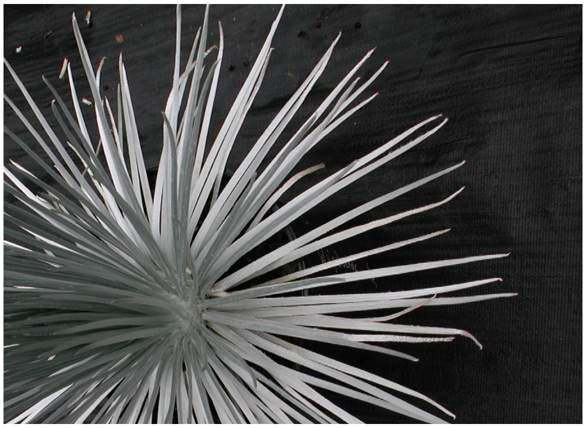
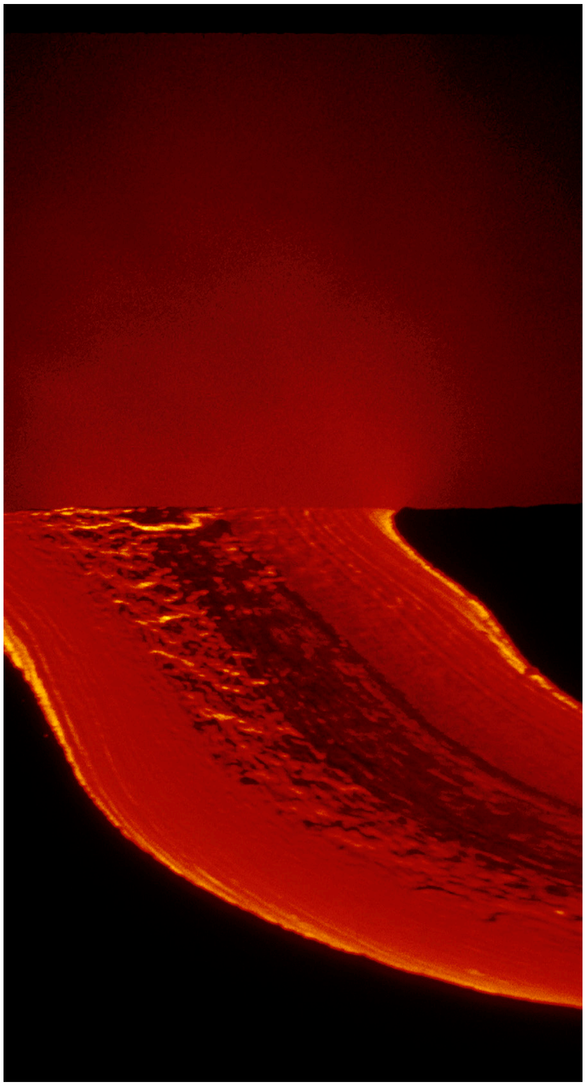


UHERO
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAI‘I

RETURN ON INVESTMENT FOR WATERSHED PROTECTION ON KAUA‘I

FEBRUARY 28, 2025



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Return on Investment for Watershed Protection on Kauaʻi

Funded by The Nature Conservancy

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Executive Summary

Native forests provide many societal benefits, including protecting freshwater resources that provide drinking water and sustain culturally, economically, and ecologically valuable springs, streams, and groundwater dependent ecosystems. The objectives of this report are to: (1) model future management scenarios for Kauaʻi's native forests that are co-developed with The Nature Conservancy (TNC) to quantify the impact of conservation efforts on water resources; (2) estimate gallons of groundwater recharge saved with existing or expanded (existing + proposed) watershed conservation efforts using a spatially explicit water balance model; and (3) to estimate conservation costs associated with management units and associated return on investment in terms of gallons of recharge per dollar spent. Building on previous work for Maui, Oʻahu, and Hawaiʻi Island that examined the economic benefits of hydrologic services from watershed protection and restoration, this project studies 16 major (> 200 acres) completed and proposed fence areas that fall within the Kauaʻi Watershed Alliance. Land cover, evapotranspiration (ET), and recharge-to-runoff ratio data are combined with State and TNC conservation cost information to estimate the gallons of recharge saved per dollar invested in watershed conservation. Over a 50-year time horizon and given an invasive canopy spread rate of 3% and a discount rate of 3%, 593 gallons of groundwater recharge are saved on average per dollar invested in existing fence units, spanning from 85 gal/$ up to 2625 gal/$ depending on the specific fenced region. When proposed fences are included, the average ROI falls slightly to 567 gal/$, with a range of 60-2641 gal/$ across various units. This study demonstrates the importance of taking a long-term view on conservation ROI, as conservation costs are often front-loaded because of initial fence construction and ungulate removal costs, while annual water benefits grow continuously as the avoided loss of recharge increases over time.

1. Introduction

Project Overview

The primary aim of this research is to estimate groundwater recharge services protected by The Nature Conservancy and partners' watershed conservation work across Kauaʻi's native forests. First, forest cover change is modeled under different conservation scenarios (no conservation, existing conservation, expanded conservation) based on existing data on invasive species spread. This is then coupled with conservation cost data and a hydrologic ecosystem service model, from which we project avoided loss of groundwater recharge over the next 50 years to provide spatially-explicit estimates of benefits, costs, and returns on investment (ROI).

Description of Kaua'i and the Study Sites

Over half of Hawaiʻi's native forest area has already been lost, and the remaining native forest continues to be highly threatened by the expansion of invasive plants and ungulates such as feral pigs (DLNR, 2011). Kauaʻi, the oldest main Hawaiian Island, has a very high diversity of native plants and a wide range of habitat types, spanning from lowland mesic to montane wet forest and bog (DLNR, 2013). Approximately 90% of Hawaiʻi's native plant species are endemic and 72% of those are threatened with 5% having already gone extinct (Rønsted et al., 2022). Kauaʻi has the highest number of single island endemic taxa in Hawaiʻi at 251 (Rønsted et al., 2022). This high level of endemism demonstrates the uniqueness and importance of Kauaʻi's forests. Invasive plant species and feral ungulates are key threats to native forests, with cascading impacts to stream and freshwater resources, including decreased groundwater recharge and increased runoff which can damage nearshore marine ecosystems and harm human health (KWA, 2003). On Kauaʻi, pigs (*Sus scrofa*), goats (*Capra hircus*), and black-tailed deer (*Odocoileus hemionus*) continuously damage native forests and spread invasive plant species, in addition to creating damaged areas where, for example, mosquitoes breed. One species of invasive mosquito, *Culex quinquefasciatus*, spreads avian malaria, killing Hawaiʻi's endangered native birds, and has therefore been targeted for population control in upper watersheds of Kauaʻi and Maui via the Incompatible Insect Technique (*Wolbachia*) and, most recently, the larvicide *Bacillus thuringiensis israelensis* (BLNR Item C-1, 6/28/24). Successful results have been seen in pilot projects of both techniques and simultaneous deployment has recently begun.

Without conservation actions, over time, native forests may only persist on steep cliffs that ungulates cannot traverse. However, when areas are fenced and pigs are removed, native vegetation in higher elevation forests has often been found to recover (Jacobi, 1976; Katahira, 1980; Higashino & Stone, 1982). Fences severely reduce the spread of most invasive plants by preventing ungulate traffic into protected areas, but birds can still introduce seeds and a few plants spread via spores in wind and water, notably Mule's foot fern (*Angiopteris evecta*) and Australian tree fern (*Cyathea cooperi*). Conservation organizations also often carry out invasive plant control efforts and restoration within fenced areas.

The Kauaʻi Watershed Alliance, formed in 2003 and whose members include the Division of Forestry and Wildlife (DOFAW), Kauaʻi's Department of Water, and private landowners, protects the island's upper watershed areas in coordination with The Nature Conservancy (TNC). TNC has established conservation agreements with a number of landowners, for example with Alexander & Baldwin, Inc. which previously owned most of Wainiha. Additionally, TNC conducts ungulate and weed control and management within fenced areas. The current fenced areas include: East Alakaʻi, Honopu, Drinking Glass, Halehaha, Koaiʻe, Hono O Na Pali, Limahuli, Wainiha, Lāʻau, and Nāmolokama (Fig. 1). Proposed fenced areas include: Awaʻawapuhi, Blue Hole, Hanalei, ʻIliʻiliʻula, Lumahaʻi, and Mōhihi (Fig. 1). Rainfall for these areas ranges between 1400 - 6900 mm and they span in elevation from 500 - 5150' (Figs. A1-A2 in Appendix 1). The forest types considered in this study include lowland wet, montane wet, montane bog, wet cliff, dry cliff, montane mesic, and lowland mesic forests (Price et al., 2016). Smaller fenced areas on Kauaʻi not considered for this study, as they are < 200 acres, include Kanaele Bog, Hawaiʻi's only remaining lowland bog, and Kuʻia Natural Area Reserve. Except for a portion of land that encompasses south Alakaʻi Swamp and Kawaikini, Kauaʻi's tallest peak, these fenced areas comprise the entirety of Kauaʻi's high elevation forests. Precipitation in this area, the Alakaʻi Plateau, turns to surface flow that feeds into seven major rivers that flow through northern, southern, eastern, and western valleys of the island, while also filtering into subterranean aquifers. The plateau acts as a living sponge absorbing moisture from passing clouds, mitigating impacts of drought and flood by providing a constant source of streamflow (Kauaʻi Watershed Alliance, 2009).

Figure 1. Existing and proposed native forest fence areas on Kaua'i (> 200 acres)

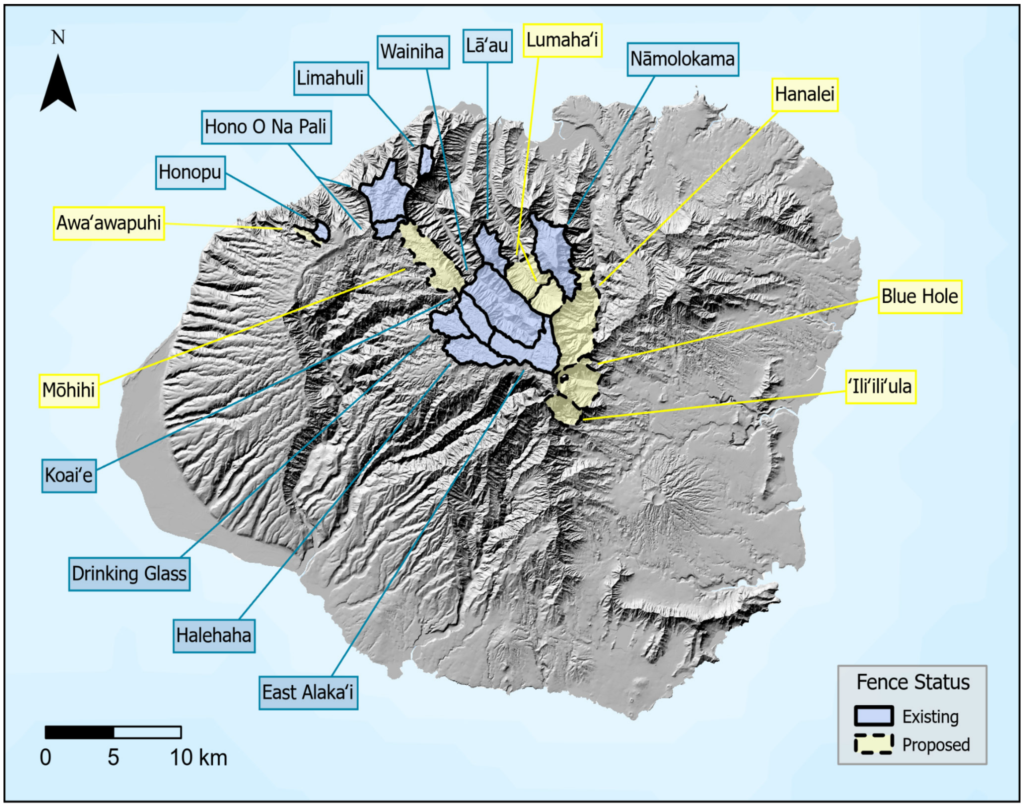
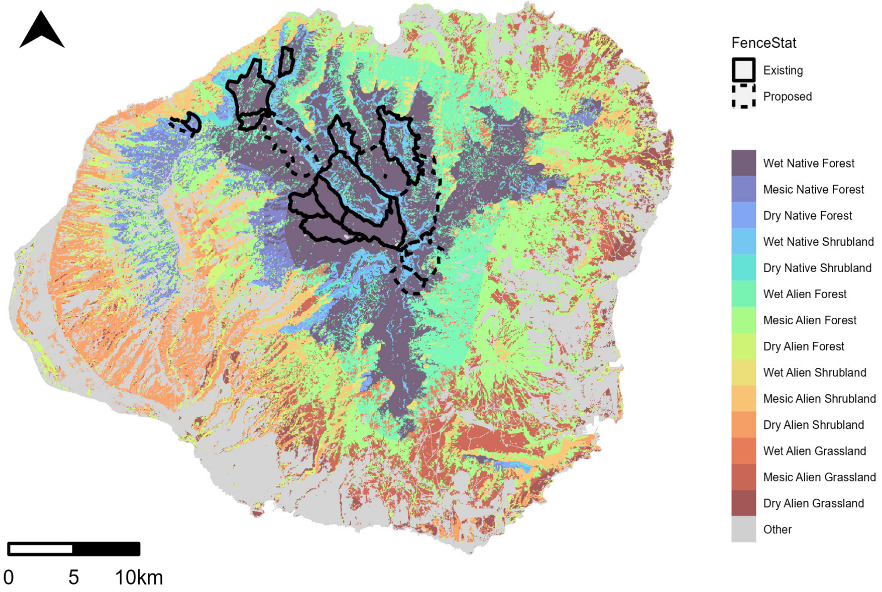


Figure 2: Simplified land cover (derived from Jacobi et al. 2017, Carbon Assessment of Hawai'i 2016 land cover map).



Protective fence projects often involve construction of 4' tall hog wire fences, establishment of weatherports and radio repeaters (in remote locations), and management and monitoring of invasive species, both flora and fauna. Some fences on Kaua'i need to be 8' to prevent deer from crossing into protected areas (Solicitation No. B19001482). Additionally, strategic fences, in companion with steep cliffs and terrain, protect large regions at relatively low cost. For example, Wainiha's 800 m of strategic fencing, in combination with the steep walls of the valley, protects just over 5,600 acres of forest (Wood, 2007).

At a cost of $700,000, fences for Wainiha and East Alakaʻi were funded in 2011 (The Garden Island, 2011). In 2018, four fencing projects on Kauaʻi received money through the State's Capital Improvement Project: Drinking Glass ($1.2 million), Hono O Na Pali ($131,000), Koaiʻe ($300,000), and East Alakaʻi (retrofit, $350,000) (Else, 2018). These front-loaded fence construction costs constitute a major portion of the overall conservation costs for protecting a native ecosystem. Maintenance, monitoring, and replacement is also needed over time to repair and replace fences. Maintenance in bog areas may require additional costs, for example if fence skirting rusts, as has been noted for East Alakaʻi (Solicitation No. B19001482), or is damaged by pigs (Wood, 2006). Areas with higher average rainfall will require more frequent replacement, the degree of which is currently unclear. Additionally, fence construction timelines may prohibit construction during the breeding and nesting seasons of forest birds and seabirds (Solicitation No. B19001482). Other costs have previously included critical studies of biological diversity (Wood, 2007, 2009, 2013), which serve to both note and protect native plants during fence construction and also present opportunities to survey and collect rare taxa, further justifying conservation efforts.

Background: Watershed Services and Investment in Hawai'i

Watershed management and hydrological processes

Watershed conservation and restoration activities have gained increasing attention in Hawaiʻi and around the world as a way to protect and enhance freshwater resources, biodiversity, cultural values, and other ecosystem services. In Hawaiʻi, understanding the links between watershed management and groundwater recharge is of particular interest because of the importance of groundwater for drinking and for culturally and ecologically important ecosystems. Watershed partnerships and other conservation organizations in Hawaiʻi protect and restore native forests through activities such as fencing, ungulate removal, invasive plant control, and native species outplanting and monitoring (Burnett et al., 2014, 2017). Research from UHERO has demonstrated important economic benefits of native forest conservation and resulting protection of groundwater recharge in watersheds on Oʻahu, Hawaiʻi Island, and Maui (see Bremer et al., 2018, 2019a, 2019b, 2021; Burnett et al., 2014, 2017; Wada et al., 2017, 2019).

There are three main mechanisms by which protecting native forest can help to protect freshwater resources: through influencing actual evapotranspiration (AET), infiltration (partitioning between recharge and runoff), and fog interception rates. First, where invasive species have higher actual evapotranspiration (AET) rates, protecting native forest can protect water yield and groundwater recharge. At the site scale, studies have found evidence that some native plant species in Hawaiʻi tend to have lower water use (i.e. evapotranspiration) compared to some non-native invasive species (Cavaleri & Sack, 2010; Cavaleri et al., 2014; Giambelluca et al., 2008; Kagawa et al., 2009). For example, Giambelluca et al. (2008) found that a site heavily invaded by strawberry guava (*Psidium cattleianum*) had 27% higher evapotranspiration compared to a native ʻōhiʻa (*Metrosideros polymorpha*) forest. Cavaleri et al. (2014) observed that native ʻōhiʻa had the lowest sap flow rate per unit sapwood compared to non-native tree species, and removing non-native trees was associated with a 54% decrease in plot-level transpiration.

Second, forest composition can influence fog interception. Takahashi et al. (2011) estimated that a native forest stand intercepted 1,188 mm of cloud water annually compared to 734 mm in a stand invaded by strawberry guava in Hawaiʻi Volcanoes National Park. However, spatial data on fog interception and the influence of native vs. non-native canopy fog interception rates are limited. Finally, protection of forests from ungulates may increase infiltration leading to a higher percentage of water infiltrating into the soil than running off. Results from Fortini et al. (2020) suggest, all other factors held constant, there is a 25.5 percent increase in infiltration for fenced forests free of signs of ungulates as compared to heavily ungulate damaged forests.

Watershed analyses of hydrologic services provided by native forest protection

At the watershed scale, a study by the U.S. Geological Survey modeled a 10% increase in groundwater recharge for several hydrological units on Hawai‘i Island when converting the current land cover to a scenario with all non-native forest replaced by native forest (Engott, 2011). Watershed conservation benefits and costs for five watershed management units on Hawai‘i Island showed substantial variability in the volume of freshwater yield saved per dollar invested, ranging from 15 gallons per dollar in the Manuka unit to over 1,800 gallons per dollar in the Pu‘u O ‘Umi unit (Burnett et al., 2014). A related analysis for multiple conservation sites on Hawai‘i Island estimated that on average 392 gallons of freshwater yield (the sum of groundwater recharge and surface water runoff) are saved per dollar invested in conservation over a 50-year time period, with conservation costs front-loaded while benefits increase continuously (Burnett et al., 2017). Bremer et al. (2019a) combined land cover and water balance modeling to quantify the benefits of protecting native forest from conversion to non-native forest in terms of groundwater recharge in East Maui, finding that planned conservation activities could protect between 13.4-32.3 billion gallons of groundwater recharge over 100 years. This translated to $2.7-137.6 million in cost savings to the local water utility (Bremer et al., 2019a).

Wada et al. (2019) developed a prioritization framework for investments in watershed protection and restoration on Hawai‘i Island based on modeled groundwater recharge benefits, accounting for both the likelihood of land cover change in the absence of conservation as well as the hydrologic impacts of that change. In the highest priority protection areas, watershed protection saved 5.2 million gallons per acre over 50 years (Wada et al., 2019; Bremer et al., 2019b; Bremer et al., 2021). Key findings included: 1) lower to mid elevation areas at high risk of invasion by non-native canopy species and higher elevation areas at risk of conversion to grassland were high priority for protection benefits; and 2) for restoration, the greatest benefits occurred in higher elevation areas with substantial fog interception, while recharge decreased with restoration in lower elevation areas (Bremer et al., 2021).

These studies highlight the importance of considering the long-term benefits of conservation, as annual benefits tend to increase over time while costs are more front-loaded due to initial fence construction and ungulate removal (Burnett et al., 2014).

2. Methods

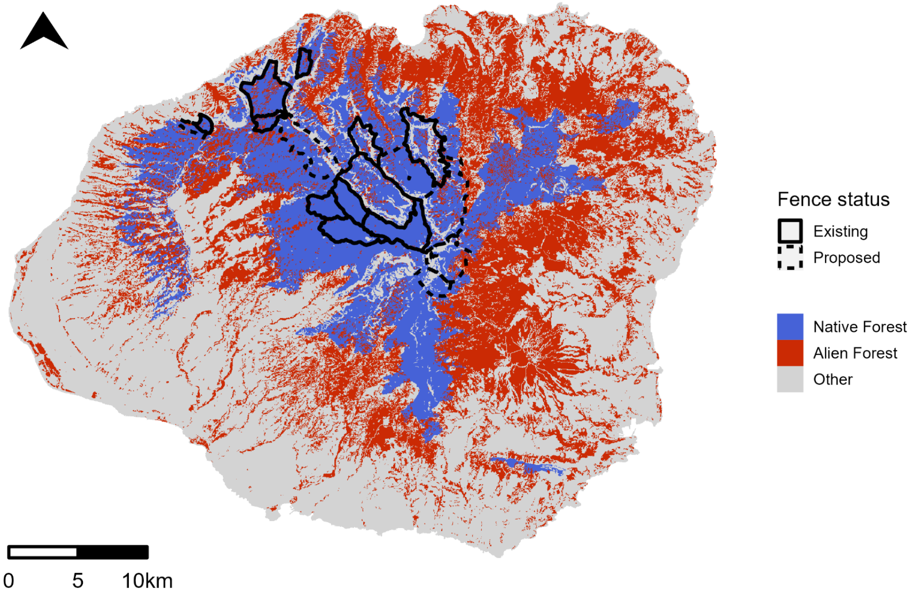
Scenario Development

Based on discussions with TNC, we developed two management scenarios, scenario one where existing fences are maintained into the future (“existing”), and scenario two where conservation is expanded to include proposed fencing (“expanded”). To assess the benefit of each of these scenarios, recharge benefits were calculated for the absence of conservation as a counterfactual (no management) scenario. A shapefile providing the outlines of existing and future proposed managed areas was provided by TNC. Figure 1 shows a map of these areas.

To model potential forest cover change under the three scenarios over a 50-year time horizon, we adapted a land cover model used in previous studies (e.g. Bremer et al. 2021; Bremer et al. 2019a,b; Wada et al. 2019) starting with the baseline land cover from the Carbon Baseline of Hawai‘i 30-meter land cover map (Jacobi et al. 2017; Figure 2). For the simulation, these land covers were categorized as native and alien forest, along with a separate “other” category (Figure 3). This is the most up-to-date land cover map currently available that includes native and non-native forest. While forest cover has likely changed since publication of this map, we consider this our baseline year 1 (2024) map.

In the *counterfactual scenario*, there is no protection from the spread of non-native forest. The spread is allowed to occur in unprotected areas, existing protected areas, and proposed protected areas. The two protection scenarios are then compared to the counterfactual scenario to estimate water recharge benefits. In the "*existing*" protection scenario, spread only occurs outside of existing fences. In the "*expanded*" protection scenario, spread only occurs outside existing and proposed fences. Each of the three scenarios were run independently, rather than simply "masking" existing and proposed management areas, as the spread model is dependent on surrounding land cover and protection status[1]. As shown in the results, this leads to minor differences in recharge benefits within existing fenced areas between the existing conservation and the expanded conservation scenario.

Figure 3. Simplified - native and non-native land covers used for land cover modeling



The spread rate of alien forest was estimated using the best available science. The most comprehensive data set available is from the O'ahu Army Natural Resource Program (2022), which tracked the canopy spread of red cedar, strawberry guava, silk oak, and christmas berry alien forest types for 889 transects across O'ahu between May 2008 and May 2021. Figure 4 summarizes the spread rates for each species within the transects. Solid lines indicate the overall mean growth rate for each species, and dashed lines indicate their median growth rates. The averages generally fall within the 2% to 4% annual growth rate range. Because of this, along with collaboration with TNC, we selected a growth rate of 3% in our land cover spread simulation. This spread rate may be considered a conservative estimate, given that past estimates of spread rate were in the 5-10% range (Burnett et al. 2017; Bremer et al. 2021, 2019a,b).

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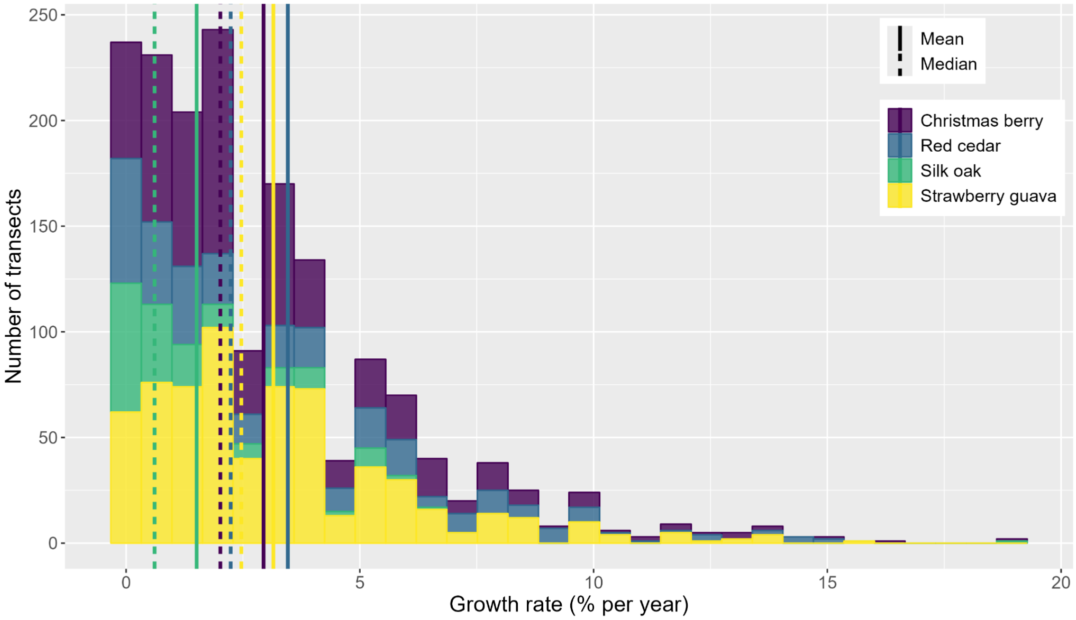
[1] For example, consider three regions susceptible to spread, A, B, and C, and only region A currently has non-native forest. In the scenario with no protection, non-native forest may spread from A through B and into C. However, if region B were protected, it may affect how (or whether) non-native forest is able to spread from A into C. Running the simulation separately for each scenario with the appropriate protections in place, rather than simply masking region B after the simulation, allows for these dynamic interactions to occur.

Figure 4. Distributions of alien forest spread rates with 889 transects on Oahu as measured by the Army Natural Resource Program



The spread rate of 3 percent was first used to determine the number of 30-meter pixels that needed to be converted from native forest to alien forest in a given year. The native forest pixels chosen for conversion were based on (1) adjacency to existing alien forest and (2) their relative susceptibility to invasion as mapped by Fortini et al. (2024). Susceptibility measures the ability of an alien species to replace the existing native species in an area, based on characteristics such as species type and climatic variables. Rasters providing the relative suitability of the alien landcovers *Leucaena leucocephala*, *Miconia calvescens*, *Morella faya*, *Psidium cattleianum*, *Schinus terebinthifolia*, and *Ulex europaeus* of invading native landcovers in the islands were obtained from Fortini et al. (2024). These were aggregated into a single invasibility raster by overlaying them and taking the max invasibility value for each pixel in the raster. The finalized invasibility raster was used to aid in determining which pixels to choose during the land cover spread simulation. Native forest pixels adjacent to existing alien forest were ordered according to their relative susceptibility, and those with the greatest susceptibility were converted until the required number of pixels according to the spread rate were converted. In instances where there were too few native forest pixels directly adjacent to alien forest pixels to convert the required number, all directly adjacent pixels were converted and the remainder required were then converted according to the same selection process described above.

After determining which pixels to convert each year, its land cover had to be converted to the most appropriate alien forest type in terms of moisture zone. In cases where the moisture zone was explicit (e.g., the native forest was classified as wet, mesic, or dry), the new alien forest type was assigned the same moisture zone. In other cases where the moisture zone was not explicit, one was assigned based on the mean annual rainfall of the pixel. To accomplish this, current rainfall from the Rainfall Atlas of Hawai‘i (Giambelluca et al. 2013) was overlaid on the land cover raster, and the distribution of rainfall for existing dry, mesic, and wet alien forest was determined. Pixels without an explicit moisture zone that were converted to alien forest were then assigned one by matching its specific mean annual rainfall to the closest median rainfall of dry, mesic, and wet alien forest types. So, for example, a pixel without an explicit moisture zone and with high mean annual rainfall would be assigned to wet alien forest upon conversion.

Groundwater Recharge Modeling

To estimate changes in mean annual groundwater recharge in the above-modeled "no protection" scenarios compared to the two protection scenarios, we used a water balance approach where:

Freshwater yield (groundwater recharge + surface runoff) = Precipitation (rainfall + fog) - actual evapotranspiration (AET).

Given a paucity of data on fog on Kauaʻi, we focus on changes in AET with forest cover change. AET is a function of atmospheric conditions, water availability, and vegetation characteristics. To estimate how changes in forest composition might change these variables and subsequently AET, we use an approach developed by Wada et al. (2017) and Bremer et al. (2019a), and utilize a large spatial dataset (for a total of 35,581 pixels across Kauaʻi) of current annual AET and a series of climatic vegetation predictor variables across Kauaʻi (Giambelluca et al. 2014). The change in AET as a result of a change in land cover was modeled using a regression method similar to that used in Bremer et al. (2019a). Within each native forest land covers susceptible to invasion and the invasive forest land cover types, we used a generalized least squares regression with AET as a function of atmospheric conditions (represented by Priestley Taylor Potential ET) and water availability (represented by available soil moisture):

$$AET_{\mathrm{i}} = \beta_0 + \beta_1 SM_{\mathrm{i}} + \beta_2 PT_{\mathrm{i}} + \varepsilon_{\mathrm{i}} \qquad (1)$$

where AET_i is the annual actual evapotranspiration of pixel i in mm/year, SM_i is the pixel-level soil moisture, PT_i is pixel-level mean annual Priestley-Taylor evapotranspiration in mm/year, and ε_i is the error term. This model was run separately on each land cover type so that a comparison could be made at the pixel level between the amount of AET before and after the land cover spread simulation. To reduce error resulting from the evapotranspiration model, modeled post-conversion AET was compared to modeled pre-conversion AET.

Changes in pixel-level AET were then aggregated for each management scenario: (1) existing conservation vs no protection and (2) expanded conservation vs no protection. The aggregated changes were then converted into volumetric values using the predicted change in evapotranspiration and the area of the pixels. These numbers allowed a comparison of changes to water yield under each scenario.

Because not all water yield translates into aquifer recharge due to runoff, change in recharge was estimated in each scenario using the water yield results. Recharge ratio values were created using a USGS water budget shapefile for the island of Kauaʻi (Kāne, 2024). This shapefile contained spatially-explicit values for annual recharge and runoff, which were converted to rasters in order to be overlaid with the water yield raster generated above. This resulted in a raster with recharge ratios calculated using the formula

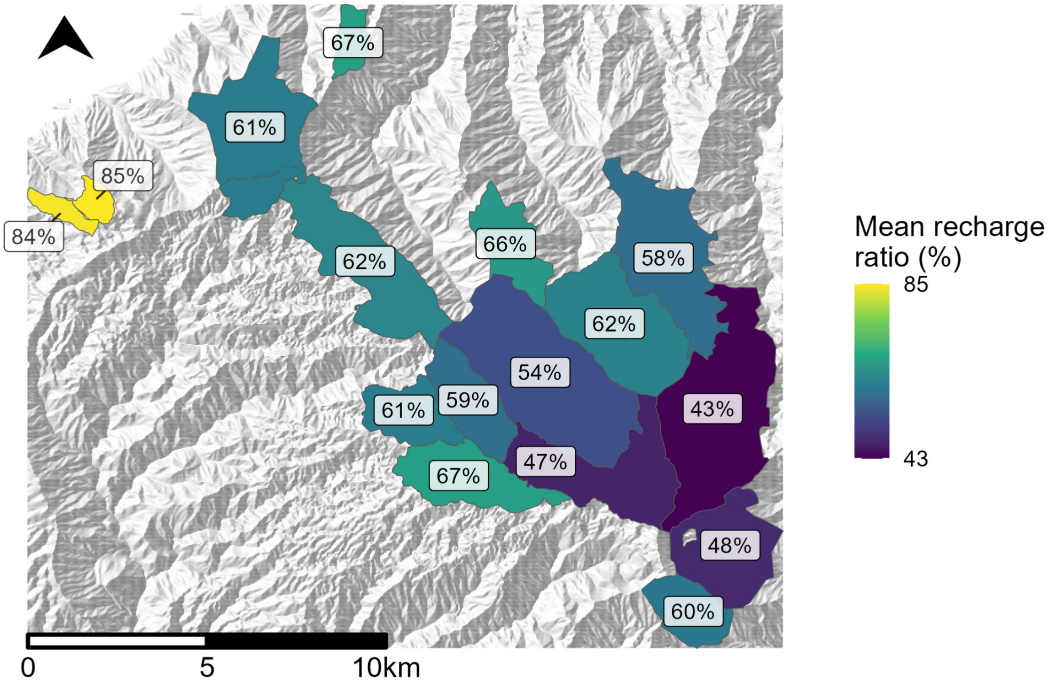
$$\text{Recharge Ratio} = \frac{\text{Recharge}}{\text{Recharge} + \text{Runoff}}$$

Thus, for each pixel i of the raster, the change in recharge in millimeters was calculated from the change in water yield in millimeters and the recharge ratios using the formula:

$$\text{Recharge}_i = \text{Recharge Ratio}_i \text{ x Water yield}_i \qquad (2)$$

Figure 5 summarizes the recharge ratios used in Equation (2) by management area, and Figures A1-A5 (in Appendix 1) provide maps of elevation, and the various climate variables, from the Climate Atlas of Hawaiʻi.

Figure 5. Summary of recharge ratios used in Equation (2)



Conservation Costs

Conservation costs for fenced units consist of the upfront costs from fence construction and initial ungulate removal followed by yearly ungulate, weed, and fence maintenance and monitoring. After 15-25 years (Barca, 2024), fences require replacement of most components, for which we estimate a cost of two-thirds the initial installation. Upon the next replacement, the entire fence is replaced at a cost equal to the initial installation.

Fence Costs

Costs for installation of existing fences were obtained or estimated from a variety of sources. For six of the units (Halehaha, Koaiʻe, Drinking Glass, Hono O Na Pali, Lāʻau, and Nāmolokama), labor costs for fence construction were obtained from DOFAW contracts and documents. Material costs were provided by DOFAW for both 4’ and 8’ fences at $11.37/LF and $13.51/LF, respectively (Yuen & O’Sullivan, 2024). A newspaper article (The Garden Island, 2011) was used to estimate the cost for Wainiha and East Alakaʻi. The cost for the Pohakea section of Hono O Na Pali was used as the best proxy for Limahuli, while Kuʻia (an area not considered in this study) was used as the proxy for Honopu. Estimated installation costs (2024$), including fence materials, ranged from a low of $39.6/LF to a high of $82.0/LF ($210,000/mi - $430,000/mi), and relate heavily to accessibility and terrain.

For proposed fences, we estimate installation costs using a combination of terrain type, accessibility, proximity to existing fences with known costs, and known ungulate threats. The costs for Lāʻau/Nāmolokama were used to estimate those of Lumahaʻi, Hanalei, Blue Hole and ʻIliʻiliʻula, while Koaiʻe was used for Mōhihi, and Kuʻia for Awaʻawapuhi. Of the seven proposed fences, the latter three would need to be 8’ tall due to nearby deer presence, while the other four would be 4’.

Additional Costs

The length and difficulty of initial ungulate extirpation or reduction after a fence was completed has varied widely on Kauaʻi, but has been reduced over time as managers improve techniques and methods. Wainiha and East Alakaʻi, for example, required five years before reaching the maintenance phase of ungulate management. Meanwhile, after Drinking Glass’ fence was constructed, a gate was initially left open with game cameras to monitor ungulate movement. Noticing seasonal migration of pigs out of the area and down into lower elevation forests in search of strawberry guava, managers closed the unit, leaving only a single pig remaining that was eventually snared.

We estimate each staff trip for ungulate management to be $5,500, made up of both helicopter transportation costs and staff time (Barca, 2024). An average trip requires three staff for four days with two hours of helicopter time. The initial burst of ungulate management for areas TNC manages is often two trips per quarter, or eight per year, reducing to one trip per quarter once ungulate levels have been sufficiently suppressed. On average, for a given area an additional monitoring trip, for a combination of weeds, ungulate, and fence monitoring, is conducted each year. Based on a DOFAW grant that funds TNC's priority weed removal and monitoring efforts on Kauaʻi for 2025-2027, we estimate an annual weed control cost of approximately $32,000 per unit. Additional costs include semi-permanent shelters known as weatherports ($27,000), often one per fence unit. As we were unable to obtain cost estimates, outside of those for fence construction, for Limahuli, Hono O Na Pali, and Honopu, we extrapolate from other fenced units with known costs on a per-unit basis.

Land cover data used in this study is not historical, only current, and therefore we simulate each unit, both completed and proposed ones, as if its fence was constructed over a two-year period starting in 2024. For each year over the 50 year time horizon, we calculate the annual cost for each fence unit and then convert the stream of costs to present value (PV), at a discount rate of 3%, such that there is a single value corresponding to each unit. Maintenance and replacement costs are not inflated.

Calculating Return on Investment

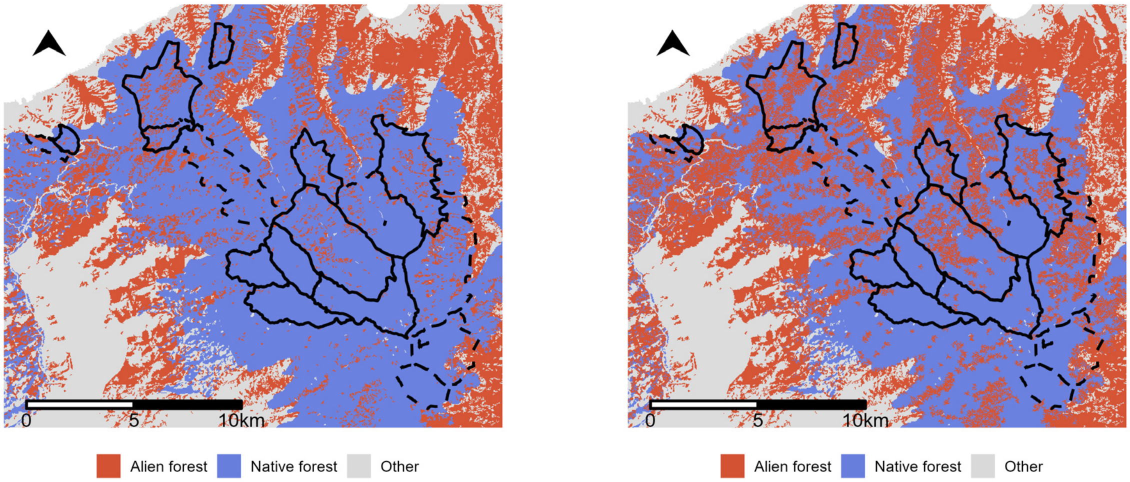
For each existing or proposed fence unit, we divide the change in modeled recharge within that unit by the present value cost of managing the unit. This results in unit-specific estimates of ROI in terms of gallons of protected recharge per dollar spent over 50-years that can be directly compared.

3. Results

Land Cover Results

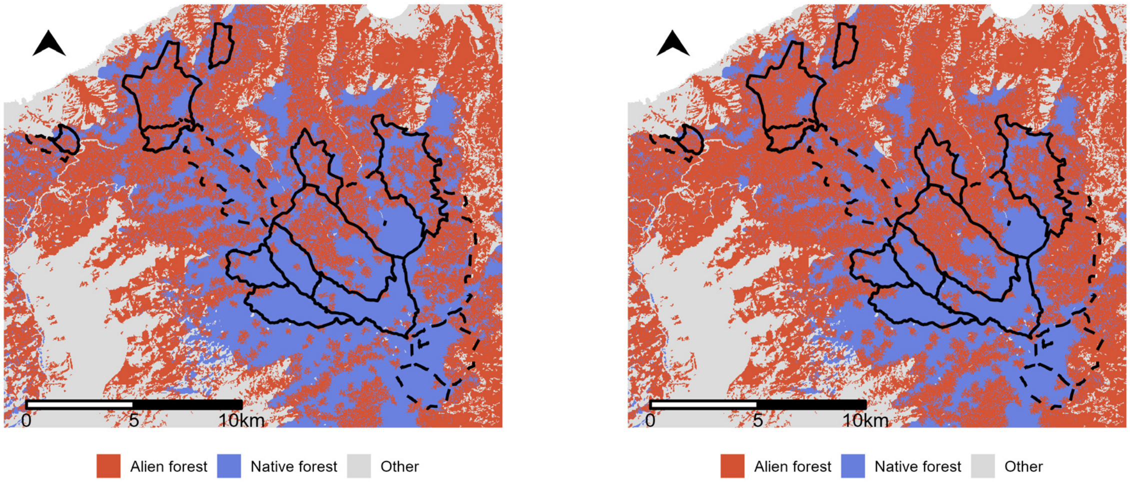
Based on data from the Oʻahu Army Natural Resources Program (2022) and discussions with TNC, a 3% spread rate was used to evaluate outcomes under existing fences, existing and proposed fences, and no conservation. Figure 6a presents the current land cover, i.e. the starting point of the spread model. Figures 6b-6f below illustrate years 10-50 outcomes of simulated non-native forest spread under the assumptions of no protection/fencing. For comparison, Figures 7a and 7b illustrate, respectively, simulated year-50 land cover for continued management of existing fence areas only and expansion to include proposed fences.

Figure 6. Spread simulation results with no protection (years 10, 20, 30, 40, 50). Solid lines denote existing fences, and dashed lines are proposed



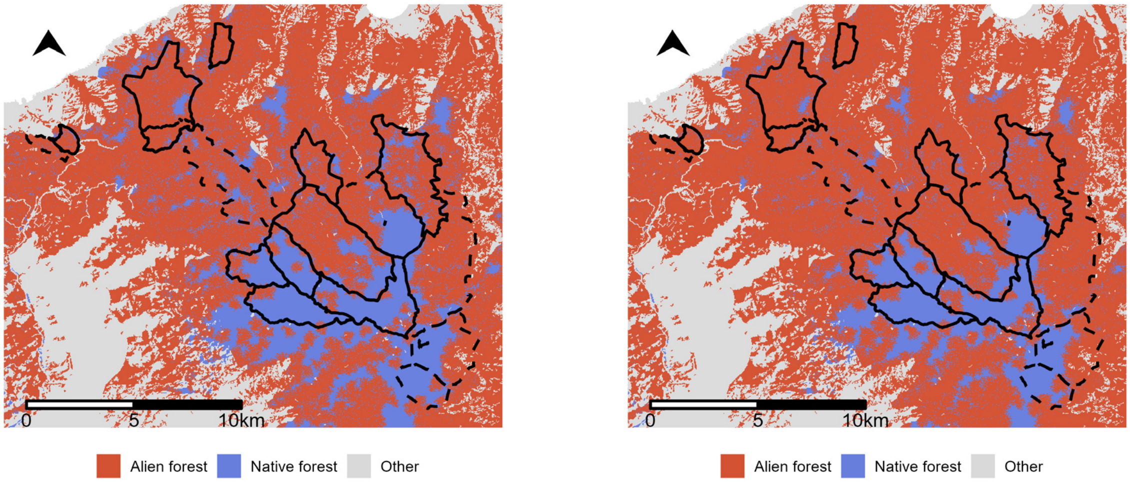
(a) Starting year (year 1)

(b) No protection (year 10)



(c) No protection (year 20)

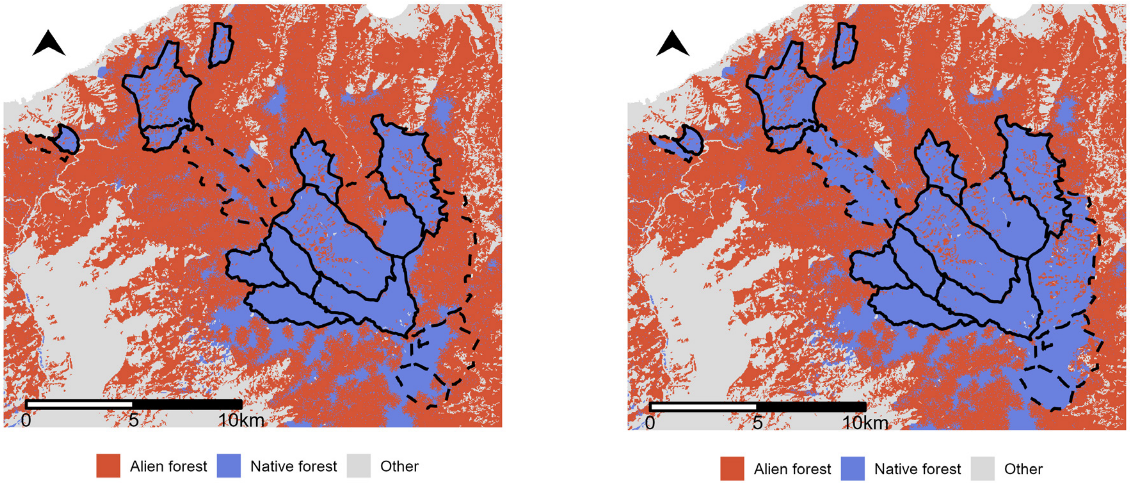
(d) No protection (year 30)



(e) No protection (year 40)

(f) No protection (year 50)

Figure 7. Spread simulation results (year 50) for (a) existing fence areas protected, (b) expanded protection to include proposed fences. Solid lines denote existing fences, and dashed lines are proposed.



(a) Existing fence areas protected (year 50)

(b) Expanded protection (year 50)

Conservation Cost Results

The 50-year present value cost of completed fence units, assuming a discount rate of 3%, varies from $1.63 million (Nāmolokama) to $6.86 million (Halehaha). These values are roughly proportional to the length of fence required to protect each unit, as the costs of fence installation, maintenance, and replacement comprise, by far, the largest share of watershed protection costs over the 50-year management period. Notably, the proportional increase in costs is not observed when comparing fence units in order of protected acreage. For example, the Wainiha unit protects the largest area (3,600 acres), yet has the third lowest PV cost ($1.96 million) of all managed units, while Limahuli protects an area one-tenth the size (360 acres) at more than double the cost ($4.02 million). This perhaps unexpected result is largely due to the fact that protection of the large Wainiha area was achievable by taking advantage of natural barriers that are not traversable by feral ungulates and therefore need not be fenced. While long term recurring costs like ungulate and weed maintenance tend to increase with the size of the managed area, they are largely overshadowed by fence costs, which are a function of installed length, rather than protected acreage. PV costs, installed fence length, and protected acreage of each completed fence unit are summarized in Table 1.

A set of six proposed fence units is presented in Table 1, with 50-year present value costs ranging from $3.2 million (Blue Hole) to $4.9 million (Mōhihi). As with the existing units, a proportional cost increase is not seen comparing fence units in order of protected acreage. This result is partly due to differences in terrain type, and therefore installation costs, and use of pre-existing natural and physical infrastructure. All but ʻIliʻiluʻula and Blue Hole would be adjacent to or connect two existing fenced areas, and all but Awaʻawapuhi would utilize natural barriers. Mōhihi's fence, for example, would span between the fences of Koaiʻe and Hono O Na Pali, with Wainiha valley's steep walls acting as a natural barrier. The present value of management costs in each management unit (in millions of dollars) is illustrated in Fig 8.

A summary of results for all management units is presented in Table 2. The weighted average daily recharge for East Alakaʻi, Halehaha, Drinking Glass, and Koaiʻe is 27 gal/acre/day.

Figure 8. PV costs of existing and proposed management areas, 50 years (in millions of dollars)

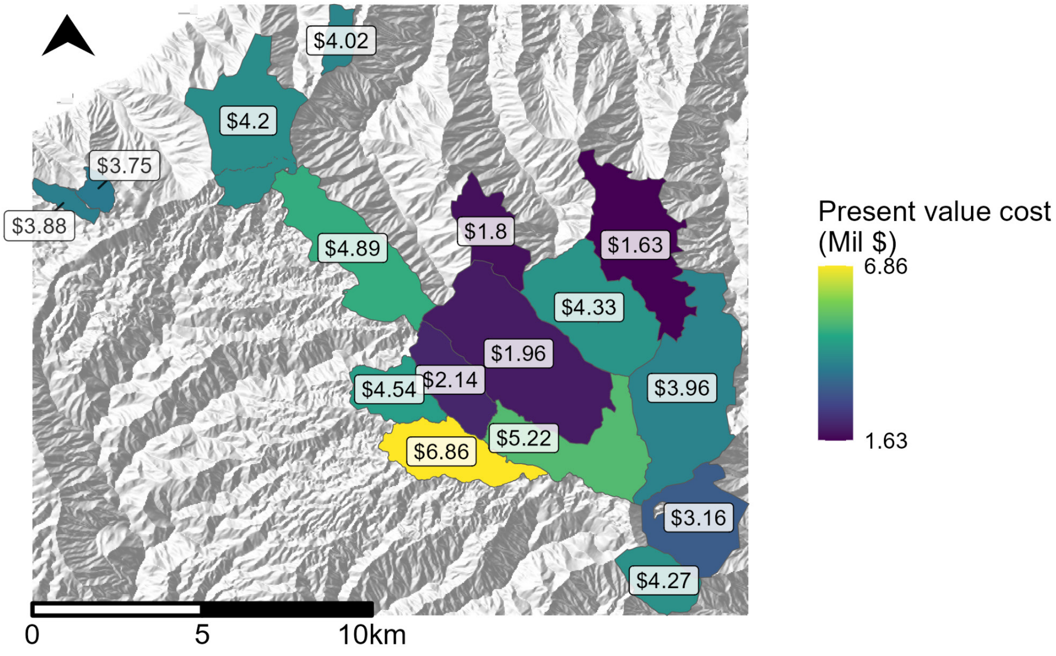


Table 1. Summary of costs for all management units. E=Existing and P=Proposed unit

Fence Units	Area (acres)	Length (miles)	Initial cost (0-2 years)	Total maintenance cost (2-50 years)	50-year PV Cost ($2024)
Wainiha (E)	3,600	0.5	$280,000	$1,680,000	$1,960,000
East Alaka'i (E)	2,000	4.7	$1,380,000	$3,830,000	$5,220,000
Halehaha (E)	1,350	7.0	$1,240,000	$3,300,000	$6,860,000
Drinking Glass (E)	900	4.6	$2,290,000	$4,570,000	$4,540,000
Koai'e (E)	1,100	0.8	$340,000	$1,800,000	$2,140,000
Lā'au (E)	1,000	0.4	$320,000	$1,470,000	$1,800,000
Nāmolokama (E)	2,300	0.2	$250,000	$1,380,000	$1,630,000
Limahuli (E)	360	3.6	$1,070,000	$2,950,000	$4,020,000
Hono O Na Pali (E)	2,400	4.1	$1,130,000	$3,070,000	$4,200,000
Honopu (E)	240	2.7	$1,030,000	$2,720,000	$3,750,000
Mōhihi (P)	2,200	5.2	$1,370,000	$3,520,000	$4,890,000
Awa'awapuhi (P)	240	3.0	$1,080,000	$2,810,000	$3,880,000
Lumaha'i (P)	2,300	2.9	$1,360,000	$2,970,000	$4,330,000
Hanalei (P)	3,400	2.5	$1,200,000	$2,770,000	$3,960,000
Blue Hole (P)	1,600	1.6	$840,000	$2,320,000	$3,160,000
'Ili'ili'ula (P)	800	2.8	$1,330,000	$2,940,000	$4,270,000

Table 2. Summary of results for all management units. E=Existing and P=Proposed units

Fence Units	Daily Recharge Protected (gal/acre/day)		Total Recharge Protected (million gal)		ROI (gal/dollar)	
	E	E+P	E	E+P	E	E+P
Wainiha (E)	76	77	5,137	5,170	2,625	2,641
East Alakaʻi (E)	14	14	504	509	97	98
Halehaha (E)	24	24	584	585	85	85
Drinking Glass (E)	49	49	784	787	173	173
Koaiʻe (E)	34	34	667	670	312	313
Lāʻau (E)	143	144	2,218	2,232	1,236	1,243
Nāmolokama (E)	87	89	3,723	3,793	2,284	2,326
Limahuli (E)	162	162	1,076	1,080	268	269
Hono O Na Pali (E)	134	134	5,860	5,875	1,396	1,399
Honopu (E)	197	202	861	886	230	236
Mōhihi (P)	-	116	-	4,662	-	954
Awaʻawapuhi (P)	-	189	-	842	-	217
Lumahaʻi (P)	-	45	-	2,710	-	626
Hanalei (P)	-	56	-	3,451	-	871
Blue Hole (P)	-	29	-	860	-	272
ʻIliʻiliʻula (P)	-	18	-	256	-	60

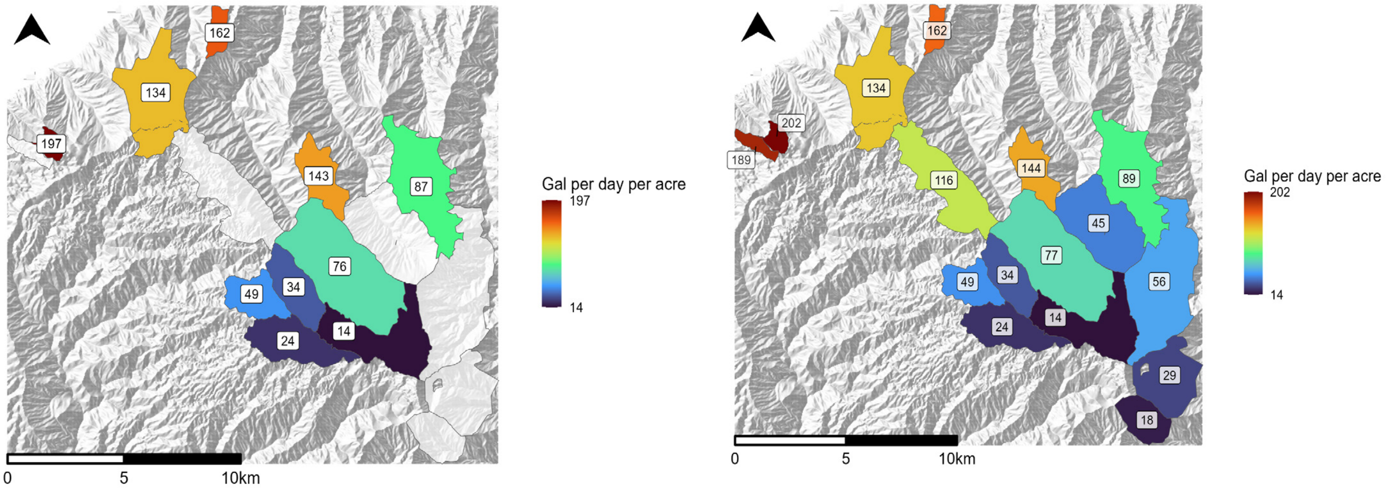
Groundwater Recharge and ROI Results

Figures 9a and 9b below illustrate modeled groundwater recharge benefits for all management areas. Recharge saved per acre expands to 14-202 gallons per day when proposed fences are included (from 14-197 gallons per day with existing fencing only), with the relatively drier Awaʻawapuhi and Honopu at the high end, and the relatively wetter ʻIliʻiliʻula and East Alakaʻi at the lower end. Awaʻawapuhi and Honopu have relatively high recharge ratios compared to the other units, so this at least partially explains why the benefits of management in terms of protected recharge are also highest. Management units with lower recharge to runoff runoff ratios appear to have lower relative benefit in terms of watershed conservation. Note, however, that these differences are also likely driven by the pattern of invasion. The East Alakaʻi management unit, for example, currently faces low invasion pressure, so the potential recharge benefits are relatively lower than in units such as Wainiha, which without protection would be much more quickly invaded and face large losses of groundwater recharge. Additionally, note there are minor differences in recharge between the scenario with only existing fences considered and the scenario with both existing and proposed fences considered. As mentioned in the methods, this is because the land cover spread simulation was run separately for each scenario to allow for the dynamic effects of fencing on land cover spread to occur.

Figures 10a and 10b illustrate modeled cumulative groundwater recharge benefits over 50 years for all management units. Cumulative protected recharge ranges from 504-5860 million gallons with existing fencing only and from 256-5875 million gallons when proposed fences are included. Hono O Na Pali and Wainiha generated the highest cumulative recharge benefits despite ranking nearer the middle in terms of recharge protected per acre. This is likely due to a combination of both units being relatively large acreage-wise and experiencing high invasion pressure in the spread simulations. The minor differences between the scenarios for the same units is caused by the differences in recharge driven by variations in land cover spread described above.

Figures 11a and 11b below illustrate return on investment across all management units. When factoring costs into the ROI calculations, the highest ROI management units are Wainiha and Nāmolokama. As discussed earlier, both Wainiha and Nāmolokama protect large areas with limited fencing due to the advantage of natural barriers, resulting in relatively high ROIs. All model results are presented in Table 1.

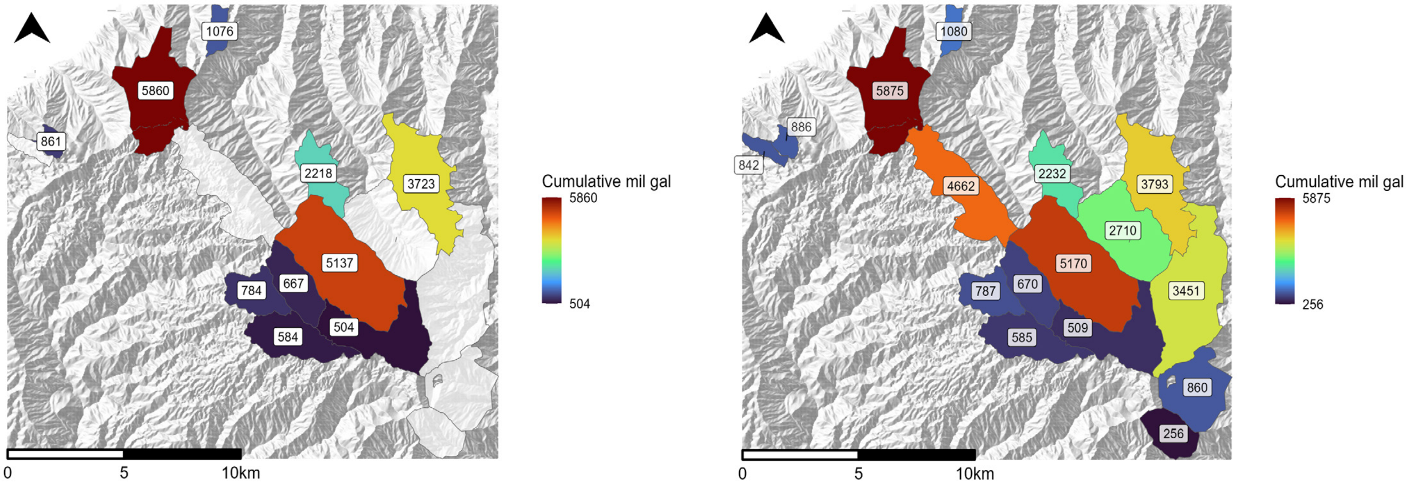
Figure 9. Groundwater recharge protected (gal/day/acre)



(a) Existing fences only

(b) Existing and proposed fences

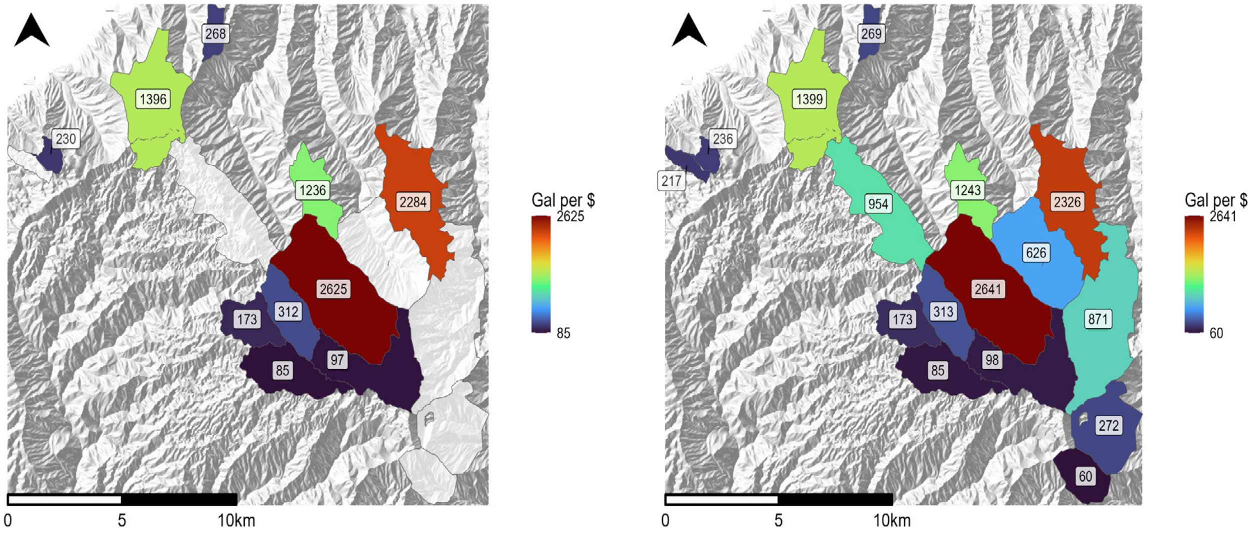
Figure 10. Cumulative recharge over 50 years (million gallons)



(a) Existing fences only

(b) Existing and proposed fences

Figure 11. ROI (gallons per dollar)



(a) Existing fences only

(b) Existing and proposed fences

4. Discussion and Conclusion

ROI of watershed protection

Using the best available data on spread rates of invasive species, existing land cover, climate, AET, and watershed conservation costs, we develop a spatially explicit model of groundwater recharge saved per dollar of conservation invested in fencing and maintenance over 50 years, for existing and proposed management units on the island of Kauaʻi. We consider the groundwater recharge benefits, as well as the return on investment on gallons per dollar invested for two management scenarios, the first considering continued maintenance of existing fences, the second management scenario expanding the existing stock of fences to include those proposed by TNC and the Kauaʻi Watershed Alliance. We find 593 gallons of groundwater recharge are saved per dollar invested on average within existing fences, spanning from 85 gal/$ up to 2625 gal/$ depending on the specific fenced region. The average ROI falls slightly to 567 gallons per dollar when proposed fences are included, and the range of ROI values for individual units expands to 60-2641 gal/$. These ROI's are still relatively high compared to similar analyses conducted on the island of Hawaiʻi, where approximately 400 gallons of freshwater yield (recharge + runoff) were protected per dollar, and on Maui, where roughly 321 gallons of recharge were protected per dollar (Bremer et al., 2019a).

The cumulative recharge benefit, aggregated across management units, increases from 21.4 billion gallons for existing fences to 34.4 billion gallons when proposed fences are included, a difference of 13.0 billion gallons. The ROI for those additional proposed units, at 529 gallons per dollar, explains why the average ROI falls slightly when expanding the management area to include proposed fences. These observed slightly reduced returns to investment in watershed protection for recharge benefits with expanded conservation suggest that the Kauaʻi Watershed Alliance has already been allocating resources efficiently by investing in fencing areas with higher ROIs first.

Groundwater recharge provided by protected native forests provides a suite of economic, social, and ecological benefits. Ninety nine percent of drinking water Hawaiʻi comes from groundwater (Tribble, 2008); by protecting groundwater recharge, the Kauaʻi Watershed Alliance helps to ensure healthy aquifers that can continue to support clean and ample drinking water supplies to support human health and well-being and our broader economy. Groundwater recharge also underpins healthy groundwater dependent ecosystems, which depend on flows of submarine groundwater recharge, including loko iʻa (fish ponds), anchialine pools, and nearshore ecosystems (e.g. coral reef and limu; Gibson et al., 2022; Okuhata et al., 2023). These systems have important economic, cultural, and ecological value and sustained groundwater for these systems is a protected public trust use of water (Sproat 2014; Gibson et al., 2022; Burnett et al., 2020). Forest conservation efforts that maintain groundwater recharge, thus help to ensure that public trust resources are protected and that these systems continue to provide important biocultural value and support traditional and customary rights. Research in Kona, for example, found that protecting native forests from conversion to non-native forest and grassland, helps to maintain salinity levels that support good habitat for a native and ecologically and culturally valuable limu, limu pālahalaha (*Ulva lactuca*) and are unfavorable to an invasive seaweed (*Hypnea musciformis*) (Bremer et al., 2021; Okuhata et al., 2023).

Spatial variability of Return on Investment in terms of Groundwater Recharge per Dollar Invested:

The highest ROI in terms of gallons of recharge saved per acre per day and gallons saved per dollar are in mid rainfall/elevation areas where invasion of non-native canopy species happens early, where the change in groundwater recharge with invasion is highest, and where management costs are relatively lower. Units that were able to build off of existing fences and/or benefited from natural barriers also tended to have higher ROIs because less fencing had to be built per acre of protected area. The spatial trend of middle elevation areas providing high groundwater recharge benefits was similarly found in a ROI study on Hawaiʻi Island (Wada et al., 2019).

There are many reasons that the Kauaʻi Watershed Alliance invests in conservation of high elevation and rainfall areas, including that these areas often have high levels of biodiversity and endemism, and support remaining habitat for native forest birds. While these areas are critical for groundwater recharge, such high elevation areas (see Appendix Figures A1 and A2) are not necessarily the highest benefit (avoided recharge loss from avoided increase in AET) areas, due to a combination of differences in the relative change in AET with forest change, relatively low recharge to runoff ratios, and the pattern of invasion. Our results also suggest that these areas do not necessarily generate the highest ROI (in gal/dollar), due to a combination of groundwater recharge benefits and the higher costs of fencing and other management activities in these areas.

For example, the East Alakaʻi management unit starts with very few invasive species, and even without fences the spread of invasives is not predicted to be as great as units such as Wainiha, which without protection would see a much more extensive invasion of alien species, and corresponding loss of groundwater recharge. However, for a longer management horizon, say 100 years, the invasion will eventually become much more pronounced in intact units like East Alakaʻi with low current invasion pressure, and consequently its long-term recharge benefits will increase. Note, however, that we did not model the impact of ungulates or fog, so the ROI for watershed protection activities in some areas, including in the fog zone, are likely underestimated.

Uncertainty

As with all modeling studies, there are a number of uncertainties in our analyses. First, our analysis is based on a 3% alien forest spread rate based on the best available data, but the actual rate of spread without conservation is uncertain and will likely depend on site conditions, specific management actions, as well as other events such as hurricanes or pathogen spread.

Second, actual evapotranspiration (AET) estimates were based on regression modeling using data from the Evapotranspiration Atlas of Hawaiʻi (Giambelluca et al., 2014), which used limited representative species water use data (i.e. strawberry guava (*Psidium cattleianum*) for non-native forest and ʻŌhiʻa lehua (*Metrosideros Polymorpha*) for native forest). The ratio of recharge to water yield was kept constant based on baseline data and was not altered with forest cover change, and our analysis did not account for the potential impact of forest management on this ratio or on fog interception. USGS runoff-to-rainfall ratios from Izuka et al. (2018) have significant spatial variability and discontinuities within a given drainage basin based partly on partitioning by catchment zone, which may lead to overestimates or underestimates of recharge for a fenced unit within or straddling between drainage basins. Finally, cost estimates are based on a subset of fence and maintenance data from the Division of Forestry and Wildlife and The Nature Conservancy and assume a discount rate of 3%, but actual costs may vary across management units and time.

Acknowledgements

This study was funded by The Nature Conservancy, Kauaʻi Terrestrial Program. We would like to thank Mele Khalsa, Lucas Behnke, Kelly Pummill, and Nicolai Barca for their collaboration and input into defining conservation scenarios and providing feedback on the modeling results in the context of field observations. We also thank Clay Trauernicht for support defining scenarios and in updating the spread model with empirical data from field surveys of invasive species spread. Finally, we thank Emma Yuen for providing conservation cost and fence data and for her input on the scenarios and broader context and utility of results.

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Appendix 1

Rasters for various climatic variables were obtained from the Hawaiʻi Climate Data Portal (Giambelluca et al., 2014). These rasters come at a 250m resolution, and were used to model evapotranspiration for the various land cover types involved in the simulations in this study. Following the model from equation (1), rasters for available soil moisture and annual Priestley-Taylor evapotranspiration (mm) were used to model actual evapotranspiration (mm) individually for each land cover of interest.

Figure A1-1. Elevation

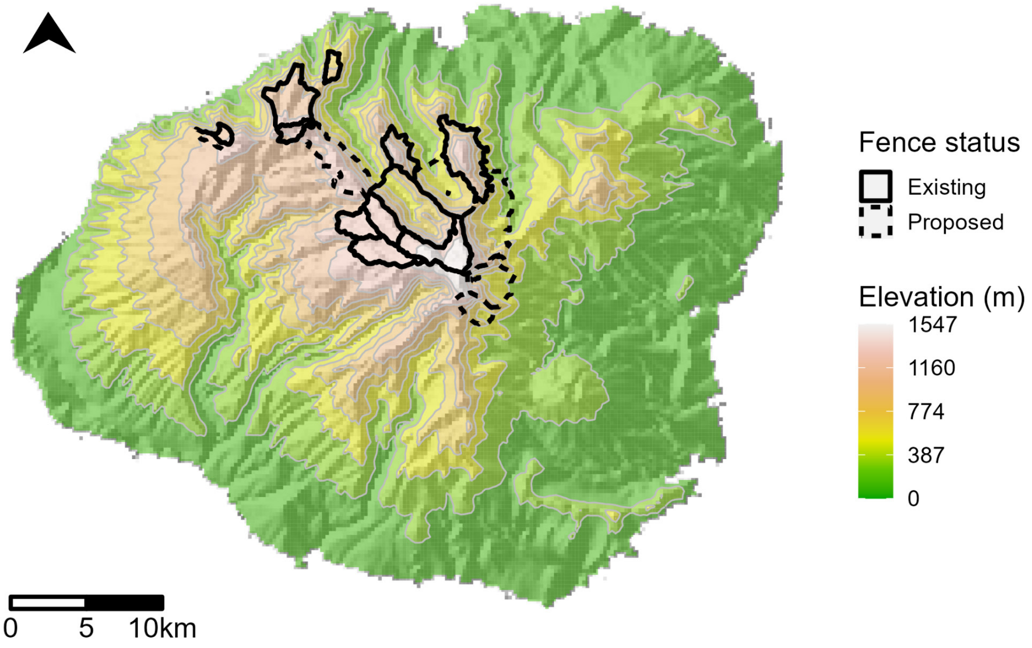

Figure A1-2. Rainfall

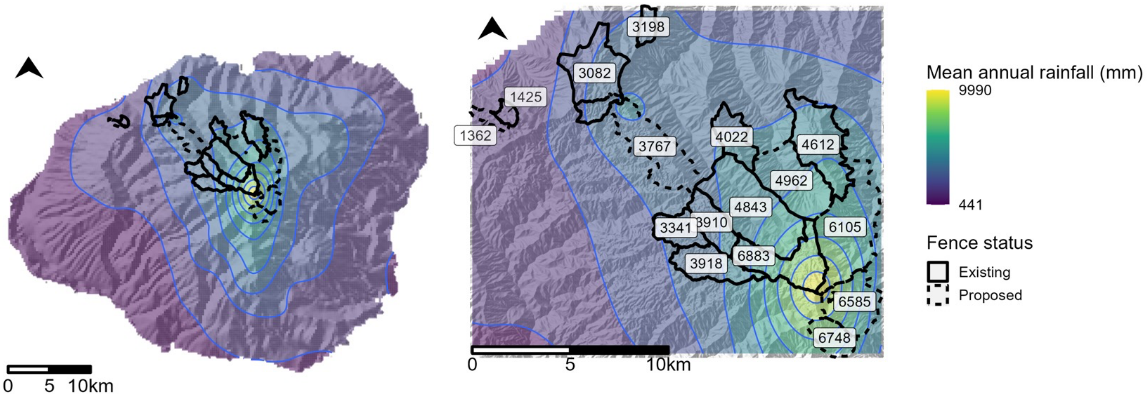

Figure A1-3. Priestley-Taylor ET

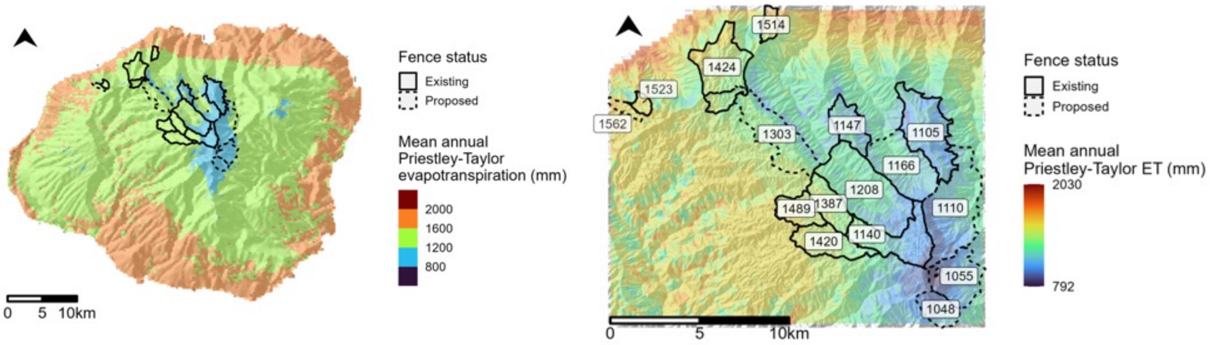

Figure A1-4. Actual ET

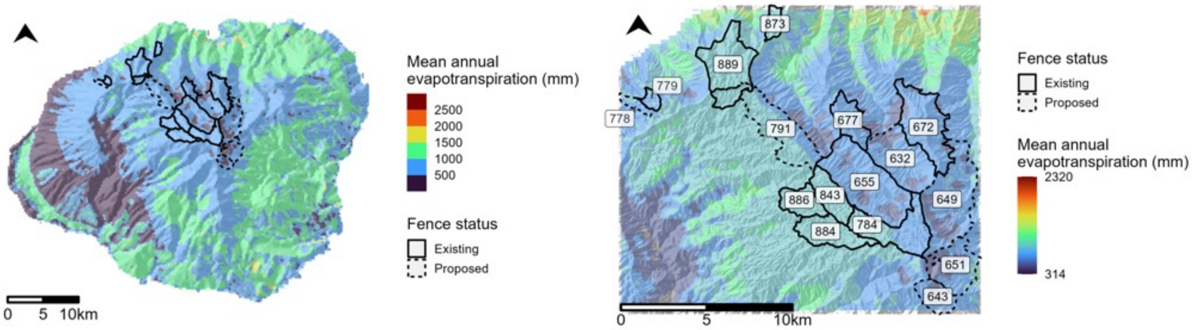

Figure A1-5. Available soil moisture