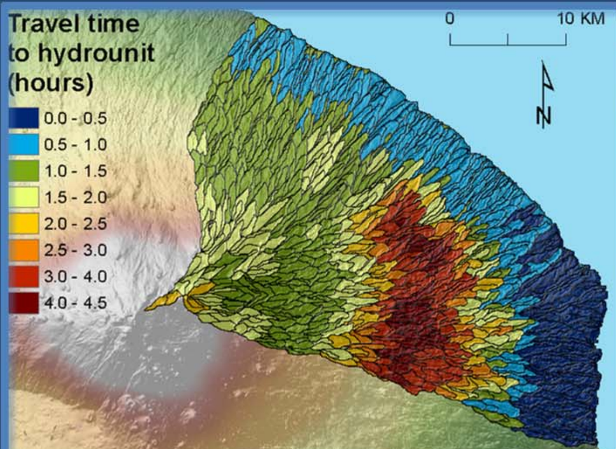
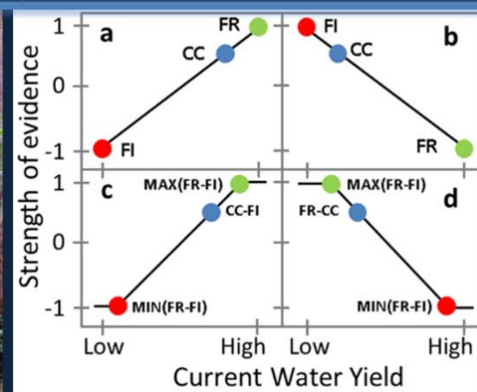
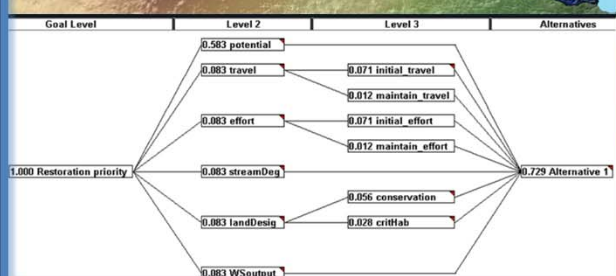
A DECISION SUPPORT TOOL FOR WATERSHED MANAGEMENT IN THE TROPICS







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Executive Summary

In the Pacific Islands, ample freshwater is the primary resource supporting human and ecological communities. Many watersheds are threatened by climate change, urban encroachment, and invasion by water-demanding exotic plant species like strawberry guava (SG; *Psidium cattleianum*). To maintain an adequate freshwater supply, adaptive management strategies are needed to address these concerns while also incorporating operational barriers to implementation.

The goal of this project was to develop a watershed decision support tool (WDST) to enhance ecosystem resilience to current invasions and future climate change through management mitigations and infrastructure improvements.

The prototype WDST incorporated:

- A distributed hydrology model to quantify effects of climate change and SG invasion on freshwater yield
- A decision support tool that linked potential changes in yield with treatment costs, accessibility, and conservation values to identify priority restoration and protection areas
- A collaborative process for developing, refining, and implementing the WDST.

The primary outputs of the WDST were priority scores identifying hydro-subunits across the study area (Figure 1) either to remove SG to increase freshwater yield or to protect areas from future SG invasion. The completed WDST enables resource managers to visualize summaries of the:

- Effects of climate change and SG invasion on water yield
- Total estimated costs of treatment
- Aquatic habitat quality
- Ownership status, and
- Synthesis of these layers that ranks each hydro-subunit based on treatment priority.

These products will allow managers to assess the hydrological benefits of watershed protection (e.g., fencing), and non-native and invasive plant removal for a given treatment area. Using the WDST, managers can customize the model to prioritize management areas that meet their specific restoration objectives.

The WDST presents these outcomes across current conditions and five climate change scenarios so managers can contrast decisions under a spectrum of potential climate outcomes.

Strawberry Guava

Date of Final Report:
March 21, 2014

Period of time covered by the report:
July 01, 2011 through March 31, 2014

Actual total cost:
PICCC Award: $120,000
Total Project Costs: $650,000

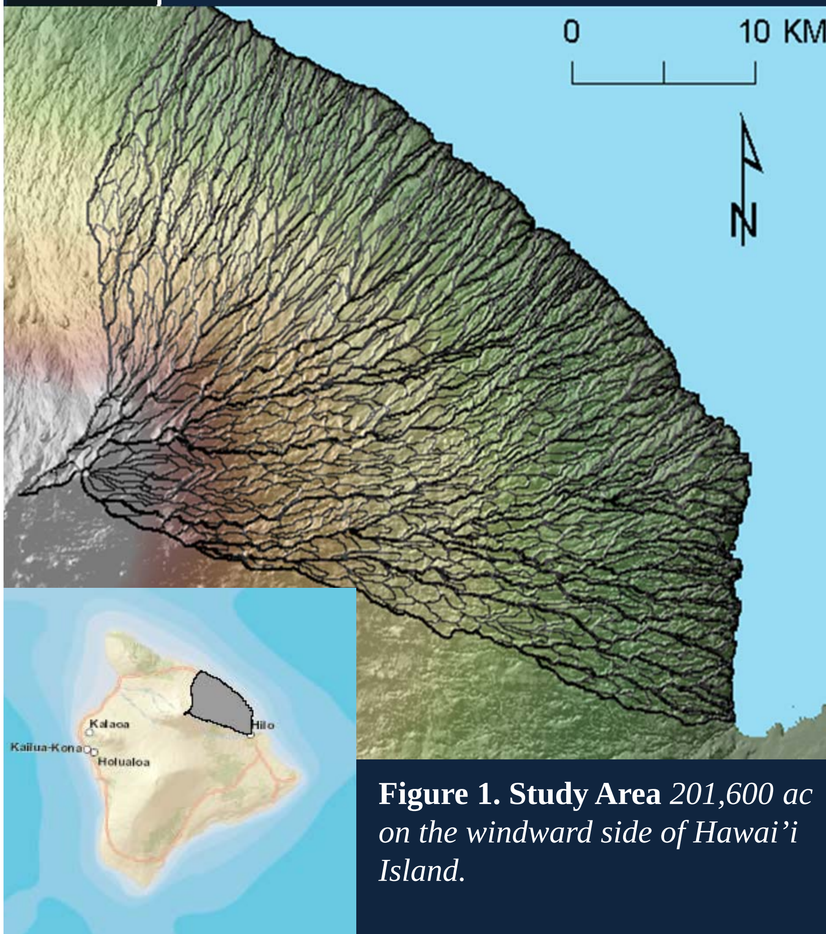


Figure 1. Study Area *201,600 ac on the windward side of Hawai'i Island.*

Introduction

On the island of Hawai'i, increasing temperature (3^{o}C per century) in mid-elevation ecosystems has exceeded the 30-yr global average (Giambelluca et al. 2008). Likewise, stream flow has declined by 10% (Oki 2004) while exotic plants continue to invade native ecosystems (Asner et al. 2005; Asner et al. 2008). Preliminary climate downscaling for the Hawaiian Islands predicts a climatic future with more intense than normal rain events separated by a greater than normal number of interspersed dry days (Chu and Chen 2005; Chu et al. 2010; Norton et al. 2011).

As in other tropical forests, invasion of native Hawaiian forests by species such as SG alters the hydrological cycle by influencing cloud and rainwater interception, evapotranspiration, stream flow and water retention, thereby affecting groundwater recharge and water inputs to streams and coastal outlet areas (Erickson and Puttock 2006; Friedlander et al. 2007; MacKenzie and Bruland 2011). Fast-growing, non-native plants generally increase stand-level evapotranspiration rates compared to native plants, especially in warming and drying climates (Cavaleri and Sack 2010). Indeed, our hydrological modeling showed that the combined influence of SG invasion and altered climate regime had sizable impact on stream flows (Figures 3 & 4).

Taken together, the influences of climate change and SG invasion have the potential to change future freshwater supply in watersheds of the North Hilo-Hamakua study area. While it is unknown how future decision making will be affected by rapid global changes, well-informed and strategic investments in watershed management are needed to increase freshwater supply for stakeholders and ecosystem values for conservation. Furthermore, without informed decision making, global changes will cause wide-scale and potentially permanent changes in forest characteristics, which could compromise future opportunities to enhance aquatic ecosystem resilience to climatic change.

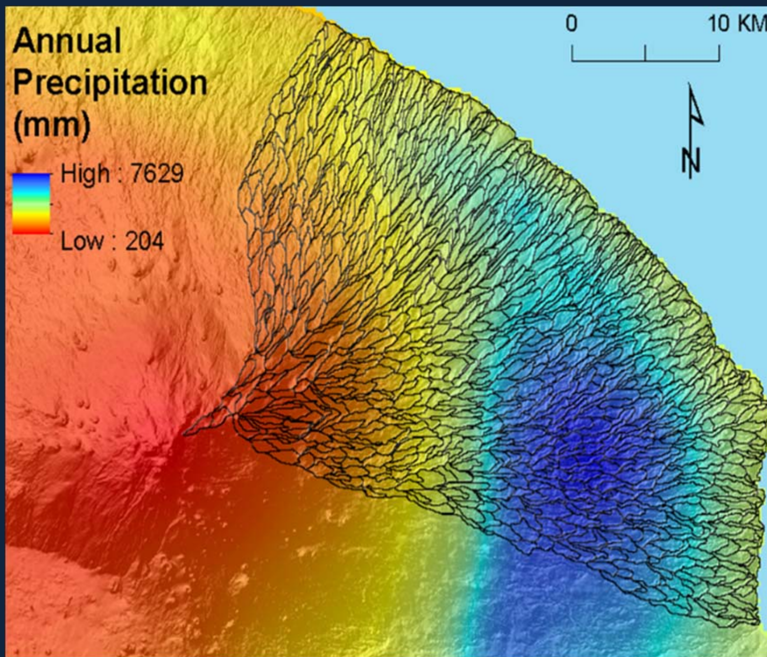


Figure 2. Mean annual precipitation across the North Hilo-Hamakua study area.

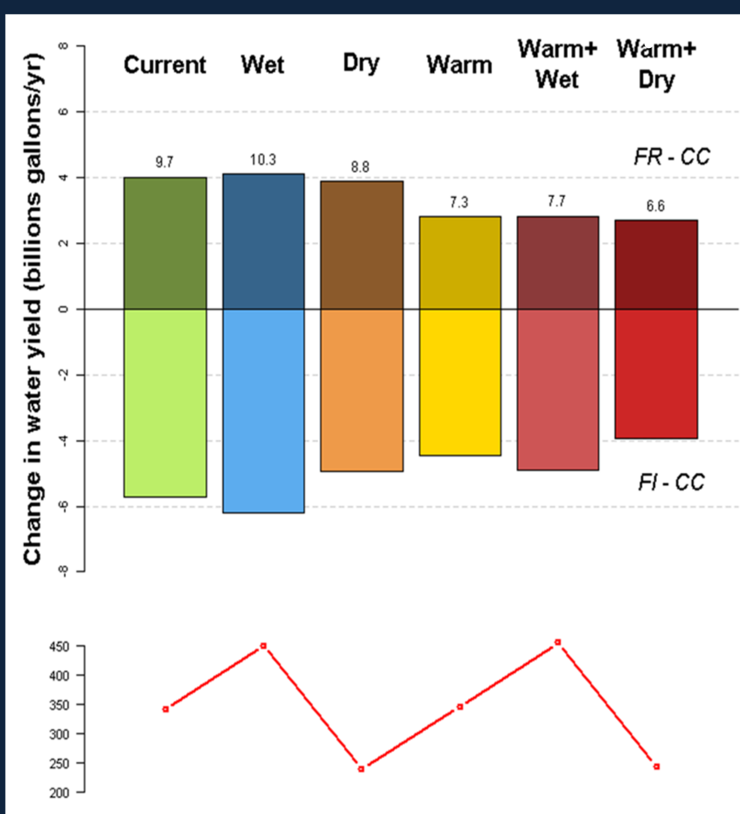


Figure 3. Bar plot of the difference in total water yield (billions of gallons/year) associated with the fully restored (FR) and fully invaded (FI) strawberry guava (SG) conditions when compared with the current invasion condition (CC) for the North Hilo-Hamakua study area. Colored bars represent comparison of total study area yield by climate scenario. The portion of the bars above the zero line (darker shading) represents the water yield gained by fully restoring the current condition, obtained by subtracting the CC total water yield from FR condition. Portions below the zero line (lighter shade) represent the water yield lost to FI when compared to CC, obtained by subtracting the CC from the FI condition. Values above the colored bars represent the total water savings achievable under the FR scenario compared to the FI scenario. The red trace in the lower line graph represents the current water yield under each climate scenario; vegetation is held constant.

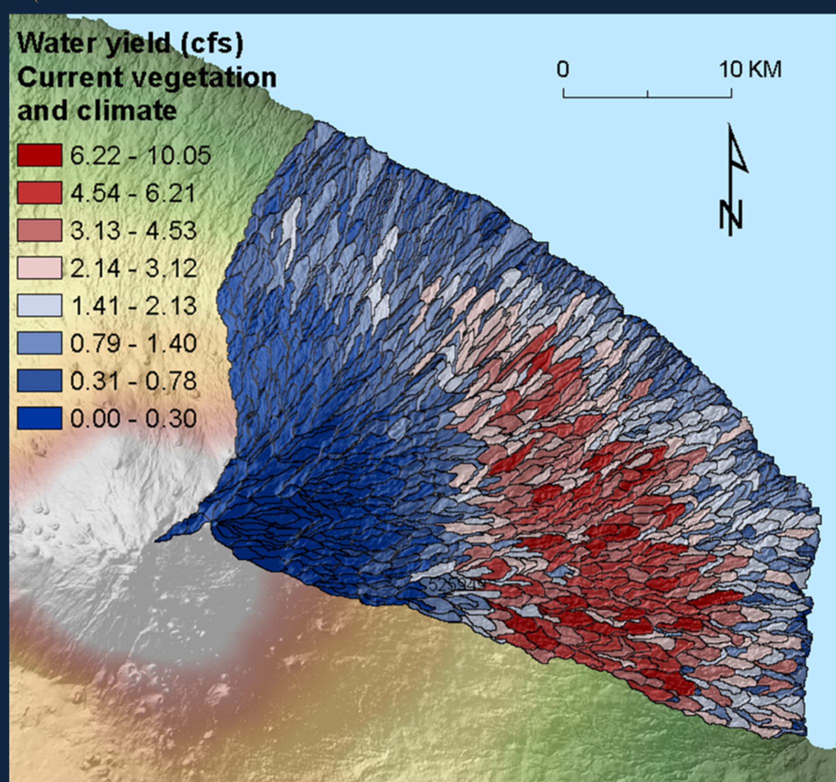
Study Area

An important feature of this research was the selection of the North Hilo-Hamakua study area (Figure 1), which encompassed 201,600 acres on the windward side of Hawai'i. The study area is dominated by spatially compact watersheds of volcanic origin, which display highly constrained climatic gradients and vary minimally in plant diversity, soil type, and geologic age (Vitousek 2004). The study area provides a unique opportunity to examine the combined influences of climate change and invasive species removal on water sustainability within watersheds spanning large climatic gradients.

The study area incorporates:

- Environmental and land-use gradients from "ridge to reef"
- Moisture regimes spanning a 150 in. mean annual rainfall gradient (Figure 2)
- Diverse assemblages of communities, cultures and industries in lower watershed reaches that depend on fresh water for agricultural, ranching, residential and industrial uses
- Evolving policies and management that seek to balance the needs of water users and nature

Figure 4. Distributed hydrology model (DHSVM) output showing the mean annual water yield (range 0-10) in cubic feet per second (cfs) for individual hydrological subunits.



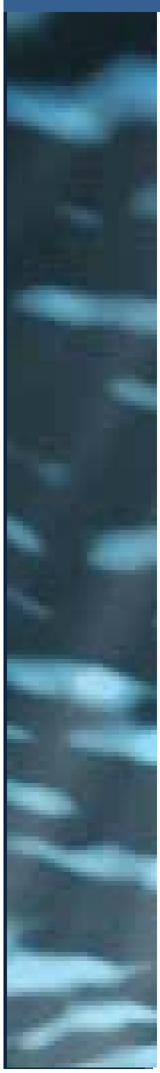
Feral pigs – primary vector of SG

Models

The WDST was composed of three modules:

- A *distributed hydrology model* that estimated water yield by hydro-subunit for the entire study area, under the current and simulated vegetation and climate conditions (Table 1);
- A *logic model* that compared water yield of each hydro-subunit under current vegetation, fully SG invaded, and full SG removal conditions;
- A multi-criteria *decision model* that incorporated treatment costs, aquatic habitat condition, and conservation status criteria into final management priority rankings.

Distributed hydrology model - Water yield was calculated at the point of outflow (pour point) for 904 hydrological subunits using the Distributed Hydrology Soils and Vegetation Model (DHSVM, Wigmosta et al. 1994), which incorporated the effects of topography, soils, and vegetation on water output for the years 2006-2012. The model was calibrated using current vegetation and climatic conditions, and model outputs matched well with observed water yields at the Honolii stream gauge (USGS stream gauge number 16717000, R^2 = 92% for monthly flow). The model was then re-run in a full factorial design of 18 combined climatic (6) and vegetation (3) scenarios (Table 1) to identify changes in water yield. Final models used hydro-subunit level mean annual water yield ($ft^3 \cdot sec^{-1}$), which ignored water contributions from adjacent upslope catchments (i.e., individual catchment contributions).



Scenario	Temp Scenario	Rainfall Scenario	Veg Scenario
1	Temperature Increase	Rainfall Decrease	Current Vegetation
2			Full Invasion
3			Full Restoration
4		Rainfall Increase	Current Vegetation
5			Full Invasion
6			Full Restoration
7		Current Rainfall	Current Vegetation
8			Full Invasion
9			Full Restoration
10	Current Temperatures	Rainfall Decrease	Current Vegetation
11			Full Invasion
12			Full Restoration
13		Rainfall Increase	Current Vegetation
14			Full Invasion
15			Full Restoration
16		Current Rainfall	Current Vegetation
17			Full Invasion
18			Full Restoration

Table 1. Eighteen climate and vegetation (strawberry guava invasion) scenarios tested throughout the study area. Data from three vegetation (current conditions, full invasion, full restoration) scenarios and six climate scenarios (current climate, +2^{o}C warmer, 20% drier, 20% wetter, +2^{o}C warmer + 20% drier, and +2^{o}C warmer + 20% wetter) were used to adjust the DHSVM water yield calculations for each hydrological subunit and watershed within the Hilo-Hamakua study area.

Models Cont.

Logic model- The NetWeaver® software (Rules of Thumb, Inc., North East, PA) was used to develop the *logic model* (NWLM), which assessed the current condition of each hydro-subunit by comparing:

- water yields under current vegetation conditions with fully invaded and fully restored scenarios (Figure 5 & 7)
- percentage SG invasion (Figure 6)

Based on these relationships, each hydro-subunit received "strength-of-evidence" (SOE) scores that ranked them based on the opportunity for restoration (removal of all SG), and protection (fencing to isolate ungulate travel and future invasion by SG) (Figure 5). For example, if water yield from a hydro-subunit under current vegetation and climatic conditions was low compared to the water yield predicted under the full invasion scenario, a high SOE score would result for SG removal because current water yield was constrained by SG invasion (Figure 5, panel *b*).

Analyses were conducted at two separate scales: the hydro-subunit level that looked at each unit in isolation (Fig 5 a, b) and a watershed-level that compared each unit to all other units in the study area (Fig 5 c,d).

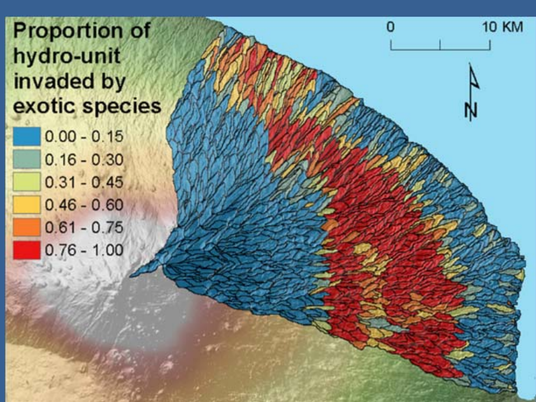


Figure 6. Proportional area of individual hydro-subunits invaded by strawberry guava.

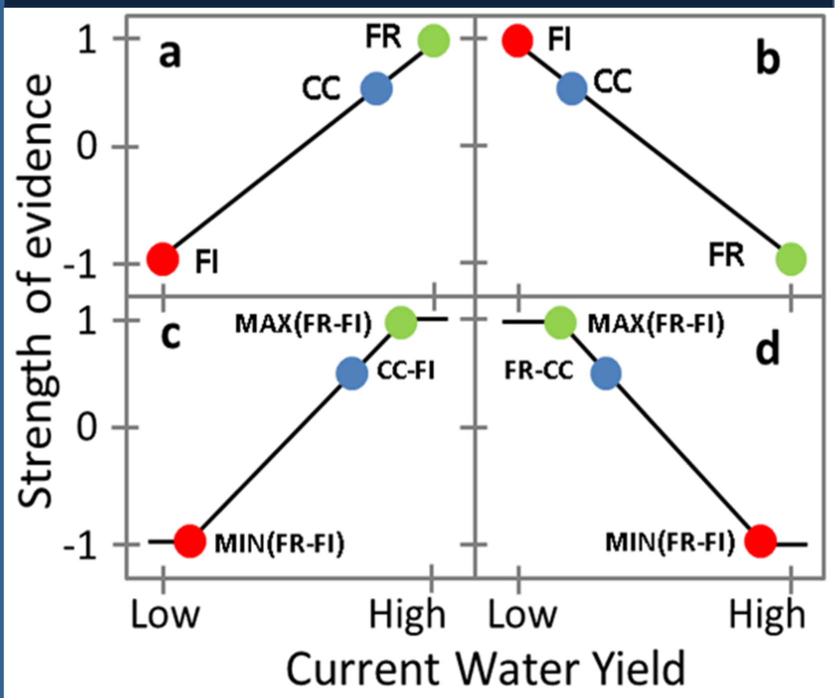


Figure 5. Illustration of NetWeaver® logic model (NWLM) evaluations to assess strength-of-evidence (SOE) scores for **Protection** and **Restoration** of hydro-subunits. Ramps *a* and *b* represent the full range of subunit data. In subunit *a* the yields under current conditions (CC) is close to the fully restored (FR) condition giving it a high SOE score for **Protection**. In b, the subunit is evaluated for **Restoration**. Since the CC water yield is low and close to fully invaded (FI) conditions, the SOE score for **Restoration** is high. Ramps *c* and *d* represent the 10th and 90th percentile range of the data. In *c*, the SOE for **Protecting** the subunits' relative water yield (CC minus FI minimum value) is evaluated against a ramp of all subunit FR-FI values. Similarly, *d* is evaluated for **Restoration** against all FR-FI values. This allows for SOE scores to be compared equally between subunits. In both cases the SOE scores for **Protection** in *c* and **Restoration** in *d* are high.

Models Cont.

Decision model- The *multi-criteria decision model* (MCDM) was developed using the Criterium DecisionPlus® v4.0.6 software, (InfoHarvest, Inc., Seattle, WA). The model incorporated SOE scores from the *logic model* along with other decision criteria that addressed the technical and economic feasibility of treatments while considering treatment costs, effort, accessibility by road or trail, land ownership status, and conservation value. Local land managers were consulted to identify the relative importance of each decision criterion, and this information was incorporated into the MCDM, via alternative criteria weightings. For example, if treatment cost was most limiting to restoration (i.e., high labor, transport and maintenance costs), then hydro-subunits associated with a high cost of treatment would get a relatively low priority (for treatment) score, despite having a high potential for positive water yield response to treatment (i.e., a high SOE score from the NWLM).

The NWLM and MCDM models are incorporated within the Ecosystem Management Decision Support (EMDS) system, which is a module within the ArcGIS® geographical mapping and analysis software (ESRI 2011). EMDS outputs are synthesized and spatially prioritized under each of the scenarios. In EMDS we can also perform data diagnostics, and assess weightings that affect decision scores.

See the Appendices at the end of this document for more information on each of the models used in the project.

Results

Strawberry guava - SG was found in nearly three-quarters of all hydro-subunits (Figure 6), and over a third of subunits had >50% SG coverage. Major SG infestation occurred below 4500 and above 1500 feet of elevation, and SG covered ~112 square miles of the study area.

Water yield - Mean annual water yield (measured in cubic feet per second, cfs) was estimated from DHSVM simulations for all hydro-subunits as the independent contribution of a subunit, excluding upslope water contributions. Under current vegetation and climate conditions, subunit-level water yield ranged from <0.1 cfs for high-elevation subunits to >7 cfs for those located in the southern and central portion of the study area, which corresponds to an area of high annual precipitation (generally > 250 inches per year; Figure 2). Mean annual water yield across all subunits was 1.6 cfs. For reference, 1 cubic foot is equal to 7.5 gallons, and a yield of 1 cfs is equivalent to 236 million gallons per year, assuming a constant yield rate.

Vegetation change from the current to fully invaded condition led to a 1.7% mean reduction in annual water yield across the study area. In total, SG full invasion led to a mean annual water yield reduction of 24.1 cfs (180 gallons/sec) across the study area (Figure 3). When full restoration and full invasion scenarios were compared, full restoration increased mean annual water yield by 308 gallons/sec, or >9.7 billion gallons/yr over the fully invaded scenario.

The warm + dry climate scenario led to a 29% reduction in water yield across all hydro-subunits compared to the current vegetation scenario (7,718 vs 10,832 gallons per second for warm+dry and current climate scenarios, respectively, (Figure 3 & 7). As expected, the greatest declines in water yield were located where current precipitation levels were highest, particularly in the south-central region of the study area. Higher elevations experienced minimal changes in water yield under a warmer+drier climate because these subunits produced little water under all scenarios.

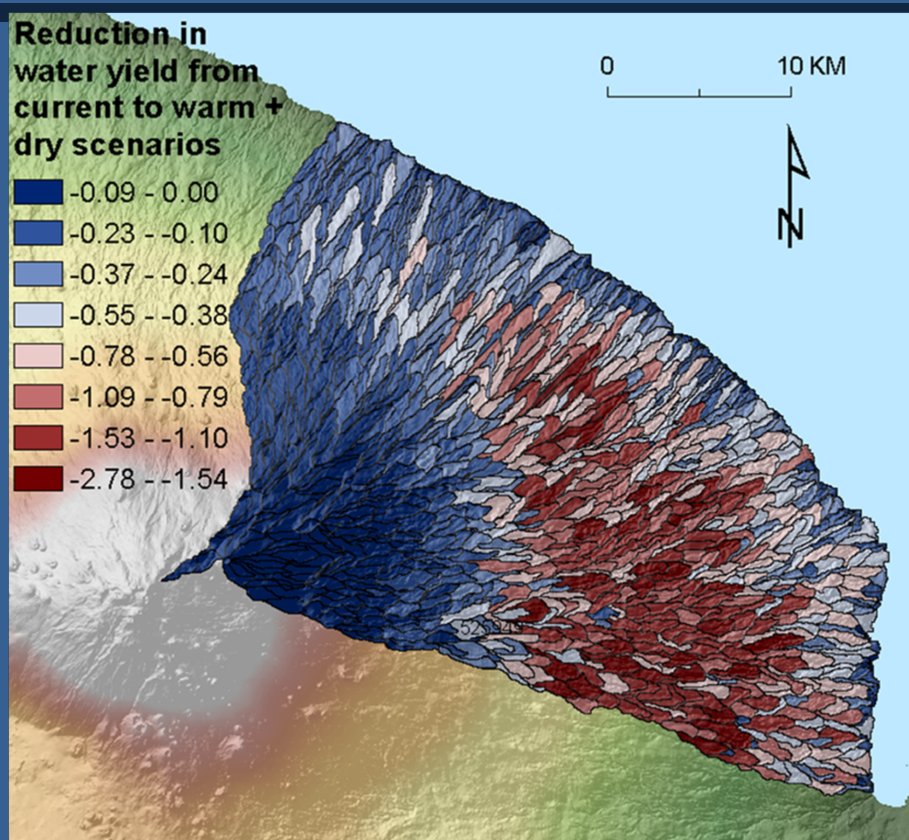


Figure 7. Changes in water yield in cubic feet per second (cfs) from the current climate scenario to the warm + dry scenario.

Logic model, Restoration treatments – Unit-level logic SOE scores for removal (Figure 8) ranged from -1 to 1, spanning the full range of evidence scores. Very low support for removal (SOE ≤ -0.5) was found for more than half of the study area. These areas corresponded with subunits outside the main SG invasion area or with those with relatively low precipitation and water yield. Approximately 30% of hydro-subunits displayed high SOE (≥0.5) for removal, the majority of which were located in severely invaded areas displaying relatively high annual precipitation and water yield. Only 5% of the hydro-subunits displayed high removal scores (SOE ≥0.5) in the watershed-level *logic model*. These subunits were located almost exclusively in the south-central portion of the project area where annual precipitation and water yield rates were highest . This small area also corresponded with high SOE scores from the unit-level analysis and is located in the heart of the SG invasion area.

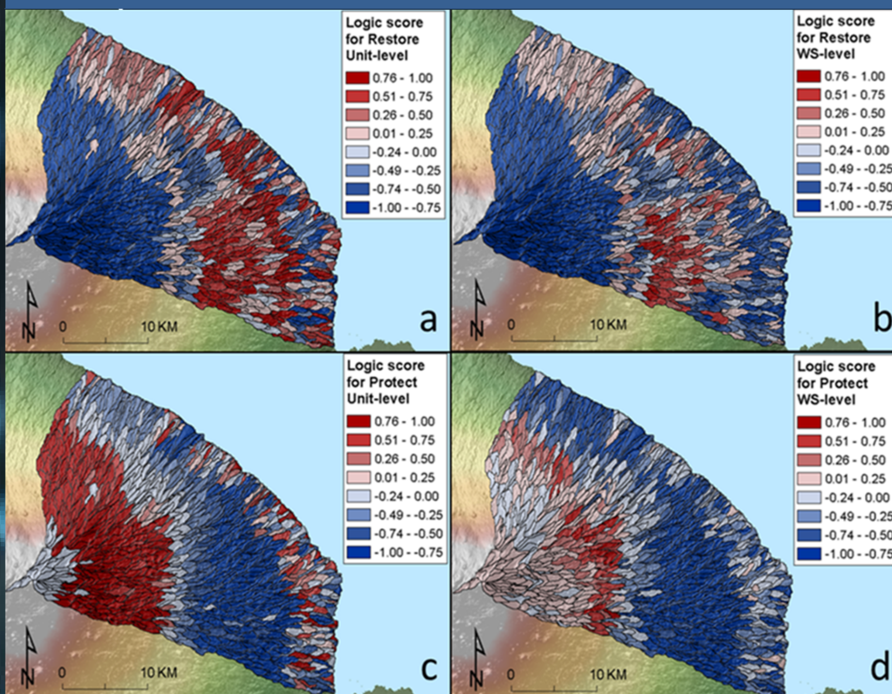


Figure 8. Strength of Evidence Scores for hydro-subunit (a,c) and watershed (b,d) level *NetWeaver*® logic models for strawberry guava (SG) removal (a,b) and protection (c,d)

We compared unit and watershed level NWLM outputs for the current and warmer + drier climate scenarios. Despite large differences in total water yield across treatments (see above), differences in SOE scores were small (Figures 7 & 8). The rank order of hydro-subunit water yields was relatively constant across all six climate scenarios (Figure 9). Future climate change will no doubt influence water yield, but the scarcity of stand-level ecophysiology data limited the strength of our conclusions regarding water yield responses to the climate scenarios. Such data would improve predictions from our DHSVM model and better inform our decision tool.

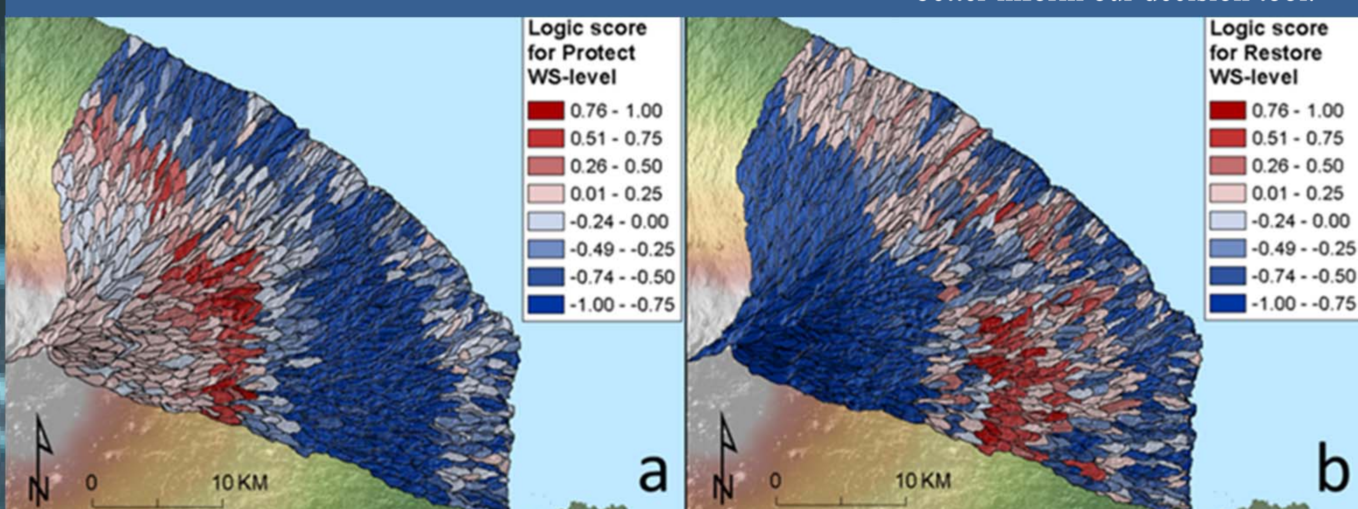


Figure 9. *NetWeaver*® logic models (SOE) Scores at the watershed level for (a) Protection and (b) Restoration from SG invasion under warm+dry climate scenario.

Logic models, Protection – High protection SOE scores for the unit-level analysis were found for 252 hydro-subunits (28%; Figure 8). These units were generally located immediately adjacent to and uphill (Mauka) of the hydro-subunits identified with high restoration SOE scores (Figure 8). Some smaller subunits closer to the ocean (Makai) also received high protection scores where SG levels were low. At the watershed-level analysis, only 4.5% of the study area was estimated as high SOE for protection.

Multi-criteria decision model (MCDM) – Initial treatment costs varied greatly among hydro-subunits (from <10 to >100 million dollars). High subunit costs were driven by poor access. Access was limited in the heart of the study area, which corresponded to high rainfall levels, high SG infestation, and the largest hydrologic response to treatment[1]. We found that two-thirds of the all of the hydro-subunits required <90 minutes of one-way travel access time, while about 14% of the subunits required ≥2 hours of one-way travel time due to limited road or trail access.

Landowner conservation scores were highest in the southern (Figures A6 & A7), mid-elevation region, which corresponded with several state forest and natural area reserves. Areas adjacent to the ocean were largely urban, exurban, and agricultural. Agricultural and other private landowners were located in the northern portion of the study are as well.

Cost alternatives that considered long-term crew camps to minimize travel time and costs and maximize crew time in the field were beyond the scope of this project. However, careful consideration of long-term, well-coordinated and supported field campaigns may significantly reduce subunit treatments costs.

Within the MCDM, primary topics from the logic model were most influential (0.5) followed by travel limitations (0.25), and land designation (0.11), which included conservation status (Figure A6) and critical habitat presence (Figure A7). Final priority scores for restoration from the MCDM (Figure 10) when water potential was emphasized ranged from 0.20 to 0.82 (Figure 8). Approximately 4% of the study area or 12,800 acres received priority scores >0.5, indicating a high potential for restoration. Many of these were located in the south-central portion of the study area where precipitation, potential freshwater yield, and SG coverage are high, but access is still poor. Without improvements made to the trail system or highly coordinated, long-term remote crew camps and field campaigns, successful restoration of these units may ultimately be impractical.

[1] Cost alternatives that considered long-term crew camps to minimize travel time and costs, and maximize crew time in the field were beyond the scope of this project. However, careful consideration of long-term, well-coordinated and supported field campaigns may significantly reduce subunit treatments costs.

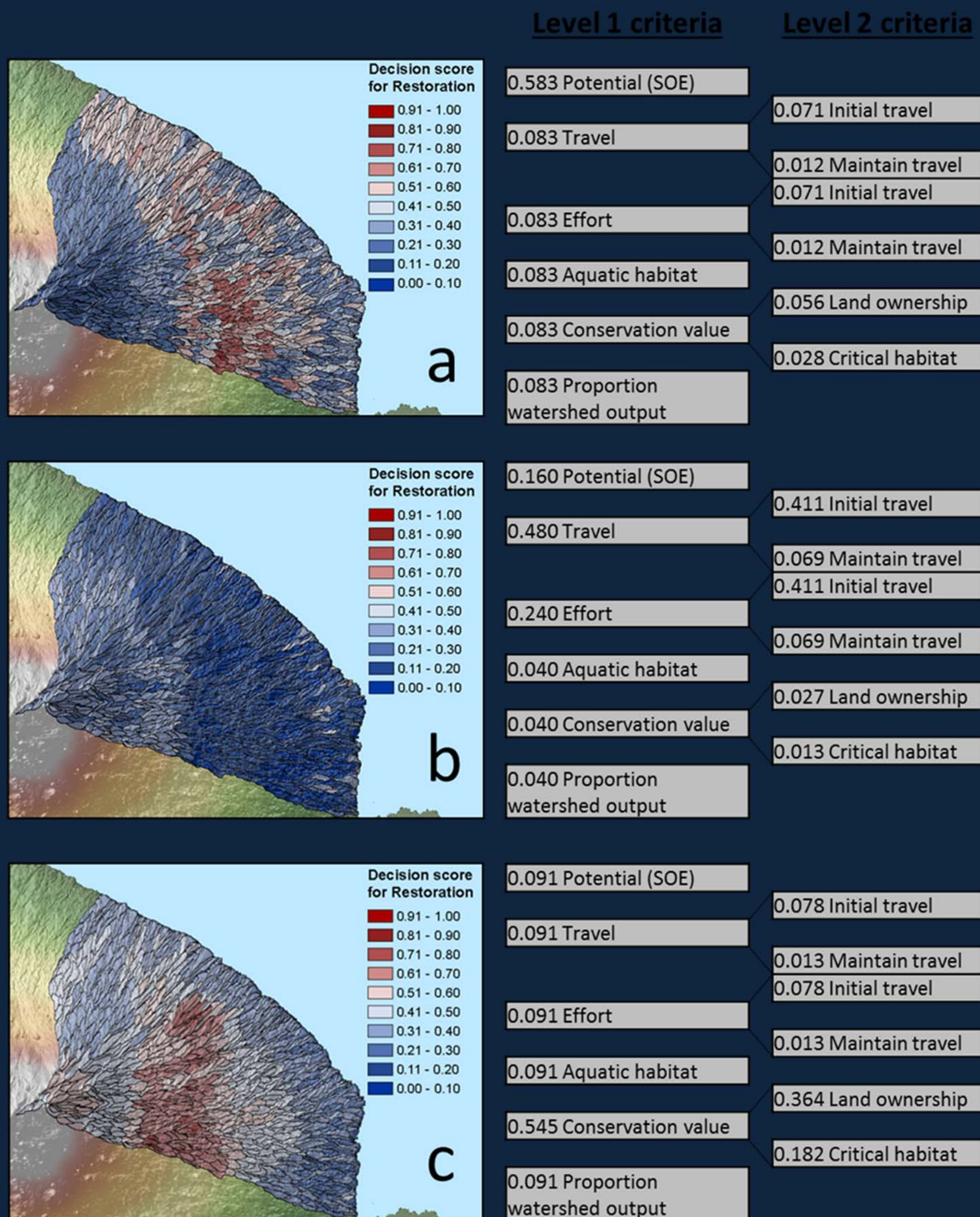


Figure 10. Decision Model Results for the primary goal of *Restoration*. Weighting emphasized (a) SOE scores over all other criteria, (b) cost and accessibility factors, and (c) conservation value (land ownership and critical habitat). . Variable names are defined in Figure A9. Numbers next to variable names represent the relative contribution of each criterion to restoration priority.

Multi-criteria decision model (MCDM) cont. – Similar results were found for the protection goal. Where potential SOE scores drove decision scores (Figure 11a), results of the Decision model closely followed those from the logic model. When cost factors were emphasized, the majority of the study unit was in low priority (Figure 11b). Both restoration and protection models produced similar results when conservation priorities were emphasized (Figure 11c), and higher priority areas closely outlined conservation landownership and critical habitat designated areas.

Model sensitivity analysis – Model development is an iterative process requiring revision and modification of initial logic to address unforeseen combinations of the data that do not respond as anticipated. For example, some hydro-subunits in the upper elevations were identified as high restoration potential with our original logic model architecture despite having no chance of being populated with SG as it was outside the upper elevation limit of forest vegetation. This was due to the fact that water output did not change under any of the three vegetation scenarios, and under the original logic, received a restoration SOE score of 1. To accommodate for these occurrences, we sequentially refined the model logic to match all cases with the intent of our original logic.

In our modeling system, DHSVM accurately represented current freshwater yields of watersheds and hydro-subunits across a large spatial domain and varying vegetation conditions. We then imposed simple climate scenarios of warming and rainfall change on the DHSVM to quantify potential future change in yield. While we lacked the data necessary to accurately parameterize the DHSVM model to incorporate climate change into our analyses, our preliminary hydrology modeling framework can be used to identify areas where water resources may be affected by future climate changes.

The MCDM successfully integrated the hydrological response to treatments with other decision criteria including the cost of implementing treatments, aquatic habitat quality and conservation status. This process led to intuitive spatial maps of hydro-subunit decision scores for SG removal and protection, whose derivation could be traced within the WDST model architecture by means of its graphical interface. We selected a series of weightings so that the decision scores reflected a relatively balanced influence of hydrological benefit, cost of treatment implementation, aquatic habitat quality and conservation status. However, all modeling results driving the EMDS decision scores may be interrogated, and models tuned and calibrated via alternative weighting schemes according to needs or objectives of managers or decision makers.

In this vein, we developed a companion web application for land managers to game with different criteria weighting schemes to meet their specific management objectives.

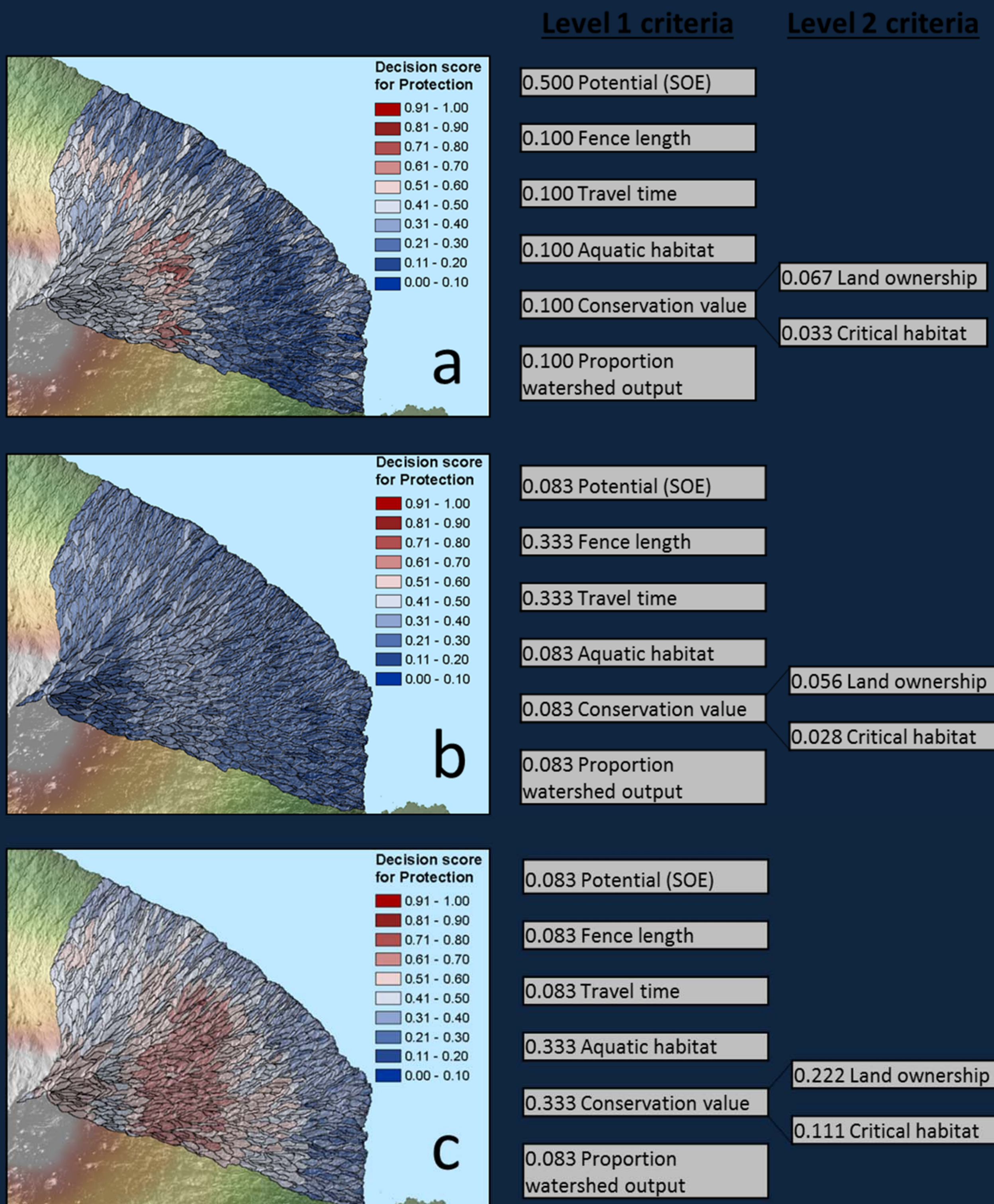


Figure 11. Decision Model Results for the primary goal of *Protection*. Weighting emphasized (a) SOE scores over all other criteria, (b) cost and accessibility factors, and (c) conservation value (land ownership and critical habitat). Variable names are defined in Figure A9. Numbers next to variable names represent the relative contribution of each criterion to protection priority.

Major Research Accomplishments

- Using the DHSVM model, developed accurate estimates of water yield for 904 hydro-subunits across the North Hilo-Hamakua study area.
- Predicted water yield under six climate scenarios: current climate, warmer (+2^{o}C), wetter (+20% precipitation), drier (-20% precipitation), warmer+wetter, and warmer+drier climate scenarios and the DHSVM model.
- Ranked SG control and protection priorities for each hydro-subunit based on relations between water yield under current vegetation conditions and full invasion and removal scenarios.
- Collaborated with land managers and conservation organizations to identify limitations to restoration activities, and to adequately estimate treatment costs.
- Used a MCDM to incorporate cost and feasibility criteria into final hydro-subunit restoration and protection decision scores.
- Identified the highest priority hydro-subunits and watersheds for SG removal and protection.
- Estimated access, treatment, and treatment maintenance costs of every hydro-subunit in the project area.
- Determined hydro-subunit water yields by climate scenario.

We developed a WDST that can be extended to other watersheds in Hawai'i as well as to other Pacific Island systems where watershed management, cost, invasive species, land use and conservation are of concern. Extension to other areas will require the data used in this application. The three main modeling systems used were DHSVM, and the NetWeaver® and Criterium DecisionPlus® software modules available within the EMDS application development platform. EMDS has been used to model and prioritize management decisions in terrestrial and aquatic ecosystems throughout the world. It is highly useful for organizing, mapping, understanding, and communicating the derivation of management treatment priorities, and establishing monitoring baseline conditions (Reynolds et al. 2014).

[2] This is an area of important future research. To improve estimate of climate change influence on water yields in the study area as elsewhere, significant new plot data are needed that measure the major plant species ecophysiological responses to temperature and precipitation conditions that are representative of the climate change scenarios.

Key Findings

- The North Hilo-Hamakua study area produces approximately 341 billion gallons of water per year under current climate and vegetation conditions. Under simulated warmer + drier climate conditions, total water yield declined by 29% to 243 billion gallons per year.

- Under current climate conditions, restoration treatments liberated 9.7 billion gallons per yr compared to the full SG invasion scenario, which is equivalent to ~10% of the observed change in water yield associated with the warm + dry climate scenario.

- We found 30% and 28% of the study landscape had high potential for SG removal and protection activities, respectively. High priority units were not evenly distributed; rather, they were clustered in a high precipitation area in the south-central portion of the study area. High protection areas were located immediately uphill (Mauka) of these high priority restoration areas.

- Despite large changes in total water yield, logic and decision model scores showed little variation among climate scenarios. The climate scenarios made no assumptions regarding changes to the spatial and temporal distribution of precipitation, and represented consistent proportional increases/decreases in annual precipitation. Furthermore, vegetation patterns were held constant across climate scenarios. Concomitant changes in vegetation cover type, ecophysiological change in water-use efficiency, and/or change in disturbance patterns could all lead to higher/lower modeled changes in water yield. However, such a modeling exercise would greatly increase the complexity of our analyses, and would increasingly be difficult to model due to lack of adequate field data to “climatize” vegetation parameters for DHSVM modeling[2].

- A major limitation to restoration activities was the lack of an adequate road and trail network, which limited accessibility to large portions of the study area. Approximately 128 hydro-subunits or 14% of the total study area required ≥120 minutes of one-way travel time to access. These access limitations greatly increased restoration cost due to the number of trips required to complete SG chemo-mechanical treatments. These subunits were characterized by high SG infestation levels, high water yield potential, and high rainfall amounts. In turn, logic model results identified the majority of these subunits as high restoration priority. Our results suggest that alterative restoration strategies, such as extended crew-camping field campaigns, or construction of an extended trail network would be needed within this area.

- We presented a variety of alternative decision model weightings to show the adaptability of the EMDS modeling framework. The alternative schemes with varied weightings of primary criteria show graphically how decision scores related these alternative weightings. When cost and access limitations were emphasized, very few hydro-subunits received scores >0.5, which highlighted access limitation as the crux of restorative management in the study area.

[2] This is an area of important future research. To improve estimate of climate change influence on water yields in the study area as elsewhere, significant new plot data are needed that measure the major plant species ecophysiological responses to temperature and precipitation conditions that are representative of the climate change scenarios.

Conclusions

Climate change will have implications for management of watersheds and the supply of freshwater in the North Hilo-Hamakua region.

Our models predicted a ~30% reduction in water yield across the study area under a future warmer and drier climate. This could potentially lead to reductions of nearly 100 billion gallons of stream water annually (Figure 5, lower panel). Reductions in water yield will be further increased by ~4 billion gallons per year under complete SG invasion. SG not only compromises local freshwater supplies, but also competitively excludes native forest species and reduces overall native biodiversity and key ecological functions. SG, the main exotic species in our project area was present across over three-quarters of the study area, and currently contributes to an estimated 1.7% decline in total freshwater production.

Our WDST can support efforts to allocate limited financial and human resources to areas with the highest potential for securing future freshwater yields while restoring native species habitats and balancing costs and benefits.

We identified study area watersheds and hydro-subunits for protection from further SG invasion and for SG restoration. High priority subunits and watersheds were identified in areas with the highest annual precipitation levels (+200 inches/year), highest SG invasion level, the highest current and potential water yield, and on state and federal lands with high species and habitat conservation values. Removing SG from these subunits would greatly increase future freshwater yields and address important public conservation concerns on public lands, but this area is not easily accessed by the current roads and trails network. Therefore, treating much of this area is likely cost prohibitive using existing access.

Successful implementation of a SG eradication program will require cross-disciplinary planning among relevant private, municipal, state, and federal agencies, as well as other key stakeholders to allocate resources to the areas identified by our models as having high restoration potential.

This will involve improving access to remote areas or budgeting for air transport and field support and relatively long field campaigns, coordinating restoration efforts among agencies, and securing stable funding resources to maintain restoration treatments into the future.

Recommendations

Future research needs include:

- Finer scale vegetation mapping
- Ecophysiological characterization of native and non-native invasive plants
- Empirical data to expand the vegetation component to include time-series responses of climate, growth rates and SG spatial changes
- Data on the ecological and hydrological benefits and costs of ungulate removal
- Refined climate change estimations for the region (e.g., dynamic downscaled climate)
- Forest structural information (as obtained by LiDAR, for example); and the sensitivity of vegetation parameters to climate change
- Expanding the modeling to include sediment yields associated with land management

Future WDST development needs include:

- Continued dialogue and validation of layer assumptions
- Review and adjustment of information input weightings
- Tailoring of map products to manager needs
- Inclusion of culturally based management practices into the decision model
- Continued collaborative efforts to implement the WDST into planning and decision making at the watershed partnership scale.

Future efforts could also benefit from extending the current effort to new geographic areas with different climatic, species, soils and management objectives to gain a sense for the flexibility of the current platform in meeting diverse needs across Hawaii and ideally the Pacific.

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Appendix 1: DHSVM Hydrologic Model

This project included both remotely-sensed and field-collected data, which were required for model parameterization and validation. Integration of these observed and modeled information sources formed the basis for the WDST. Data collection, model parameterization, and model validation are described below for the three main models used in the study.

DHSVM is a distributed hydrology model, which provides a dynamic representation of the spatial distribution of soil moisture, evapotranspiration, and runoff produced at the resolution of the digital elevation model (DEM, in this instance, 30-m). The model summarizes the water yield for a given pixel starting at the top of a watershed and progressing downhill. Water flow was enabled in each of the 4 cardinal directions and via each of pixel corners depending on the elevation of the 8 pixels surrounding a given pixel. Water yield was calculated for each of the 904 hydro-subunit within the study area in 3 hour time steps using input data for the period 2006-2012, for a total of 20,440 time series calculations for each of the nearly 1 million, 30-m pixels.

Spatial data requirements for this application of DHSVM included a 30-m DEM, a vegetation land cover type map for each vegetation scenario (Table 1), a soil type and soil depth map, spatial distribution maps of mean monthly temperature (Giambelluca et al., 2013), and a map stream locations (hydrography layer). Temporal data inputs included climate data consolidated to 3-hr time steps for air temperature, precipitation, relative humidity, solar radiation and wind speed, from each of six climate station locations within or adjacent to the project area (Table 2), and stream gaging data to calibrate DHSVM flow projections.

Topography data - Watershed and hydro-subunit boundaries, stream networks, and elevation data used within DHSVM were generated from a U.S. Geological Survey (USGS) 30-m resolution DEM obtained for the study area (http://planning.hawaii.gov/gis/). The DEM was post-processed to smooth "sinks" in the coverage to enforce water flow downhill. Channel initiation was assumed when drainage area equaled 250 acres (100 hectares); this was necessary to develop standardized hydro-subunits (the smallest unit of analysis) that were of a manageable patch size for treatments, and that conformed to logical hydrologic divides. Additional downstream hydro-subunits were created when drainage area exceeded 120 acres (50 hectares). This resulted in 904 hydro-subunits with a median size of ~220 acres (90 hectares). Stream layers were created by defining flow pathways downstream of each initiation point. Parameters that were estimated for each stream segment included active channel widths and depths and channel gradient and roughness. Channel characteristics across the region were estimated based on equations provided by Parker et al. (2007).

Soils data - The DHSVM requires spatially explicit information on soil texture and depth, which determine the rate and volume of water moving through the soil profile in both saturated and unsaturated conditions. Soil depth controls the volume of soil moisture as well as the interception of soil moisture by streams and roads. Soil depth and textural classes were mapped from U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) dataset (2008). Forty-two NRCS soil series were combined into 16 soil types based primarily on textural class. Values needed to define each soil textural type were estimated based on published literature (e.g. Abu-Hamdeh et al., 2000; Coen and Wang, 1989; Hantush and Kalin, 2003; Saxton and Rawls, 2006; U.S. Department of Agriculture, Natural Resources Conservation Service 2008; VanShaar et al., 2002). A single soil depth of 1.5 m was defined for the project area, which was based on the maximum depth available in soil surveys.

Climate data - Meteorological data including precipitation, air temperature, wind speed, relative humidity, and short- and long-wave radiation were collected from six climate stations from within or immediately adjacent to the study area (Table A1). Climate stations were part of the University of Hawaii and USDA Forest Service network of Hawaii Island Climate Stations, the Remote Automated Weather Station (RAWS) network, the NRCS Soil Climate Analysis Network (SCAN), and NOAAs weather station network. Periods of missing data were filled using regression analysis with other station data. Long-wave radiation was not measured at any of the stations, but was estimated from shortwave radiation, precipitation and air temperature following methods of Bowling and Lettenmaier (1997).

Vegetation data - An initial spatial representation of the current vegetation cover was obtained from the USGS Gap Analysis Program (GAP) land cover dataset. These data provide a wall-to-wall coverage at a reasonable resolution for large-scale hydrologic analysis. Upon review of the GAP data and ground truthing the spatial accuracy of the SG invaded area, we noted a general underrepresentation of the current distribution of SG in forested environments. We subsequently refined these data to better represent the current distribution of SG. To do so, we fit a linear regression model [Eq. 1] using observed SG relative abundance (% stand basal area represented by SG) and 20 permanent vegetation plots located within the study area, along with current precipitation and elevation data associated with each plot.

$$SG_{RA} = -194.1 + (0.0645 * Elev) + (0.0342 * Precip) \qquad \text{[Eq. 1]}$$

Eq. 1 was used to predict SG_{RA} across the study area, where SG_{RA} represented SG relative abundance. Model estimates were then used to reclassify each vegetation pixel into one of four SG classes:

Fully Invaded	$SG_{RA} > 10$
Moderately Invaded	$5 < SG_{RA} \leq 10$
Lightly Invaded	$0.1 \leq SG_{RA} \leq 5$
Native/ No Invasion	$SG_{RA} < 0.1$

Vegetation physical and ecophysiological parameter values required by DHSVM as initial input were established for each land cover type from literature values (e.g. Giambelluca et al., 2009, Kagawa et al. 2009, Asner et al., 2003, Ares and Fownes 1999). Parameters included stand-level percent canopy closure, stomatal resistance, photosynthetically active radiation, rooting depth, leaf area index (LAI), and others (Table A2). Where we could not find data from local studies, parameters were assumed from non-Hawaii data sets. DHSVM model calibration was conducted by comparing model water yield calculations with observed values from the Honolii stream gage (USGS stream gage number 16717000) for water years 2006 to 2012. We initially ran the DHSVM under current climate and vegetation and adjusted soil hydraulic properties (primarily vertical and lateral hydraulic conductivities, i.e., increasing soil depth beyond 1.5-m) to minimize the difference between modeled and observed flow and better reflect the current conditions. Model error was estimated using the coefficient of determination (r^2) and the Nash-Sutcliffe efficiency measure (NSE; Nash and Sutcliffe, 1970), which is a normalized statistic that calculates the ratio of the residual variance to the measured data variance. NSE values range between negative infinity and 1.0. An efficiency of NSE=1 corresponds with a perfect match of modeled discharge to the observed data (Moriasi et al. 2007). An efficiency of 0 indicates that model predictions are as accurate as the mean of the observed data, while an efficiency < 0 occurs when the observed mean is a better predictor than the modeled discharge. Final model calibrations exhibited high correspondence between modeled and observed water yield at the Honolii stream gauge: Modeled mean annual flow (r^2 = 0.99, NSE = 0.93) and mean monthly flow (r^2 = 0.92, NSE = 0.91).

Climate and Vegetation Scenarios

Six climate scenarios were simulated to identify changes in potential water yield at hydro-subunit and watershed scales. In addition to the current vegetation condition, conditions were altered to represent full invasion of the forest environment by SG, and to likewise remove all SG from the forest environment to simulate a full native forest condition. Fully removed/restored water yield trade-offs among these vegetation scenarios were directly evaluated in the NWLM.

Vegetation scenarios - Two scenarios were created that modified the current condition to create end-member conditions for potential SG invasion and removal: full invasion representing the condition where all native forest cover had been invaded and converted to the SG cover type ($SG_{RA} > 10$), and full removal ($SG_{RA} < 0.1$), representing the condition of complete removal by weeding of SG and assuming the site had returned to native species assemblages. These end-member scenarios were then used to compare hydro-subunit level water yield under current vegetation conditions against theoretical lower and upper water yield limits for the subunits and watersheds.

Climate scenarios – Six climate scenarios were examined (Table A1).
Precipitation scenarios included:

- current (no change)
- drier (20% less precipitation)
- wetter (20% more precipitation)

Two temperature scenarios included:

- current (no change)
- warmer (+2^{o}C).

In total, there were six combined climate scenarios leading to a full factorial of 18 scenarios.

Station Name	North Coordinate	East Coordinate	Elevation (m)
Laupahoehoe Tower	2205606	260171	1151
Pua Akala SCAN	2191036.207	255561.9338	1949
Hakalau RAWS	2193369.791	255885.298	1951
Island Dairy SCAN	2213110.007	261102.6241	354
Puu Mali RAWS	2205220.609	244585.5809	2165
Hilo AP	2182127.719	285046.1958	11

Table A1. Climate station data used in this analysis

Parameter	Description	Units	Comments
Vegetation Description	Name of vegetation type	Text	
Overstory Present	Whether an overstory is present	TRUE/ FALSE	
Understory Present	Whether an understory is present	TRUE/ FALSE	
Fractional Coverage	Canopy cover	Percentage, 0-1	Assumes understory is 100%
Trunk Space	The base height to the first branches	Fraction of total height, 0-1	
Aerodynamic Attenuation	Canopy attenuation coefficient for wind profile	Extinction coefficient	Not included
Radiation Attenuation	Shortwave radiation extending to the ground surface (canopy attenuation)	Attenuation coefficient	Fixed value
Impervious Fraction	Percent of ground cover that is impervious	Percentage, 0-1	Estimated for rocky and built environments
Height	Height of each vegetation layer (canopy and understory)	Meters	Used plot data where available
Maximum Resistance	Maximum stomatal resistance for each vegetation layer (canopy and understory)	s/m	Modeled from Giambelluca
Minimum Resistance	Minimum stomatal resistance for each vegetation layer (canopy and understory)	s/m	Modeled from Giambelluca
Moisture Threshold	Soil moisture threshold above which soil moisture does not restrict ET for each vegetation layer	0-1	Constant from Giambelluca
Vapor Pressure Deficit	Vapor pressure deficit above which stomatal closure occurs for each vegetation layer	Pa	Modeled from Giambelluca
RPC	Fraction of shortwave radiation that is photosynthetically active for each layer	0-1	Constant from Giambelluca
Number of Root Zones	Number of rooting zones	Integer	Estimated
Root Zone Depths	Thickness of soil layers	Meters	Estimated
Overstory Root Fraction	Fraction of the roots of the overstory in each root zone	0-1	Estimated
Understory Root Fraction	Fraction of the roots of the understory in each root zone	0-1	Estimated
Overstory Monthly LAI	Overstory leaf area index (one-sided) for each month		Modeled from MODIS
Understory Monthly LAI	Understory leaf area index (one-sided) for each month		Modeled from MODIS
Overstory Monthly Alb	Overstory albedo for each month		Modeled from MODIS
Understory Monthly Alb	Understory albedo for each month		Modeled from MODIS

Table A2.The vegetation parameters and descriptions that were applied to the modified GAP land cover data set for DHSVM simulations.

Appendix 2: EMDS Model

The Environmental Management Decision Support model (EMDS) is an application development framework used to develop customized logic models and decision models. In EMDS, logic models are designed with the NetWeaver® software to logically evaluate the status of a system. For this study, we considered the water yield of hydro-subunits and watersheds under three vegetation and six climate scenarios. Logic models are transparent and evaluation results are readily interrogated within models via graphical interfaces. Decision models are designed using the Criterium DecisionPlus® software, and they take the results from the primary topics of the logic model (NWLM), in this case, hydro-subunit and watershed level water yields, and incorporate technical and economic feasibility, efficacy, and logistical considerations that may be relevant to identifying preferred treatment areas. The logic for decision-making is also transparent and results can be directly traced through the architecture of the model to the influence of specific decision criteria, criteria weightings, and the influence of the logical operators used (Reynolds et al. 2009, 2014, Wang et al. 2004, Janssen et al. 2005, White et al. 2005). Outputs from these models are combined to produce wall-to-wall maps that provide detailed decision scores that can incorporate ecological condition and any other relevant social, political, and economic limitations to treatments deemed important by model designers.

NetWeaver® logic model (NWLM)

In the current application, hydro-subunit level water yield was the data source used as input to the *logic model*. The NWLM was implemented to calculate two separate strength-of-evidence (SOE) scores for **Restoration**--evaluating the proposition that there is high strength of evidence to support SG removal to enhance water yield and **Protection**--evaluating the proposition that there is high strength of evidence to support prevention of the spread of SG to maintain water yield. Within the *logic model*, the water yield under current vegetation conditions (CC) was compared that associated with full invasion (FI) by SG and full removal (FR) by control of SG (Figure 5). SOE scores near 1 indicate very high support for the proposed treatment (e.g., removal or protection), scores near -1 represent very low support for treatment, and scores near 0 indicate neutral support for either treatment.

SOE scores were calculated for the main goals of restoration and protection separately. SOE scores for each goal were calculated at two scales: the hydro-subunit, scale where water yield was evaluated for each subunit in isolation (hereafter, unit-level; Figure 5 a, b), and the watershed scale where water yield for each hydro-subunit was evaluated in relation to all other hydro-subunits in the study area (hereafter, watershed-level; Figure 5 c, d). The unit-level analysis examined each hydro-subunit separately and calculated hydro-subunit FI, FR, and CC water yield. End points of each ramp were the hydro-subunit water yield values for the FR (upper end point) and FI (lower end point), and the current condition was the CC water yield (Figure 5 a, b). Where CC was near FI and far from FR, this indicated current water yield was similar to the yield predicted for full SG invasion, and eradicating SG from these units would increase water use within the subunit and potentially lead to an increase in annual water yield. Alternatively, if CC was near the yield predicted for FR and far from FI, this would indicate water yield was near its maximum potential, and continued invasion of SG would compromise water production. This was an intuitive initial modeling basis within the NWLM. However, we learned through model implementation that small hydro-subunits and those in drier portions of the study area produced little water, such that very small changes in water yield among scenarios could lead to artificially high SOE scores even though actual increase in water production was small. To address these cases, we installed a switch in the model to pre-screen for these special cases.

Netweaver model (cont.)

The watershed-level analysis incorporated measured change in water yield among the three simulated vegetation conditions for entire watersheds (Figure 5 c, d). This standardized the data values represented in the ramp function, which put all hydro-subunits on a common footing for comparison, enabling unbiased identification of subunits that would most contribute to improved water yield after treatment. Upper and lower bounds on this ramp were represented by the 90th percentile (upper) and 10th percentile (lower) difference in water yield between the FI and FR vegetation conditions and the current invasion condition (Figure 5 c, d). For removal treatments, benefit was calculated as the difference in yield between current and full restoration. For protection, benefit was calculated as the difference in yield between current and full invasion. The 90th and 10th percentiles were used in lieu of maximum and minimum values to avoid the influence of outliers on SOE scores.

At each level of analysis, the water yield ramp (Figure 5) of the logic model was combined with a separate ramp of the subunit level of SG invasion (Figure A1) using a Union operator. The Union operator was used to average the water yield and SG contributions to calculate a final SOE score for restoration and protection at the subunit and watershed analysis levels and for each of the 6 climate scenarios.

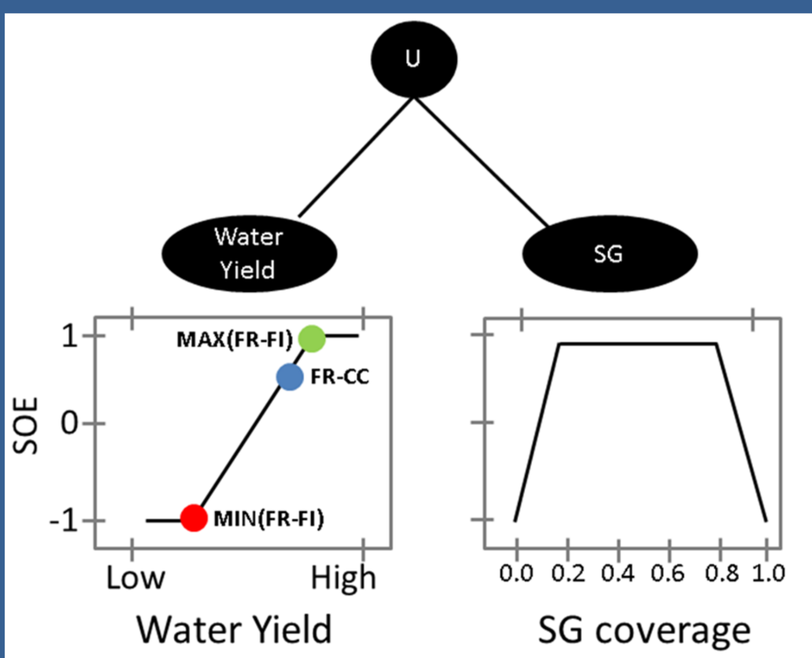

Figure A1. Example of the *NetWeaver®* logic model architecture for watershed-level restoration. The left panel shows the fuzzy logic ramp for response to SG removal and the right depicts the current SG infestation levels. These two ramps were averaged together using a logic union (U) operator in the *NetWeaver®* logic engine.

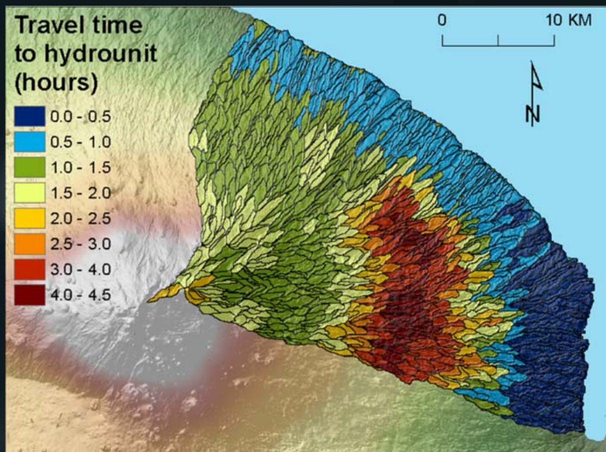

Figure A2. Travel Time to each hydro-unit from Hilo base facility

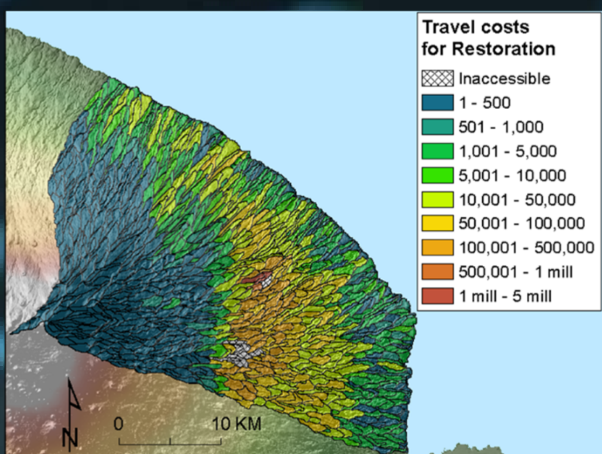

Figure A3. Travel Cost for initial restoration based on $0.56/mi

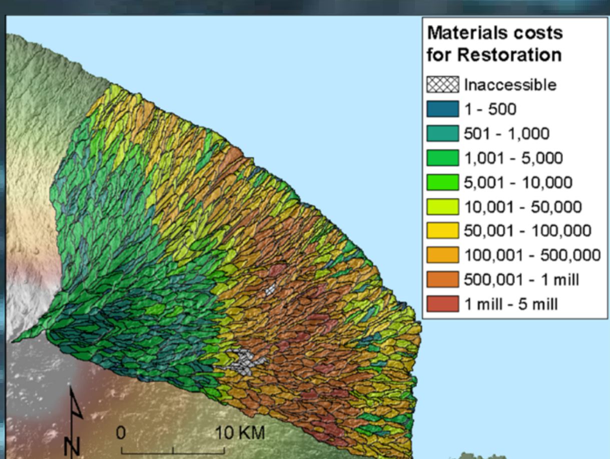

Figure A4. Materials Cost for initial restoration and maintenance

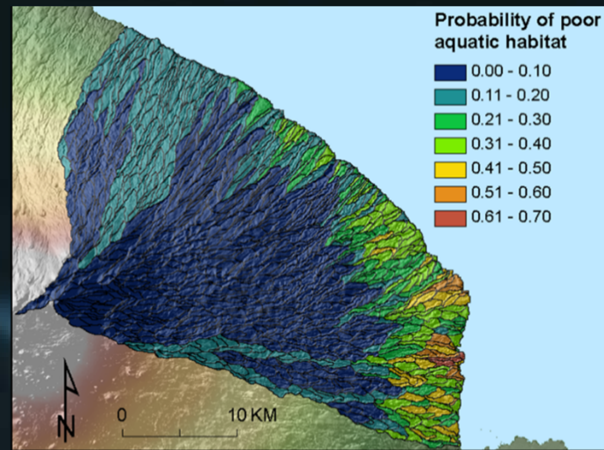

Figure A5. Habitat Degradation Risk form the National Fish Habitat Partnership 2010 index

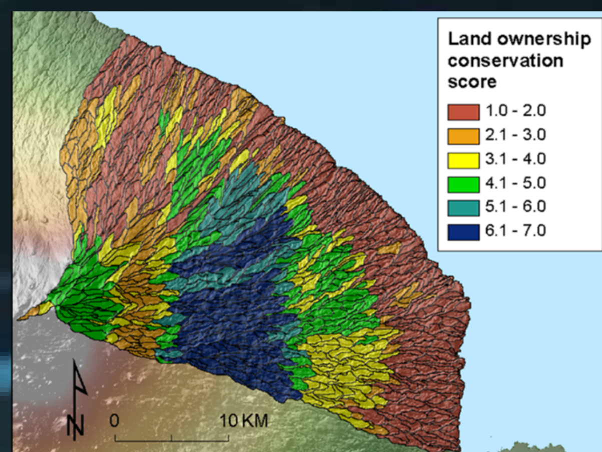

Figure A6. Mean Conservation Score based on landowner management priorities

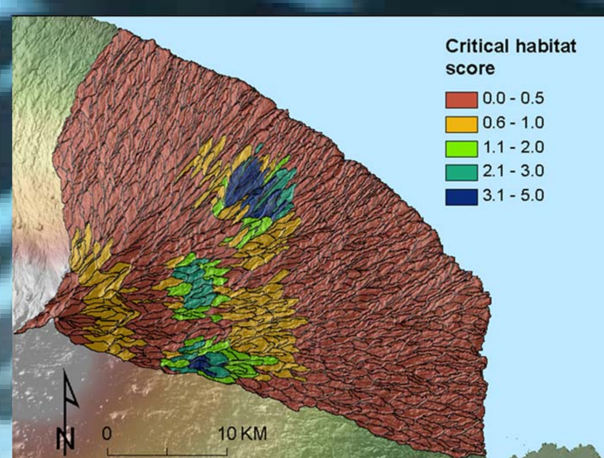

Figure A7. Critical Habitat - number of species of concern per hydro-unit

Multi-Criteria Decision Model (MCMD)

Workshops were held with managers to identify the factors most limiting to SG treatments. These factors included:

- cost of access including transportation costs, transit times, and hourly wages while in travel status, as determined by road and trail access factors (Figure A2 and A3)
- treatment costs as determined by SG stem density class (Figure A4) or fencing needs
- efficacy as determined by the required costs of maintenance treatments over a 5-year period
- aquatic habitat quality (Figure A5)
- land ownership/conservations status (Figure A6)

In an MCDM, these factors are termed decision criteria.

A primary criterion can have one or more secondary or sub-criteria, and there is no limit on the number of sub-criteria levels that may occur in a model. Once the relevant criteria and sub-criteria have been identified, the importance level of each criterion and sub-criterion to prioritization is assessed in the Criterium DecisionPlus® software. Within the software each criterion is pairwise compared to each other criterion for degree of influence on a 9 point scale. A score of 1 indicates that criterion A and B are equal in weight, whereas a score of 9 indicates that criterion A is maximally important in comparison with criterion B. Once each combination of criteria is assessed, an N x N matrix of weights is created where *n* equals the number of criteria in the model. From this matrix, a series of N priority scores are calculated, which in turn are used as weights to calculate a weighted average among all criteria. The weighted average calculated for each landscape unit (here, hydro-subunits) is the final priority score for that unit.

We conducted a cost analysis to quantify the expenses associated with both restoration (SG removal) and protection (fencing). These analyses were expressed at the hydro-unit level and reflect exchanges with land managers charged with leading watershed partnership efforts on Hawaii Island.

Multi-Criteria Decision Model (cont.)

Removal Treatment Costs – Standard weed removal practices for SG employ chemical and mechanical treatments, where a machete is used to stump (small diameter) or wound individual SG trees followed by an application of selective silvicide (tree herbicide; costs based on a Garlon® prescription) to the open wound. Cost for chemo-mechanical treatments was determined as a function of the following variables:

- Transportation time to a given pixel on the landscape,
- Time for a 3-person crew to conduct treatment work in a pixel, based on a 10 hr workday,
- Cost of materials to treat a pixel,
- Number of trips for a 3-person crew to complete a hydro-subunit,
- Number of trips, time, and cost of materials to complete follow-up maintenance treatments.

Using a combination of TIGER road data (http://www.census.gov/geo/maps-data/data/tiger-line.html) and field surveys by Mauna Kea Watershed Alliance partner organizations, a first approximation of a trail and road network map was constructed for the study area (Figure A8, the area circled in red is only accessible on foot). Each road segment was given a surface classification and an average speed of travel to compute an approximate time to destination when originating from the Forest Service base station in Hilo (IPIF) where Mauna kea Watershed alliance Staff are based.

Transportation times were calculated as the least-cost distance (fastest) route from IPIF to every 30-m pixel along the mapped road and trail network. The point along a given road or trail closest to any given pixel in the study area (not road or trail) was identified and served as the stopping point for crew driving and foot travel to initiate the start of treatment. Transportation cost was calculated as the Internal Revenue Service standard mileage rate for travel ($0.56 per mile), which was confirmed as the actual cost rate incurred by Mauna Kea Watershed Alliance personnel, who were practiced in SG treatment application in the field.

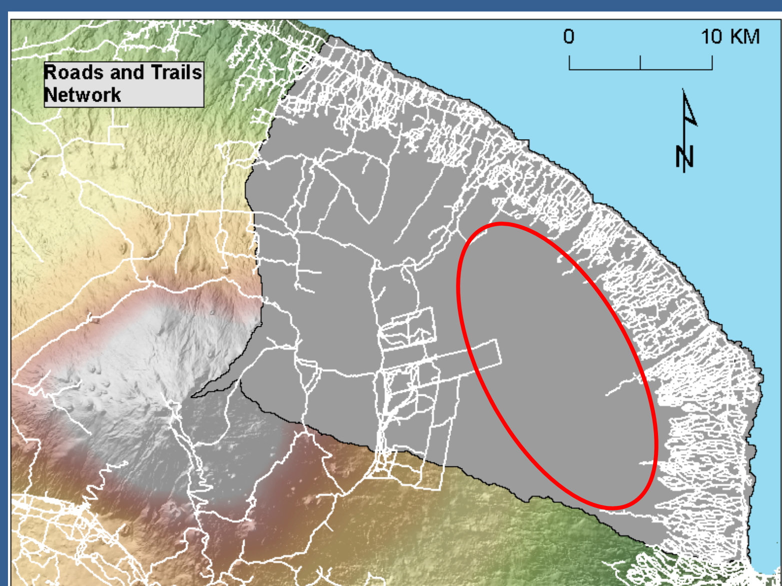

Figure A8. Composite Roads and Trails Map

Multi-Criteria Decision Model (cont.)

Travel time to a given pixel in the landscape from the nearest road or trail node was calculated using a path distance function (incorporating slope distance) and average walking speeds through each vegetation type. Walking speeds were based on the understory fraction of each vegetation type, where open grass would be at approximately 4 miles per hour (mph) on flat ground, with diminishing values for increased shrub and SG concentrations in forest environments (incorporating slope distance). Travel time to return to IPIF at the end of the day was also calculated for each pixel as twice the arrival time. Actual labor time (excluding travel time) spent on mechanical treatments was calculated using estimated single acre treatment times estimated from prior field campaigns by Mauna Kea Watershed Alliance field personnel:

- Fully Invaded: 350, 3-person crew hours/acre
- Moderately Invaded: 56, 3-person crew hours/acre
- Lightly Invaded: 5.6, 3-person crew hours/acre
- All others (sweep treatment): 0.4, 3-person crew hours/acre

These data were used in combination to estimate the:

- number of return trips required for a three-person crew to complete the initial restoration of a hydro-subunit (assuming 10 hour work days and time to actually conduct treatments)
- the cost of initial treatment (transport, labor, materials)
- five-year maintenance treatment costs (transport, labor, materials).

Item five-year maintenance was calculated as:

$$Treatment\ costs\ =\ (\#\ trips\ *\ vehicle\ costs) +\ (\#\ trips\ *\ labor\ costs) + \left(\sum_{1}^{m}(\#\ acres\ SG\ class\ m * treatment\ costs\ SG\ class\ m)\right) \qquad \text{[Eq. 2]}$$

where the class value m was either fully-, moderately-, lightly-, or non-invaded by SG. Labor cost was assigned at $20.00/hr/person, and a 4 day week and 10 hour work day was assumed to reduce treatment trip numbers to each unit and total cost.

Following initial treatments, maintenance was assumed to be the labor, transportation and materials costs for progressively declining SG invasion severity:

- Stands with no/little SG incurred the cost of a sweep treatment once every five years, and as such were included only once for all pixels without SG invasion present.
- Lightly invaded stands incurred the costs of a sweep treatment in year two.
- Moderately invaded stands incurred the costs of a light invasion treatment in year two and a sweep treatment in year three.
- Fully invaded stands incurred the cost of a moderate invasion treatment in year two, light invasion treatment in year three, and those of a sweep treatment in year four.
- A five-year cost time series was generated to quantify the total cost of mechanical SG removal for all hydro-subunits.

Multi-Criteria Decision Model (cont.)

Protection (fencing) costs - To protect areas from future spread of SG by pigs fences are installed in the treated section of forest, pigs are removed from the fenced area, and the fence closed and maintained to prevent re-encroachment. Costs to implement fencing are highly variable and depend on the terrain, material, and transportation costs for crew access to shallow vs. steep terrain (ground vs. air transport). We worked with managers of the three watershed partnerships on Hawaii Island to ascertain a full range of fencing costs and the attributes that defined cost, and we assumed that fencing the widest part of each subunit would provide an approximate scalar for determining subunit fencing cost. We calculated the slope distance for each subunit at its widest point and estimated the length of fencing required to span that distance. Total fencing cost was estimated as the average of high (contractor installed at $150,000/mi. fenced) and low (watershed partnership installed at $64,000/mi. fenced) cost installation. An average value of $20.27/ft ($66.49/mi.) was applied to the estimated width value to estimate the relative fencing costs of a subunit. We did not include the costs of animal treatments/ removals in this estimate.

Land conservation status – We used property ownership maps (Tax Map Keys, TMK) to classify land ownership into seven conservation categories. Categories were classified on an ordinal scale as follows, with a value of 7 indicating the highest conservation value:

1. Private and other owned
2. County of Hawaii
3. State, other (not State Forest land)
4. Private Conservation land
5. State Forest land
6. State Conservation land
7. Federal land

The TMK maps were converted to raster format where each raster cell received a score of 1-7 based on the above classification. A zonal mean land status was computed in a GIS for each hydro-subunit, and scores were then altered based on an aggregation statistic where the mean land status score for each hydro-unit was averaged across all adjacent hydro-subunits. These two values were then averaged together to create a conservation status score.

Critical habitat – Critical habitat was identified from land surveys that identified core habitat areas for species of conservation concern. Within our study area there were 1000s of ha of USFWS designated critical habitat for the finch-like bird Palila (*Loxioides bailleui*), and several plant species including:

Clermontia pyrularia *Phyllostegia racemosa* *Cyanea shipmanii*
Clermontia lindseyana *Clermontia peleana* *Phyllostegia warshaueri*
Cyrtandra giffardii *Cyrtandra tintinnabula* *Cyanea platyphylla.*

Each critical habitat layer was converted to raster format, with the value of each raster corresponding to the number of species of concern found in that location. Final critical habitat scores ranged from 0-5, with 5 representing the maximum observed number of coincident species. Maps and associated SHP files were provided by the Mauna Kea Watershed Alliance.

Multi-Criteria Decision Model (MCMD) cont.

Aquatic habitat quality – Stream habitat quality was estimated for each stream reach in the study area using the National Fish Habitat Partnership 2010 mapped indices of stream degradation risk (http://fishhabitat.org/content/nfhp-data-system), which estimate the cumulative impact of 15 different anthropogenic disturbance features that are known to degrade in-stream habitats (Esselman et al. 2011). Disturbance features included: the amount of adjacent urban land use, row crop agriculture, pasture land, impervious land surfaces and densities of human populations, dams, roads and crossings, and permitted point sources of pollution and other toxic substances. We generated local catchment (node to node reaches between stream confluences) and upstream catchment (inclusive of that local reach and the entire upstream catchment of the watershed) scores for all reaches. Degradation risk was summarized for each reach, and to each hydro-subunit by means of area weighted averaging. Scores ranged from 0-1, with 1 indicating the poorest predicted habitat condition (high degradation potential) and 0 indicating high quality habitat (the best predicted habitat condition=no or low degradation).

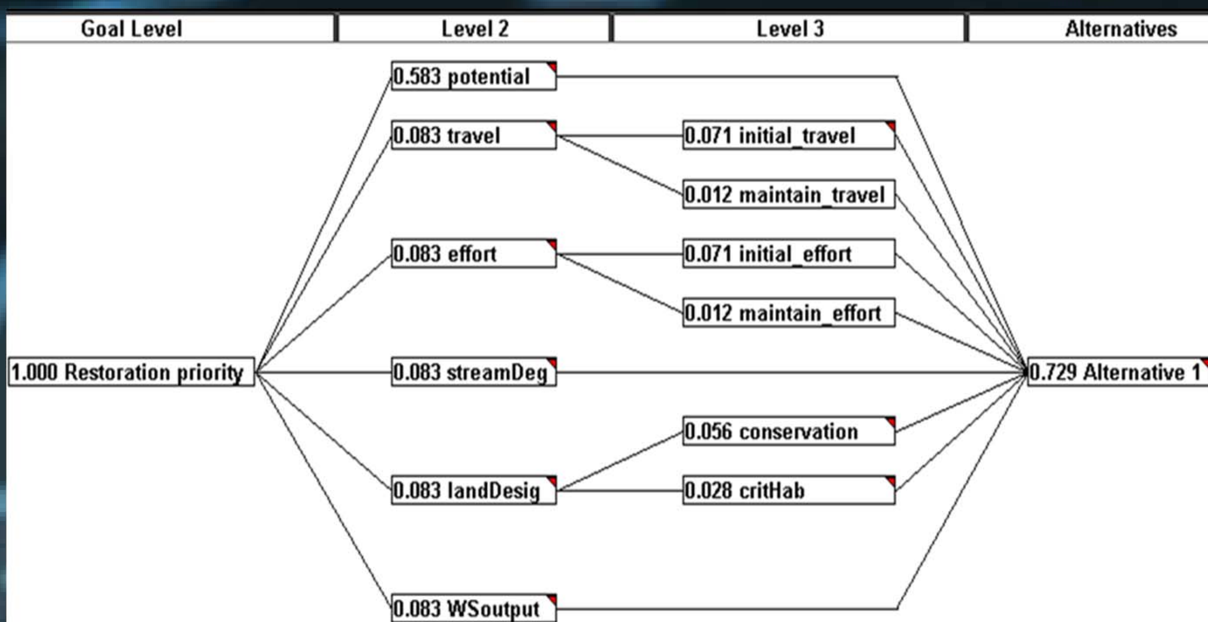

Figure A9. Example of Criterium DecisionPlus (CDP) decision model architecture for SG restoration. Variables are:

- Potential - SOE scores from the *NetWeaver®* logic model
- Travel - cost to and from hydro-subunit for initial restoration and maintenance
- Effort - material costs related to initial treatment and ongoing maintenance
- LandDesig - combination of conservation score and critical habitat scores
- Wsoutput - proportion of total water yield contributed by each hydro-subunit

Numbers next to the variable names represent each criterion's relative contribution to restoration priority.