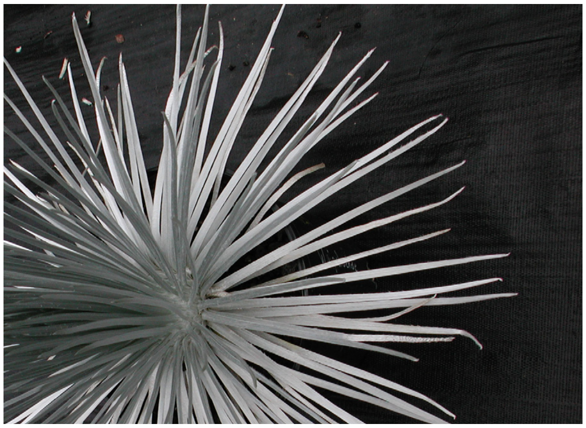

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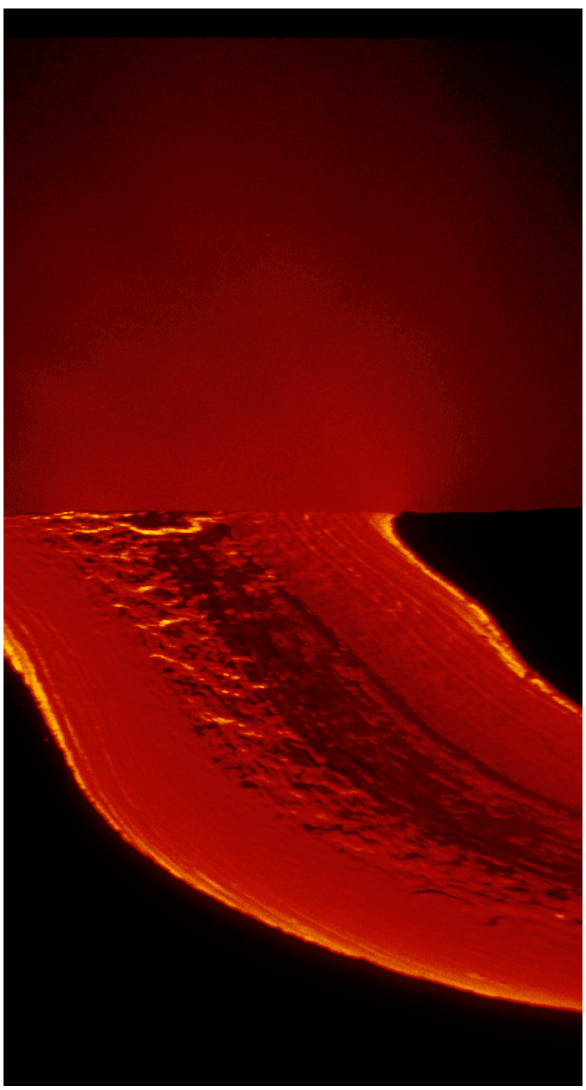
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAIʻI

PROJECT ENVIRONMENT

# Identifying Areas of Cost-effective Watershed Management for Groundwater Recharge Protection on Hawaiʻi Island

Prepared for the Hawaiʻi Community Foundation

JANUARY 2019



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# Identifying areas of cost-effective watershed management for groundwater recharge protection on Hawaiʻi Island



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## 1. INTRODUCTION

Hawai'i depends heavily on groundwater to meet much of its freshwater needs, and the availability of groundwater hinges, in part, on the ecohydrological processes of our watersheds. While data are limited, existing studies suggest that intact watersheds with healthy native forest are expected to capture more fog (Takahashi et al. 2011) and transpire less water (Cavaleri et al. 2005; Cavaleri and Sack 2010; Kagawa et al. 2009; Giambelluca et al. 2008) than invaded forest dominated by non-native species. Expert and local observations also suggest greater infiltration under a healthy, diverse, and intact understory. Investing in watershed protection is costly, however, so it is important to understand the return on investment (ROI), i.e., how much recharge is being gained per dollar invested. With a limited budget for investment in watershed conservation for enhanced or sustained recharge, it is also important to understand how cost-effectiveness varies over the landscape. Ideally, investments with the goal of increasing recharge would be made in the most cost-effective areas that are also recharging highly-stressed aquifers where rising scarcity is a concern.

While considerable effort has been placed on measuring potential benefits of conservation interventions, explicit quantification of the costs of implementation, especially over time, is rare (Iacona et al. 2018). Formal analyses evaluating the benefits of conservation, even taking a biophysical approach, have been slow to develop. Approaches that incorporate economics have developed even more slowly (Hughey et al. 2003). Cost-effectiveness analyses may increase the likelihood of improved performance in conservation management.

Returns on investment in conservation vary significantly over space, and failing to consider the environmental and economic factors driving benefits and costs in each management area can lead to inefficient outcomes. Using data from Costa Rica's Nicoya Pensinsula, Wünscher et al. (2008) created and tested a decision support tool that targets areas with high returns by considering environmental services the management area may provide, given the risk of losing services specific to each site, and assessing the cost associated with investing in the environmental service. Povak et al. (2017) developed a decision support tool for management of invasive strawberry guava (*Psidium cattleyanum*) in East Hawai'i Island, and found that high management costs were associated with poor access, long travel times, and heavy invasive species infestations that required multiple visits for initial treatment and maintenance. While remoteness, high infestation, steep and highly dissected topography, and high annual precipitation are correlated, these areas also have a high potential water yield and therefore high potential returns. Gaining a better understanding of how these factors are driving costs can therefore improve efficiency of conservation investments.

In collaboration with the County of Hawai'i Department of Water Supply (DWS), we identified three priority management areas on Hawai'i Island: Kohala, Kona, and Ka'ū. These critical recharge areas were identified by DWS as important recharge areas for four aquifers where current withdrawals are near current or future sustainable yield limits: Mahukona, Waimea, Keauhou, and Kealakekua. We then developed a statistical model to assess how land cover change would affect evapotranspiration and subsequently groundwater recharge—building off existing evapotranspiration, climate, land cover, and recharge datasets—to identify areas of high potential recharge benefits within the priority areas following forest protection activities. Cost data from nearby watershed management units were used to calculate average management costs for each priority area, and then were combined with the potential recharge benefit map to generate a map of cost-effectiveness.

## 2. DESCRIPTION OF THE STUDY SITES

Through discussions with the County of Hawai‘i DWS, we identified three priority groundwater recharge areas on Hawai‘i Island— Kohala, Kona, and Ka‘ū —based on spatial proximity to important pumping wells within vulnerable aquifers (Fig. 1). Given our objective of estimating cost-effectiveness of watershed management within the priority areas, we focused on obtaining data from management units in the immediate vicinity. Costs were obtained for a total of seven units: Kaiholena, Maka‘ālia, Lahomene, Kona Hema, Kipuka, Ka‘ūpūlehu, and Pu‘u Wa‘awa‘a.

### 2.1 Kohala priority area

The State Division of Forestry and Wildlife's (DOFAW) Natural Area Reserves System (NARS) encompasses 125,000 acres of Hawai‘i's most unique ecosystems. The Pu‘u O ‘Umi NAR ranges from the west upper slopes and summits of the Kohala mountains on the northern end of Hawai‘i Island down to the sea cliffs at the coast. Given DOFAW's limited resources and because most NARs are comprised of relatively intact native forest, management effort is primarily focused on building and maintaining fences and ungulate removal, rather than on weed control. Cost data used in this study were obtained for the Lahomene management unit within the Pu‘u O ‘Umi NAR (Burnett et al. 2017).

### 2.2 Kona priority area

Costs from four management units within the Kona area were used for this study. Located on the leeward side of the island, our study area ranges in elevation from sea level to over 8000 ft and covers the full spectrum of major forest

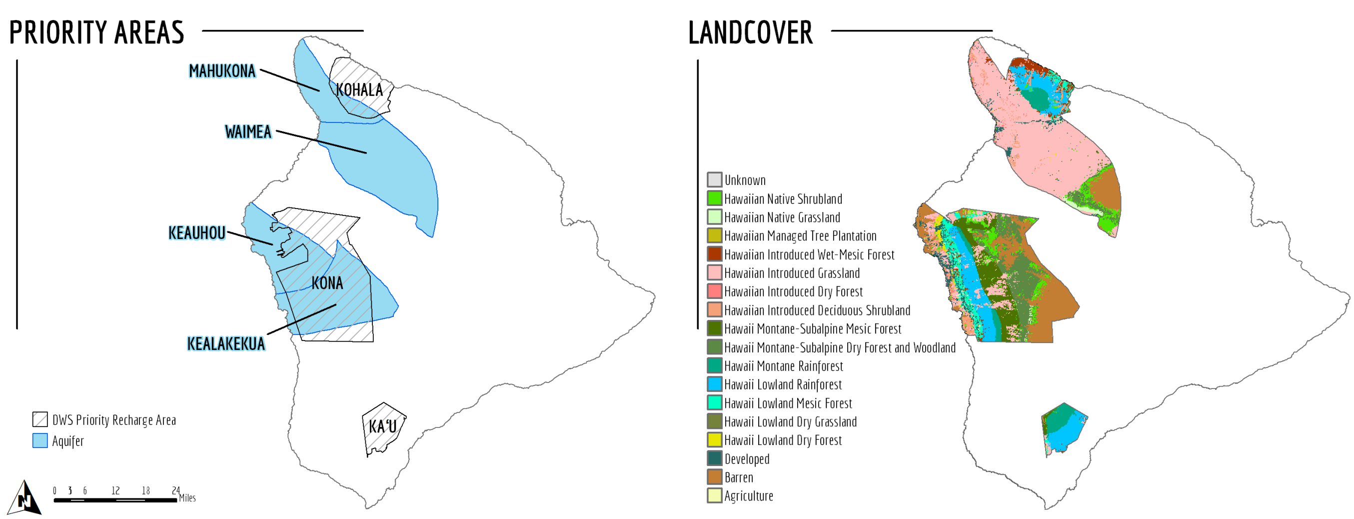


*Figure 1: Priority Areas (hatched) and associated vulnerable aquifers (blue) (left); current land use (right).*

types in Hawai'i (Fig. 1). Kona contains some of the State's last remaining tracts of tropical dry forest, considered by many as culturally important and one of the most endangered ecosystems in Hawai'i. Because rainfall in this region increases with elevation, reaching a peak annual average of 60-80 inches at approximately 3300 ft asl (Brauman et al. 2010), Kona is also home to large tracts of native mesic forest and rainforest, much of which fall within the fog zone.

The first site is located within the 7515-acre Kona Hema Preserve, which is comprised of three adjoining forest parcels in South Kona on the leeward slopes of Mauna Loa. The Nature Conservacy (TNC) installed 25 miles of fencing to exclude feral ungulates, and over 600 pigs and 100 sheep have been removed since 2000. Weed control is limited to targeted areas at a rate of roughly 50 acres controlled per year. Cost data for TNC's Kona Hema management unit included fence installation and maintenance, as well as ongoing monitoring and control of weeds and ungulates (Burnett et al. 2017).

The second site, the 810-acre Kipuka management unit, is located within Manuka, the largest NAR managed by DOFAW, extending from sea level to an elevation of 5000 ft. Like in Lahomene, management effort and corresponding costs in Kipuka are limited primarily to building and maintaining fences and ungulate removal (Burnett et al. 2017).

The third management unit is located within the Ka'ūpūlehu ahupua'a, which is situated on the leeward coast of Hawai'i Island, extending from sea level to 8000 ft and covering 25,700 acres. Sparsely vegetated lava fields cover about one-third of the low elevation area, and a large portion of the total area is currently used for ranching. Estimated management costs were based on a native restoration scenario covering 3435 acres of the mid-elevation portion of Ka'ūpūlehu, which is classified as perennial grassland (Bremer et al. 2018). Costs included fence installation and maintenance, ungulate removal, and weed control.

Our final site in the Kona priority area is situated within the Pu'u Wa'awa'a watershed, which spans 40,000 acres of the North Kona region of Kekaha. Stretching from sea level to within 1.2 miles of Hualālai volcano's summit, Pu'u Wa'awa'a contains some of the state's largest tracts of remnant native dry forest, as well as a mix of land uses including managed grazing in mid-elevation grasslands, and conservation and restoration efforts focused primarily in forested areas at higher elevations. Estimated management costs for a 16,111-acre native forest protection scenario were scaled up based on expenditures on past management efforts (Wada et al. 2017) and included fence installation and maintenance, ungulate removal, and weed control.

### 2.3 Ka'ū priority area

Located between roughly 1970 and 5770 ft in elevation on the southwest flank of Mauna Loa volcano on the southern end of Hawai'i Island, the 3548-acre Ka'ū Preserve is part of the largest and most intact expanse of native forest in the state. The four separate parcels of land that make up the preserve consist primarily of intact native forest and form a boundary between the largely native alpine and subalpine forest above and agricultural land below. Cost data used in this analysis were obtained for the Kaiholena and Maka'ālia fenced units within the Ka'ū Preserve (Burnett et al. 2017), which are managed by TNC. In 2007, TNC installed 5 miles of fencing in the Kaiholena unit, which has been kept free of feral pigs since 2009. Fence construction for the adjacent 968-acre Maka'ālia management unit was recently completed. Ungulate and weed maintenance are ongoing in both units.

# 3. METHODS

## 3.1 Counterfactual scenarios

For each study area, we developed a counterfactual scenario representing likely spread of non-native forest over time in the absence of conservation activities. The initial year (2018) is based on land cover from Tom Giambelluca's Evapotranspiration of Hawai'i website (http://evapotranspiration.geography.hawaii.edu/). This map was aggregated from the commonly utilized LANDFIRE land cover map (LANDFIRE 2012). We assumed that if conservation activities were to stop in 2018 (the current year), non-native forest (introduced wet-mesic forest in the LANDFIRE dataset) would spread at a rate of 5% per year along the edges of existing non-native forest. While there is limited information on spread rates of non-native species, we consider this conservative as an existing study documented 9-12% spread rates of non-native species like strawberry guava (Geometrician Associates LLC 2010). We assumed that only native forest covers within similar climatic zones as introduced wet-mesic forest could be invaded. This included: Hawai'i montane forest; Hawai'i rainforest; and Hawai'i mesic forest. Given that spread can occur in different spatial configurations, we ran 1000 simulations of potential spread pathways for each year over 50 years (see average land cover maps over time in Fig. 2, 3, and 4).

## 3.2 Water benefits of watershed management

To calculate the potential changes in groundwater recharge over time in the counterfactual 'without conservation' scenario in the three sites, we focused on projected increases in actual evapotranspiration (AET) with conversion of native to non-native forest. Although changes in forest cover can affect the water balance in other ways, including through changing fog interception and infiltration rates (Wright et al. 2018; Takahashi et al. 2011), we did not have sufficient data to include these in our analysis. Rather, we focused on estimating the avoided increase in AET that is expected to occur in the absence of conservation and subsequent invasion of non-native forest, adapting an approach developed by Wada et al. (2017).

To estimate how invasion of non-native forest might change AET, we utilized a large spatial dataset of current annual AET and a series of climatic and vegetation predictor variables across Hawai'i Island characterized by LANDFIRE land cover type (~5000 points of non-native forest) (Giambelluca et al. 2014). We divided the dataset into three subsets of mokus around the study sites: Kohala, Kona, and Ka'ū. Within each of these subsets, we selected pixels classified as introduced wet mesic forest (non-native forest). We then modeled AET as function of net radiation; available soil moisture; air temperature; wind speed; and leaf area index (LAI) utilizing generalized least squares regression following Wada et al (2017). Available soil moisture (as calculated by Giambelluca et al. (2014) is influenced by rainfall only and not forest type. We incorporated spatial autocorrelation structures (Zuur 2009) and selected the

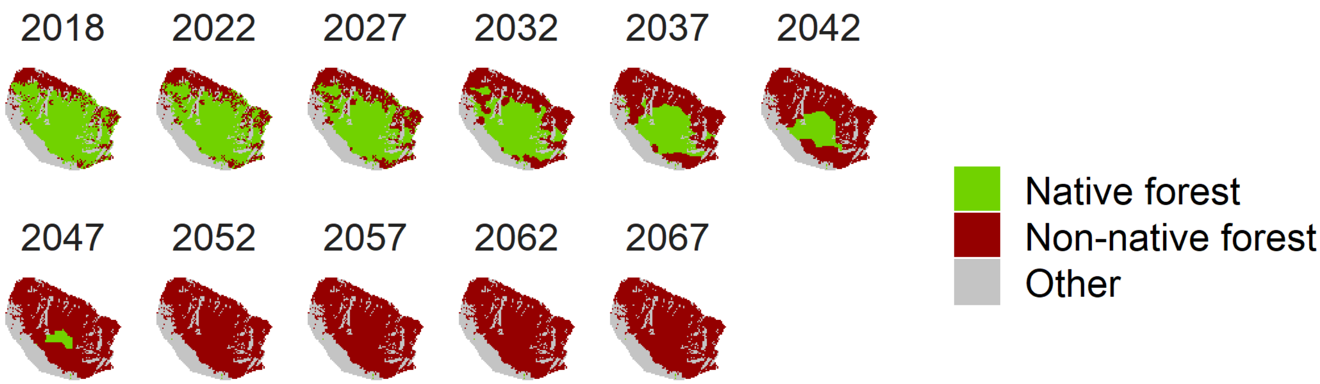


*Figure 2: Potential spread of non-native forest in the absence of conservation activities in Kohala priority area.*

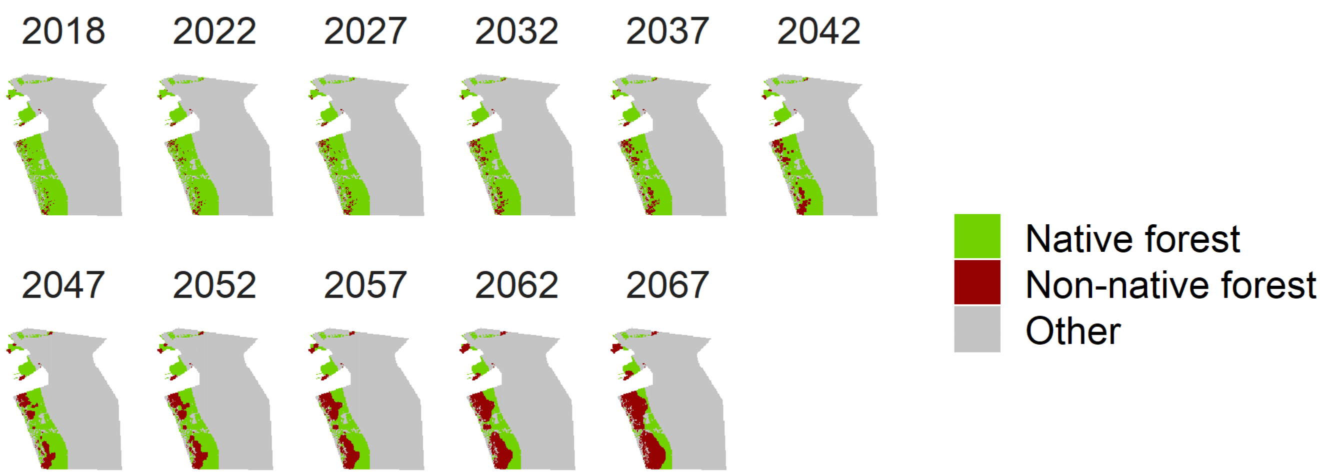


*Figure 3: Potential spread of non-native forest in the absence of conservation activities in Kona priority area.*

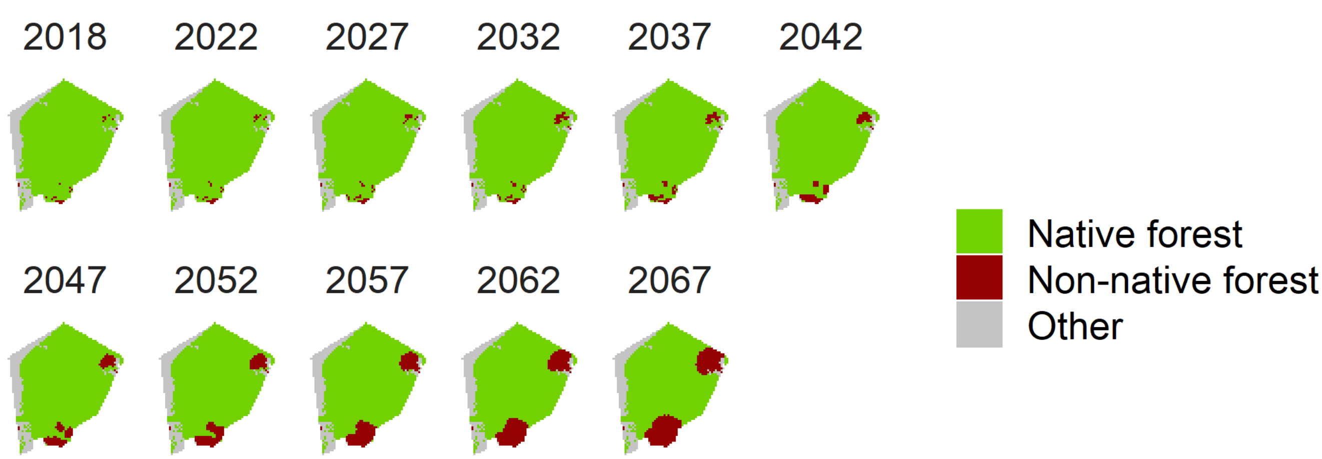


*Figure 4: Potential spread of non-native forest in the absence of conservation activities in Kaʻū priority area*

regression model with the lowest AIC (Akaike Information Criterion; a standard method for model selection) value. Adjusted $R^2$ for the regressions were between 0.95-0.96.

We then used the site-specific regression equation to estimate how AET was projected to change over time in the absence of conservation in the counterfactual scenario for each year from 2018-2067 in each of the three study sites. For each year's counterfactual scenario, we applied the regression equation to all pixels which were converted to introduced wet-mesic forest from the original native forest cover. LAI was estimated as the median value of the LAI of existing introduced wet-mesic forest pixels on Hawaiʻi Island; LAI was not correlated with precipitation, temperature, or elevation, justifying the selection of an overall median value. Baseline AET (from Giambelluca et al. (2014)) was utilized for non-invaded unchanged pixels. AET of invaded pixels was calculated 1000 times for each year in accordance with the land cover maps generated by the invasion simulation described above. To estimate the amount of avoided freshwater yield loss that could be considered avoided loss of groundwater recharge, we used recharge to freshwater yield ratios (0.51 in Kohala; 0.94 in Kona; 0.84 in Kaʻū) published in the Hawaiʻi Island Recharge U.S. Geological Survey study (Engott et al. 2011). As stated before, we lack sufficient data to include altered infiltration or fog interception rate due to land cover change as part of the model so assume this stays constant for all forest types (as is done in USGS water balance modeling studies). Avoided loss of groundwater recharge over time was estimated as the difference between the modeled AET in the counterfactual scenario and the baseline AET.

### 3.3 Present value costs of watershed management

Cost data points obtained for each of the seven management units generally fell into one of the following categories: fence installation, maintenance, and scheduled replacement; initial ungulate removal and maintenance; weed control; and general maintenance, which may be a combination of fence, ungulate, and/or weed related costs (Table 1).

Given that watershed management costs are incurred over time, determining cost-effectiveness of management activities using the raw cost data would require direct comparison of cost trajectories, which is difficult to interpret. To remedy this issue, we estimated the present value (PV) cost of management in each unit over a 50-year time

| | | FENCE | | | | UNGULATE | | WEED | GENERAL |
|---|---|---|---|---|---|---|---|---|---|
| PriorityArea | Site | Install | Wire Replace | Full Replace | Repairs | Initial | Maintain | Maintain | Maintain |
| Kohala | Lahomene | ✓ | | ✓ | ✓ | | | | |
| Kona | Kona Hema | ✓ | ✓ | ✓ | | ✓ | | | ✓ |
| | Kipuka | ✓ | | ✓ | ✓ | | | | |
| | Kaʻūpūlehu | ✓ | ✓ | ✓ | | ✓ | | ✓ | |
| | Puʻu Waʻawaʻa | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| | Kaiholena | ✓ | ✓ | ✓ | | ✓ | | | |
| Kaʻū | Kaiholena | ✓ | ✓ | ✓ | | ✓ | | | ✓ |
| | Makaʻālia | ✓ | ✓ | ✓ | | ✓ | | | ✓ |

*Table 1. Types of management costs obtained for each site*

period, assuming an annual inflation rate of two percent and discount rate of three percent. The resulting present values were then used to calculate weighted average costs for each priority area and cost-effectiveness within and across each area.

### 3.4 Cost-effectiveness of watershed management over space

Because data from our seven management units are unevenly distributed across our three priority areas, we generated a weighted average of present value management costs for each priority area and combined them with recharge benefit maps to generate estimates of cost-effectiveness over space. That is, each pixel was assigned a cost-effectiveness value—volume of recharge protected per dollar. High cost-effectiveness means a relatively large groundwater benefit is generated for every dollar invested in watershed management.

## 4. RESULTS

### 4.1 Water benefits

Conservation of all of Kohala's forest susceptible to invasion (under our assumptions) (39,815 acres) would avoid the loss of approximately 378.7 billion gallons of water yield and 193.1 billion gallons of groundwater recharge over 50 years (Fig. 5). Conservation of all of Kona's remaining native forest susceptible to invasion (28,216 acres) would avoid the loss of approximately 97.7 billion gallons of water yield and 91.8 billion gallons of groundwater recharge over 50 years (Fig. 6). Conservation of all of Kaʻū's remaining native forest susceptible to invasion (5,127 acres) would avoid the loss of approximately 20.9 billion gallons of yield and 17.6 billion gallons of groundwater recharge over 50 years (Fig. 7).

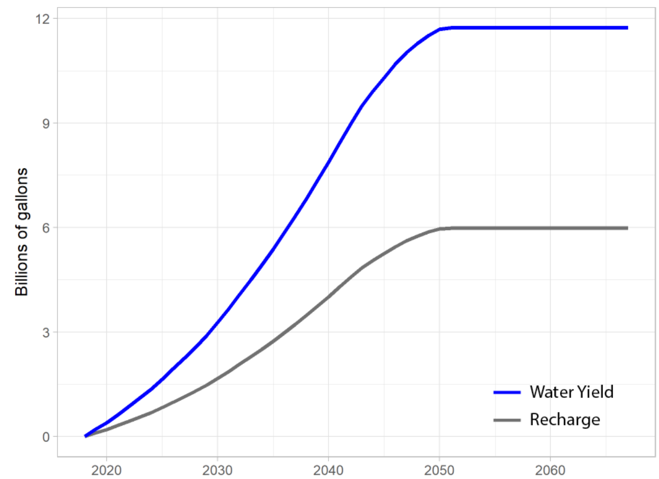


*Figure 5: Kohala avoided loss of groundwater recharge and water yield over 50 years (2018-2067)*

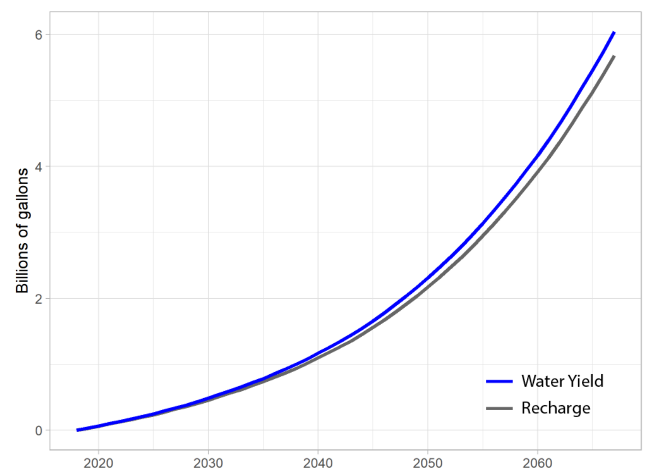


*Figure 6: Kona avoided loss of groundwater recharge and water yield over 50 years (2018-2067)*

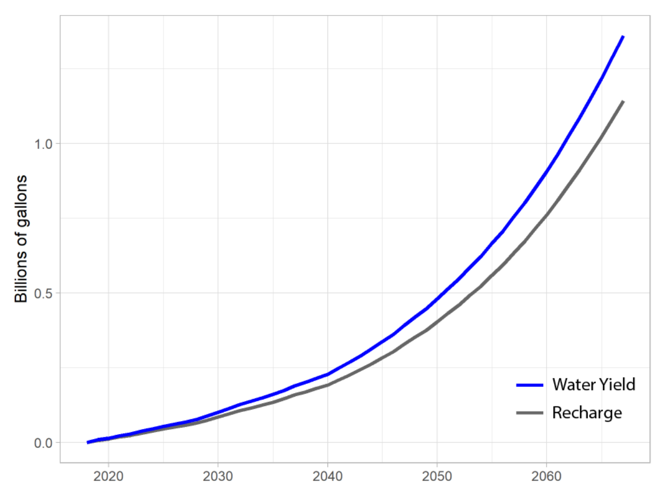


*Figure 7: Kaʻū avoided loss of groundwater recharge and water yield over 50 years (2018-2067)*

Fig. 8 shows the spatial configuration of this benefit. The highest benefits tend to be in lower elevation areas given that they are likely to be invaded first and also have higher air temperature and net radiation and thus higher evapotranspiration rates (Fig. 9). It is important to note that fog and infiltration rates are not included here, which could change the spatial configuration of benefits (and would likely shift the benefits towards higher elevation and higher precipitation areas). Priorities would also likely shift higher if the timeline was extended beyond 50 years as there would be more time for benefits to compound in higher elevation areas. Regardless, this demonstrates the value of protecting low elevation forests which are often outside of current priority zones.

### 4.2 Economic outcomes

Total present value costs of management over 50 years ranged from a low of $1.2 million in Kipuka to a high of $34.2 million in Pu'u Wa'awa'a. After controlling for total area protected in each unit, however, the range of costs contracted; per-acre PV costs were bounded below by Lahomene at $643 per acre and above by Maka'ālia at $3472 per acre. Total PV cost, PV cost per acre, and weighted average PV cost by priority area are summarized for all units in Table 2.

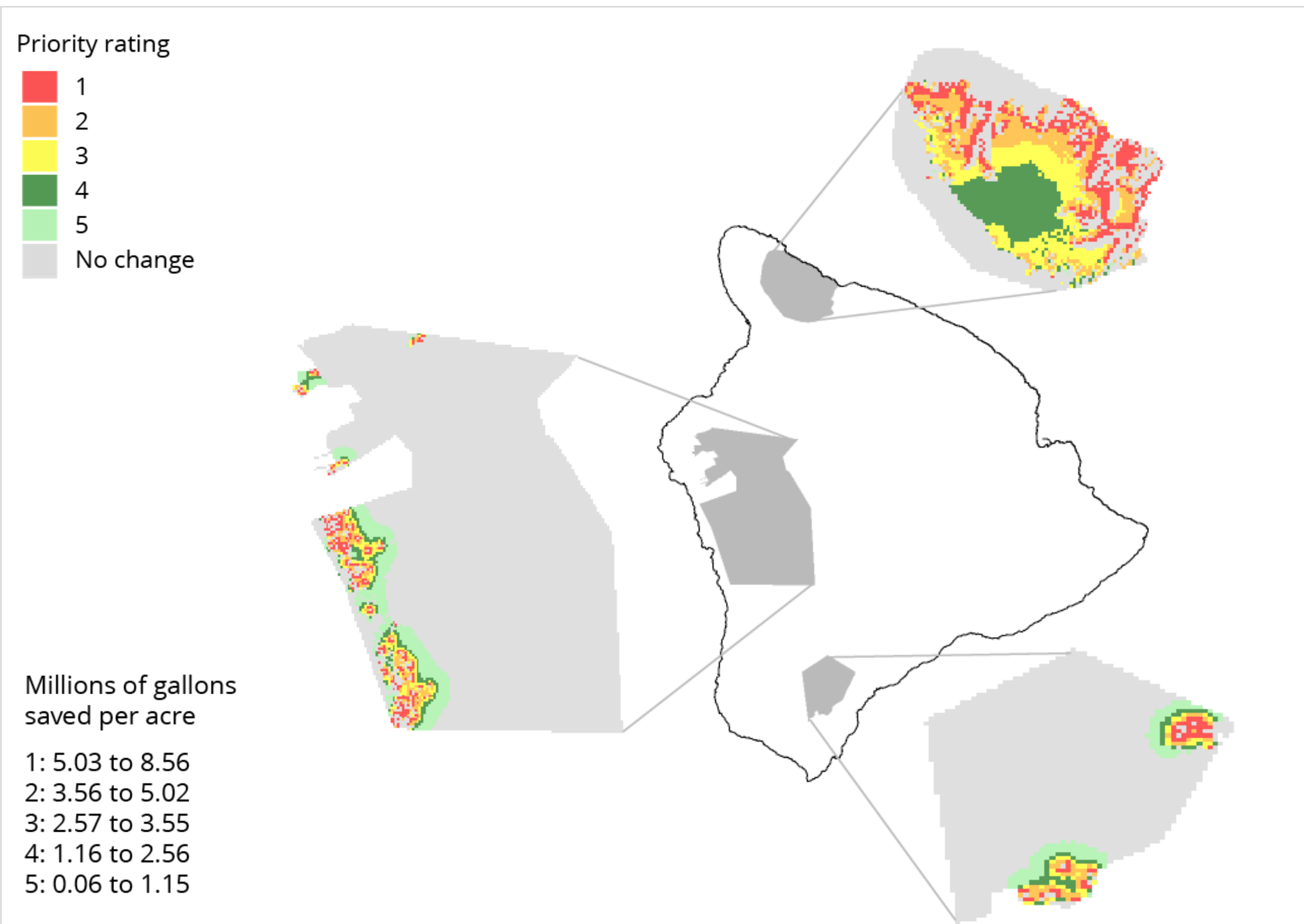


*Figure 8: Prioritization by total avoided loss of groundwater recharge in each site*

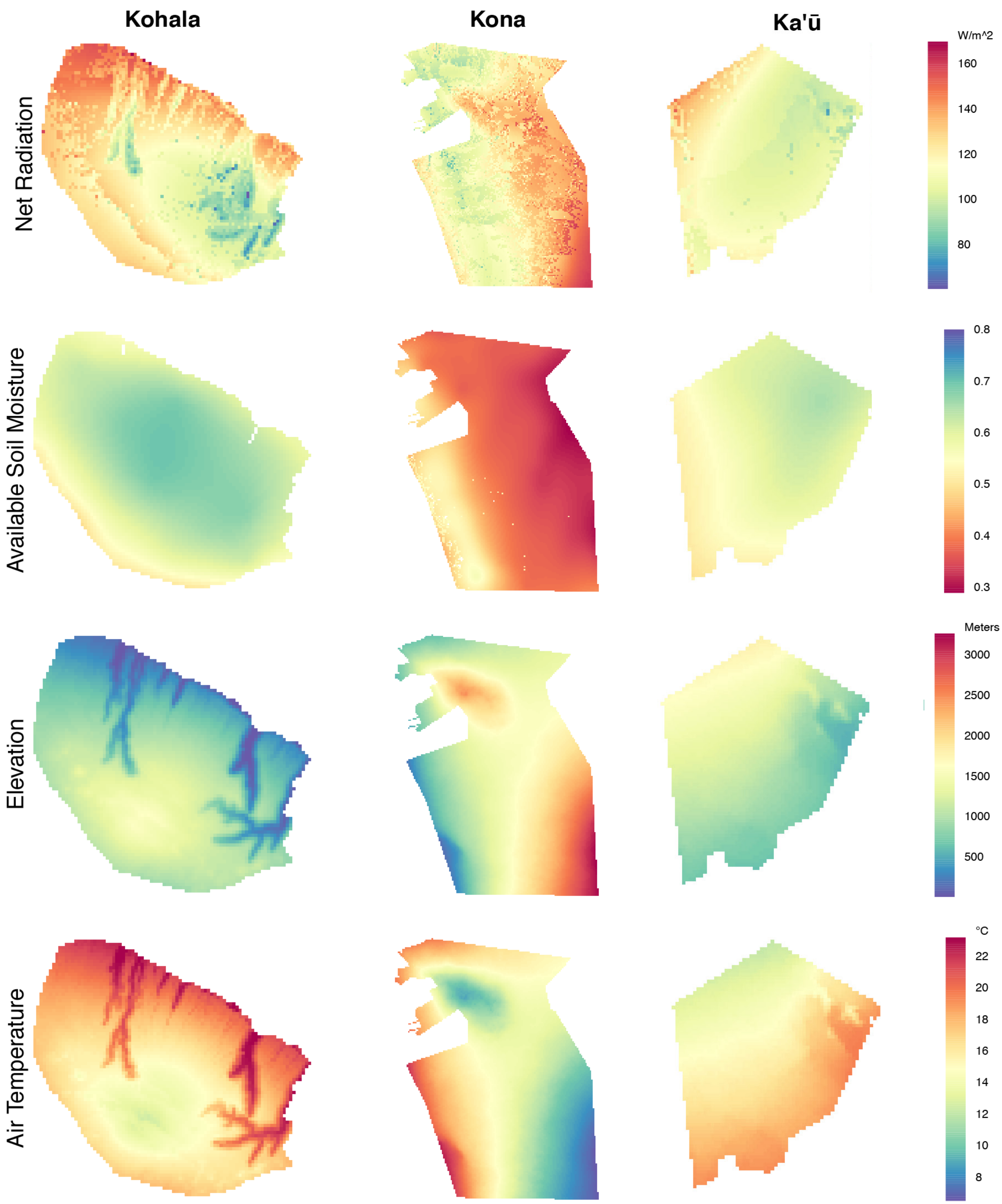


*Figure 9. Net radiation, available soil moisture, elevation, and air temperature for each priority area*

| Priority Area | Site | Area (acres) | Total PV Cost (million $) | PV Cost per acre ($/acre) | Weighted Average |
|---|---|---|---|---|---|
| Kohala | Lahomene | 1,930 | 1.2 | 643 | 643 |
| Kona | Kona Hema | 7,515 | 24.4 | 3,466 | 2,426 |
| | Kipuka | 810 | 1.2 | 1,439 | |
| | Kaʻūpūlehu | 3,435 | 7.8 | 2,282 | |
| | Puʻu Waʻawaʻa | 16,111 | 34.2 | 2,122 | |
| Kaʻū | Kaiholena | 1,128 | 3.9 | 3,460 | 3,466 |
| | Makaʻālia | 968 | 3.4 | 3,472 | |

*Table 2. Present value costs across management units*

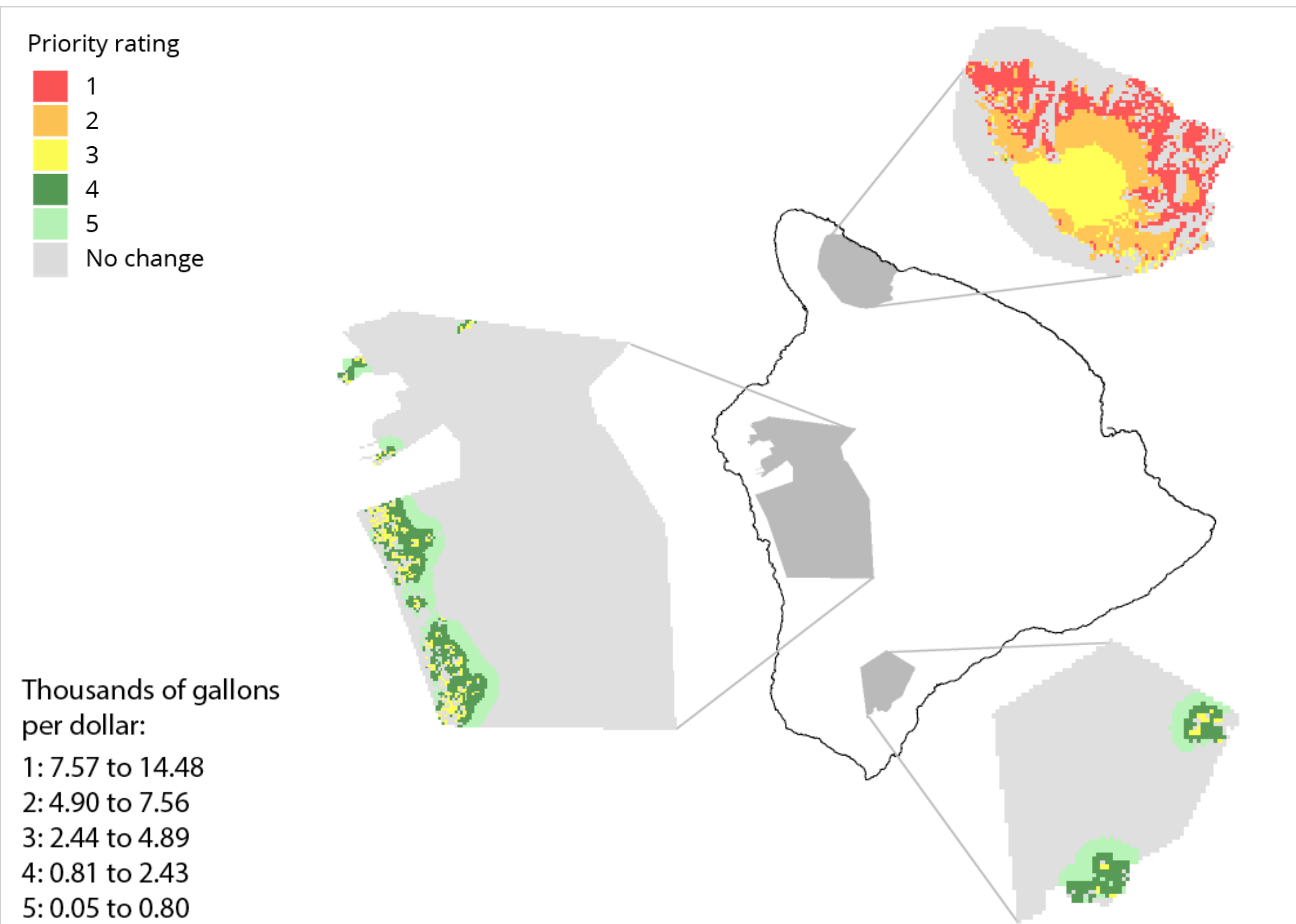


*Figure 10: Prioritization by cost-effectiveness of watershed protection by area*

Of the three study sites, cost-effectiveness was lowest in Kaʻū, with most of the region falling into priority zones 4 and 5, which correspond to returns on investment in watershed protection in the range of 50 gallons per dollar to less than 2,000 gallons per dollar. Due to large potential recharge benefits (avoided loss) and low reported management costs, cost-effectiveness was highest in the Kohala priority area, where nearly all pixels were categorized as priority zone 3 or higher. Most notably, large swathes of priority 1 zones in lower elevation areas towards the coast generated estimated benefits of between 7,000 and 14,000 gallons per dollar invested.The simulation results for Kona showed patchy areas of moderate cost-effectiveness (up to priority zone 3), with higher effectiveness in the ~500-700 m elevation range.

## 5. DISCUSSION/CONCLUSIONS

Given the objective of protecting or maintaining groundwater recharge through avoiding an increase in evapotranspiration, our results suggest that low elevation areas at high risk of invasion by non-native species should be considered for priority watershed protection. While perhaps counterintuitive and seemingly at odds with most current management practices of prioritizing higher elevation areas, our results are driven in part, by the dynamic nature of the simulation. Because evapotranspiration increases and recharge declines only after land cover conversion occurs, potential losses aggregated over time will depend on both the speed of non-native forest spread and the starting point of the invasion. Given our assumed rate of spread and the fact that most non-native pixels in the current LANDFIRE land cover map are located in lower elevation areas at our study sites, much of the higher elevation areas (with the exception of Kohala where there is more non-native forest to start with) are never converted within the 50-year timespan of the model. However, higher spread rates and including incipient populations of non-native species not represented in the current land cover maps would result in more potential recharge losses (and hence benefits) in higher elevation areas away from the coast. Similarly, a larger initial proportion of non-native to native forest would result in more area being converted over time, including higher elevation areas.

Kohala's high threat of invasion (larger initial proportion of non-native to native forest), combined with its high solar radiation, temperature, and rainfall relative to other priority areas result in the highest cost-effectiveness across the three study sites. However, limited cost data in Kohala may be underestimating the full cost of protection in that region. Additional cost data could change the relative ranking of cost-effectiveness across the three sites but would not affect the priority zones within the Kohala region.

Water benefits in this report are based on evapotranspiration, due to limited data of differences in fog interception and infiltration rates between non-native and native forest. Incorporating these additional water balance components, as new information becomes available, could change the spatial configuration of benefits. For example, there is evidence in specific sites that native forest has higher cloud water interception than non-native forest (Takahashi et al. 2001). While it is challenging to take site specific data and apply it at broad spatial scales, if we incorporated these assumptions into our modeling, we would expect recharge benefits in the higher elevation fog zone to be higher than currently estimated. Likewise, enhanced infiltration capacity of native forest compared to non-native forest would shift benefits towards higher rainfall zones. Current research being conducted by the USGS, University of Hawai‘i, the Honolulu Board of Water Supply, and the Maui Department of Water Supply should shed light on these ecohydrological processes in native versus non-native forest cover.

Our conclusion that lower elevation areas at higher risk of invasion should be considered for priority watershed protection is not meant to imply that current conservation efforts in high elevation areas are not necessary, efficient, or important. On the contrary, many currently protected areas are being managed for multiple objectives in addition to recharge, such as biodiversity conservation, flammability reduction, and cultural value. Efforts to maximize recharge protection need not conflict with other management objectives and, in fact, may be well suited for a mosaic approach to maximize ecosystem services across Hawai‘i Island.

Acknowledgements: We are grateful to Hawai‘i Community Foundation for the financial support of this project, and for partial funding from the National Science Foundation's Research Infrastructure Improvement Award (RII) Track-1: ‘Ike Wai: Securing Hawai‘i's Water Future Award # OIA-1557349. We are grateful to Keith Okamoto and Kurt Inaba of County of Hawai‘i Department of Water Supply for their direction and guidance regarding aquifers of interest and corresponding watersheds; Colleen Cole of Three Mountain Alliance, Cody Dwight of Kohala Watershed Partnership, Cheyenne Perry of Mauna Kea Watershed Alliance, and Emma Yuen and Nick Agorastos of Division of Forestry and Wildlife for continuing discussions about watershed protection activities and budgets; and to Silvia Sulis and Victoria Ward for graphic design.

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