowledge systems can be challenging (Wheeler and Root-Bernstein, 2020). Biocultural approaches, such as Indigenous agro-ecology, offer an integrated solution to a suite of conservation and sustainability issues (Sterling et al., 2017).

The finding that IRM practices can aid recovery of endangered species in Hawai'i contributes to a growing body of literature on such practices, supporting global sustainability through regionally-appropriate social-ecological systems approaches. Successfully managing sustainable ecological systems now and into the future requires an understanding of the local socio-ecological context (Hughes et al., 2017). Techniques may be place-specific requiring Indigenous local knowledge (McGregor et al., 2010). The Indigenous practice of burning wetlands in northern Australia, for example, when timed with seasonally shifting land and water interfaces, improves access to food and promotes species diversity, including native breeding waterbirds (McGregor et al., 2010). Indigenous Resource Management practices in other locations sustain over 40 % of high-altitude wetlands through irrigation techniques that expand and maintain wetlands while meeting human needs for domestic animal production (Verzijl and Quispe, 2013). Furthermore, integrating place-based Indigenous knowledge into conservation planning aids in decolonizing the field of conservation.

5. Conclusions

In conclusion, findings of this study suggest that Indigenous Resource Management (IRM), including agro-ecology, offers potential to simultaneously achieve sustainability and conservation goals. Roughly 29 % of current potential Hawaiian waterbird nesting habitat is projected for inundation by the year 2100. This loss would likely result in the decline of currently endangered waterbird populations. Restoration of Hawaiian agro-ecosystems (*lo'i*), through a combination of IRM and conventional conservation practices, can compensate for projected losses and expand waterbird habitat. As all three waterbird species in this study are endangered and habitat-limited, expanding nesting habitat is critical to achieve recovery goals for these species into the future.

More broadly, social-ecological systems approaches, such as IRM, are critical to building resilience into threatened systems. This modeling study further suggests that Indigenous agro-ecology, specifically wetland agro-ecology, can solve local problems while aligning with international policies (e.g., United Nations Declaration on Indigenous Rights). Restoration of wetland agro-ecosystems can also contribute toward meeting multiple United Nations Sustainable Development Goals simultaneously, by providing food and supporting biodiversity and the recovery of endangered species, while also supporting Indigenous communities.

Declaration of Competing Interest

The authors declare no conflicts of interest.

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