Final Report

Project Name: Evaluating management effectiveness for land-based sources of pollutants
Begin Date: 8/1/2014 **End Date**: 2/28/2017
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Geographic location of the project: West Maui
Award number: NA14NOS4820089

Management summary

Motivation: Land-based sediments and nutrients threaten shallow coral reef ecosystems in Hawaii. To most effectively address threats from land-based source pollutants (LBSP) and enhance coral reef resilience in priority sites, the Hawaii Coral Reef Strategy calls for an integrated ecosystem-based management approach, as opposed to one focused on single sectors. At the West Maui state and NOAA priority site, several broad management efforts to improve reef health are underway. There is a critical unfulfilled need to evaluate the multiple potential resource management strategies and actions, especially given the broad suite of ecosystem threats, resource uses, costs, and stakeholder objectives at play. In this project, we focus on quantifying LBSP, specifically the sources, sinks, flows, and management levers. Land use managers considering the effects of different nutrient or erosion mitigation options, such as riparian buffer zones, cover crops, or better landscaping practices, currently lack critical information and tools to predict the LBSP outcomes and costs. The tool built in this project enables managers to evaluate the relative management and cost effectiveness of management strategies, spatially optimize specific actions based on impact and/or cost, and quantify the trade-offs associated with alternative strategies.

Methods: The project's main activities were to: (1) identify, map, and quantify key land-based stressors to the coral reef ecosystem that are driven by land use and currently targeted by management; (2) identify and map feasible and appropriate best management practices (BMPs) to mitigate stressors' impacts; (3) develop and test a novel spatial predictive model that quantifies change in land-based stressor due to specific management actions; (4) simulate key stressors under different management practices using predictive model; (5) evaluate the benefits and costs of different management scenarios; (6) conduct a tradeoff analysis of alternative management strategies to inform spatial planning of the most effective BMPs; and (7) recommend implementation strategies for cost- and environmentally-effective spatial management.

Results: We identified, mapped, and quantified key land-based pollution sources in a highly participatory process. We developed spatial models capable of predicting sediment and nutrient pollution from the landscape, stream banks, and on-site disposal systems. We analyzed the cost-effectiveness and trade-offs posed by alternative strategies for tackling erosion from unmaintained agricultural roads. We assessed the relative benefits of alternative strategies across the landscape to mitigate sediment from fallow agricultural fields, nutrients applied to landscaping, and upgrades of on-site disposal systems. We assessed the sensitivity of these benefits to future land use and climate conditions.

Technical summary

Objectives and scope:

Land-based sediments and nutrients directly impact the water quality of coastal Hawaii, and pose one of the biggest threats to the health of shallow coral reefs ecosystems in the main Hawaiian Islands (Dugan 1977; Erftemeijer et al. 2012; Fabricius 2005; Friedlander et al. 2005; Wolanski et al. 2003). Global climate change is projected to increase storm intensity, thereby increasing peak flows and total surface runoff, which are directly correlated to increased sediments and nutrients delivered to coastal environments (Hamilton 2010). The Wahikuli-Honokowai watershed management plan describes sediments and nutrients as principal pollutants causing significant impacts on the reef (Sustainable Resources Group International 2012). Researchers believe that the stressor of most concern to coral reef ecosystems is the nutrient and organic-rich silt (Weber et al. 2006). The Hawaii Department of Health's list of impaired water bodies in Hawaii lists sediments as the most significant LBSP (2006). Nutrients have been implicated in macroalgae blooms in the coastal environment, and sediment-bound nutrients have been shown to contribute a significant percentage of the overall nutrient load in other watersheds in Hawaii. For these reasons, we have chosen to focus our analysis on sediment export and nutrient loading from the conservation and agricultural lands of Wahikuli and Honokowai.

To most effectively address threats from land-based source pollutants (LBSP) and enhance coral reef resilience to climate change in priority sites, the Hawaii Coral Reef Strategy (HCRS) calls for an ecosystem-based management (EBM) approach, as opposed to sector-based management, which is viewed as inadequate to handle multiple source effects (The State of Hawaii 2010). The Coral Reef Conservation Program (CRCP) identifies LBSP as one of the three key threats (along with overfishing and climate change), calling for integrated coastal management to enhance reef resilience and function. Local objectives include reducing human impacts on coral reefs by using ridge-to-reef approaches to control land-based source pollutants.

Land managers concerned about reef health have at their disposal a suite of erosion and nutrient control measures that are appropriate for different land uses (Blanco-Canqui et al. 2008). However, given the long list of management options, land managers need tools to help them identify the most effective and appropriate erosion and nutrient control actions to implement within an integrated ridge-to-reef management framework.

The primary goal of this project is to connect land use management decisions to outcomes for key land-derived stressors of coastal marine systems, including sediment and nutrients, by providing a novel predictive model that estimates and maps stressor change due to specific land management actions.

Approach:

Activities of the project included the following activities; note the results section details the methods:

(1) Identify, map, and estimate quantities of key land-based stressors to the coral reef ecosystem that are driven by land use and currently targeted by management

(2) Identify and map feasible and appropriate best management practices (BMPs) to mitigate stressors' impacts
(3) Develop and test a novel spatial predictive model that quantifies change in land-based stressors due to specific management actions
(4) Simulate key stressors under different management practices using the developed impact assessment tool
(5) Evaluate the benefits and costs of different management scenarios in economic terms when feasible
(6) Conduct a tradeoff analysis of alternative management strategies to inform spatial planning of the most effective BMPs
(7) Recommend implementation strategies for cost- and environmentally-effective spatial management

Results:

Activity 1: Identify, map, and estimate quantities of key land-based stressors to the coral reef ecosystem that are driven by land use and currently targeted by management

To identify key sources of land-based pollution, we reviewed existing and emerging watershed management plans, and all literature related to the sites. We extensively consulted stakeholders in West Maui, engineers with extensive experience in the sites, USGS geomorphologists, community members, state and federal agency staff, and others. Early in the project, we confirmed the prioritization of two major pollutants: sediment and nutrients. We conceptualized the system (Figure 1), and presented this conceptualization at a broad stakeholder workshop organized by the US Army Corps of Engineers as part of their planning process in November 2015 that followed an iterative, structured decision-making process. This meeting was followed up by multiple other roundtable discussions and interviews, and prioritized: sediment from fallow agricultural lands and erosion from abandoned agricultural roads.

We also actively participated in field research to ensure the best available information was informing our modeling. We supported USGS field assessments establishing locations of legacy sediment deposits in streams and across the landscape. This work also estimated annual erosion rates of different erosion processes (i.e., hillslope, bank). Extensive fieldwork with the USGS resulted in an Open File Report detailing legacy sediment deposits (https://pubs.er.usgs.gov/publication/ofr20151190) (co-author Falinski is the PhD student funded by this project) (Stock 2015). A major shift in thinking brought about by this fieldwork was that hillslope erosion from the agricultural areas may not be a major source of sediment, rather in-stream erosion was a priority concern. Additional fieldwork in the Summer of 2016, led by USGS, mapped in-stream sediment deposits in three watersheds. This work confirmed that in-stream erosion is important, but noted that given intense rainfalls, roads and agricultural land could play a key role.

We furthermore built a new collaboration with the Department of Health to better estimate effluent from cesspools. As a result of our efforts, the groundwater expert (Whittier) has joined the Federal Agency Strategy Team supporting planning in West Maui.

The mapping and baseline estimates are presented under Activity 3 below.

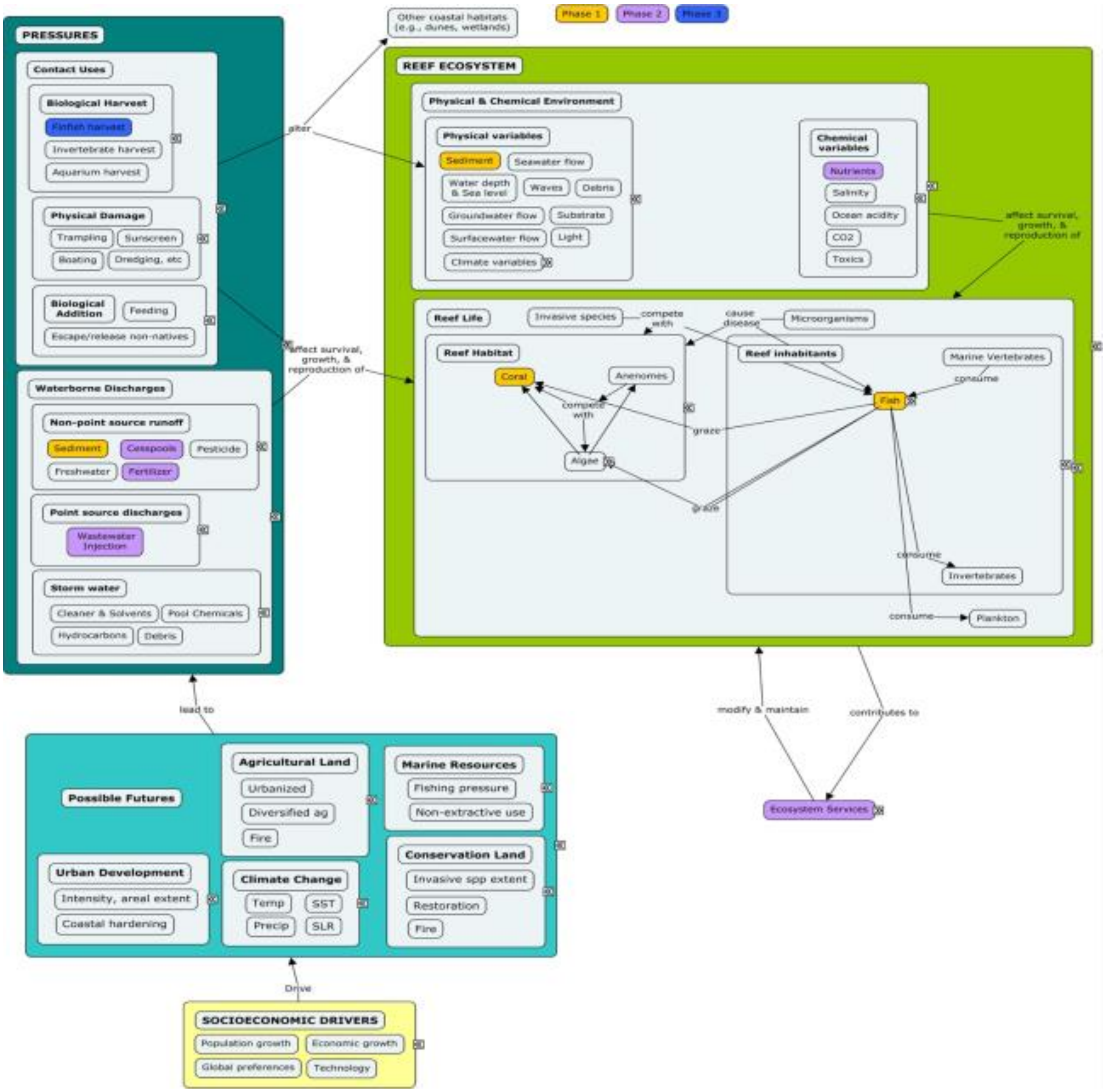

FIGURE 1 CONCEPTUAL SYSTEMS MODEL CREATED BY UH TEAM FOR DISCUSSION AT USACE-MODERATED STAKEHOLDER MEETING IN NOVEMBER 2015, HIGHLIGHTING BROADER SYSTEMS, INCLUDING COMPONENTS THAT ARE OF INTEREST TO THE BROADER STAKEHOLDER GROUP, SUCH AS FISHING AND ECOSYSTEMS

Activity 2: Identify and map feasible and appropriate best management practices (BMPs) to mitigate stressors' impacts

Once the key pollutants and their likely sources were established, we identified best management practices based on the input of the West Maui Ridge-2-Reef managers and other stakeholders, literature review, and expert elicitation. We scoured the existing management plans, actively engaged in the process of developing the new watershed management plan for the northern watersheds, held meetings with project leader Tova Callender to establish which best management practices were being considered for application in west Maui, and discussed options with local, state, and national experts. For sediments, we co-hosted a workshop to develop some prototype alternatives in 3/31/2016. For nutrients, we developed rapid prototype alternatives based on likely options we extracted from the draft watershed management plans (Group 70 International 2015; Sustainable Resources Group International 2012), the Alternatives session hosted 3/31/2016, and discussion with the Working Group (5/5/2016). Based on these discussions we prepared several Rapid Prototype "maximum potential benefit" alternatives, including creating corresponding spatial layers and attribute tables as inputs to the system models. The short list of these options included ungulate control to prevent streambank destruction and tilling in stream beds, cover crops to mitigate sheet erosion from fallow agricultural land, bank stabilization to retain sediments that remained from sugarcane and pineapple days, implementation of water bars on agricultural roads, and improvement of dirt bike trails through stabilization.

Thinking on BMPs changed quite a bit over the course of the project, including a shift towards in-stream measures. In line with decision support modeling, we reflected this evolving landscape in our modeling – we adapted off-the-shelf, simple models to capture early management priorities (i.e., sediment from fallow agricultural lands and roads), then developed a bespoke model to capture more complex, emerging priorities (i.e., stream bank erosion). Our final effort focused on modeling wastewater effluent. We shared what the various modeling tools were able to do and presented visual analyses of example scenarios to the watershed coordinator and the FAST. We discussed what could be done with off-the-shelf efforts vs. bespoke models that we would need to build.

Activity 3: Develop and test a novel spatial predictive model that quantifies change in land-based stressors due to specific management actions

We created four specific models: (1) sediment from the landscape (which we also applied to roads); (2) sediment from stream banks; (3) nutrients from the landscape; and (4) nutrients from cesspools. We give a brief overview of these models below.

Sediment from landscape.

We adapted the model InVEST Sediment Delivery Ratio Model to map sediment sources from hillslope erosion (Figure 2) (Hamel et al. 2015; Sharp et al. 2015). Model input needs and sources are described in Table 1 below. Each of the 46 LULC classes crop factor (c-factor) and management (p-factor) were parameterized using literature values (see Appendix). The InVEST model struggles to capture some key geomorphological and climatic traits of Hawaii that are important for accurate assessments of total annual sediment load. These include the lack of estimates for channel and bank erosion, which we handle with a separate model. The InVEST SDR model is spatial, so it can roughly handle spatial patterns in rainfall, but it uses an average annual rainfall, which ignores short, intense storms typical of the tropics. Moreover, although climate change scenarios can be included in the form of modified annual rainfall effects, other paths by which climate change will affect sediment and nitrogen retention sequestration are not included. Partial results of our model "testing" for Hawaiian conditions were published late 2016 (Hamel et al. 2017).

TABLE 1. INVEST SDR MODEL INPUT NEEDS AND SOURCES

Digital Elevation Model (10m)	USGS
Rainfall erosivity index	SSURGO
Soil erodibility	SSURGO
Land use/land cover (2.4m)	NOAA CCAP
Watersheds	DAR
Biophysical table for RUSLE, including C and P factors	Modified after Falinski 2016; SSURGO
Threshold flow accumulations	Falinski 2016
Calibration parameters for the sediment delivery ratio	Falinski 2016
Maximum sediment delivery ratio	Falinski 2016
Annual precipitation	Private landowners unpublished data; Rainfall Atlas; NOAA; USGS

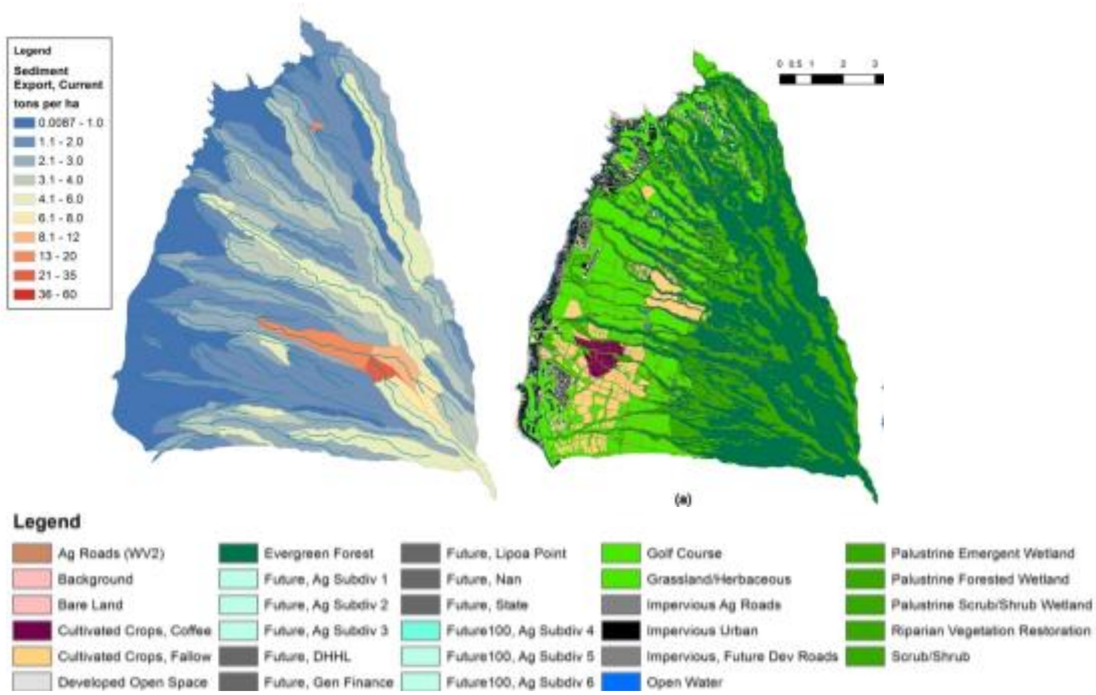

FIGURE 2. ANNUAL SEDIMENT LOADS (LEFT PANEL) USING INVEST (RUSLE + SEDIMENT DELIVERY RATIO) FOR 2010 LAND COVER (RIGHT) (CREDIT: FALINSKI, 2016)

Sediment from roads.

Abandoned agricultural roads form a dense network spanning different zones (agricultural and conservation) and landowners, as seen in Figure 3. Agricultural roads that are not maintained act as sources of sediment and conduits of runoff are often tied directly into the hydrologic system (Figure 4). The best management practice recommended for road rehabilitation is water bars, which slow water and can accumulate sediments adjacent to the roads. Based on concerns about the erosion from agricultural roads, we used the InVEST model to estimate sediment from roads. We found that the annual sediment load reaching the coastline according to the InVEST model is ~18,900 tons/yr. If all roads are fixed, the sediment delivered to the coast would be reduced to ~10,600 tons/yr – a 43% reduction. SDRs for roads were between 0 and 34%, depending on slope, with a weighted average by length of 5.9%. Once repaired, SDRs ranged between 0 and 18% with a weighted average of 3.9%.

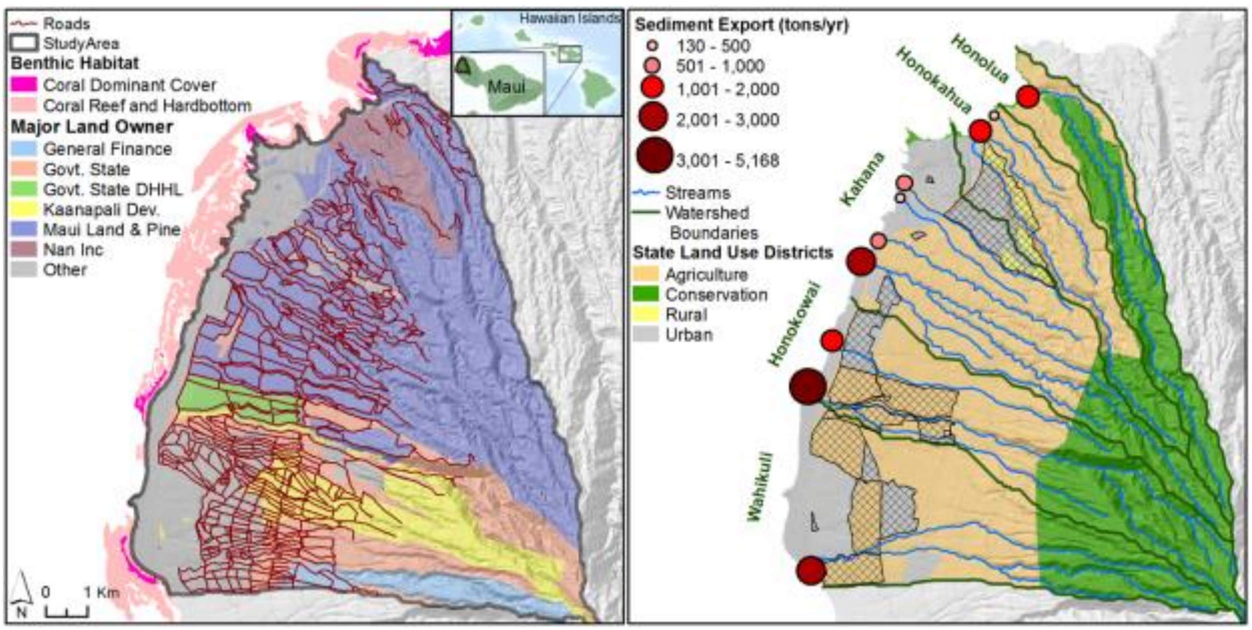

FIGURE 3 A. LOCATION OF AGRICULTURAL ROADS, BENTHIC HABITAT, LARGE LANDOWNERS. B. MAJOR STREAMS CONNECTING WATERSHED TO COAST, WITH BASELINE (I.E., TOTAL) SEDIMENT EXPORT AT COASTAL POUR POINTS, LAND USE ZONES, AND (IN BLACK HASH) AREAS SLATED FOR DEVELOPMENT AC

FIGURE 4 EVIDENCE OF GULLYING IN FORMER AGRICULTURAL ROADS, WEST MAUI, HAWAI‘I.

Bank erosion.

Based on USGS findings about the importance of instream erosion, a UH-USGS-UVM team built a Bayesian Belief Network model to estimate sediment delivery to the coast from bank erosion (with co-funding from USACE and PICSC). We modeled potential and actual bank erosion under baseline conditions using the ARIES modeling platform (Villa et al. 2014). The model was coded by into ARIES (Villa et al. 2014) by Drs. Bagstad and Voigt (http://aries.integratedmodelling.org/). We developed an expert opinion-based BBN model of potential bank erosion, with three parent nodes: disturbance types (presence of feral pigs, road crossings, multiple, or no disturbance), presence of fill terraces, and soil susceptibility to erosion as model inputs. The BBN structure is presented in Figure 5.

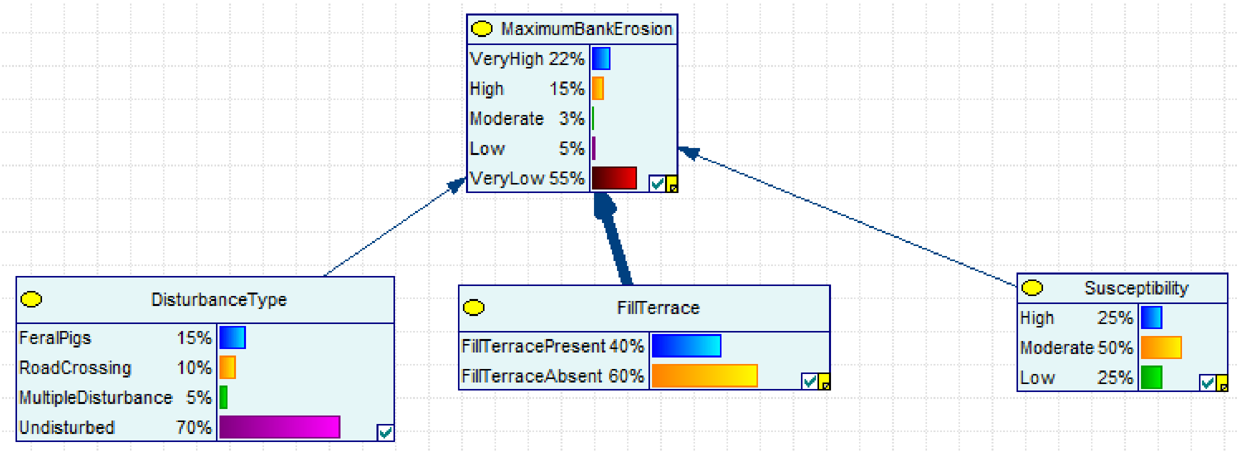

FIGURE 5. BAYESIAN BELIEF NETWORK MODEL STRUCTURE BUILT IN GENIE 2.0. BANK EROSION IS EXPRESSED IN TONS/HECTARE/YEAR. BARS REPRESENT THE PRIORS. ARROW THICKNESS DENOTES THE RELATIVE INFLUENCE OF EACH NODE IN COMPARISON TO ALL OTHER NODES, THICKER ARROWS REPRESENT GREATER INFLUENCE.

Table 2 summarizes key model inputs. Conditional probability tables determine the probability of a state for a specified model element (in this case the potential for bank erosion) given the state of other variables influencing that variable, in this case the presence of fill terraces, one or more disturbances, and erosion susceptibility. Multiple expert elicitations were held to populate these tables.

TABLE 2. BBN MODEL INPUT NEEDS AND SOURCES

Digital Elevation Model (10m)	USGS	BBN
Fill Terrace Presence/ Absence (2.4m)	USGS	BBN
Susceptibility Map (10m)	USGS	BBN
Land use/land cover (2.4m)	NOAA CCAP	BBN
Watersheds (2.4m)	DAR	BBN
Management Measures	Map of where measures are placed on the landscape.	BBN
Alternatives	Modified land-use layers to reflect alternatives developed (see Alternatives)	
Pig exposure	DOFAW, Rec Model	Disturbance layer input
Road crossings	Intersection of roads from LULC layer and Streams from Watersheds layer, within ag zone	Disturbance layer input

Disturbance	Interaction of Pig Exposure and road crossings	BBN
Exposure Function	Expert elicited function based on empirical estimates, details below	Deterministic Function
Precipitation Event Details	Range between min 7mm and max 40mm (see Bank Erosion)	Numerical input to exposure function that delineates desired event to model

To calibrate the model, we compared model results to estimates of the total annual sediment load from bank erosion for the 15 subwatersheds with observed sediment export (Stock et al., forthcoming SIR). Our calibrated model gave results that were within 86-143% of observed loads, and all except three watersheds (Honolua and Kaopala and Wahikuli Gulch, were within 5% of those reported by Stock et al. (Table 3). Total predicted erosion was 878 T/yr, compared to 922 T/yr observed, a difference of less than 5%.

TABLE 3 MODELED VS. MEASURED STREAM LOADS. GRAY WATERSHEDS WERE CLASSIFIED AS EPHEMERAL, WHITE AS INTERMITTENT.

	Watershed	Annual load from bank erosion (T/yr)[1]	Modeled annual load from bank erosion (T/yr)	Modeled results as a % of estimated
2	Honolua Stream	91	131	143%
4	Mokuleia Bay	23	22	96%
6	Kanauiki	27	28	104%
8	Mokupea Gulch	46	48	104%
9	Honokahua Stream	45	43	96%
13	Napili 2-3	44	42	97%
14	Napili 4-5	56	53	95%
16	Honokeana	43	42	98%
20	Kaopala Gulch	62	54	86%
22	Kahana Stream	285	223	78%
26	Mahinahina	45	44	98.4%
28	Honokowai Stream	62	59	96.7%

30	Hanakaoo	26	26	103.6%
31	Kahua	25	24	97.7%
35	Wahikuli Gulch	42	37	88.6%
	TOTAL	922	878	95.3%

Figure 6 illustrates the output of the Bayesian model in terms of areas where there is more or less probability of bank erosion. Maximum erosion was 25.75 T/ha*yr for the northern ten intermittent watersheds and 9.65 T/ha*yr for the five ephemeral watersheds.

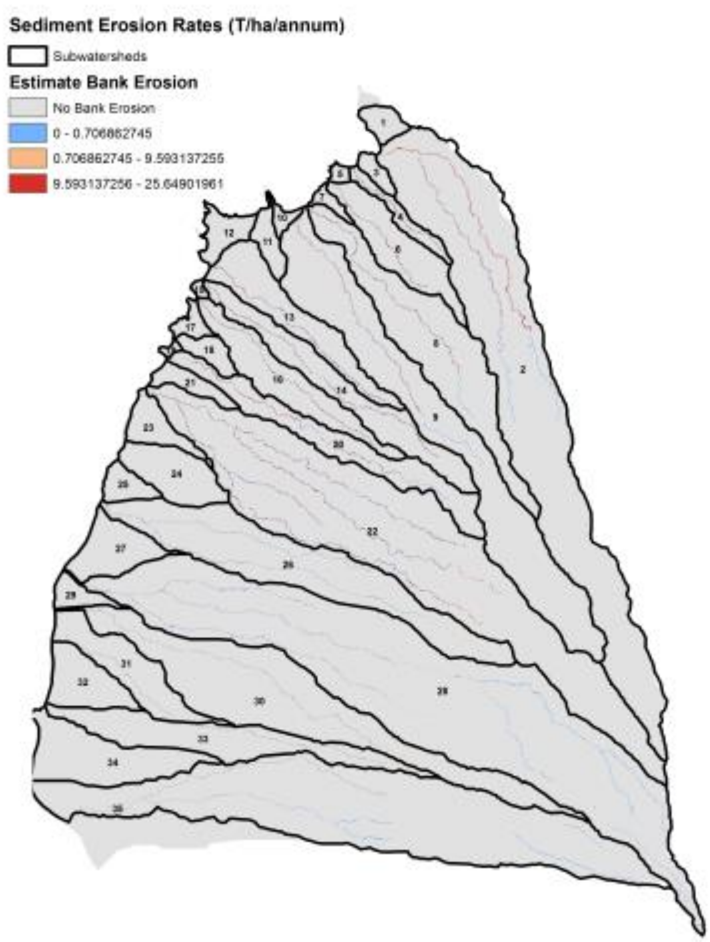

FIGURE 6 OUTPUTS OF THE BAYESIAN MODEL SHOWING AREAS OF HIGH, MODERATE, AND LOW PROBABILITY OF BANK EROSION.

We observed spatial variation in the likelihood of bank erosion based on our model. Some of the observed patterns are an artifact of the fill terrace modeled layer (i.e., for the unmapped streams where USGS did not do in-depth field reconnaissance, we randomly selected 40% of the stream length within the old agricultural zones as having fill terraces). This highlights the importance of surveying remaining streams to map fill terraces. Combining field data from USGS with the spatial distribution of the bank erosion in Figure 6, it will be possible to spatially target management actions in the most egregious watersheds. Now that areas more or less likely to erode have been mapped, a next step would be to ground-truth the results with field validation.

Nutrients from landscape and cesspools.

Due to the lack of established parameters, calibration data for nutrients, and previous application of models to Hawaii to specifically estimate nutrient loads, we have decided to again use the most parsimonious model, InVEST, to estimate nutrient loads from the landscape. The InVEST nutrient delivery model estimates nutrient sources from watersheds and their transport to nearby waterways, as well the contribution of vegetation to purifying water through the removal of nutrients (Sharp et al. 2015). The InVEST nutrient delivery model computes nutrient sources from different classes of land use/cover (LULC) in the study watersheds and their transport to the stream. The resulting spatially-explicit information help us to quantity the nutrient retention service of vegetation as well as the disservice of urban development. The retention service is important for maintaining surface water quality, and addressing water quality issues.

The InVEST nutrient model input needs and sources are described in Table 4 below. Nutrient load, retention efficiency, and subsurface proportion of nutrient delivery were specified for each LULC class using literature review. All input parameters are summarized in Appendix A.

Nitrogen export and delivery varies substantially according to rainfall gradients (Figure 7).

TABLE 4. INVEST NUTRIENT MODEL INPUT NEEDS AND SOURCES.

InVEST	
Digital Elevation Model (10m)	USDA/NRCS
Land use/land cover map	NOAA CCAP
Nutrient runoff proxy (rainfall) – current long term annual average (1978 - 2007) and projected long term annual average (2070 - 2100)	(Giambelluca et al. 2013), (Timm et al. 2015)
Watersheds shapefile	Modified Hawaii Statewide GIS Program Map
Biophysical table with data on water quality coefficients by land use/cover class	(Falinski 2016), Appendix A. Table 2
Retention efficiencies	Modified Falinski 2016, Appendix A. Table 2
Falinski 2016	Modified Falinski 2016, Appendix A, Table 2
Falinski 2016	Modified Falinski 2016, Appendix A, Table 2

In Hawaii, InVEST NDR has a number of limitations. It does not fully capture microclimates, topography and geology essential for accurate assessment of nutrient retention service. Next, data poor watersheds in west Maui further limits the ability of the model to quantify uncertainty. Model's structural uncertainty reduces its performance as well. Since the model provides a quick assessment of nutrient retention/export over long-term annual average climate conditions, and we cannot observe inter-annual variability from the outputs. Spatially, average upslope is used to calculate hydrological connectivity (i.e., the likelihood of pixelated nutrient reaching the stream). Therefore, it is possible that the model cannot accurate spatial heterogeneity of the study area either. In addition, there is no empirical data for our watersheds to test the validity of the model. Therefore, relative rather than absolute values of nitrogen export values are reported in the study. Moreover, the model has a high sensitivity to inputs such as nutrient load, retention efficiency, and rainfall in the study area. Uncertainties in input parameters, especially for the future land use and climate scenarios, would cause significant change in the predictions. However, much effort has been made to reduce the uncertainty by using extensive literature review. Finally, as suggested in the manual, threshold flow accumulation has been calibrated by visually comparing the results of model generated stream network against study area stream map. This calibration step resulted in exclusion of some of the urban development closer to the coastline in the model simulations. Though not significant, the total excluded urban area reduces the nitrogen export from the study watersheds.

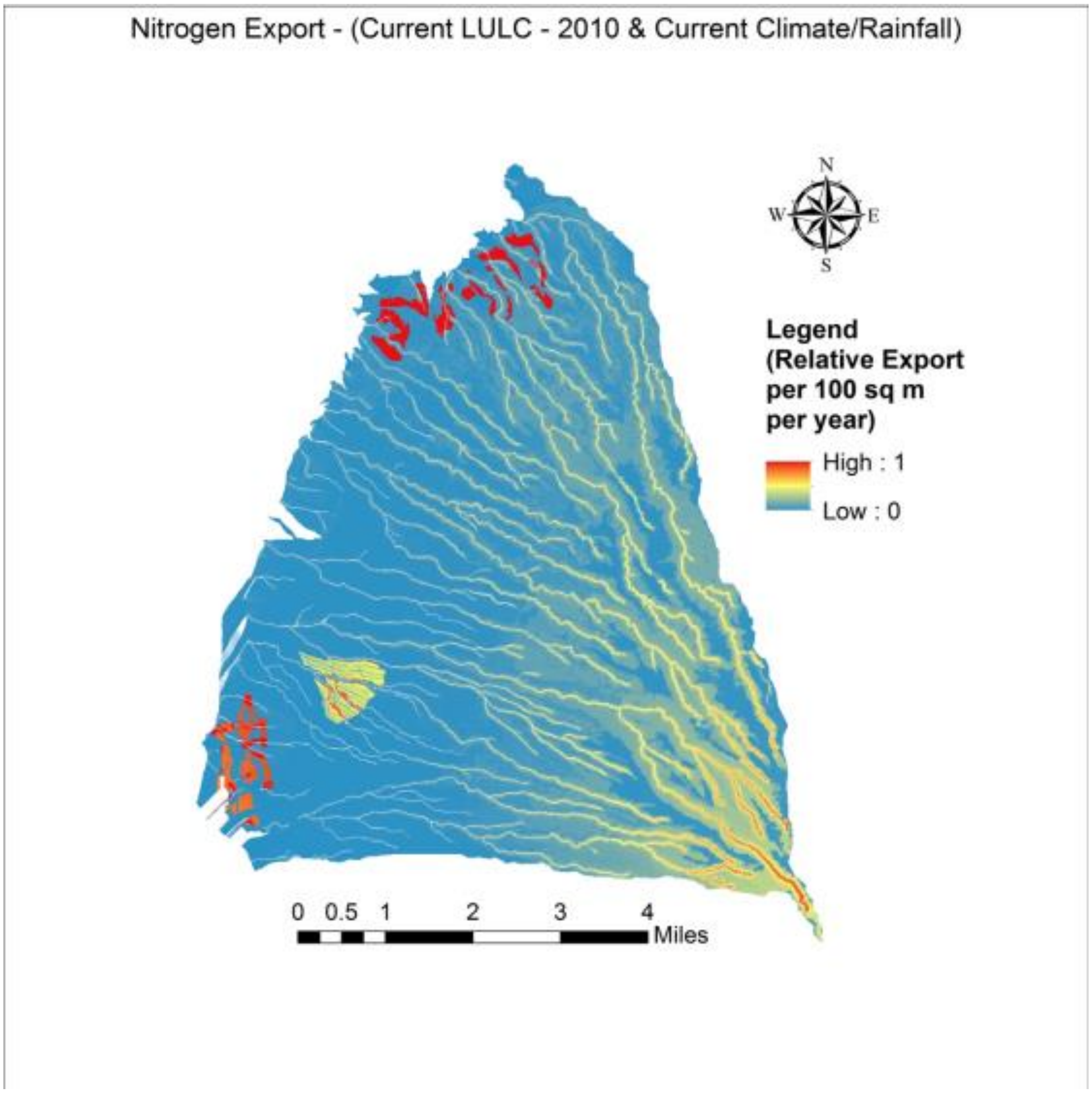

FIGURE 7. ANNUAL NUTRIENT LOADS FROM INVEST NUTRIENT DELIVERY RATIO BASED ON CURRENT LAND COVER AND RAINFALL (CREDIT: HTUN AND BARNES)

Cesspools.

Much of Hawaii uses onsite waste disposal systems (OSDS) (e.g., cesspools and septic tanks) that may leach excess nutrients and pollutants into groundwater that flows to the ocean. The contaminants of greatest concern are nutrients that cause excessive bio-productivity. We estimate Nitrogen as it can be a limiting nutrient in aquatic and marine waters, making it a contaminant of concern. To model this impact spatially we used data on OSDS in the form of point data from UH and DOH (Whittier and El-Kadi 2014). The inherent risk to the reef posed by an OSDS varies by the quantity of effluent, the system type, and the method of effluent treatment. This study classified OSDS by the type of treatment the wastewater effluent receives. Figure 8 below lists the OSDS classes (Whittier and El-Kadi 2014).

Nitrogen flux and phosphorous flux for each Tax Map Key (TMK) parcel (http://qpublic9.qpublic.net/hi_hawaii_search.php) was estimated for OSDS following (Whittier and El-Kadi 2014), updated to reflect recent empirical data (pers comm. Robert Whittier, DoH). We converted the points to raster by summing nutrient flux values within 500 m x 500 m pixels with OSDS in units of kg/day and effluent in gallons per day. Next, focal statistics was used to calculate the total flux within a 1.5 km radius of each oceanic cell, approximating a falloff rate equivalent to the 2-year travel time (~3km; Whittier and El-Kadi 2014). Nitrogen flux coming from onsite waste disposal systems (OSDS) (e.g. cesspools and septic tanks) was determined by calculating the total flux within a 1.5 km radius of each oceanic cell.

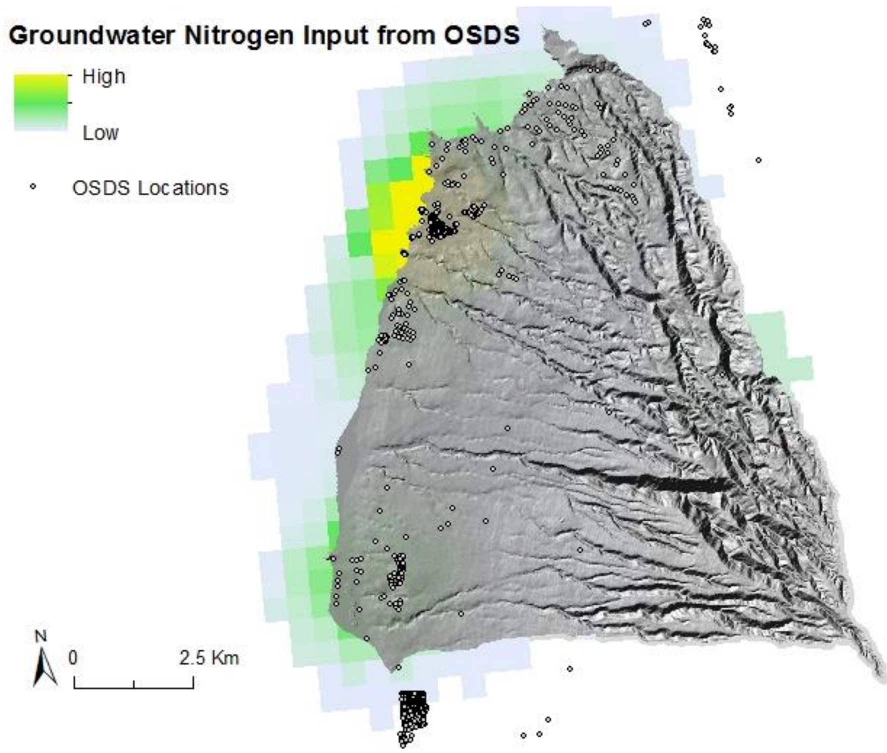

FIGURE 8. ANNUAL NUTRIENT LOADS FROM OSDS BASED ON WHITTIER AND EL KADI (2014) (CREDIT: BARNES, WHITTIER, LECKY)

Activity 4: Simulate key stressors under different management practices using the developed impact assessment tool
Activity 5: Evaluate the benefits and costs of different management scenarios in economic terms when feasible
Activity 6: Conduct a tradeoff analysis of alternative management strategies to inform spatial planning of the most effective BMPs
Activity 7: Recommend implementation strategies for cost- and environmentally-effective spatial management

Roads

Our first effort focused on guiding decisions related to agricultural roads. This particular management decision was important, since the manager was considering proposals to implement water bars in Honokowai and Wahikuli watersheds. We paired our road erosion model with a cost model to identify cost-effective solutions. These results were published in Oleson (201?).

We conducted trade-off analysis (Lester et al. 2013) to compare the efficacy of management scenarios in reducing sediment runoff from the landscape at minimal cost. The most effective management outcomes, where you cannot get more erosion mitigation for the same cost, or the same mitigation for less cost, are indicated in a tradeoff plot by the outer bound of points (termed the efficiency frontier) (Figure 9) (Oleson et al. 2017). Outcomes interior of the efficiency frontier are sub-optimal because they produce the same or less sediment reduction at a higher cost than other existing solutions (Caro et al. 2010; Lester et al. 2013). Differences between these outcomes in the tradeoff plot indicate changes in efficacy in achieving the policy objective.

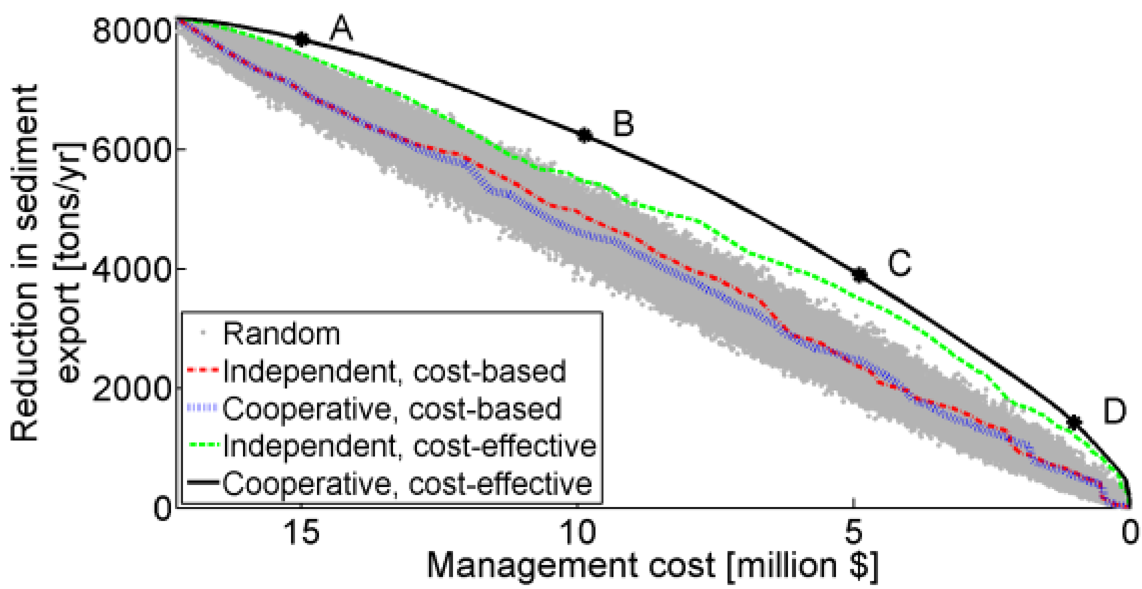

Figure 9. Comparison of different distributed solution strategies for mitigating erosion of sediment from agricultural roads. A. Each point on the graph represents a set of road segments that can be repaired at a given cost and reduction in sediment export. Landowners can choose to make decisions independently (focus on their own roads) or cooperatively (all roads are on the table regardless of whose land they are on). The roads to repair could be chosen based on total cost ($/segment) or cost effectiveness (tons sediment reduced/$). B. Panels A-D represent different specific options in the optimal scenario (i.e., solutions on the efficiency frontier) for different budgets and sediment management targets. (from: Oleson et al 2016)

Erosion and nutrients from the landscape

Our second alternatives focused on landscape measures. However, before modeling any specific management actions, we needed to create future scenarios. Measures to control sediment and nutrients will be implemented on the landscape, and will need to function under future conditions, including changed land use and climate conditions. We have collated and created future scenario data.

We used current land use (Figure 10) as a baseline LULC map based on modified 2010 NOAA CCAP LULC product. Future land use scenarios for 2030 and 2100 were based on collaborative scenarios produced by PacRISA and combined with ground-truthed data from PhD student Kim Falinski (Credit: Falinski, Htun, Brewington). For OSDS models, additional assumptions were required, as OSDS density is determined based on (a) the rate and location of development rather than overall population density, (b) the type of OSDS, (c) the type of dwelling and number of occupants, and (d) what percentage of new homes and public and commercial structures are connected to sewer, or centralized non-OSDS management systems.

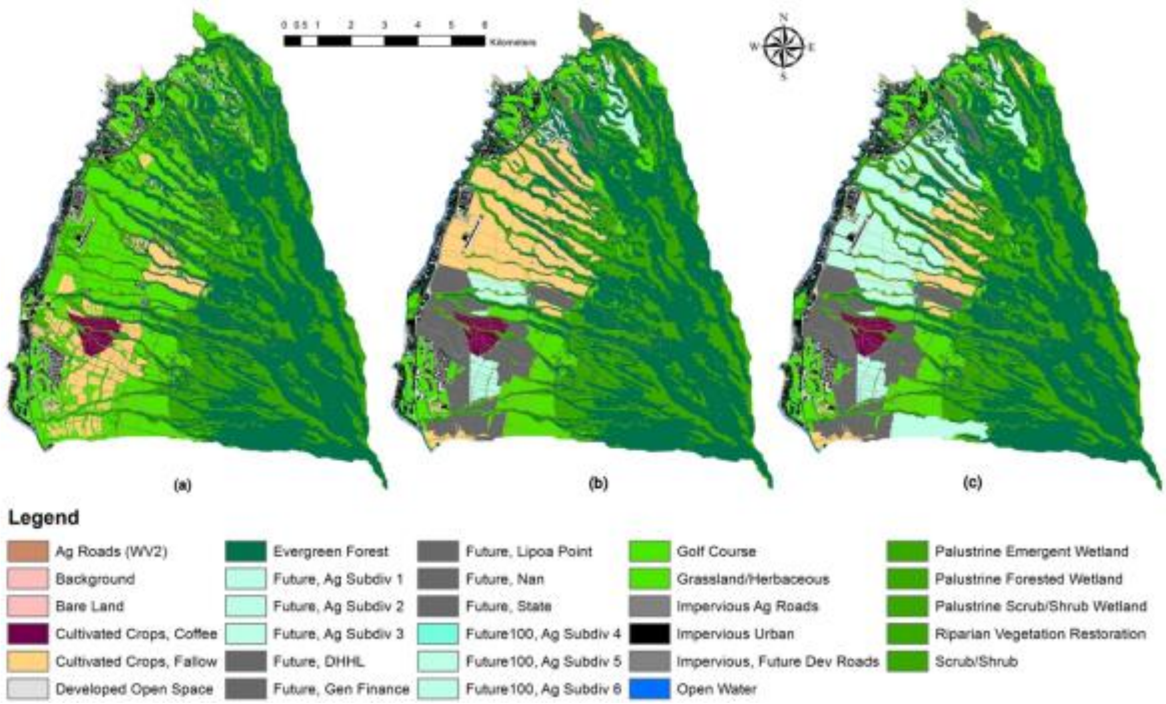

FIGURE 10. LAND USE SCENARIOS IN (A) 2010 (CREDIT: HTUN), (B) 2030 AND (C) 2100, PREPARED BASED ON COLLABORATIVE MAPS PRODUCED BY PACRISA AND FALINSKI'S GROUND-TRUTHING (CREDIT: FALINSKI, HTUN, BREWINGTON)

We used baseline rainfall from the Rainfall Atlas of Hawaii, 1978-2007 (Giambelluca et al. 2013). To estimate changes in rainfall in 2100 (Figure 11), we used predicted rainfall from the statistically downscaled long-term (30-yr average) data based on 32 global climate models according to the International Panel on Climate Change's Representative Concentration Pathway (IPCC RCP 8.5) (Timm et al. 2015) future absolute rainfall, we added the median predicted anomalies for late-century climate to the baseline scenario. Because the data available from the IPCC RCP 8.5 was separated into wet and dry seasons, we calculated wet and dry season absolute values separately and then summed for annual rainfall. The wet season was defined as November-April and dry season as May-October rainfall (Timm et al. 2015).

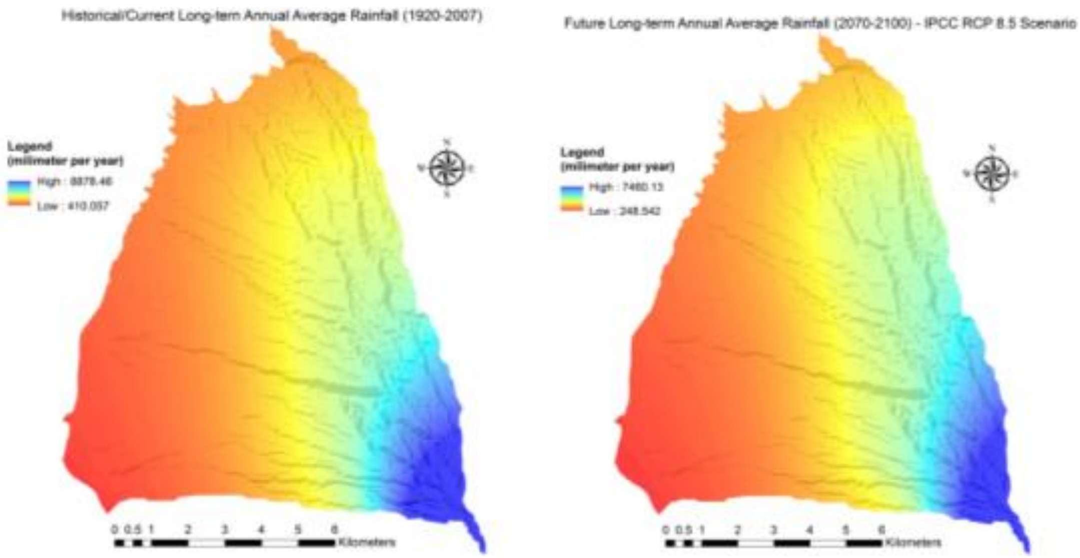

FIGURE 11. HISTORICAL/CURRENT AND FUTURE RAINFALL (SOURCES: (GIAMBELLUCA ET AL. 2013) AND (TIMM ET AL. 2015)) (CREDIT: HTUN)

The main options for reducing landscape nutrient inputs are to (a) reduce export, and (b) reduce application. Two alternatives also developed for sediment were deemed to also be appropriate for modifying N exported by the landscape: (a) Riparian buffers, (b) Convert fallow agriculture to forest. The Working Group members were interested in investigating the synergies. A third alternative specifically targeted at understanding the potential benefits of improved land management (through measures that address either nutrient application or export): (c) Reduce nitrogen application by land use class. Landscape alternatives were constructed by modifying NOAA CCAP's 2010 and 2100 land use scenarios. Alternatives for OSDS were developed in consultation with the working group, FAST and Bob Whittier (DoH), and based on likely options for management actions. We constructed multiple combinations of these alternatives and future land use/rainfall. All of these analyses have been delivered to the West Maui Ridge to Reef Initiative FAST.

Comparison among scenarios (**Error! Reference source not found.**) indicated that riparian vegetation restoration alternative had the highest reduction of sediment load, while future land use/cover (2100) with the projected future climate/rainfall and riparian vegetation restoration alternative produced the highest nitrogen export. This figure is an example of the analysis that the models enable.

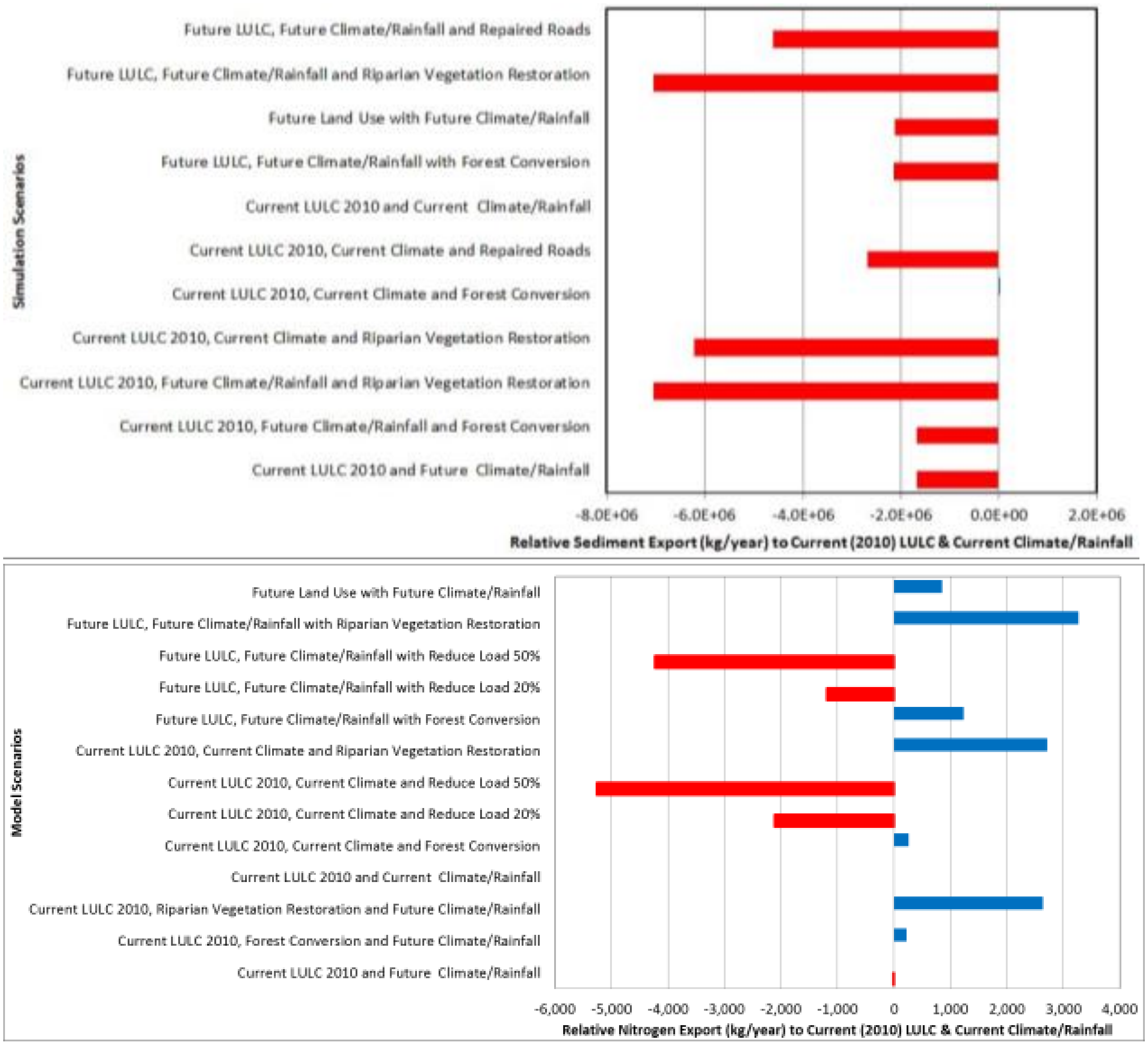

FIGURE 12. COMPARISON OF RELATIVE A. SEDIMENT EXPORT B. NITROGEN EXPORT FOR ALL THE MODELLED SCENARIOS FROM 2010 LULC & CURRENT RAINFALL.

Various scenarios were run to estimate OSGS flux under future conditions (Table 5). Please note that these are preliminary, and an ongoing effort is refining them.

TABLE 5. COMPARISON OF RELATIVE NUTRIENT EXPORT DUE TO OSDS FOR RELEVANT SCENARIOS AND ALTERNATIVE COMBINATIONS, AS DESCRIBED IN TABLE 8.

	Scenario/Alternative Combination	Total N Flux (kg N/L/day)
1	Current Land Use, Status Quo (cesspools not upgraded)	60.9
3	Current Land-use, and convert all other OSDS to Class I	73.4

4	2030 Land-use, Status Quo	65.1
6	2030 Land-use, and convert all other OSDS to Class I	91.9

Next Steps:

Next steps include building out trade-off models for the alternatives that the managers are considering. What we present here are illustrative examples, meant to demonstrate the capabilities of our models. We are actively working on defining the proposed alternatives and costing these out, such that we can do a trade-off analysis similar to what we did for the roads case.

Outcomes and performance evaluation:

Outputs of the project include:

(1) Identification of key land-based stressors to the coral reef ecosystem (conceptual map)
(2) Location of land-based stressors, including sediments and nutrients (nitrogen, sediment) (map)
(3) Comparison of different land-based regulation-related ecosystem service tools (conference poster for sediment, USACE report)
(4) Models to quantify and map sediment and nutrients (code, data layers, parameters)
(5) Spatial map of management hotspots, where proposed changed may be most necessary and/or feasible (maps)
(6) Graphical analysis of tradeoffs between stressor levels and costs of management (publication)
(7) Final report and manuscripts for peer reviewed publications (Two publications out; two more in prep)

Outcomes include: (1) improved understanding of the physical and economic tradeoffs associated with different LBSP management efforts; (2) spatial awareness and understanding of the sources of LBSP in west Maui; (3) increased use by managers of a novel LBSP predictive model designed for use in Hawaii; (4) opportunity for dialogue with watershed managers about how to best use limited resources to reduce LBSP; (5) improved economic efficiency of management. We have had a number of discussions with FAST members to assess our project's impact. Informal findings indicate a greater awareness of stressors, expected vs. modeled impacts of management, and the benefits of cost-effective management decision making. A number of things suggest that our models and analysis is actually being put to use to support decision-making. For instance, the watershed coordinator recently reached out to us to update some of the decision modeling for the roads. She has also used the predictive maps of bank erosion, and of cesspool effluent in her efforts.

Outreach efforts:

Work associated with this project has been presented at the following meetings, among others:

- Hawaii Conservation Conference, July 2014
- Sediment to Sea, Dec 2014
- American Geophysical Union, Dec 2014
- The Natural Capital Project's 10-year anniversary meeting, May 2015

- Work related to this project was presented at the World Conservation Conference in September 2017, as part of the Water Pavilion's land-sea management session.
- We participated in a "data day" with the West Maui watershed coordinator, to walk her through all our data and analysis in early 2017.

Results were handed over to the West Maui Ridge to Reef Initiative Funding Agency Support Team and Working Group throughout the project, including in an 81-page final report submitted to the FAST.

We have two peer reviewed publications out, and two more in preparation.

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Appendix A. Biophysical Parameter tables for INVEST models

Table 6. Biophysical Parameters for each Land Use Class for INVEST Sediment Delivery Ratio Model (After Falinski 2016)

LULC_desc	lucode	usle_p	usle_c	C-factor citation	P-factor citation
Background	0	1	0	0.003, SCS Puerto Rico 1980	
Unclassified	1	1	0	0.003, SCS Puerto Rico 1980	
Developed High Intensity	2	1	0.001	Lopez et al. 1998	
Developed Medium Intensity	3	1	0.01	Interpolated between Developed, High and Low Intensities	
Developed Low Intensity	4	1	0.02	Lopez et al. 1998	
Developed Open Space	5	1	0.03		
Cultivated Crops	6	1	0.24	Cox and Madramootoo 1998	
Pasture/Hay	7	1	0.05	0.012 Lianes 2009; 0.016 degraded	
Grassland/Herbaceous	8	1	0.009	FAO 1989	
Deciduous Forest	9	1	0.009	Lianes 2009	
Evergreen Forest	10	1	0.003	FAO 1989	
Mixed Forest	11	1	0.007	FAO 1989	
Scrub/Shrub	12	1	0.005	Lianes et al. 2009	
Palustrine Forested Wetland	13	1	0.001	Miteva et al, 2014	
Palustrine Scrub/Shrub Wetland	14	1	0.001	Miteva et al, 2014	
Palustrine Emergent Wetland	15	1	0.001	Miteva et al, 2014	
Estuarine Forested Wetland	16	1	0.001	Miteva et al, 2014	
Estuarine Scrub/Shrub Wetland	17	1	0.001	Miteva et al, 2014	
Estuarine Emergent Wetland	18	1	0.001	Miteva et al, 2014	
Unconsolidated Shore	19	1	0.005		
Bare Land	20	1	0.404	Ruhoff et al, 2006; NRCS	
Open Water	21	1	0		
Palustrine Aquatic Bed	22	1	0		
Golf courses	23	1	0.003	Mankin, 2000	
Impervious Urban	30	1	0.02	Lopez et al. 1998	
Impervious Ag	31	1	0.9		

Ag Rds (WV2)	32	1	0.9	Ramos-Scharron, 2015	
Impervious, Future Dev Roads	33	1	0.02	Used the same as Developed, Low Intensity	
Cultivated Crops, Coffee	40	1	0.1082	0.1-0.3 Mati and Veihe, 2001; 0.61 (0% rock, 60% canopy cover; first year), 0.069 (average for mature); Assumed 5 growing seasons until maturity and no maintained understory.; FAO 1989 = 0.09	
Cultivated Crops, Fallow	41	1	0.12	Used the same as Grassland/Herbaceous	
Future, Gen Finance	42	1	0.02	Used the same as Development, Low Intensity	
Future, Ag Subdiv 1	43	1	0.05	Used the same as Development, Open Space	
Future, State	44	1	0.02	Used the same as Development, Low Intensity	
Future, DHHL	45	1	0.02	Used the same as Development, Low Intensity	
Future, Nan	46	1	0.02	Used the same as Development, Low Intensity	
Future, Lipoa Point	47	1	0.009	Used the same as Grassland/Herbaceous	
Future, Ag Subdiv 2	48	1	0.03	Used the same as Development, Open Space	
Future, Ag Subdiv 3	49	1	0.03	Used the same as Development, Open Space	
Grazing land	50	1	0.12		
Cultivated Crops, Pineapple	51	0.8	0.4	Mati, 2001; Roose 1977 (0.2-0.5, in Africa); NRCS 0.4, 0.3 with green manure	Foster, 1983
Cultivated Crops, Sugarcane	52	0.8	0.5125	Evensen, 2001 (0.55 0.57 0.58 0.35);	Foster, 1983
Future100, Ag Subdiv 4	60	1	0.02	Used the same as Development, Low Intensity	
Future100, Ag Subdiv 5	61	1	0.02	Used the same as Development, Low Intensity	
Future100, Ag Subdiv 6	61	1	0.02	Used the same as Development, Low Intensity	
Repaired Ag roads	116	1	0.009	Used the same as Grassland/Herbaceous	

Table 7. Biophysical Parameters for each Land Use Class for INVEST Nitrogen Delivery Ratio Model

LULC_desc	lucode	load_n	Citation/Explanation load_n	eff_n	Citation/Explanation eff_n	crit_len_n	proportion_subsurface_n	Citation/Explanation proportion_subsurface_n
Background	0	0.000		0.75		50	0.8	
Unclassified	1	0.000		0.75		50	0.8	
Developed High Intensity	2	11.111	(Beaulac and Reckhow 1982; Line, White et al. 2002; 138 Goldstein)	0.1	InVEST example shows 0.05. So, 0.1 assumption is plausible.	50	0	Changed to make more sense for imperviousness of LULC.
Developed Medium Intensity	3	7.500	(Lin 2004; 23.9 Line, White et al. 2002)	0.15		50	0	Changed to make more sense for imperviousness of LULC
Developed Low Intensity	4	5.000	(Best estimate; NatCap average (2.7))	0.25		50	0	Changed to make more sense for imperviousness of LULC
Developed Open Space	5	7.500		0.5	Miteva, 2014	50	0.8	
Cultivated Crops	6	10.700	Miteva et al, 2014	0.75		50	0.8	
Pasture/Hay	7	6.700	(Young, Marston et al. 1996 (5.0); Line, White et al. 2002 (6.7); Miteva (5.4); Brodie 5.6*forest); Adamus and Bergman (crops)	0.52	Miteva, 2014	50	0.8	
Grassland/Herbaceous	8	3.100	(Wilcke and Lilienfein 2005)	0.9	Used the same as Pasture/Hay	50	0.8	
Deciduous Forest	9	4.700	(Heartsill-Scalley, Scatena et al. 2007)	0.8		50	0.8	

Evergreen Forest	10	14.125	(Vitousek and Sanford 1986 average is 8.2; Heartsill-Scalley, Scatena et al. 2007; Vitousek 1984 has comprehensive list; average for InVEST database is 23.7; Brodie is 8.9)	0.8	Miteva, 2014; Exported value divided by eff_n (11.3/0.8)	50	0.5	
Mixed Forest	11	4.700	n/a	0.8		50	0.8	
Scrub/Shrub	12	5.500		0.5		50	0.8	
Palustrine Forested Wetland	13	1.620	Miteva et al, 2014	0.9		50	0.8	
Palustrine Scrub/Shrub Wetland	14	1.620	Miteva et al, 2014	0.9		50	0.8	
Palustrine Emergent Wetland	15	1.620	Miteva et al, 2014	0.9		50	0.8	
Estuarine Forested Wetland	16	1.620	Miteva et al, 2014	0.9		50	0.8	
Estuarine Scrub/Shrub Wetland	17	1.620	Miteva et al, 2014	0.9		50	0.8	
Estuarine Emergent Wetland	18	1.620	Miteva et al, 2014	0.9		50	0.8	
Unconsolidated Shore	19	0.000		0.75		50	0.8	
Bare Land	20	1.500	Miteva et al, 2014	0.5		50	0.8	
Open Water	21	2.889	Miteva et al, 2014	0.1		50	0.8	
Palustrine Aquatic Bed	22	1.620	Miteva et al, 2014	0.75		50	0.8	
Golf courses	23	438.700	Average of White et al. 2002; (31.2) Kerek, Drijber et al. 2003, (7) Tetratech 1993; Kaluarachi and Almasri - 148 kg/ha) - see Falinski 2016 description	0.86	Kerek et al, 2003; 90% Soicher and Peterson	50	0.9	

Impervious Urban	30	8.333	Homes & Roads based on: Lin 2004; Line, White et al. 2002	0.1	InVEST example shows 0.05. So, 0.1 assumption is plausible.	50	0	Changed to make more sense for imperviousness of LULC
Impervious Ag	31	7.500		0.75		50	0.8	
Ag Rds (WV2)	32	3.100		0.75		50	0.8	
Impervious, Future Dev Roads	33	3.100		0.75		50	0	Changed to make more sense for imperviousness of LULC
Cultivated Crops, Coffee	40	140.000	Management Plan - 280; only half of the field are planted at any one time at present.	0.86	Harmand, 2007 (considering amount exported over added, shaded coffee)	50	0.8	
Cultivated Crops, Fallow	41	3.100	Using grassland numbers	0.64	Miteva, 2014	50	0.8	