

Article

Using Systematic Conservation Planning to Identify Climate Resilient Habitat for Endangered Species Recovery While Retaining Areas of Cultural Importance

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Abstract: The effective management of at-risk species often requires fine-scale actions by natural resource managers. However, balancing these actions with concurrent land uses is challenging, particularly when compounded by the interplay of climate shifts, and escalating wildland–urban interface conflicts. We used spatial prioritization tools designed for biodiversity conservation to help resource managers on the Island of Lāna'i prioritize mutually exclusive land use objectives: endangered species recovery and subsistence and recreational hunting. We weighed the current and anticipated future distributions of threatened and endangered plant species against the distribution of non-native game mammals to plan for species recovery more effectively. Prioritization results identified multiple footprints that could support recovery of all endangered species targets in climate resilient areas while retaining the majority of existing hunting areas. However, very little native vegetation was retained in conservation footprints without deliberate inclusion, which increased footprint area by 268%. Scenarios which prioritized contiguous conservation areas also dramatically increased conservation footprint area, although these scenarios may reduce associated fencing costs. This work demonstrates how spatial prioritization may guide localized species recovery efforts by supporting long-term conservation planning that addresses anticipated climate-driven increases in conflict between conservation and other land uses, with clear applicability beyond Lāna'i.

Keywords: spatial conservation prioritization; systematic conservation planning; climate resilience; threatened and endangered species; hunting and conservation conflict



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1. Introduction

Congruency across areas of human activity and high biodiversity, and subsequent biodiversity losses, are well-documented [1–3]. Pressures on these important areas are predicted to increase in the face of climate change, particularly due to the expanding wildland–urban interface, increased visitation to protected areas, and associated human–wildlife conflict [4–7]. The increased incidence of severe weather events associated with climate shifts such as hurricanes, drought, and wildfires and subsequent expected species range shifts are expected to aggravate these conflicts and exacerbate extinction risk [8–11]. Systematic approaches to species recovery and management, at landscape and site-specific scales, that explicitly identify areas for conservation and alternative land uses may help reduce conflict and pressures on natural resources [12]. Although much research has been conducted to inform climate resilient conservation actions, the responsibility to enact these measures ultimately falls to natural resource managers who may need to balance

conservation of native biota with other priorities. National parks, regional reserves, and protected areas commonly have a dual mandate to conserve natural resources and provide public access, resulting in a conservation conflict [13–16]. Providing resource managers with realistic, actionable tools may relieve some of the challenges associated with balancing these dual responsibilities.

Across the state of Hawai‘i, non-native game mammal hunting is a culturally important and popular recreational activity [17,18]. However, at a local level, providing subsistence and recreational hunting opportunities is incompatible with the conservation of threatened and endangered (T&E) species largely due to habitat damage, including herbivory, bark stripping, trampling, and subsequent erosion [19–21]. Hence, mutually exclusive areas for these activities are required [19,21]. The adverse ecological effects of non-native game mammals on native ecosystems in the Hawaiian Islands have been extensively documented and are perhaps the greatest obstacle to the landscape-scale recovery of T&E Hawaiian plant species [22–24]. Many endemic Hawaiian plant species have declined and become endangered as a direct or indirect result of herbivorous non-native game mammals [24]. Combined with the interactive effects of climate change [25], the spread of invasive plant species [26,27], and changing wildfire regimes [28], many native species are expected to experience changes in distribution and range contraction [29]. To support the recovery of terrestrial native species while maintaining subsistence and recreational game hunting opportunities, the identification of suitable habitat for both objectives is needed.

Providing hunting opportunities has been forefront in land-use decisions across the Hawaiian Island of Lāna‘i followed by the piecemeal conservation of small areas for endangered flora and fauna, a practice commonly used for expanding conservation reserves until fairly recently [30,31]. However, in 2012, land managers renewed interest in developing a comprehensive conservation strategy for the island. This includes a plan for an 8100 ha conservation area along the eastern portion of the island to restore native vegetation, reduce erosion, and sediment runoff to nearshore reefs, improve watershed health and protect endangered and endemic species populations [32]. Meeting the objectives of this plan may require climate resilient substantial realignment of existing hunting areas that are important for recreation and subsistence use. The planned conservation area was not evaluated in terms of whether it provides sufficient climate resilient recovery areas for T&E species or how much high-quality hunting area will be retained across the island, which are important factors for meeting federal recovery guidelines and facilitating hunter buy-in. Balancing conflicting interests using an approach that ensures the values and needs of each party are transparently integrated in management decisions has been shown to improve outcomes [33] and may be important for reducing this potential conservation conflict.

In this work, we used spatial prioritization tools to identify the minimum recovery area for a suite of T&E species under climate resilient conditions, defined as the overlap between current and future (2100) species climatic envelopes [34], for the Island of Lāna‘i while balancing for the contrasting objective of providing high quality areas for culturally significant subsistence and recreational hunting. To achieve this, we set up spatial prioritization scenarios that addressed two primary objectives: (1) identify the minimum extent of climate resilient areas required to recover terrestrial T&E plant species in Lāna‘i and (2) preserve the majority of existing hunting areas for continued subsistence and recreational hunting opportunities. Given this competing legacy of hunting and the rising interest for conservation in Lāna‘i, we explore the potential tradeoffs between these objectives, how recently developed landscape-level conservation plans may influence land-use prioritization, and the extent to which these different land uses can co-exist. We also explore how landscape level results can be interpreted to inform species-specific planning for T&E recovery actions. This approach to identify discrete areas of high conservation and hunting value provides a potential framework for resource managers responsible for both the protection of native species and public access in a more transparent and equitable way.

2. Materials and Methods

2.1. Study Area

The Island of Lānaʻi is the sixth-largest Hawaiian Island (364 km²) and lies approximately 14 km west of Maui Island [20]. It is part of a four-island complex, Maui Nui, that was once inter-connected with Maui, Molokaʻi, and Kahoʻolawe Islands [35]. Approximately 98% of the island is privately held by one landowner. The island's natural resource management company, Pūlama Lānaʻi, oversees 159 km² of private hunting lands on the island and leases an additional 140 km² to the state of Hawaiʻi Department of Land and Natural Resources, Division of Forestry and Wildlife for public seasonal ungulate and game bird hunting activities.

Prior to the introduction of ungulates, Lānaʻi had well-developed dry forests and shrubland areas, 16 native bird species, and numerous endemic arthropod and mollusc species. The introduction of goats (*Capra hircus*) and sheep (*Ovis aries*) in the 1800s destroyed most native forests, and the dramatic erosion and coastal accretion to the island is attributed to their presence. In the 1900s, numerous plants were introduced to reduce erosion, and many of those became invasive. Additional ungulate species including pigs (*Sus scrofa*) and cattle (*Bos taurus*) were introduced to the island for ranching. Axis deer (*Axis axis*) and European mouflon sheep (*O. musimon*) were introduced in 1920 and 1954, respectively, by the territorial government of Hawaiʻi to improve opportunities for subsistence and recreation hunting [36], along with several non-native game bird species. Axis deer and mouflon are the only remaining non-native ungulates [37]. Subsequently, many terrestrial endemic species became extinct [20] and only 15% of the native habitat remains. Remaining native habitat is primarily comprised of dry and mesic shrublands and wet forest with some fern-dominated areas above 250 m ASL. Non-native habitat occurs from sea level to summit and includes low-elevation mixed forests, grasslands, mixed grasses and shrubs, shrublands, and single-species dominated shrub and forest areas [38,39].

Currently, axis deer and mouflon are both hunted and are the only remaining non-native ungulates [37]. In a 2017 statewide survey of hunters, Lānaʻi received the most use of all public hunting areas, and its annual harvest of game mammals has increased more than tenfold since the 1950s [17,40]. Nevertheless, there were nearly 17,000 axis deer and mouflon counted during a 2013 aerial survey with animals detected across the entire island [41].

2.2. Spatial Prioritization Framework

We used a spatial prioritization framework that allowed us to designate areas for the purposes of either conservation or hunting, while weighting selection based on ecologically meaningful metrics, including species richness and habitat suitability indices. We also included constraints such as areas that must be included or excluded from consideration and parameters to penalize fragmented landscape configurations. We used Marxan with Zones [42] for outlining prioritization parameters, and the package *prioritizr* [43] in an R-environment to process prioritization scenarios [44]. The Marxan with Zones approach provides a transparent way to include equity into complex decision-making tasks and has been shown to successfully facilitate local stakeholder buy-in [12,42]. While spatial prioritization tools are largely used for biodiversity conservation planning [45,46], the approach lends direct application to species-specific recovery planning.

2.3. Inputs

Identifying Study Area Scale and Constraints

We defined two zones for the prioritization exercise, conservation and hunting, which were set as mutually exclusive. The purpose of the conservation zone was to identify areas suitable for recovery of T&E species. With guidance from Pūlama Lānaʻi natural resource and operations managers, we first identified areas to be excluded from conservation or hunting zones (i.e., locked-out), such as residential areas; state and federally owned lands used for public services, e.g., airport and post office; and areas proposed for development.

We also identified areas to be necessarily included within the conservation zone for some scenarios either due to existing or future conservation protection status or because deemed important for conservation by Pūlama Lānaʻi cultural resource managers; these were deemed ‘lock-in’ area constraints (Figure 1). We included boundary constraints to improve contiguity in conservation and hunting areas in order to reduce perimeter length, and ultimately fencing requirements, as fences are essential to protect conservation areas from ungulates in Hawaiʻi [47]. We used methods outlined by Watts et al. [42] to calibrate appropriate values. All data inputs were standardized to a 240×240 m resolution to provide footprints at the fine scale used by natural resource managers for conservation actions and to correspond with the lowest-resolution existing data [48].

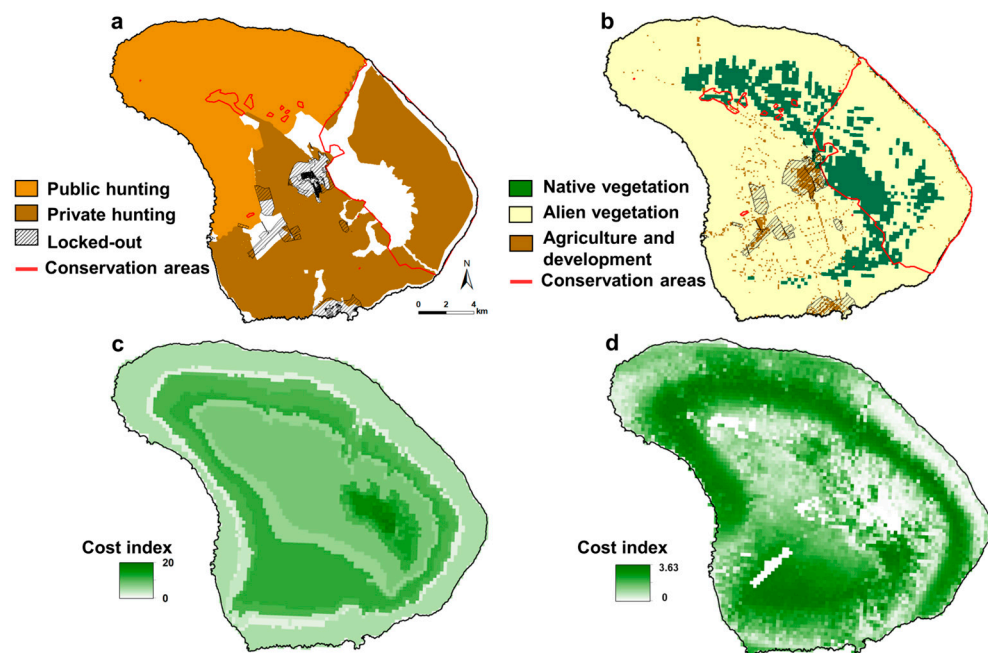


Figure 1. The Hawaiian Island of Lānaʻi with spatial prioritization inputs shown including: (a) current hunting areas used as input for determining the hunting zone, while white areas have no designation; (b) coarse vegetation categories as classified by the Carbon Assessment of Hawaii [38]; (c) costs for using areas for hunting; and (d) costs for using areas for conservation. The cost of hunting is the sum of threatened and endangered species ranges considered for recovery on Lānaʻi, with each species counting as 1, while the cost of conservation is the scaled maximum habitat suitability value for axis deer and mouflon [41]. Conservation areas (lock-in constraints) and areas removed from inclusion in the conservation or hunting zone (locked-out) are displayed in the top figure panels. The large, outlined area on the eastern portion of the island indicates the 8100 ha of planned conservation area.

Developing Species Lists and Hunting Inputs

We used an existing list of T&E native plant species compiled by the Hawaiʻi and Pacific Plants Recovery Coordinating Committee, a group of experts relied upon by the U.S. Fish & Wildlife Service (USFWS) to provide species-specific recovery information, for consideration in prioritization scenarios. As well as the 46 terrestrial T&E plant species identified by the Coordinating Committee, additional T&E species that potentially overlap in range include: 8 terrestrial plants, 1 mammal, 4 seabirds, 2 waterbirds, 4 insects, and 2 snails [49]. We used climate-defined species ranges (ranges) developed by Fortini et al. [34] that represent each species’ potential habitat under current and end of century climate conditions to represent potential species recovery habitat. Current ranges were assessed by botanical experts familiar with Hawaiian plant species (see Acknowledgments), thus addressing model accuracy and validation concerns discussed by Moilanen et al. [50] and Carvalho et al. [51]. Future ranges were fitted using regional dynamically downscaled

climate models under an end-of-century (2080–2099) IPCC A1B greenhouse gas emission scenario representing a moderately warmer future climate [34]. For each species we considered the overlap between current and projected future ranges to identify areas relevant to management today that are also potentially resilient to projected climatic shifts. In the 10 cases where there was no range overlap, the current range was used as a species' potential recovery habitat to ensure conservative restoration planning. Thirty-one species met these range criteria (Appendix A). Additional species were considered based on the Hawai'i and Pacific Plants Recovery Coordinating Committee's list but were ultimately excluded because recovery criteria or species ranges did not include Lāna'i (Appendix B). We included a native vegetation dataset by Jacobi et al. [38] to identify overlap across the conservation zone. We also included a native vegetation target for the conservation zone in one scenario to evaluate how its inclusion would change the configuration of the conservation and hunting zones. Realistically, recovery actions can occur more quickly and at a lower cost within existing native vegetation. Moreover, current management prioritizes the protection of all existing native vegetation. Current hunting areas were used as potential hunting areas, separated by land management type, resulting in two groups: public (hunting lands leased and managed by the state of Hawai'i) and private (hunting lands directly managed by Pūlama Lāna'i, Figure 1a).

Cost Inputs

We used two sets of cost data following the Marxan with Zones process: costs of using area for conservation, and costs of using area for hunting [48]. We used ecological criteria to set these cost estimates as opposed to monetary values because monetary costs could be managed for during another step of the conservation planning process. The sum of T&E species range overlap, with each species counting as 1, served as the cost to hunting. Thus, areas that can suitably host more T&E species were more costly to appropriate for hunting. Values ranged from 0–20 (Figure 1c). For conservation costs, we used island-specific habitat suitability models for mouflon and axis deer developed by Hess et al. [41]. Ungulate models did not include future suitability as they were based on environmental variables which did not lend to modeling under future scenarios, including normalized difference vegetation index (NDVI) and cloud cover. Ungulate habitat suitability served as a proxy for prime hunting areas. Highly suitable areas would likely be considered more valuable to hunters and more costly to repurpose for conservation because more animals would likely be present. Suitability values were combined for axis deer and mouflon, and the maximum value for each raster grid cell was retained. Values were multiplied by a factor of 4 to ensure they were within a similar range of hunting costs but without strongly competing for areas that could support many T&E species (Figure 1d). We kept conservation costs somewhat low compared to hunting costs to encourage selection of areas with high species range overlap, as the objective for the conservation zone is to minimize land area needed to recover all T&E species.

Defining Conservation and Hunting Targets

Species-specific recovery data for T&E species were determined by the Hawai'i and Pacific Plants Recovery Coordinating Committee, including the number of plants per population and number of populations required for species recovery for the Island of Lāna'i [48]. We used the USFWS metric of number of individuals/ha to create area-based recovery targets (Appendix A). When included, a native vegetation target value of 95% was set. We could not include a target of 100% because approximately 3% of native vegetation occurs within locked-out areas. Hunting targets were set to 70% and 55% of existing public and private hunting areas, respectively. This was in part due to the desire to maintain more than half of existing hunting areas because public hunting areas are designated explicitly for hunting, hunting is an important subsistence practice for many Lāna'i residents, and guided hunts on private lands are an important source of local revenue.

Spatial Prioritization Scenarios

We evaluated a small subset of scenarios to focus on those most realistic to conservation planning in Lānaʻi. Using the T&E species habitat targets and hunting targets, we ran four scenarios: no boundary constraints or lock-in areas; no boundary constraints or lock-ins and a 95% native vegetation target in the conservation zone; boundary constraints and no lock-in areas; and boundary constraints with lock-in areas (Appendix C). Scenarios with boundary constraints result in more contiguous footprints which were preferable to managers. Contiguity is important for reducing the perimeter–area ratio, particularly for reducing fence costs and minimizing the number of management units. Nevertheless, boundary constraints may have a large impact on footprint configuration by reducing fragmentation and may cause over-selection relative to minimum target area requirements [43].

After generating footprints we evaluated the replacement index [43,52] which ranks the importance of a given unit (raster pixel) to meeting conservation and hunting targets based on constraints considered. This is useful because there are many potential landscape configurations that can meet all targets, and within a zone the importance of a given unit to meeting targets varies [43]. Hence, identifying which areas are most important to meeting targets can help inform tradeoff considerations. We also calculated zone boundary length to understand how scenarios with and without lock-in constraints affect the zone perimeter.

Because management for T&E recovery occurs at the population and species levels, we further explored scenarios to identify species-specific recovery information. While prioritization scenarios provide a footprint for each zone, they do not provide single-target (i.e., species) location details. To achieve that, we overlapped the footprint with individual species ranges and the native vegetation map.

3. Results

Targets were met for all scenarios indicating many potential configurations for recovery of T&E species and preservation of the majority of hunting areas across Lānaʻi. Highly suitable areas for both mouflon and axis deer were retained when footprints were compared to ungulate suitability models [41]. Conservation and hunting zone tradeoffs were apparent when comparing scenarios with lock-in and boundary constraints to those without. Boundary constraints consolidated areas for both zones, and more area was designated to the conservation zone when they were included (Figure 2). The inclusion of a native vegetation target within the conservation zone in one scenario largely determined zone configurations (Appendix D).

Conservation zone selection concentrated heavily on the central and eastern portions of the island when boundary constraints were excluded, while including such constraints shifted the selection of areas from the eastern side of the island to the south (Figure 2). The scenario with lock-in constraints demonstrated that 99% of the T&E recovery area targets can be met within current and planned conservation units, with small amounts of adjacent area needed to meet all targets. Footprints that most reduced the size of the conservation zone footprint included no lock-in constraints and no native vegetation target (Table 1). Without explicit lock-in constraints or targets for native vegetation, only 21% of native vegetation was retained in the conservation zone.

We also compared scenarios with and without boundary constraints to understand how selecting for contiguous areas affects the amount of management area and its spatial distribution. Prioritizing for more contiguous zones reduced the conservation zone perimeter by three-fold compared to no boundary constraints and resulted in more block-like zone shapes. Adding lock-in constraints increased the perimeter by 71% compared to the scenario with only boundary constraints, although it conserved nearly four times the land area (Table 1).

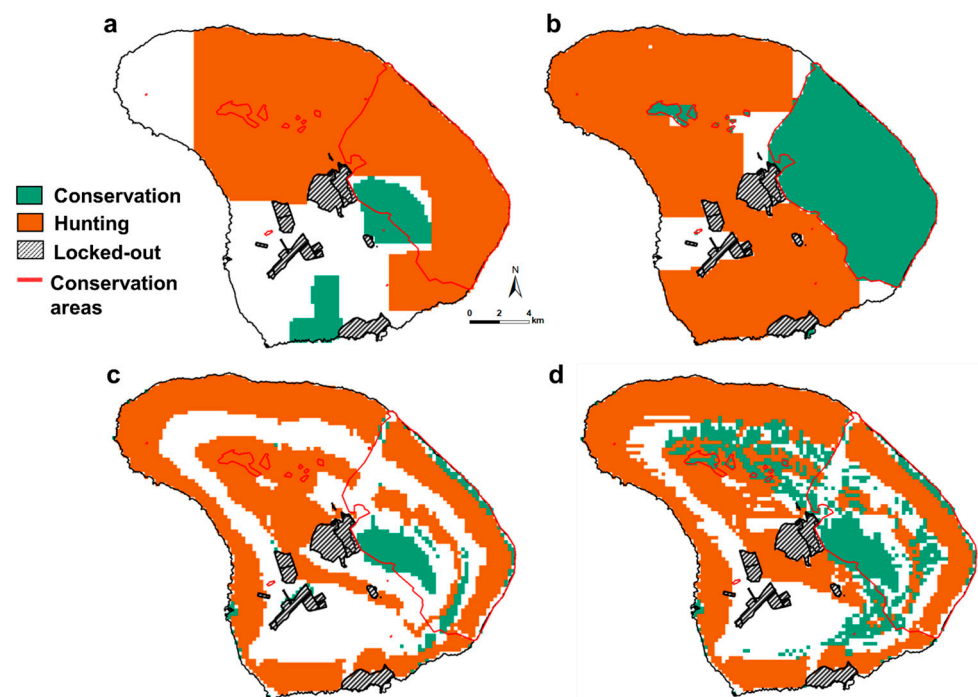


Figure 2. The Hawaiian Island of Lānaʻi with spatial prioritization footprints showing the conservation zone for meeting threatened and endangered species targets, and the hunting zone for meeting hunting targets, under four different scenarios: (a) boundary constraints; (b) boundary and lock-in constraints; (c) no boundary penalties; and (d) 95% native vegetation target included in the conservation zone and no boundary penalties. The planned conservation is the large area outlined in red on the eastern portion of the island. Zone targets were met across all scenarios.

Table 1. Area (ha) assigned to conservation and hunting zones for each suite of scenarios. Conservation zone perimeter length is presented as a proportion of the smallest boundary length determined across all runs, which was the scenario with boundary constraints and no lock-ins. For example, the first scenario has a perimeter length 3.29 times greater than the third.

Scenarios	Area (ha) by Zone		Conservation Zone Perimeter Length
	Conservation	Hunt	
No boundary constraints, no lock-ins	2269	18,512	3.29
No boundary constraints, no lock-ins, native vegetation	6076	18,259	10.20
Boundary constraints, no lock-ins	2794	21,087	1
Boundary constraints, lock-ins	10,230	23,437	1.71

The replacement index served to identify which areas on the island were critical to efficient T&E species recovery based on scenario constraints (Figure 3). The index identified a core area, locally known as Lānaʻi Hale, that is considered irreplaceable to meeting T&E recovery goals. When the same index was calculated for the hunting zone, the replacement values were lower, although they covered a much larger portion of the island, including nearly the entire low-elevation perimeter of Lānaʻi.

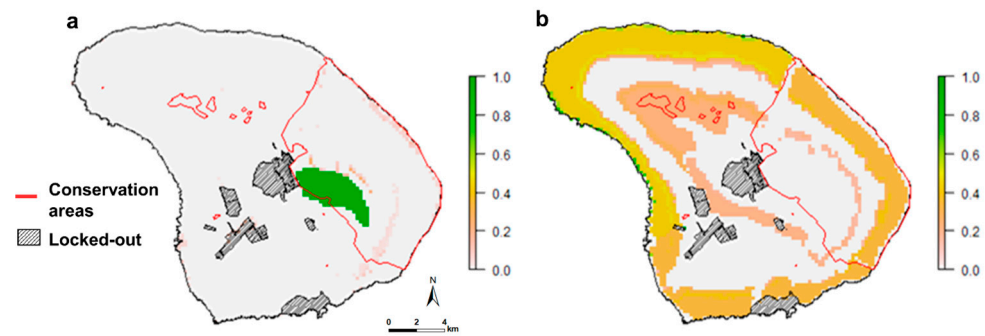


Figure 3. The Hawaiian Island of Lānaʻi with a replacement index for a scenario with threatened and endangered species and hunting targets and no lock-in or boundary constraints. The replacement scale indicates how important or irreplaceable an area is to meeting recovery targets on a scale from 0–1. (a) represents the conservation zone, and (b) represents the hunting zone.

To translate multi-species recovery footprints into species-level recovery planning, we overlaid species distribution maps with the footprint including T&E and hunting targets with no boundary constraints, and existing native vegetation data [38] (Figure 4). For example, by overlaying the conservation zone with the *Abutilon eremitopetalum* range and the current distribution of native vegetation we can identify areas that may be suitable for immediate recovery efforts such as establishing new populations. The entire recovery target for *A. eremitopetalum* can occur within native vegetation in the conservation zone, and an additional 339 ha occurs within the footprint providing numerous options for resource managers. Additional metrics to incorporate for species-level recovery planning could include accessibility indices such as distance to roads and trails, or a biodiversity heatmap to determine whether to reestablish *A. eremitopetalum* populations within areas that overlap with many other species ranges.

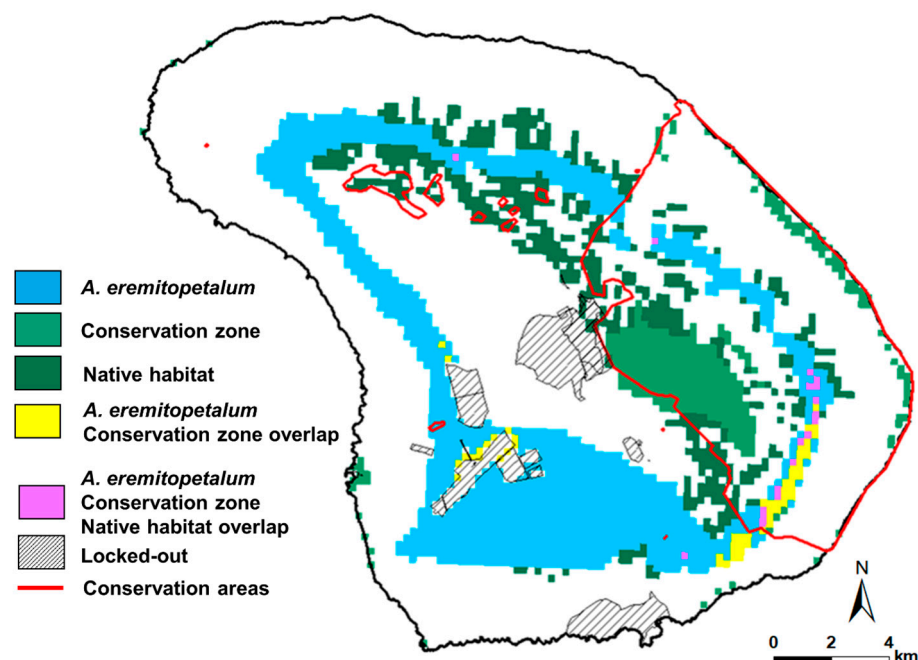


Figure 4. The Hawaiian Island of Lānaʻi with an example conservation zone footprint, the *Abutilon eremitopetalum* range overlaid, and its overlap with native vegetation. An additional 339 ha beyond the target was conserved within the conservation zone, and the full target fit within the overlap of the footprint and native vegetation. Understanding where *A. eremitopetalum* occurs within native vegetation may be of interest to conservation practitioners to reduce restoration costs.

4. Discussion

Factoring the potential for conflicts between species recovery efforts and human use, along with climate resiliency considerations, into conservation planning efforts may mitigate future conflict across areas of high conservation value and yield more durable outcomes [7,33]. This work explicitly identifies climate resilient recovery areas for T&E species at a landscape scale while identifying areas of high suitability for hunting both as a local, subsistence practice and a recreational activity. Because all targets were met with undesignated land area remaining, it is possible additional hunting areas could be retained without jeopardizing optimal conservation recovery areas. Highlighting such examples using spatial prioritization tools may help build trust across stakeholders during the conservation planning process.

In circumstances where resources are limited, managers may be hesitant to use species distribution models that include future climate scenarios in planning because of uncertainty in future conditions, despite understanding that it is prudent for long-term recovery efforts. By using the overlap between current and future predicted ranges as species input data whenever possible, we mitigated aversion to inherent uncertainty in climate models for decision-makers while using the most current and robust species models available. It is important to reduce climatic vulnerabilities when possible because there are other uncertainties equally important to consider during recovery planning, such as ongoing plant invasion and continued human development [29,53,54]. Future climate scenarios have been incorporated in spatial prioritization efforts [55–58], although previous approaches assume that habitat connectivity would yield long-term persistence via dispersal. However, it would be unlikely for T&E species considered to sufficiently disperse unassisted because they are typically dispersal-limited [59]. Moreover, the conservative approach to climate resilient recovery of rare species using the overlap of current and future suitable areas may be more amenable from both regulatory and implementation perspectives compared to those that rely on dispersal. While the approach we used is discussed in reviews by Hannah et al. [60], Heller and Zavaleta [61], and Reside et al. [62] as ways to include climate change tools for regional and site-specific planning efforts, here we employ it in a model system, demonstrating its practical application.

We recognize that omitting future habitat data for species lacking overlap of current and future ranges prevented us from producing climate resilient scenarios for all T&E species. In these instances of no overlap, it may be best to leave decisions regarding inclusion of species data to conservation practitioners with localized knowledge. Nevertheless, this process should be perceived as an iterative exercise that can be updated as new data or circumstances arise, which could remedy existing limitations.

Comparing suites of scenarios across boundary and lock-in constraints can be useful to understand how tradeoffs influenced zone designations. For example, when comparing the hunting zone across scenarios, no lock-in constraint scenarios retained a substantial portion of coastal habitat, indicating that its value for hunting outweighs the value for conservation, while inland areas including Lānaʻi Hale were always included in the conservation zone. From a management perspective, it may be most efficient to focus immediate game mammal control efforts upslope to protect those important recovery areas. Additionally, calculating how much native vegetation was retained within the conservation zone across scenarios is a useful metric for managers. Practically, T&E species recovery will be prioritized within native vegetation to reduce restoration costs and efforts when compared to degraded habitat. Overlap with native vegetation is also important because ongoing plant invasion threatens common species which are ecologically and culturally important, and may not be recoverable once population numbers decline further [63,64]. Without specifically including a native vegetation target, only 20–48% occurred within the conservation zone. However, recovering the T&E species within native vegetation is less spatially efficient. Quantifying these tradeoffs for resource managers allows them to make more informed conservation decisions.

Assessing multiple scenarios is also important to identify patterns across footprints [56,65,66]. This is because areas repeatedly included within a zone, despite changing targets or costs, may signal the importance of such locations while areas that vary allow for evaluation of how tradeoffs may influence landscape scale recovery planning. Additional post-prioritization metrics can be calculated to allow managers to interpret advantages and disadvantages themselves, such as real-world costs or other conflicting land-use priorities. For example, we measured the conservation zone perimeter length for scenarios to provide a metric for fence costs, as fences are a critical component of native species conservation in Hawai'i. When considering targets with lock-in constraints, the conservation zone area was much larger than the minimum needed to meet all targets. However, because it is an area already planned for conservation it may be of use to resource managers to quantify such a tradeoff: the footprint requires a 71% greater perimeter length compared to the scenario with only boundary constraints while it protects nearly four times the area. The real-world costs associated with discontinuous zone areas such as increased fence materials and more perimeter to monitor and maintain may not be preferred to scenarios that consolidate perimeter length.

We demonstrate that replacement indices can provide insights when prioritizing species recovery efforts, although this metric is typically used to identify areas of high vulnerability and irreplaceability in order to maximize retention of biodiversity [67,68]. As observed in Figure 3, when no native vegetation target was set, there were conservation areas deemed irreplaceable within existing hunting areas as well as within the planned conservation area. There were also areas of lower rank scattered along eastern and western coastlines and patches across the southern portion of the island. Managers could use this information to determine whether and where to create smaller conservation units outside of the planned conservation area to protect additional climate resilient habitat for species recovery. Creating populations on the western and southern portions of the island may reduce extinction vulnerability should catastrophic weather events or wildfires occur. Replacement indices can also be used when assessing zone configurations. Because of the boundary constraints and pixel-based units, zone shapes may appear arbitrary to managers. Interpreting these zones as starting points and incorporating replacement indices, along with other relevant data, to help reconfigure management zones that better reflect conditions on the ground may be useful to managers. Regarding hunting, indices may help rank the importance of hunting areas across the island and can be used to identify areas for focused resource management. They may also serve useful to stakeholders to demonstrate that prioritization was not biased towards conservation or hunting during the analysis.

5. Conclusions

Spatial prioritization tools have been used to identify optimal areas for biodiversity conservation across terrestrial, marine, and freshwater systems [69–71], and here we demonstrate a new application to inform climate resilient species recovery planning efforts while balancing for human uses in areas such as national parks, regional reserves, and protected areas. Although this work focused on a small amount of land area with two conflicting uses, the spatial prioritization analysis helped identify climate resilient scenarios for the recovery of numerous T&E species while maximizing the area for subsistence and recreational hunting opportunities which are mutually exclusive land uses throughout Hawai'i. Conservation efforts that acknowledge the potential for conflict and incorporate local and indigenous practices when setting planning goals may increase likelihood of success. Much of the published literature uses spatial prioritization approaches to identify conservation areas to complement existing reserves for meeting biodiversity targets, and most applications have identified areas for common and rare species protection with few applications addressing fine-scale recovery of T&E species. We demonstrate that these tools are easily adaptable to and valuable for the consideration of diverse recovery planning scenarios, and this work has already influenced the approach to landscape-scale planning efforts in Hawai'i. In fact, in collaboration with the State of Hawai'i Division of Land

and Natural Resources and dozens of partners, a similar effort using spatial prioritization approaches to identify recovery habitat for hundreds of T&E species across the state is now underway. Our work serves as a case study for the many conservation managers who strive to balance localized species recovery efforts and alternative land-uses in order to reduce conflict and meet objectives, within a climate resilient lens.

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Conflicts of Interest: Authors Jonathan Sprague and Rachel S. Sprague were employed by the company Pūlama Lānaʻi. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Species considered for prioritization analysis based on a list compiled by the Hawaiʻi and Pacific Plants Recovery Coordinating Committee, a group of experts relied upon by the U.S. Fish & Wildlife Service (USFWS) to provide species-specific recovery information, for consideration in prioritization analyses. Species name and any subspecies or variety distinctions is recorded, whether currently present on Lānaʻi, the type of climate-defined species range (range) used in the analysis, and the minimum proportion of available area of the range required to meet USFWS recovery population criteria. Range type used was either the current range of predicted suitable habitat for the species or overlap between projected range under IPCC A1B climate scenarios and current ranges [34]. Overlap was used whenever possible. The proportion of range required was used as the target threshold in prioritization analyses. * Indicates that more than 100% of range available habitat was required to meet minimum USFWS recovery criteria; in this case we included all available habitat. All species included are listed by USFWS as threatened or endangered.

Species	Currently on Lānaʻi	Range Type Used	Proportion of Range Required
<i>Abutilon eremitopetalum</i>	Yes	Current	0.061512
<i>Abutilon menziesii</i>	Yes	Overlap	0.002952
<i>Achyranthes splendens</i> var. <i>rotunda</i>	No	Overlap	0.007493
<i>Bidens micrantha</i> subsp. <i>kalealaha</i>	Yes	Overlap	0.007787
<i>Bonamia menziesii</i>	Yes	Overlap	0.052192
<i>Canavalia pubescens</i>	Yes	Overlap	0.007454

Species	Currently on Lānaʻi	Range Type Used	Proportion of Range Required
<i>Cenchrus agrimonoides</i> var. <i>agrimonoides</i>	No	Overlap	0.009817
<i>Ctenitis squamigera</i>	Yes	Current	0.116549
<i>Diplazium molokaiense</i>	No	Current	1
<i>Gardenia brighamii</i>	Yes	Overlap	0.243153
<i>Hesperomannia arborescens</i>	No	Current	0.093239
<i>Hibiscus brackenridgei</i> subsp. <i>brackenridgei</i>	Yes	Overlap	0.061269
<i>Isodendron pyrifolium</i>	No	Overlap	0.008044
<i>Labordia tinifolia</i> var. <i>lanaiensis</i>	Yes	Current	1 *
<i>Mezoneuron kavaense</i>	Yes	Overlap	0.001557
<i>Neraudia sericea</i>	No	Overlap	1 *
<i>Nothocestrum latifolium</i>	No	Overlap	0.003115
<i>Panicum fauriei</i>	Unknown	Overlap	0.030484
<i>Phyllostegia haliakalae</i>	No	Current	0.484406
<i>Pleomele fernaldii</i>	Yes	Current	0.276803
<i>Portulaca sclerocarpa</i>	No	Overlap	0.003894
<i>Pseudognaphalium sandwicense</i> var. <i>molokaiense</i>	No	Overlap	0.002485
<i>Schenkia sebaeoides</i>	No	Overlap	0.051641
<i>Sesbania tomentosa</i>	Yes	Overlap	0.005078
<i>Silene lanceolata</i>	No	Overlap	0.098108
<i>Solanum incompletum</i>	No	Current	0.109162
<i>Spermolepis hawaiiensis</i>	Yes	Overlap	0.007454
<i>Tetramolopium lepidotum</i> subsp. <i>lepidotum</i>	Yes	Overlap	1 *
<i>Tetramolopium remyi</i>	Yes	Current	0.040409
<i>Vigna o-wahuensis</i>	No	Overlap	0.004969
<i>Zanthoxylum hawaiiense</i>	No	Current	0.137787

Appendix B

List of species considered, but not included, for analysis based on expert consultation and recovery criteria. Threatened and endangered status (T&E) is recorded, species name and any subspecies or variety distinctions, and reason it was not included. No habitat available on Lānaʻi as identified by using climate-defined species ranges (ranges) and/or no recovery criteria for Lānaʻi identified by U.S. Fish & Wildlife Service (USFWS) were reasons for exclusion. * Indicates that no range was available for the species across the state.

Status	Species	Reason for Exclusion
T&E	<i>Adenophorus periens</i> , extirpated; possibly extinct	No range
T&E	<i>Asplenium dielirectum</i> , extirpated	No range *
T&E	<i>Clermontia oblongifolia</i> subsp. <i>mauiensis</i> , extirpated	No range
T&E	<i>Cyanea gibsonii</i>	No range
T&E	<i>Cyanea lobata</i> subsp. <i>baldwinii</i>	No range
T&E	<i>Cyanea munroi</i>	No range
None	<i>Cyrtandra lydgateii</i>	No recovery criteria; no range
T&E	<i>Cyrtandra munroi</i>	No range
Extinct	<i>Delissea Lānaʻiensis</i>	No range *
Extinct	<i>Haplostachys munroi</i>	No range *
T&E	<i>Kadua cordata</i> subsp. <i>remyi</i>	No range
T&E	<i>Kadua laxiflora</i>	No range
Extinct	<i>Melanthera populifolia</i>	No range *
T&E	<i>Melicope munroi</i>	No range

Status	Species	Reason for Exclusion
None	<i>Metrosideros waialeale</i>	No recovery criteria; no range
Extinct	<i>Phyllostegia glabra</i> var. <i>Lānaʻi</i> ensis	No range
T&E	<i>Santalum haleakalae</i> var. <i>Lānaʻi</i> ense	No range *
None	<i>Sticherus owhyhensis</i>	No recovery criteria; no range
T&E	<i>Tetramolopium conyzoides</i>	No recovery criteria; no range *
T&E	<i>Viola Lānaʻi</i> ensis	No range
T&E	<i>Wikstroemia bicornuta</i>	No recovery criteria; no range

Appendix C

Justification for scenarios considered in spatial prioritization analysis. T&E indicates threatened and endangered status as determined by the U.S. Fish & Wildlife Service. The conservation zone will support T&E species targets while the hunting zone will support hunting targets, with zones exclusive of one another.

Scenarios	Justification
T&E species and hunting targets: no lock-in constraints, no boundary constraints	Identify most efficient areas for T&E species recovery efforts while balancing for highly suitable hunting areas.
T&E species and hunting targets: no lock-in constraints, boundary constraints	Identify areas for T&E species recovery efforts and highly suitable hunting areas while encouraging zone contiguity. This will aggregate zone areas for reducing the number of management areas and likely reduce fence construction and maintenance costs. Larger conservation areas may be more appealing to managers to conserve habitat for non-target species.
T&E species and hunting targets: lock-in constraints, boundary constraints	Confirm larger conservation area (lock-in) can provide recovery habitat for T&E species and maintain sufficient hunting area. Identify where additional conservation areas are needed.
T&E species and hunting targets, 95% native vegetation target included in conservation zone: no lock-in constraints, no boundary constraints	Identify how much additional area is needed to conserve existing native vegetation and meet T&E species targets. Demonstrates the extent to which the two conservation goals overlap.

Appendix D

The Hawaiian Island of Lānaʻi with maps of footprints where all threatened and endangered species targets were met in the conservation zone (green) and 70% of public and 55% of private hunting areas targets met in the hunting zone (orange). Both scenarios included a boundary penalty, and neither included lock-in constraints (conservation areas, outlined in red). Figure A1a displays a footprint with no native vegetation target included, while Figure A1b includes a 95% native vegetation target. Inclusion of the native vegetation target drives, and largely reconfigures, the conservation zone. Minimizing the area needed for T&E species recovery would occur largely outside of native vegetation, requiring substantial restoration efforts before creating new species populations. It also highlights that removal of axis deer and mouflon need not occur immediately throughout the planned conservation area on the eastern portion of the island in order to protect existing native vegetation and recover T&E species.

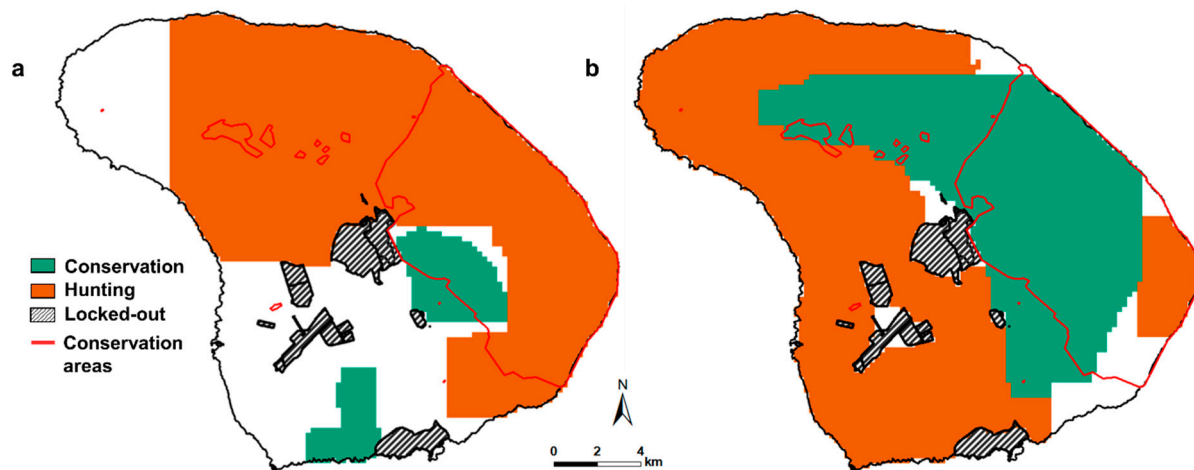


Figure A1. The Hawaiian Island of Lānaʻi with maps of conservation footprints where all threatened and endangered species targets were met in the conservation zone (green) and 70% of public and 55% of private hunting areas targets met in the hunting zone (orange).

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