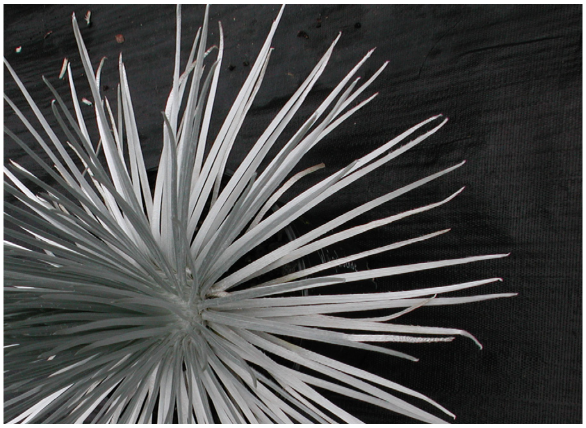


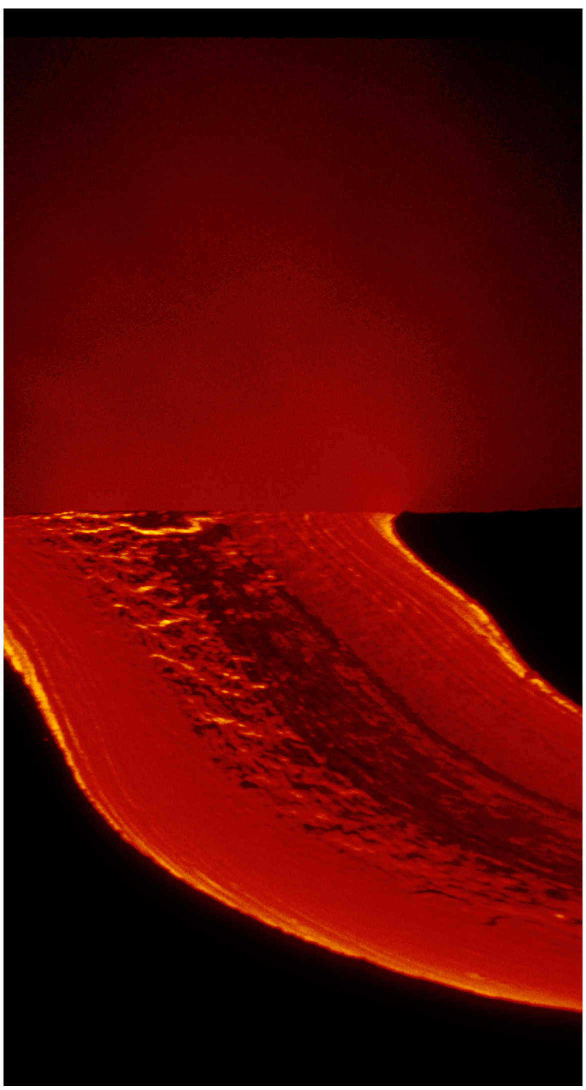
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAIʻI

PROJECT ENVIRONMENT

Identifying priority watershed management areas for groundwater recharge protection on Hawaiʻi Island

Prepared for the Hawai'i County Department of Water Supply
University of Hawaiʻi Economic Research Organization (UHERO) and the Water Resources Research Center (WRRC)

NOVEMBER 12, 2019



UHERO
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Identifying priority watershed management areas for groundwater recharge protection on Hawaiʻi Island

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EXECUTIVE SUMMARY

This report provides an analysis of the relative effectiveness of watershed conservation and restoration efforts in terms of groundwater recharge benefits in Hawaiʻi County Department of Water Supply (DWS) priority aquifers and recharge areas in Kohala, Kona, and Kaʻū. With financial support from DWS and the National Science Foundation, EPSCoR ʻIke Wai project, this study builds upon a previous effort funded by the Hawaiʻi Community Foundation (HCF). Specifically, this report extends the previous report for HCF by: 1) expanding the area of interest to include priority recharge areas as well as target aquifers identified by DWS; 2) including an analysis of potential spread of non-native grassland into native forest areas; 3) including an analysis of changes in potential fog interception with change in land cover; and 4) adding an assessment of priority areas for native forest restoration.

Using a combination of land cover and water balance modeling, we created priority maps for watershed protection and restoration based on the highest potential groundwater recharge benefits compared to "no protection" or "no restoration" scenarios. The results of this report are based on best available data at the time of the work. Ongoing data collection by the United States Geological Survey (USGS) and the University of Hawaiʻi at Mānoa to better characterize hydrologic processes associated with different forest types should eventually help to refine these estimates.

Watershed protection:

We find that watershed protection likely generates substantial recharge benefits across the three study areas. Protecting all areas projected to be most susceptible to invasion could prevent the loss of up to 187 billion gallons, 318 billion gallons, and 18 billion gallons of recharge over 50 years in the Kohala, Kona, and Kāʻu study areas respectively. A summary of the aggregate estimates of the annual and daily recharge with protection compared to without protection are shown in Table 1.

Table 1: Summary of watershed protection benefits. *Note: area susceptible to invasion based on assumption of a 5% spread of non-native forest and a 2% spread of non-native grassland in the absence of protection.*

Site	Area susceptible to invasion over 50 years (acres)	Estimated recharge protected over 50 years (billion gallons)	Estimated recharge protected in year 50 (billion gallons per year)	Estimated recharge protected in year 50 (million gallons per day)
Kohala	38,255	187	5.7	15.6
Kona	37,328	318	16.7	45.7
Kaʻū	5,127	18	1.1	3.1

Based on a spatial analysis of these benefits, we found that the highest priority areas for watershed protection could prevent the loss of over ~5.2 million gallons of recharge per acre over 50 years. The following general areas were identified as particularly high priority for watershed protection.

- Lower to mid elevation native mesic forest areas at high risk of invasion by high water use non- native canopy species;
- Higher elevation areas (with substantial fog interception potential) at high risk of conversion to non-native grassland or bareground.

Reforestation:

We found substantial potential for recharge benefits of reforestation in areas with high fog interception. We do not present aggregate benefits of full restoration of all available areas as the direction of change in projected recharge depends on the location. We identified ~117,282 acres, 24,587 acres, and 1,097 acres of potential restoration areas in the Kohala, Kona, and Kāʻu areas respectively.

Based on spatial analysis of these benefits, we found restoration may increase recharge by ~9.5 million gallons or more per acre over 50 years in the highest priority areas. In summary:

- The greatest benefits from restoration will likely occur in higher elevation areas with substantial fog interception.
- Restoration in areas without substantial fog interception may reduce recharge as evapotranspiration rates generally increase when reforesting grassland.

This report is based on the best available spatially explicit data and involved discussions with watershed partnerships and the State Department of Forestry and Wildlife. However, there are important key uncertainties that are important to bear in mind. As with all studies of this nature, further eco-hydrologic studies are critical for refining this analysis and we strongly encourage revising this analysis as additional data become available. Several key uncertainties are highlighed below:

- "No protection" counterfactual scenarios are based on a 5% annual spread assumption of fast growing non-native forest (all sites) and a 2% assumption of non-native grassland scenarios (Kohala and Kona). These are best estimates based on available studies and expert opinion, but are uncertain. We thus provide estimates of the potential benefits of protection over the full study areas as 'snapshot' benefits expressed in gallons per acre per day (Appendix Figures 1 and 2).

- Actual evapotranspiration (AET) estimates are based on regression modeling using data from the Evapotranspiration Atlas of Hawaiʻi (Giambelluca et al. 2014), which uses representative species water use data (i.e. strawberry guava for non-native forest; and ʻōhiʻa lehua for native forest) and remotely sensed climate and vegetation data. Ongoing research by the University of Hawaiʻi and USGS should help to refine model inputs.
- The ratio of recharge to runoff was kept constant for each study site based on baseline data and was not altered with land-use change or specific pixel conditions. Ongoing research by the University of Hawaiʻi and the USGS may help to refine these estimates.
- Fog analysis was carried out following USGS methods (Engott 2011). As further data and methods become available for fog interception analysis, we recommend updating this component.

2. INTRODUCTION

Hawaiʻi depends heavily on groundwater to meet the majority of its freshwater needs. 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 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 high water-use, non-native species. 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 where conservation activities potentially generate the most benefits (Povak et al. 2017).

This report focuses on priority areas identified by County of Hawaiʻi Department of Water Supply (DWS): Kohala, Kona, and Kaʻū (Figure 1). These critical recharge areas were identified by DWS as important for four aquifers where current withdrawals are near current or future sustainable yield limits: Mahukona and Waimea (Kohala); Keauhou and Kealakekua (Kona), as well as for recharging wells in the Kaʻū priority area. (Figure 1). We developed a statistical model to project how native forest protection and restoration would potentially affect groundwater recharge spatially across the landscape in these three areas. We focus on potential changes in evapotranspiration and fog interception to identify areas where native forest protection and restoration are most likely to provide groundwater recharge benefits.

Description of the study sites

Through discussions with DWS, we identified three priority groundwater recharge areas on Hawaiʻi Island—Kohala, Kona, and Kaʻū. Priority areas included the four aquifers described above (Mahukona, Waimea, Keauhou, and Kealakekua) as well as additional areas considered important for recharge of prioritized areas and wells.

Kohala priority area

The Kohala priority area, includes the Mahukona and Waimea aquifers as well as the Kohala mountains (reaching 5840 ft asl), which likely recharges these aquifers. Topography throughout the area is highly varied, including steep valleys, narrow drainage gullies, and broad pastureland. Average annual rainfall peaks at over 160 inches at the 3500-ft elevation between Waipiʻo and Honokāne valleys on the windward side of Kohala Mountain. Together with rainfall, fog water intercepted by vegetation in areas above 2500 ft is vital for recharge of North Hawaiʻi's groundwater aquifers (KWP 2007; Engott 2011; Figures 1 & 2)

Kona priority area

Located on the leeward side of the island, the Kona study area includes the Keauhou and Kealakekua aquifers, and a slightly expanded area based on hypothesized recharge areas for important wells. The study area ranges in elevation from sea level to over 8000 ft and covers the full spectrum of major forest types in Hawaiʻi (Figure 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 Hawaiʻi. 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 (Figures 1 & 2).

Kaʻū priority area

Located between roughly 1970 and 5770 ft in elevation on the southwest flank of Mauna Loa volcano on the southern end of Hawaiʻi Island, the 3548-acre Kaʻū 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 (Figures 1 & 2).

3. METHODS

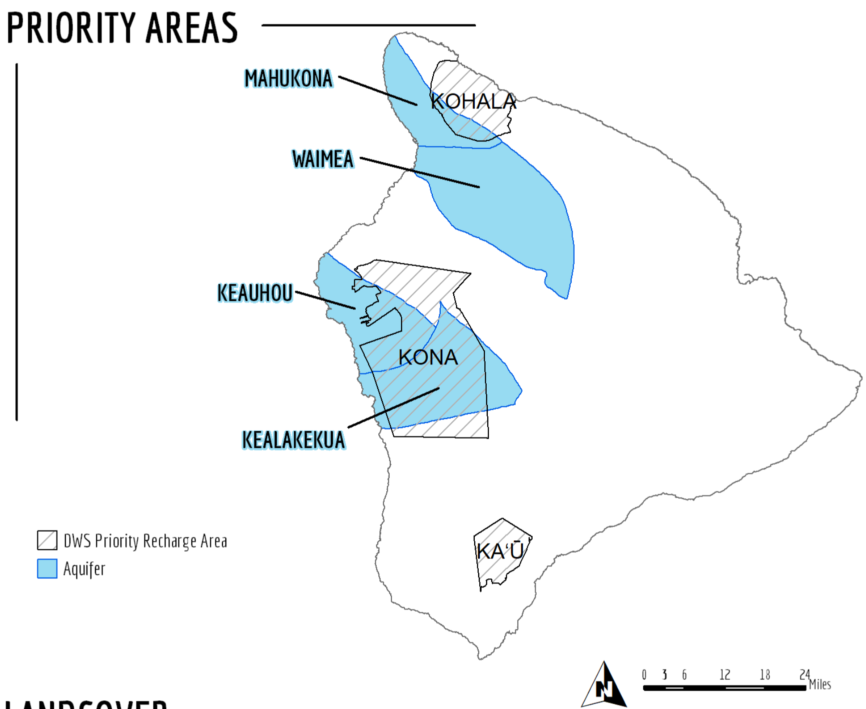
Within each study area, we assessed where: 1) *watershed protection* (i.e. native forest protection; management to prevent invasion by non-native vegetation); and 2) *watershed restoration* (reforestation of non-native grassland areas with native forest) would produce the greatest benefits for groundwater recharge.

3a. Watershed protection

Counterfactual 'no protection' scenarios

To assess where native forest protection provides the most benefits, we developed counterfactual or "no protection" land cover scenarios. These land cover scenarios represent what could potentially happen in the absence of conservation actions including fencing and ungulate and weed control. By preventing these 'no protection' scenarios from happening, watershed conservation efforts provide groundwater recharge benefits.

Figure 1: Three priority groundwater recharge areas and four underlying aquifer units on Hawai'i Island along with current land cover (based on LANDFIRE 2012).



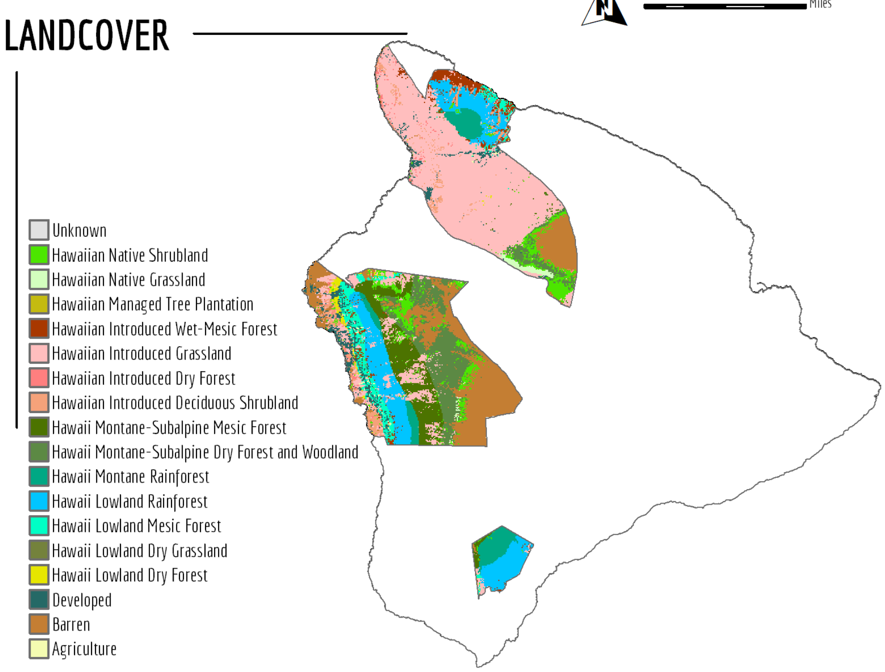
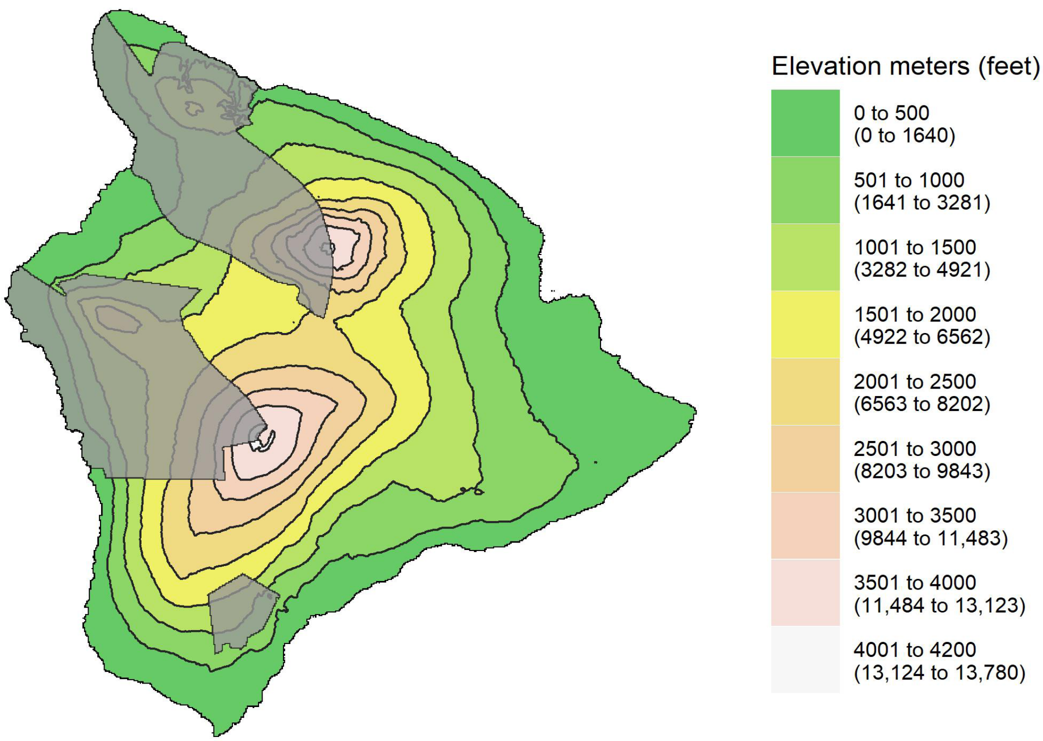


Figure 2: Digital Elevation Map (in meters and feet in parentheses) of Hawaiʻi Island (priority areas in gray). Note that results refer to this base map.



To create these 'no protection' scenarios, we started with the baseline land cover map based on a 250 m land cover map from the Evapotranspiration of Hawaiʻi website[1]. This map was aggregated from the commonly utilized LANDFIRE land cover map (LANDFIRE 2012). We assumed that if conservation activities were to stop now (Year 0; the current year), non-native forest (Hawaiʻi Introduced Wet-Mesic Forest in the LANDFIRE dataset) would spread at a rate of 5% per year into native forest areas. While there is limited information on spread rates of non-native species, this is in line with expert opinion on potential spread rates and more conservative than the documented 9-12% spread rates of non-native species like strawberry guava (Geometrician Associates LLC 2010; see description of spread model in Bremer et al. 2019). We assumed that only native forest covers within similar climatic zones as Hawaiʻi Introduced Wet-Mesic Forest could be invaded. Forest types susceptible to invasion were: Hawaiʻi Montane Forest; Hawaiʻi Montane Rainforest; and Hawaiʻi Lowland 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 Figure 3a-c).

1 http://evapotranspiration.geography.hawaii.edu/

We additionally included the potential spread of non-native grassland into native forest areas in the Kohala and Kona priority areas. Expansion of bare ground and non-native grassland dominated areas due to ungulate activity in the Kohala mountains is considered a serious threat to native forest and watershed health. The existing bare ground/ non-native grassland areas are not captured in the LANDFIRE (2012) land cover map due to the relatively small size of individual patches. In order to include these areas, we manually digitized currently visible bare ground/non-native grassland areas from Google Earth imagery and ground truthed this with Department of Forestry and Wildlife (DOFAW) staff working in the area. We then modeled a 2% spread of non-native grassland (Hawaiʻi Introduced Perennial Grassland in LANDFIRE) into native forest areas. As with the invasion rates of non-native forest, spread rates of non-native grassland are also under-studied, but we consider 2% a reasonable estimate following Blackmore and Vitousek (2000), who found that non-native grassland cover increased by >200% over a 40-year period (1954-1994) in a study in Puʻu Waʻawaʻa even in the absence of fire.

Based on input from DOFAW and the Three Mountain Alliance watershed partnership (TMA) that grassland spread was also an important threat to higher elevation areas in Kona, we also considered potential spread of non-native grassland into higher elevation native mesic and dry forest, woodland, and shrubland areas in Kona. Unlike Kohala, the existing grassland areas were better captured within the LANDFIRE (2012) land cover map. We utilized the same 2% spread rate assumption to project potential spread of non-native grassland into the following land covers: Hawaiʻi Montane Subalpine Dry Forest and Woodland; Hawaiʻi Montane Subalpine Mesic Forest; and Hawaiʻi Montane Subalpine Dry Shrubland.

Figure 3a: Potential spread of non-native forest and grassland into native forest areas over 50 years in Kohala study area (assumed spread rate = 5% per year for non-native forest and 2% for non-native grassland).

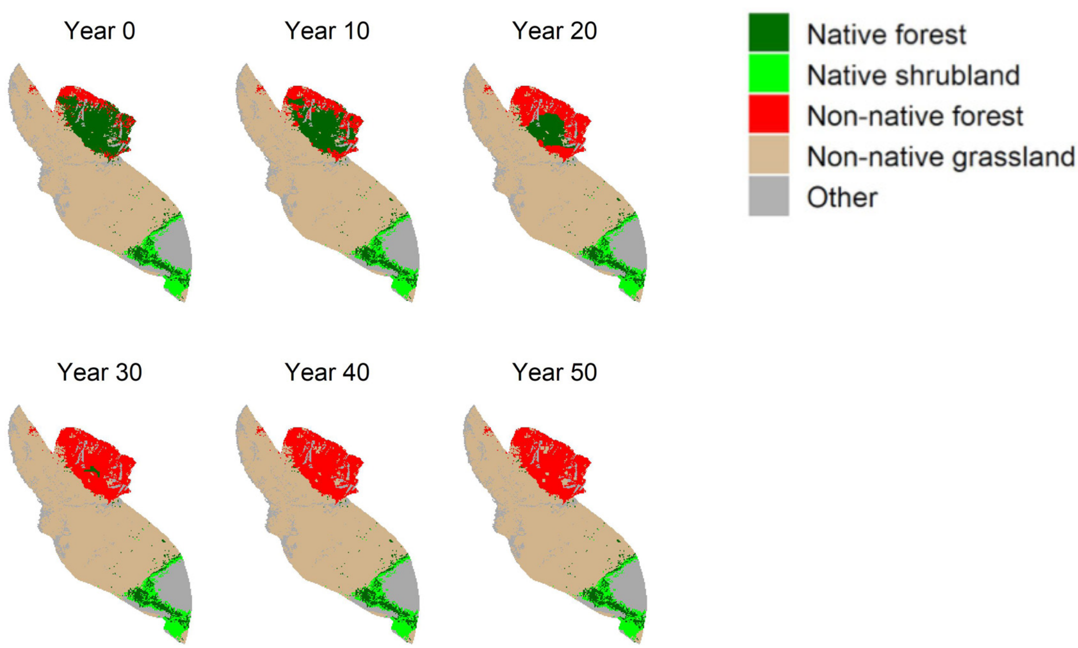


Figure 3b: Potential spread of non-native forest and grassland into native forest areas over 50 years in Kona study area (assumed spread rate = 5% per year for non-native forest and 2% for non-native grassland).

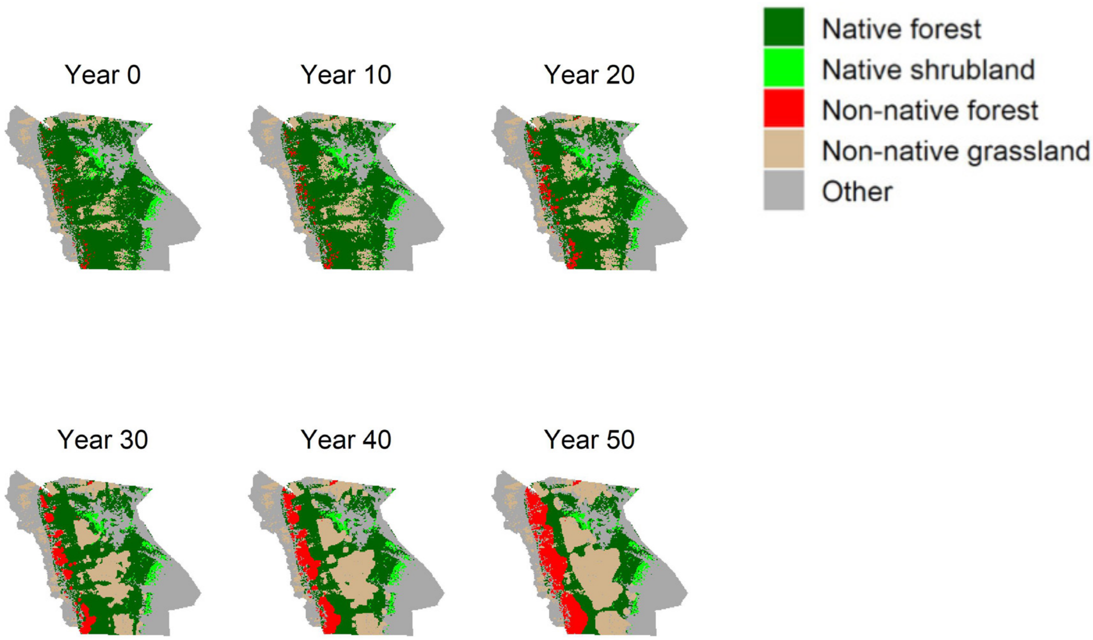
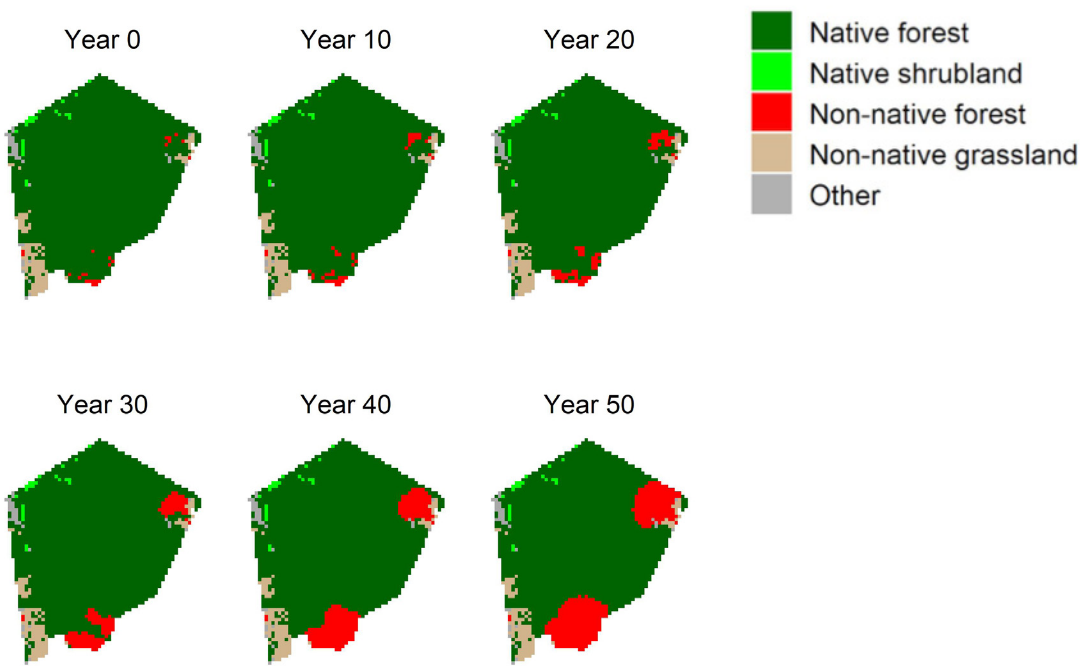


Figure 3c: Kaʻū potential spread of non-native forest into native forest areas over 50 years (assumed spread rate = 5% per year for non-native forest).



Water benefits of watershed protection

To calculate changes in mean annual groundwater recharge in the counterfactual 'no protection' scenarios compared to the baseline land cover, we developed a water balance model where:

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

Changes in forest land cover type can affect the water balance in multiple ways, including through changes in: actual evapotranspiration (Giambelluca et al. 2014; Kagawa et al. 2009); fog interception (Takahashi et al. 2011); and potentially the amount of water that infiltrates soils and recharges groundwater aquifers versus runs off as streamflow (Wright et al., 2018). Unfortunately, there are insufficient data available to model changes in infiltration spatially with forest cover change. Although existing studies suggest that forests have higher infiltration rates than grassland (Perkins et al. 2018), modeling this land cover change would require assessment of overland flow, which is beyond the scope of this study. However, we were able to take advantage of a large spatial data set of AET as a function of land cover type and a series of climatic and vegetation variables (Giambelluca et al. 2014) to project potential changes in AET with expansion of non-native forest (Hawaiʻi Introduced Wet Mesic Forest) and non-native grassland (Hawaiʻi Introduced Perennial Grassland) into native forest areas. We also included a simple fog interception analysis following a recent USGS recharge study of Hawaiʻi Island (Engott 2011).

Actual evapotranspiration (AET):

AET is a function of atmospheric conditions, water availability, and vegetation characteristics. To estimate how invasion of non-native forest might change these variables and subsequently AET, we adapted an approach developed by Wada et al. (2017) which utilized a large spatial dataset of current annual AET and a series of climatic and vegetation predictor variables across Hawaiʻi Island characterized by LANDFIRE land cover type (288,008 points) (Giambelluca et al., 2014). We divided the dataset into moku (social-ecological land divisions) around the study sites: Kohala, Kona, and Kaʻū. Within each of these subsets, we selected pixels classified as Hawaiʻi Introduced Wet Mesic Forest (n = 189 in Kaʻū, n = 1020 in Kohala, and n = 400 in Kona) and utilized a generalized least squares regression with AET as a function of net radiation; available soil moisture; air temperature; wind speed; and leaf area index (LAI). 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 regression model with the lowest AIC (Akaike Information Criterion; a standard method for model selection) value. For the Kona and Kohala areas, we also modeled Hawaiʻi Introduced Perennial Grassland (non-native grassland; n = 1807 in Kohala and n = 3607 in Kona) using the same approach. Pseudo-R^2 for the non-native forest regressions were between 0.93-0.97, and the pseudo-R^2 for the non-native grassland were 0.80 for Kohala and 0.90 for Kona[2].

2 Psuedo R^2 is similar to an R^2 in that it is a measure of correlation between expected and modeled values, but is used here since generalized least squared (GLS) regressions are fitted using log likelihood.

We then used the site and land cover specific regression equations to estimate change in AET over time in the 'no protection' scenarios. To do so, we modeled AET for projected land cover in years 0 through 50 produced by the spread model 'no protection' scenarios described above (see Figures 3a-c). That is, we applied the land cover and site-specific regression equations to all pixels which were converted to Hawai'i Introduced Wet Mesic Forest or to Hawai'i Introduced Perennial Grassland[3]. 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.

Fog interception:

Cloud water interception or fog interception has been shown to be important in tropical forests in Hawai'i (Takahashi et al. 2011; Juvik and Nullet, 1995; DeLay and Giambelluca, 2010; Giambelluca et al., 2010; Juvik et al., 2010). Thus, we also modeled changes in fog interception following USGS methods (Engott 2011) where fog interception is calculated as:

$$F = R * FIR * FCE$$

Where R= rainfall (from the Rainfall Atlas of Hawai'i; Giambelluca et al. 2013); FIR= fog interception ratio, which is a function of elevation and geographic zone (see Engott 2011); and FCE= fog capture efficiency, which is a function of land cover type. Engott (2011) assigned an FCE of 0 to grassland, 0.5 to shrubland and woodland, and 1 to forest. According to these assumptions, fog interception only would change with spread of grassland into shrubland and forest areas. However, given very limited data alongside local observations that intact native forests may capture more fog than less intact invaded forests (Takahashi et al. 2011), we also provide an analysis of the changes that would occur if non-native forest was assigned an FCE=0.9 rather than 1. This is a conservative estimate based on Takahashi et al. (2011) which found that cloud water interception (fog) was 29% of throughfall and stemfall in native forest versus 16% in non-native forest in Hawai'i Volcanoes National Park. Results should be interpreted with caution and require additional data collection, but help to illuminate the potential for fog interception to be an important driver of spatial prioritization.

To estimate the amount of avoided freshwater yield loss (avoided increase in AET + avoided loss of fog interception) that could be considered avoided loss of groundwater recharge vs. streamflow, we utilized the USGS water balance study for Hawai'i Island (Engott et al. 2011; 32-33), to calculate a groundwater recharge vs. surface runoff to freshwater yield (groundwater recharge + surface runoff) ratio by aquifer unit. The resulting recharge to water yield (recharge + runoff) ratio was 0.51 in Kohala (for Kohala Mountains based on Waimanu aquifer unit);

3 Leaf Area Index (LAI) for invaded areas was estimated as the median value of the LAI of existing Hawai'i Introduced Wet-Mesic Forest or Hawai'i Introduced Perennial Grassland pixels on Hawai'i Island; LAI was not changed in the case of invasion of Hawai'i Montane Subalpine Dry Forest and Woodland by Hawai'i Introduced Perrenial Grassland as the values were similar between these land uses. LAI was not correlated with precipitation, temperature, or elevation, justifying the selection of an overall median value, but this adds an important additional element of uncertainty that is important to acknowledge.

0.94 in Kona (based on Kealakekua and Keauhou aquifers); 0.84 in Kaʻū (based on Naʻalehu aquifer unit). As stated before, we lacked sufficient data to include altered infiltration rates due to land cover change as part of the model so we assume the ratio stays constant with land-use change (as is done in USGS water balance modeling studies).

We present prioritization results in two ways relevant to water resources management. First, we show the spatial distribution of aggregated benefits of protection over 50 years (in millions of gallons per acre) following the trajectory of benefits defined by our spread model. To do so, we calculated the change in recharge (per pixel) for each year compared to the baseline (Year 0) and summed the change over 50 years. Second, given that there are uncertainties in our spread model and that the land cover maps are not at a fine enough scale to project potential incipient populations of invasive species, we also provide an estimate of the potential benefits of protection of all native forest in the three study areas (in gallons per acre per day). That is, we show the potential change in recharge (average gallons per day) if any given native forest pixel were to convert to non-native forest or grassland. While we suggest that prioritization take into account threat and aggregated benefits (50 years or other designated time frame), these maps may be useful in cases where there are demonstrated threats that our land cover map did not pick up. The aggregated benefit in these cases will depend on the year of conversion and time over which benefits are aggregated. For each prioritiziation map we created 5 prioritization categories. To do so, we set the lowest priority below the 20th percentile of pixels and the highest priority above the 80th percentile of values. We then created the 2nd-4th priority zones by dividing the values between the 20th and 80th percentiles into 3 categories with equal spacing of values.

3b. Watershed restoration

Given interest from DWS in supporting native reforestation efforts in areas with potential recharge benefits, we also considered the potential benefits of native forest restoration in areas currently classified as Hawaiʻi Introduced Perennial Grassland and that were in areas at elevations above 2500 feet where fog interception is expected (Engott et al. 2011; Appendix Figure 3). We produced reforestation scenarios in suitable elevation climatic zones following Wada et al. (2017; note that no reforestation was deemed feasible where MAR was less than 13.8 inches):

- Hawaiʻi Lowland Dry Forest: elevation < 1000 m (~3280 ft); and MAR between 350 mm (13.8 inches) and 750 mm (29.5 inches).
- Hawaiʻi Lowland Mesic Forest: elevation < 3280 ft and MAR > 29.5 inches
- Hawaiʻi Montane Subalpine Mesic Forest: elevation > 3280 ft

AET was modeled following methods described above, but with regression equations created for the reforested native forest cover types. Given the low number of pixels per study region of existing forest areas, regressions were created using the full set of 3016 Hawaiʻi Island-wide pixels for Hawaiʻi Lowland Dry Forest and a random subset of 7,000 pixels for Hawaiʻi Lowland Mesic Forest and Hawaiʻi Montane Subalpine Mesic Forest. Pseudo-R^2 was 0.69 for

Hawai'i Lowland Dry Forest, 0.92 for Hawai'i Lowland Mesic Forest, and 0.81 for Hawai'i Montane Subalpine Mesic Forest. Fog interception was included using the approach described for the forest protection scenarios. The same recharge to water yield ratios were used as described in section 3a, but we adjusted these for the Kohala study area where reforestation occurred in the Waimea aquifer (recharge to water yield ratio = 0.92) and the Mahukona aquifer (recharge to water yield ratio = 0.33; Engott 2011). We provide results aggregated over time assuming that all areas are reforested in 2019 and that changes in AET and fog shift from values of grassland to values of forest linearly from 0 to 20 years, after which we assume the area is considered forest.

4. RESULTS

4a. Water benefits of watershed protection

Conservation of all of Kohala's native forest susceptible to invasion at our spread rate and time horizon assumptions (38,255 acres) was projected to avoid the loss of ~187 billion gallons of recharge over 50 years. Annual recharge in Year 50 is projected to be ~5.71 billion gallons per year (15.6 MGD) lower without protection compared to Year 0 (Figure 4a). Conservation of all of Kona's remaining native forest susceptible to invasion (37,328 acres) was projected to avoid the loss of ~318 billion gallons of recharge over 50 years. Annual recharge in Year 50 was projected to be 16.7 billion gallons per year (45.7 MGD) lower without protection compared to Year 0 (Figure 4b). Conservation of all of Ka'ū's remaining native forest susceptible to invasion (5127 acres) was projected to avoid the loss of ~18 billion gallons of recharge over 50 years. Annual recharge in Year 50 was projected to be ~1.14 billion gallons per year (3.1 MGD) lower without protection (Figure 4c).

Figure 4a: Potential avoided loss of groundwater recharge and water yield in Kohala with full watershed protection over 50 years (assuming equal fog interception among forest types).

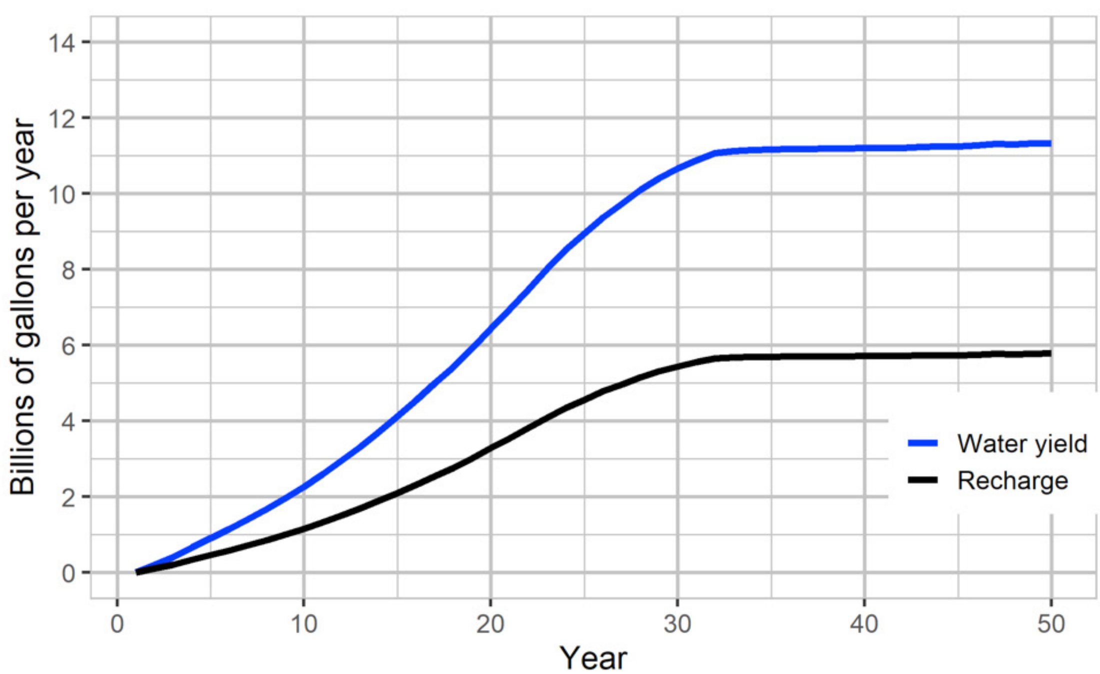


Figure 4b: Potential avoided loss of groundwater recharge and water yield in Kona with full watershed protection over 50 years (assuming equal fog interception among forest types).

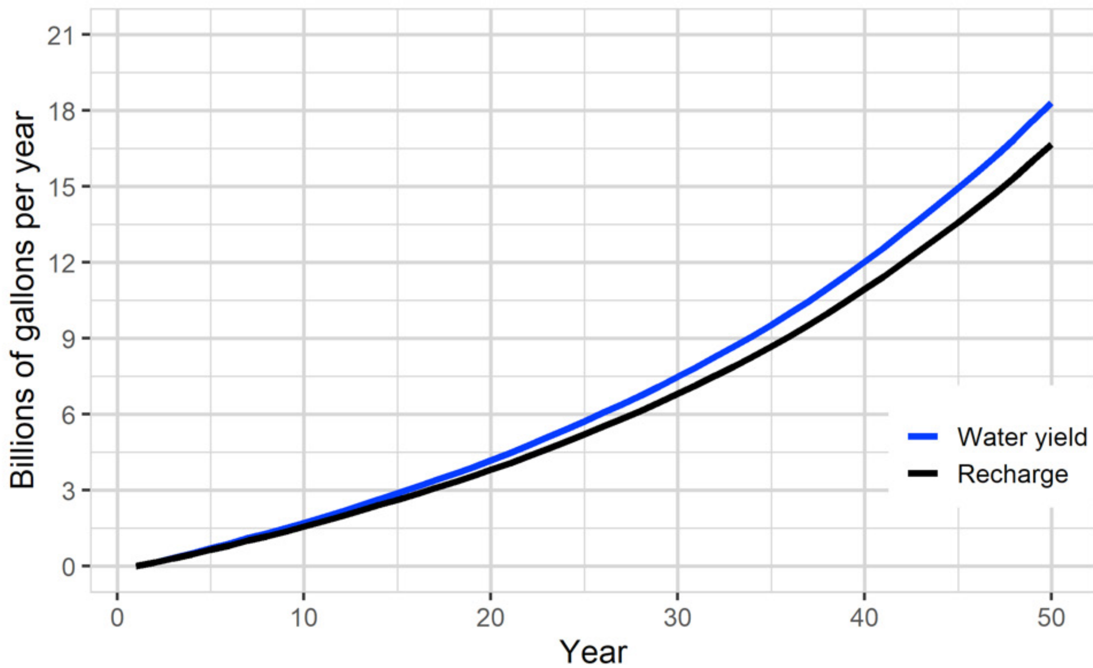


Figure 4c: Potential avoided loss of groundwater recharge and water yield in Kaʻū with full watershed protection over 50 years (assuming equal fog interception among forest types)

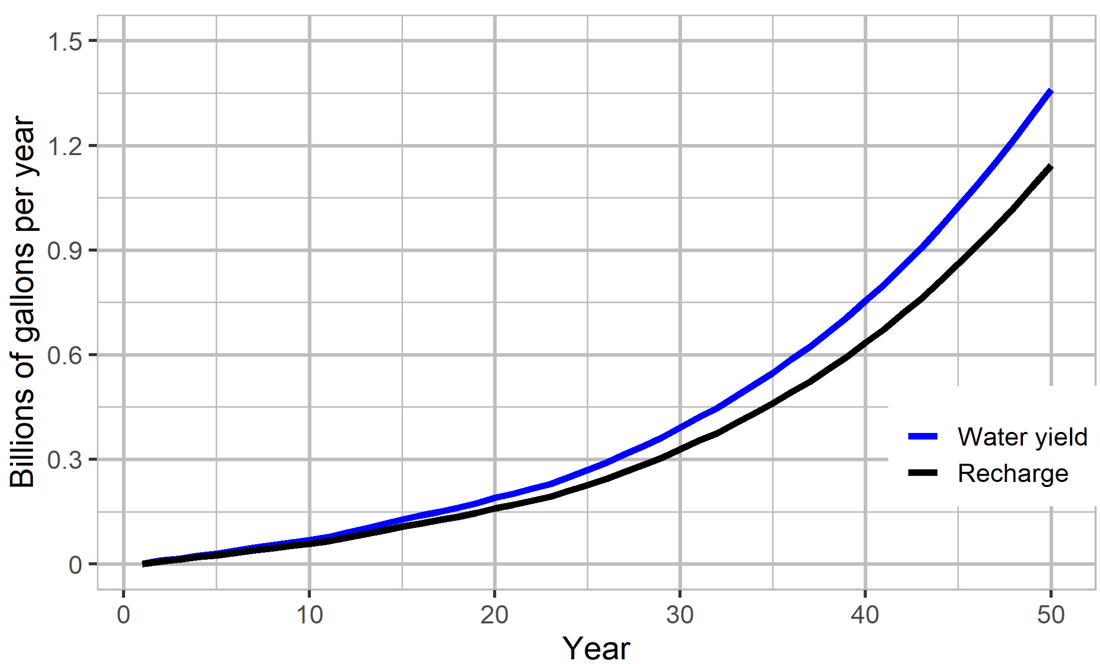


Figure 5 shows prioritization of investments based on the aggregated water benefits over 50 years (in millions of gallons per acre). Protection in all areas priorities 1-5 provide positive benefits for groundwater recharge. Aggregated over 50 years, the highest benefits tend to be in mid to lower elevation areas given that they are likely to be invaded first and also have higher air temperature and net radiation and thus higher evapotranspiration rates (Appendix Figure 4). Benefits are also high in Kohala, as the initial higher amount of non-native forest accelerates the spread and therefore the benefits of protection (see Figures 3a-c). The same priority map is shown in Figure 6 assuming a fog capture efficiency of non-native forest of 0.9 instead of 1.0 (non-native as intercepting 10% less fog than native forest). Altering the fog interception ratio of non-native forest had little influence on priority areas based on aggregated benefits, with the exception of Kohala where some high elevation areas become higher priority.

Figure 5: Avoided loss of groundwater recharge with watershed protection from invasion of non-native forest and non-native grassland (in millions of gallons per acre) aggregated over 50 years and assuming equal fog interception by all forest types. Blue = highest priority

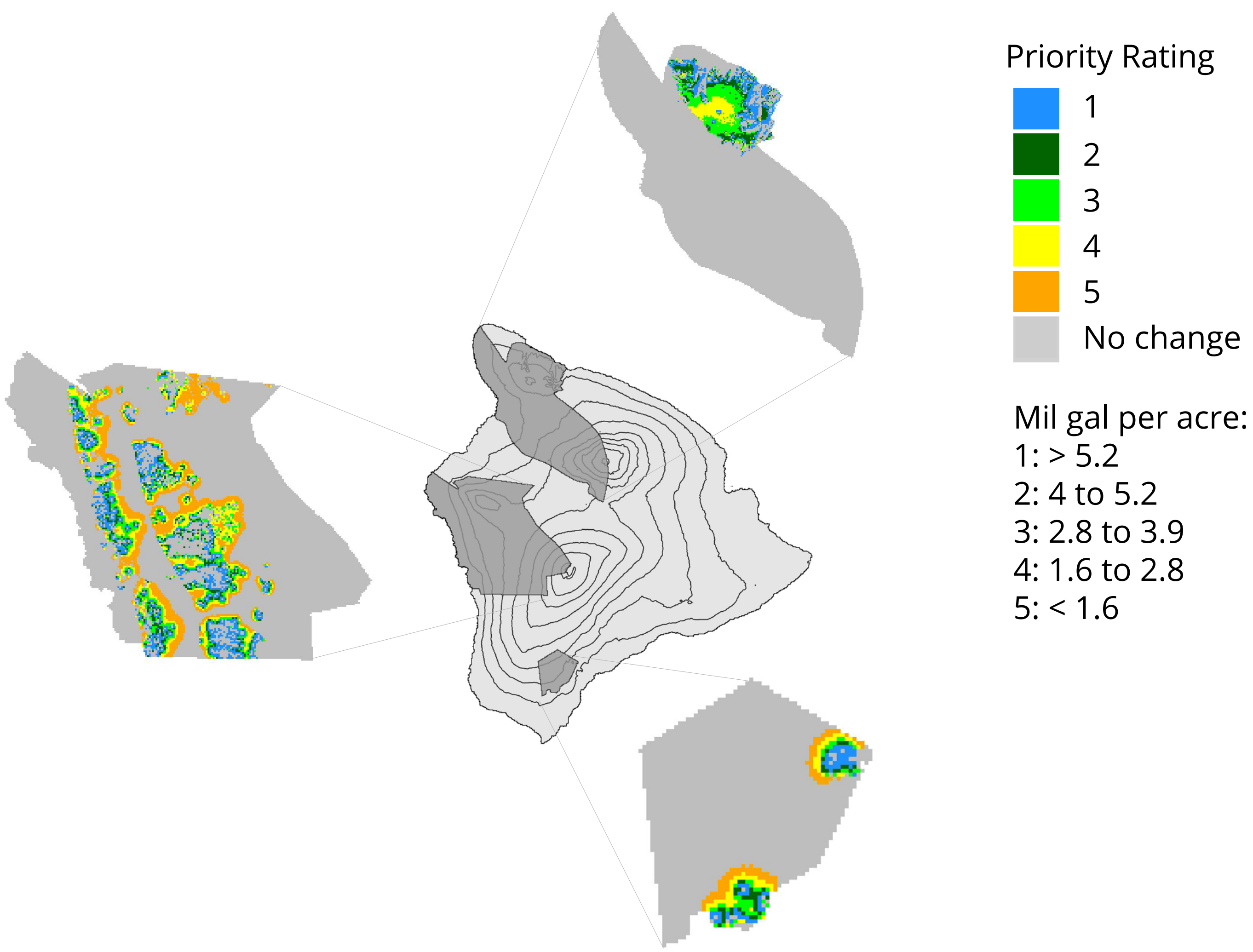
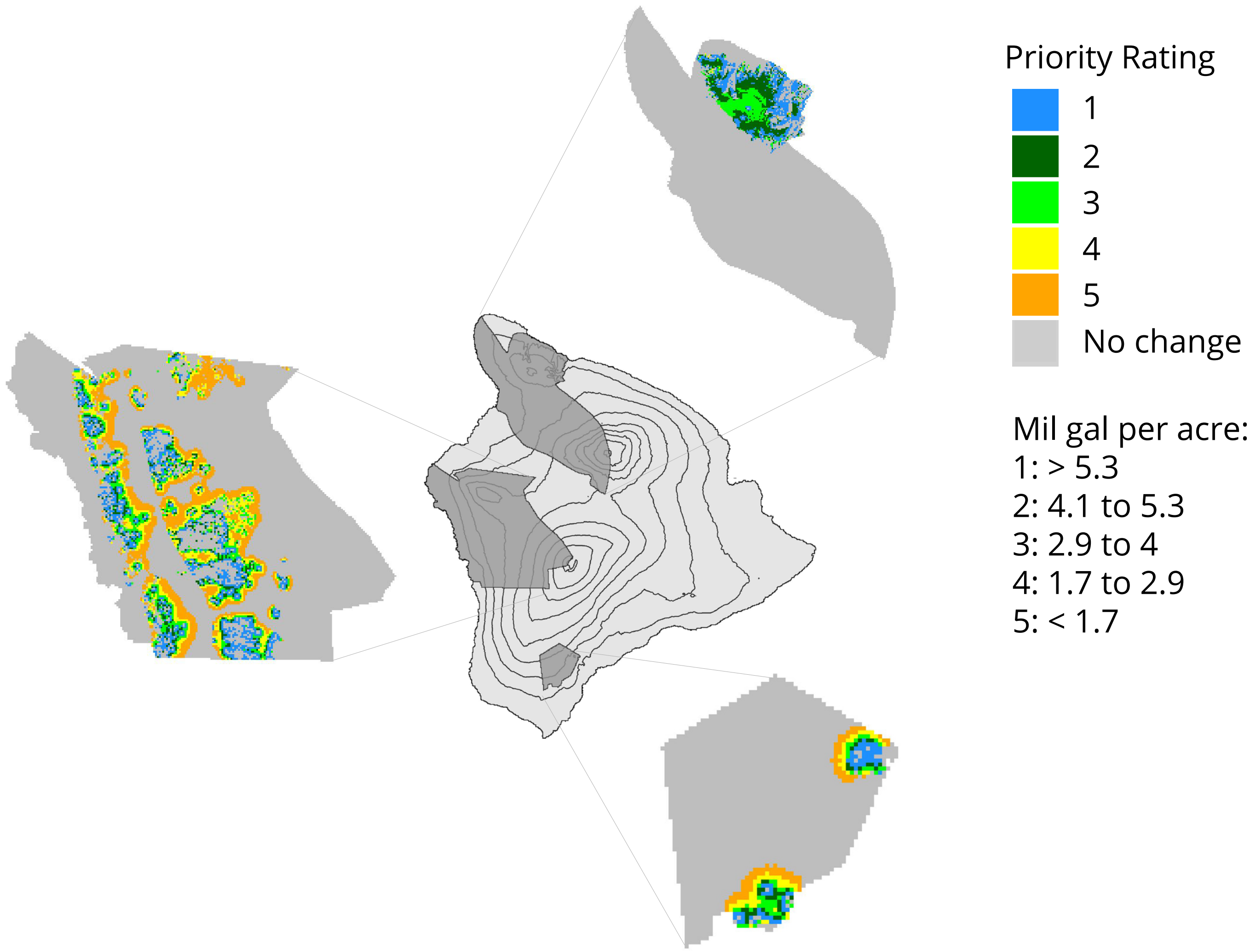


Figure 6: Avoided loss of groundwater recharge with watershed protection from invasion of non-native forest and non-native grassland (in millions of gallons per acre) assuming 10% lower fog capture efficiency of invaded forest. Blue=highest priority.

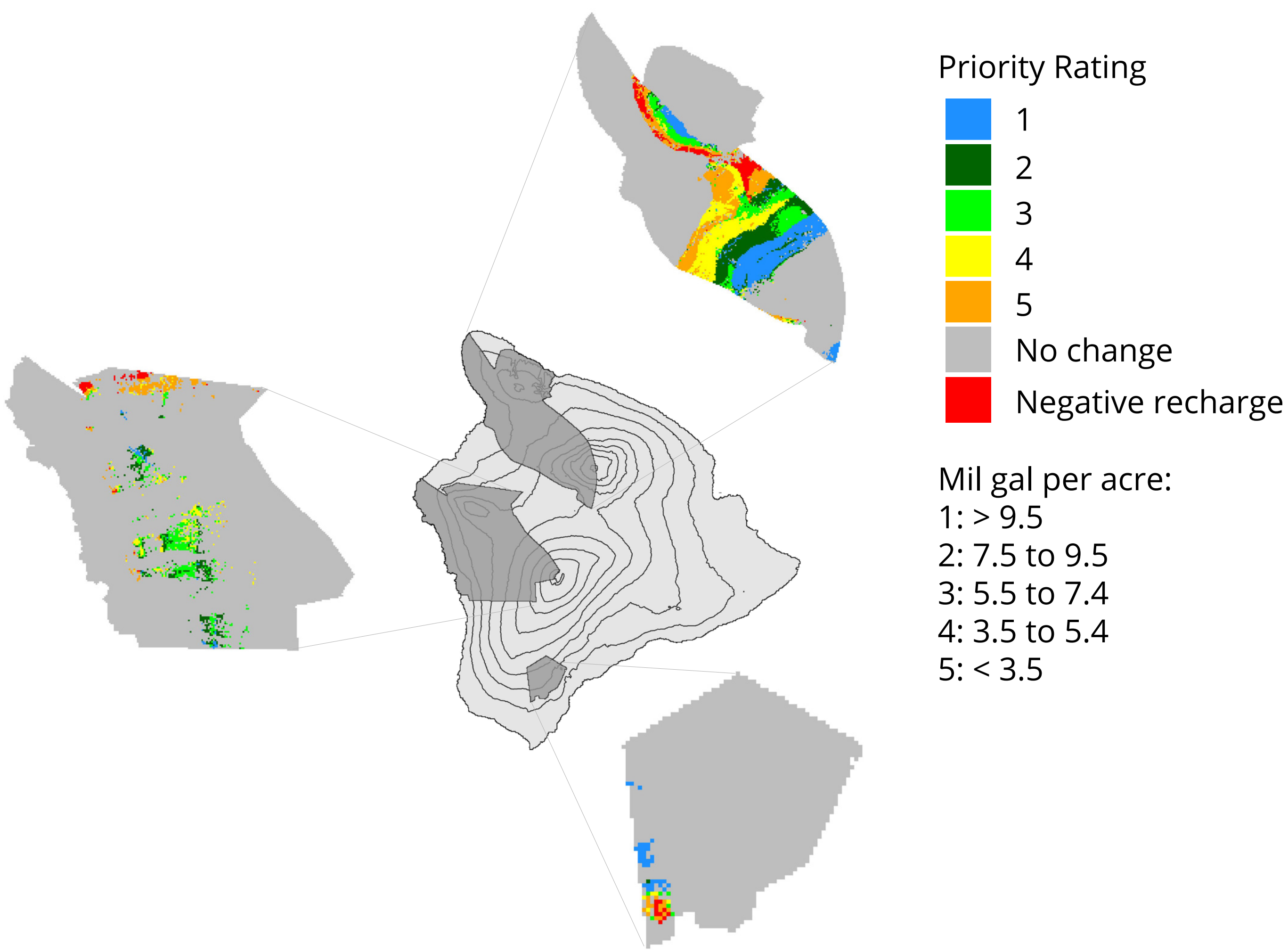


Figures 5 and 6 show aggregated benefits over time and emphasize a focus on the most threatened areas, which we suggest is a useful way to think about prioritizing investments in watershed protection for groundwater recharge. However, our estimates of the trajectory of spread are uncertain, and may be updated with additional information on incipient populations of invasive species or additional information on spread rates and patterns. Accordingly, we also provide an analysis of the potential benefit of protection of all native forest areas in the three study areas in Appendix Figures 1 and 2 (expressed in average gallons per day per acre). These maps will be important where threats may exist that we were not able to account for in our spread model. Aggregated benefits will depend on the year of conversion.

4b. Water benefits of native forest restoration

Reforestation of grassland areas resulted in an increase or decrease in recharge depending on the spatial location. In particular, reforestation in areas with significant fog interception (Appendix Figure 3) is projected to result in an increase in recharge, whereas in other areas the increased evapotranspiration without additional fog input results in a decrease in recharge. Figure 7 shows the aggregated benefit (assuming linear growth between Year 0 and Year 20 and full maturity at Year 20) in millions of gallons per acre. Priority areas are generally higher elevation areas that coincide with high fog interception. In contrast, the red, lower elevation areas have little to no fog interception and increases in AET with reforestation reduce overall recharge.

Figure 7: Aggregated change in recharge with reforestation of non-native grasslands over 50 years (in millions of gallons per acre). Blue = highest priority.



5. DISCUSSION/CONCLUSIONS

Given the objective of protecting or enhancing groundwater recharge, our results suggest that both watershed protection and reforestation in the three DWS priority areas offer potential benefits, particularly when spatially targeted. For forest protection, we found the following areas of particularly high importance: 1) lower to mid elevation areas at high risk of invasion by non-native canopy species; 2) higher elevation areas (with substantial fog interception potential) at high risk of conversion to non-native grassland or bareground.

Our watershed protection 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 forest pixels 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 to non-native forest within the 50-year timespan of the model. However, faster spread rates would result in more potential recharge losses (and hence benefits) in higher elevation areas. Similarly, a larger initial proportion of non-native to native forest would result in more area being converted over time, including higher elevation areas.

Water benefits in this report are based primarily on evapotranspiration, due to limited data of differences in fog interception and infiltration rates between non-native and native forest. However, we did incorporate analysis of the difference in results if native forest is assumed to be more effective at fog capture than invaded forest, following Takahashi et al. (2011). While altering the fog capture efficiency of non-native forest to be 0.9 rather than 1.0 changed the amount of recharge benefits, we found that it did not generally result in major changes in prioritization of areas (with the noted exception of Kohala high elevation areas increasing in priority where differences in fog are assumed). Incorporating updated information regarding water balance components will be critical and could change the spatial configuration of benefits. Current research being conducted by the USGS and the University of Hawaiʻi at Mānoa should shed light on these ecohydrological processes in various native and non-native forest cover types.

Our conclusion that lower to mid 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. As demonstrated by our inclusion of potential spread of non-native grassland areas, these higher elevation areas may be subject to degradation through ungulate activity. The land cover maps we used do not show small, isolated populations of invasive plants that are scattered across higher elevations; thus, the projection that these areas will remain native dominated during the study period may be an under-estimate of the threat of conversion (particularly in Kaʻū). For this reason, we have included Appendix figures 1 and 2, which show a snapshot of potential benefits (i.e. potential avoided loss) of protection of all native forest in the three study regions irrespective of current estimates of threat. Moreover, many currently protected high elevation 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.

We also found that reforestation in higher elevation areas with high fog interception could generate recharge benefits comparable, and in some cases, even higher than forest protection. However, spatial targeting is critical as reforestation can increase AET so benefits occur primarily in areas where fog interception outweighs changes in AET.

This report is based on the best available spatially explicit data and involved discussions with watershed partnerships and the State Department of Forestry and Wildlife. However, there are important key uncertainties that are important to bear in mind. As with all studies of this nature, further eco-hydrologic studies are critical for refining this analysis and we strongly encourage revising this analysis as additional data become available. Several key uncertainties are highlighed below:

- “No protection” counterfactual scenarios are based on a 5% annual spread assumption of fast growing non-native forest (all sites) and 2% assumption of non-native grassland scenarios (Kohala and Kona). These are best estimates based on available studies and expert opinion, but are uncertain. We thus provide estimates of the potential benefits of protection over the full study areas as ‘snapshot’ annual benefits (Appendix Figures 1 and 2).

- Actual evapotranspiration (AET) estimates are based on regression modeling using data from the Evapotranspiration Atlas of Hawai‘i (Giambelluca et al. 2014), which uses representative species water use data (i.e. strawberry guava for non-native forest; and ‘ōhi‘a lehua for native forest). Actual values will vary spatially in a way that we were not able to include. These estimates are currently being updated by ongoing research by the University of Hawai‘i and the USGS.

- The ratio of recharge to runoff was kept constant for each study site based on baseline data and was not altered with land-use change or specific pixel conditions. Ongoing research by the University of Hawai‘i and the USGS may help to refine these estimates.

- Fog analysis was carried out following USGS methods (Engott 2011). As further data and methods become available for fog interception analysis, we recommend updating this component.

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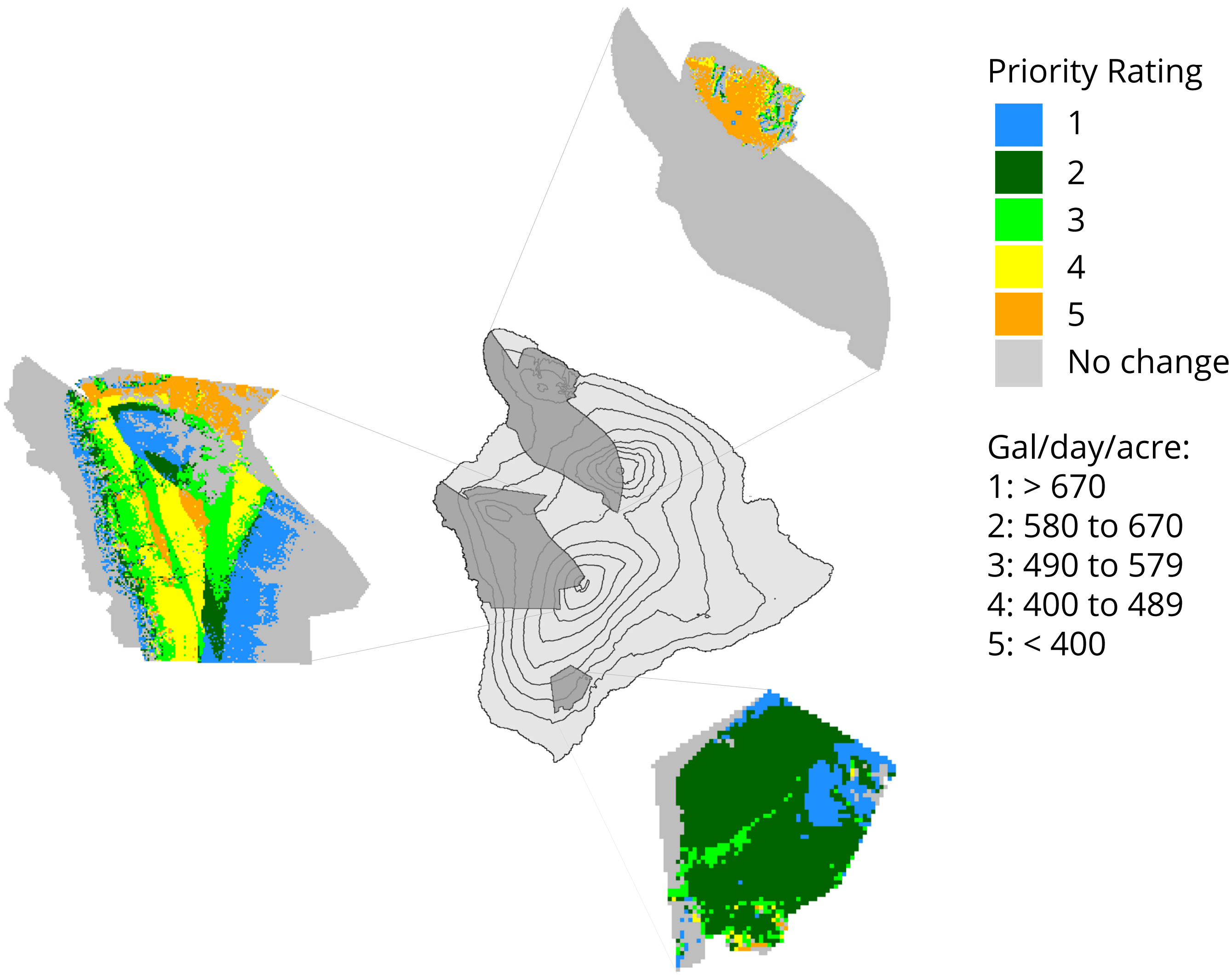
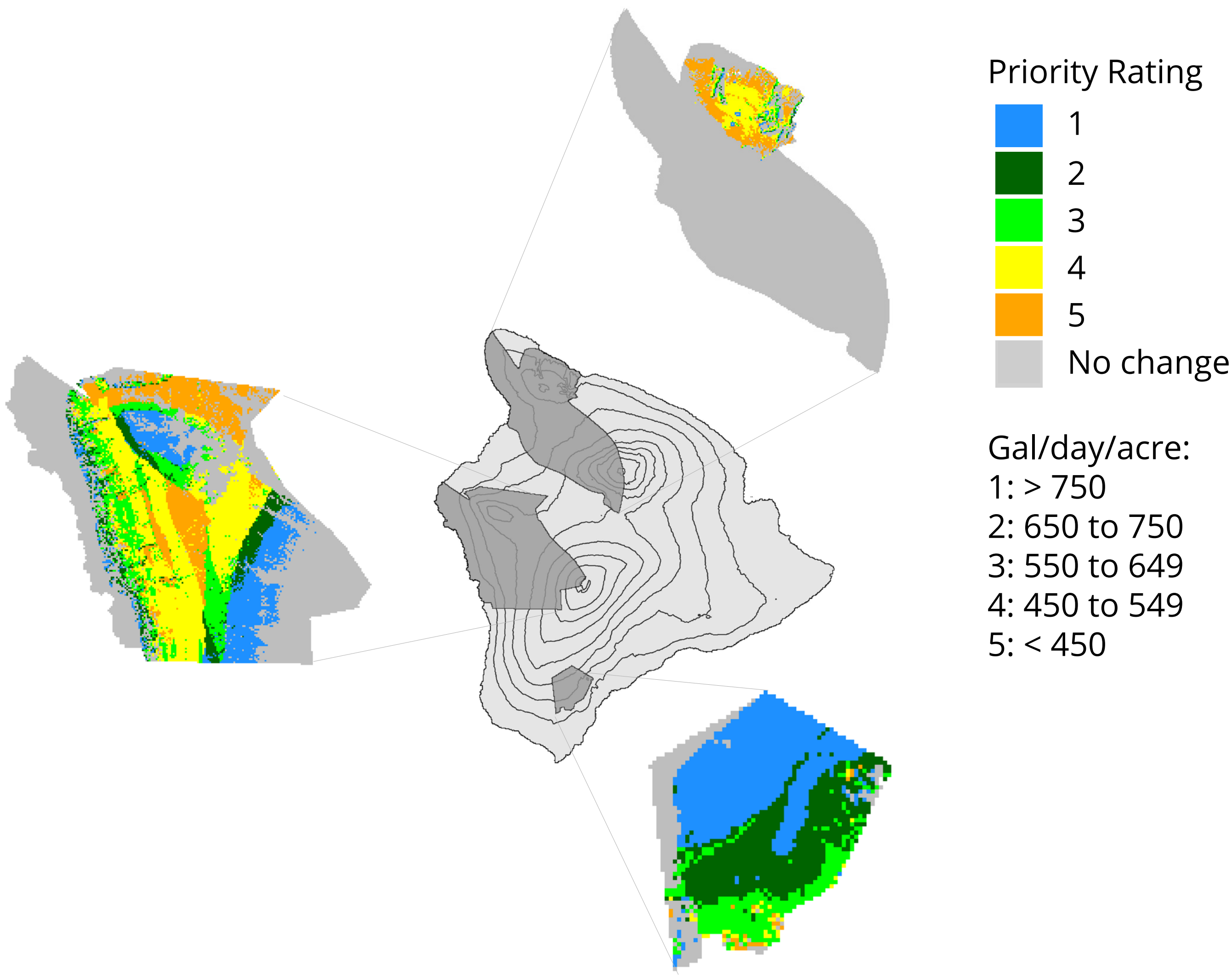
APPENDIX FIGURES:

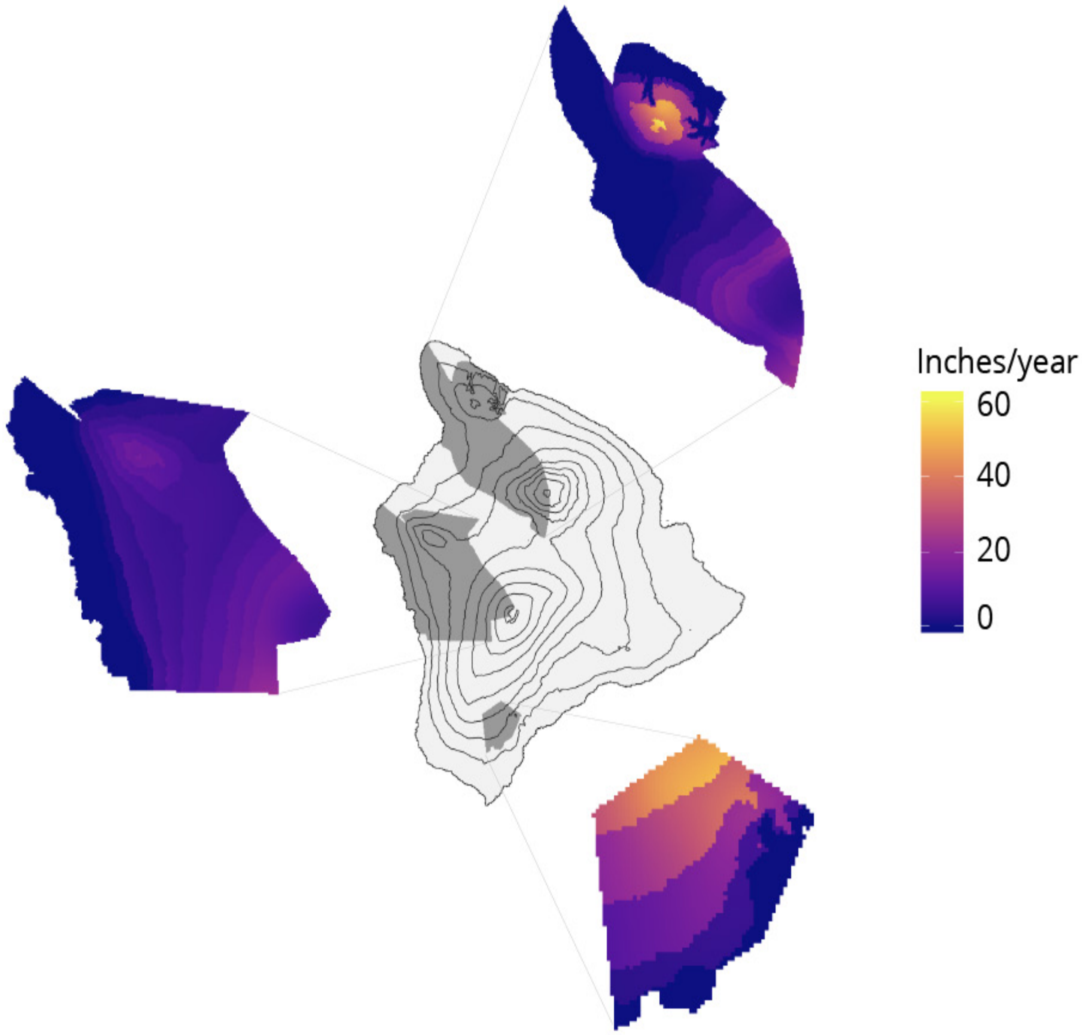
Appendix Figure 1: Potential avoided loss of groundwater recharge (average gallons per acre per day) over the full study area (assuming equal fog interception between forest types). Note: this analysis does not take into account existing threats, but could be used in case of evidence of susceptibility of invasion. Aggregated benefits would depend on the year of conversion.



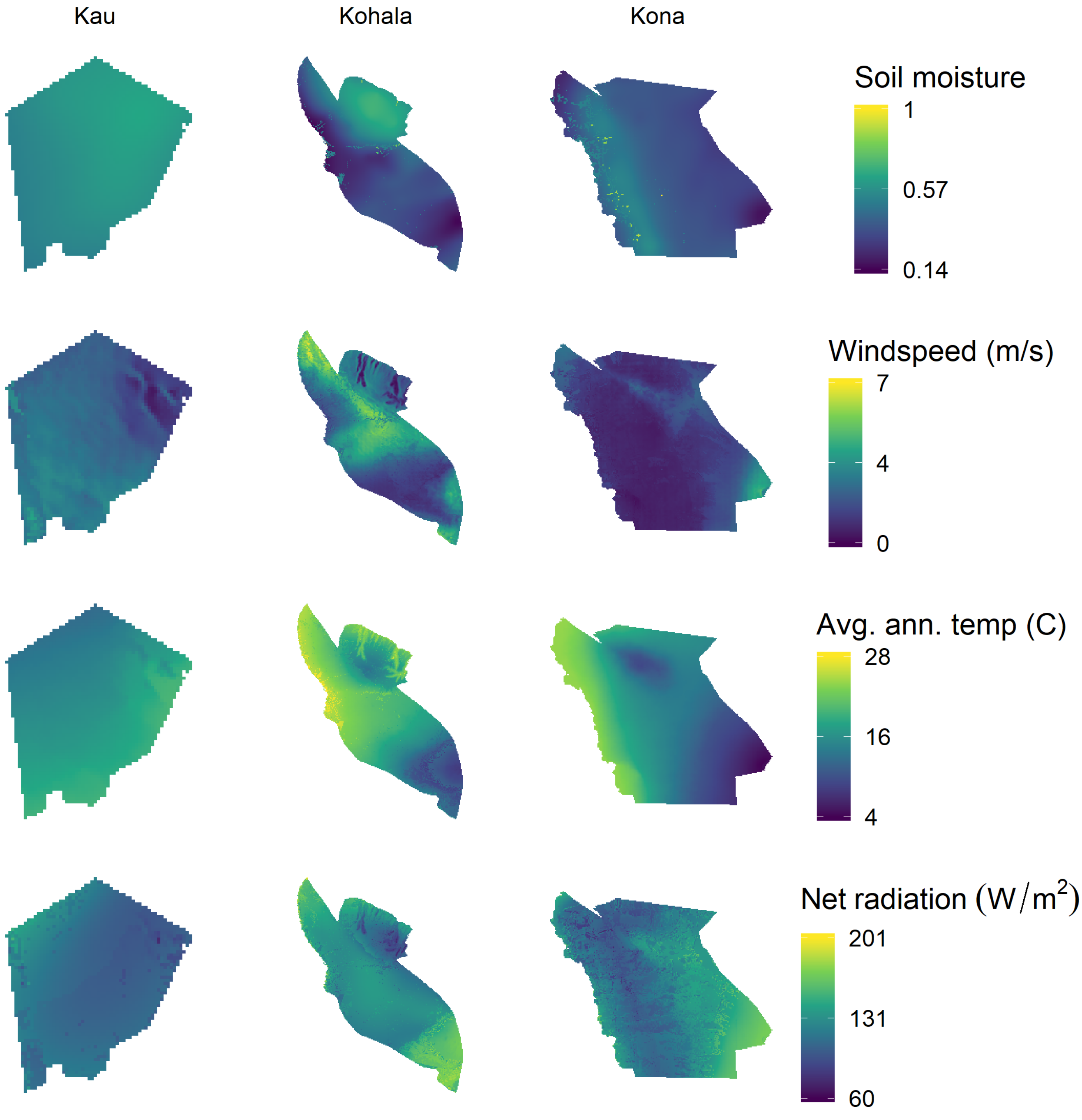
Appendix Figure 2: Potential avoided loss of groundwater recharge (average gallons per acre per day) over the full study area (assuming 10% greater fog interception in in-tact native forest). Note: this analysis does not take into account existing threats, but could be used in case of evidence of susceptibility of invasion. Aggregated benefits would depend on the year of conversion.



Appendix Figure 3: Potential fog interception in study areas.



Appendix Figure 4. Available Soil moisture, windspeed, average annual temperature, and net radiation in the study areas.



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