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A decision support tool for the conservation of tropical forest and nearshore environments on Babeldaob Island, Palau

Nicholas A. Povak[a,b,*], Christian P. Giardina[c], Paul F. Hessburg[a], Keith M. Reynolds[d], R. Brion Salter[a], Chris Heider[e], Ed Salminen[e], Richard MacKenzie[c]

[a] USDA-FS, Pacific Northwest Research Station, Forestry Sciences Laboratory, Wenatchee, WA 98801, United States
[b] Oak Ridge Institute for Science and Education, Oak Ridge, TN 37830, United States
[c] USDA-FS, Pacific Southwest Research Station, Institute of Pacific Islands Forestry, Hilo, HI 96720, United States
[d] USDA-FS, Pacific Northwest Research Station, Forestry Sciences Laboratory, Corvallis, OR 97331, United States
[e] Watershed Professionals Network (WPN), PO Box 8, Mount Hood-Parkdale, OR 970441, United States

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ABSTRACT

Nearshore ecosystems (e.g., mangrove forests, sea grass beds, coral reefs) are some of the most biologically diverse and ecologically productive on Earth, while providing essential goods and services to human communities. Because these ecosystems are subject to threats from both land and sea, their conservation and management requires a ridge to reef approach. Here, we developed a watershed decision support tool (DST) for Babeldaob Island, Republic of Palau, aimed at prioritizing catchments for reforestation of fire degraded savanna or protection of native forest against conversion to savanna. We use a distributed hydrology model to estimate catchment-level sedimentation and water yield for three vegetation scenarios: (1) current vegetation; (2) a hypothetical fully-forested Babeldaob Island; and (3) a hypothetical Babeldaob Island that has been fully converted to savanna. Using the DST, we integrated model results with geospatial information on treatment cost, efficacy, and conservation value to identify where reforestation and forest protection investments would provide the greatest benefits to coral reef health. Modeled sediment yields were lowest for catchments with > 80% tropical forest cover and highest for those with < 40% forest cover. Sediment hotspots were concentrated near coastal population centers. Modeled catchment-level groundwater recharge showed high variability across vegetation scenarios with no clear relationship was identified between recharge and percentage land cover in forest or savanna. The DST identified 14% of catchments as high priority for reforestation of grassland-savanna, and 11% of catchments for protection of native tropical forest. Most high priority reforestation catchments were located near the coast, while all high protection areas were further inland. Results from the DST suggest that road access and slope will not limit reforestation, but the remoteness of inland high priority catchments may limit protection efforts.

1. Introduction

Mangrove forests, sea grass beds, and coral reef ecosystems represent some of the most biologically diverse and ecologically productive environments on the planet (Martínez et al., 2007), but also some of the most threatened. Climate change and human development contribute most to current high rates of degradation (Fabricius, 2005; McGill et al., 2015), which have global scale implications (Chin et al., 2011). Impacts of these losses have direct consequences for Pacific Island communities that rely on them for food, medicine, and services and for the tourism-based economy these systems support (e.g., diving, snorkeling, and ecotourism).

Of the many human impacts on coastal tropical environments, forest land clearing ranks among the most detrimental (Fabricius, 2005). Excess runoff from exposed soils entering nearshore environments introduces large volumes of inorganic nutrients and particulate organic matter that can bury root systems of mangroves, reduce sunlight available to aquatic vegetation, and bury or smother seagrass beds or coral reefs (Fabricius, 2005; Storlazzi et al., 2015). When chronic, these impacts reduce diversity of native plant and animal assemblages (Fabricius, 2005; Thaman, 2002).

Ridge-to-reef land management activities focus on preserving, or, where needed, restoring tropical forests to protect the composition, structure, and functioning of near-shore ecosystems and off-shore reef

* Corresponding author at: 1133 N Western Ave, Wenatchee, WA 98801, United States.
E-mail address: nicholas.povak@usda.gov (N.A. Povak).

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communities. While the consequences of deforestation to upland and offshore communities are well known, land clearing to support agricultural food production, burning to create habitat for game animals or to improve hunting access, and other cultural land-uses can outweigh public support for conservation. Aggravating these tradeoffs, land managers and policy makers often lack data resources and technology-based tools to assess the trade-offs of competing resource management strategies (White et al., 2012). To be effective, such tools need to emphasize cost-effectiveness and allow a user to understand the consequences of different management options that accurately reflect local to national scale societal needs. These tools also need to be informed by the best available data.

Geospatial analysis and decision support tools (DSTs) have been used for decades to assist managers with strategic decision-making needed to most effectively achieve conservation goals and meet the needs of diverse stakeholders (Reynolds and Hessburg, 2014). To this end, a DST is a computer program that facilitates user efforts to analyze multiple spatial datasets and prioritize one or more socio-ecological benefits. Crucially, models also incorporate logistical and operational considerations that are often integral to land management decision making. Thus, a DST can provide a formalized process and quantitative framework for understanding the implications of diverse management alternatives within a geospatial planning environment.

While common in temperate regions, the application of DSTs has been limited in tropical systems (Povak et al., 2017). However, as climate change, land-use, and invasive species all increasingly impact tropical ecosystems, DSTs could provide increasingly valuable framework for assessing management actions for achieving desired outcomes. Here, we present a DST designed to inform forest restoration and protection planning in The Republic of Palau (Fig. 1), an equatorial island archipelago in the Micronesia Biodiversity Hotspot (Meyer, 2000) at the western edge of Polynesia. Palau supports highly biodiverse lowland rainforests with some of the highest rates of floral endemism in Micronesia (Costion et al., 2012, 2009; Donnegan et al., 2007). However, human-ignited fires for agriculture, urban expansion, and access have all caused losses of native forest, with resulting conversions to savanna causing concomitant increases in sediment loads to neighboring streams and nearshore environments.

Because there are no natural ignition sources in Palau, fires are entirely human caused. Active land clearing with fire in Palau dates back more than 3000 years (Costion et al., 2012; Endress and Chinea, 2001). Fires remove protective vegetation cover and expose soils to heavy rainfall events that can cause severe erosion (Golbuu et al., 2011a; Koshiba et al., 2014). Furthermore, forest patches in degraded areas recover slowly, even inside protected areas. For example, Dendy et al. (2015) found that natural recolonization rates by forest plants of savanna edges measured just $\sim 2\ \mathrm{cm} \cdot \mathrm{yr}^{-1}$ due to low soil fertility, but that fertilization increased rates fivefold and also led to large increases in tree growth, flowering, and fruit production (Dendy et al., 2015).

The current study focuses on Babeldaob Island, the largest in the Palauan archipelago, and the second largest island in Micronesia (Fig. 1). Babeldaob has a long history of land clearing for agricultural and other land uses. The high annual rainfall, erodible volcanic soils, and steep terrain (Costion et al., 2012; Endress and Chinea, 2001; Koshiba et al., 2014) result in high erosion levels when forests are converted to grassland-savanna, urban and agricultural conditions.

We used a calibrated distributed hydrology model to estimate catchment-level sedimentation and water yield for three reference vegetation management scenarios: (1) current vegetation conditions; (2) a hypothetical fully forested Babeldaob Island; and (3) a hypothetical Babeldaob Island that is fully deforested and entirely in grassland or savanna condition. Using the Ecosystem Management Decision Support System (EMDS, Reynolds and Hessburg 2014), we integrated model results for the three scenarios in a decision support application, with geospatial information on treatment cost, efficacy, and conservation value of land areas. Our purpose was to identify opportunities for forest management to reduce current sediment loads by reforesting fire-tended savanna habitats. The model also allowed us to identify areas where loss of native tropical forest could lead to new sediment hot spots.

This work also allowed us to explore the utility of numerical modeling-based decision support in a data poor but resource rich environment. Accordingly, we used the most current and complete datasets available for our sediment and hydrology modeling ; however, gauged stream data were unavailable for model calibration and sensitivity analyses. As such, model estimates should be taken with caution when comparing to other studies. Moreover, while land grading and road construction can exacerbate impacts of land-use change on erosion (Victor et al., 2004), our models did not incorporate these sediment sources because detailed road data required by the models were unavailable. Modeled estimates, therefore, captured only potential land use contributions to total sediment loads. The exclusion of the road network did not adversely influence DST, which only required information on the relative changes in sediment across the three vegetation scenarios.

2. Methods

2.1. Study area description

The Republic of Palau is an independent island nation within Micronesia comprised of more than 300 islands with a combined land area of 365 km^2 spanning an exclusive economic sea zone of 603,978 km^2. The Republic stretches from 2 to 8° north latitude, supports 1519 km of coastline, and lies approximately 800 km east of the Philippines and north of Papua New Guinea. The largest of the islands, Babeldaob, is volcanic in origin, and represents about 80% of the Republic's total land area. Palau has a tropical moist climate, and the mean annual temperature at the capital city of Koror is 27 °C. The island has distinct but mild dry (January – April) and wet (June – August) seasons. Total annual precipitation varies between 3000 and 4000 mm (mean = 3730 mm). Rainfall increases with elevation and occurs in short, intense storms that are irregularly distributed throughout the year. Elevation ranges from sea level to 213 m at Mt. Ngerchelchuus.

Palau land cover is ~ 82% tropical moist forest, including significant areas of agroforest and secondary forest (Donnegan et al., 2007). Dominant types on Babeldaob are upland evergreen broadleaved, mangrove, and swamp forest (Cole et al., 1987). Much of the remaining 18% is in grassland and savanna types, which are the result of repeated human burning, which for some sites has been happening for centuries (Costion et al., 2012). Babeldaob Island provides most of the savanna habitat across the Palauan islands.

2.2. Decision support tool model workflow

Our DST workflow begins with discussions among stakeholders (Fig. 2) to identify and define the management problem, elaborate specific data needs and develop the model setup (see *3.4 Spatial data*). Step 2 involved running a pair of landscape-level hydrology models to estimate groundwater recharge and sediment under various vegetation scenarios (see *3.3 Distributed hydrology and sediment modeling)*. Model outputs were summarized to fine-scale catchments delineated across the island and submitted to a logic model (Step 3, see *3.7.1 The NetWeaver© Logic model*), which assessed the relative capacity of catchments to retain more sediment if restored to tropical forest or produce more sediment if converted to savanna. Such an evaluation can direct management decisions regarding where on the landscape to 1) protect current tropical forest to prevent large inputs of sediment, or 2) restore tropical forest within savanna patches that current produce high levels of sediment. In addition to the logic model assessment of the ecology of the island ecosystem as it relates to sediment production, a separate multi-criteria decision model (Step 4, see *3.7.2 Multi-criteria decision*

Fig. 1. Proximity map for Babeldaob Island in the Republic of Palau, Micronesia.

model (MCDM)) was developed to incorporate logistical constraints due to the effort required to treat a specific catchment, as well as other management consideration including the biodiversity value of a catchment and the amount of savanna-forest edge within a catchment. Finally, in Step 5 these priorities were mapped in a GIS, and the MCDM re-evaluated to determine the effect of assigning various weighting schemes across individual criteria influenced model results.

2.3. Distributed hydrology and sediment modeling

We developed a pair of distributed hydrology models to quantify average monthly catchment-level groundwater recharge and sediment yield for the period 1984 – 2005, across three vegetation scenarios: current vegetation conditions (CC); complete savanna coverage or fully savanna (FS); and complete forest coverage or fully forest (FF). Modeling across vegetation scenarios allowed us to quantify changes in sediment yields and groundwater recharge in each catchment as a function of land cover. We hypothesized that increasing forest cover would lead to increases in groundwater recharge and reduced sediment loads, whereas increasing savanna coverage would lead to increases in sediment loads and reductions in groundwater (Ilstedt et al., 2016; Malmer et al., 2010). By maximizing forest and savanna coverage in contrasting hypothetical scenarios, we could explore the potential minimum and maximum values for catchment-level groundwater recharge and sedimentation as related to changes in land cover. These values were then compared with levels under current vegetation conditions to identify catchments where reforestation could improve current hydrology and sediment regimes and protecting tropical forest would prevent degradation of these resources.

Groundwater recharge was estimated using the Distributed Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta et al., 1994), a complete water, energy, and mass balance model that can be used to examine the influence of topography, vegetation, and soils on water flux through a catchment, including tropical watersheds (Povak et al. 2017). The DHSVM dynamically represents the spatial distribution of soil moisture, evapotranspiration, and runoff. Depth of groundwater recharge (m) was calculated in three-hour time steps, across the 22-year period of record, for each of the ~370,000 study area pixels. Spatial data requirements for this application of DHSVM included a DEM, a wall-to-wall land cover map to represent each vegetation scenario, soil type and depth, mean monthly precipitation, and stream hydrography. Temporal data inputs included climate data consolidated to 3-hr time steps for air temperature, precipitation, relative humidity, solar radiation and wind speed.

Vegetation-related physical and ecophysiological parameter values required by DHSVM as initial input data were established for each land-cover type (see *3.3.5 Vegetation*) from literature values. Parameters included stand-level percent canopy closure, stomatal resistance, photosynthetically active radiation, rooting depth, leaf area index (LAI), among others. Data were unavailable for Babeldaob Island; instead, parameters were applied from the island of Guam (Mafnas, 2010), which, as with nearby Palau, is covered in heavily weathered soils that support a topical moist, broadleaved evergreen forest growing in a mildly seasonal climate with a short dry season.

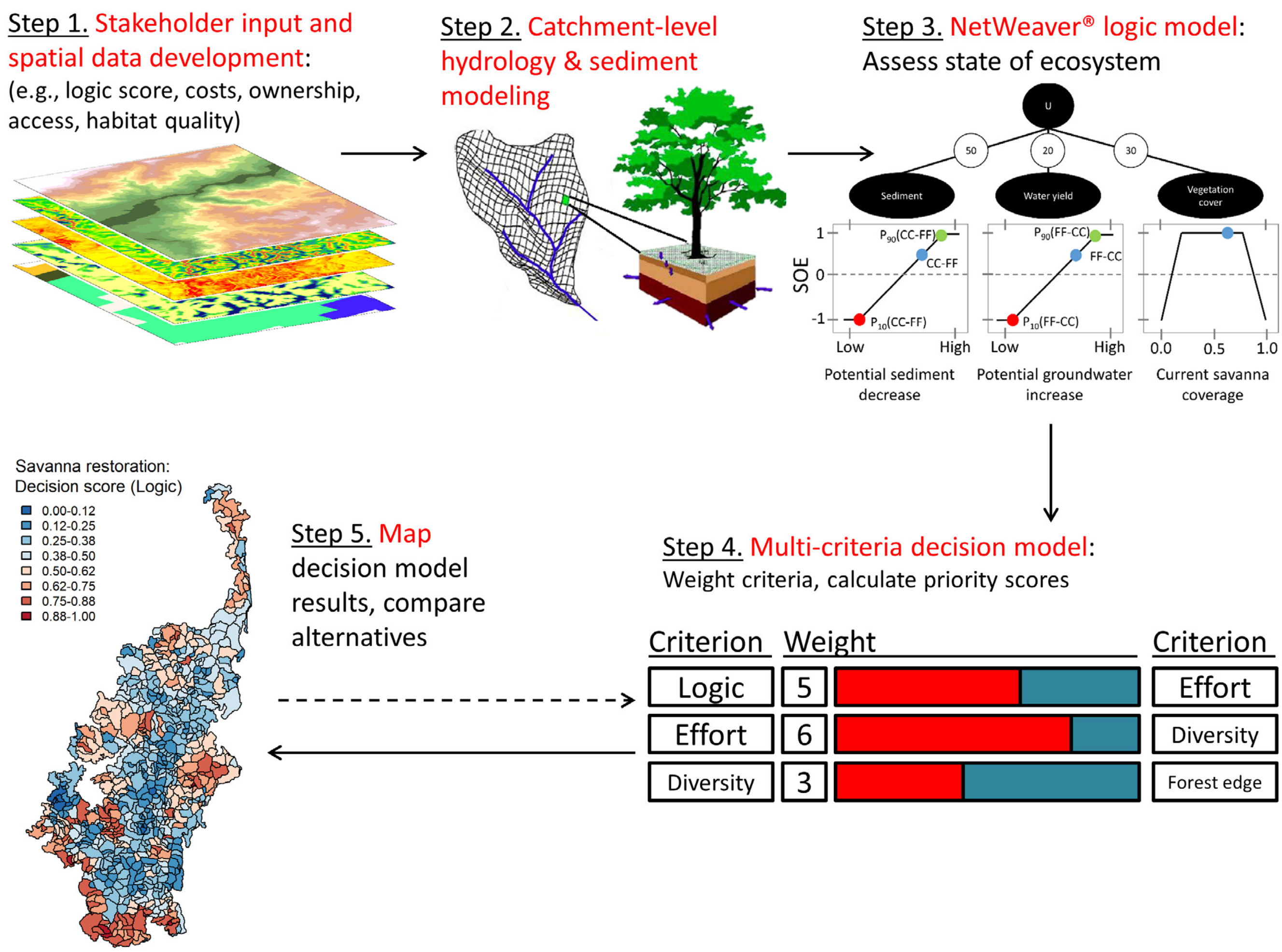

Fig. 2. Workflow used to quantify catchment-level sediment and groundwater recharge for the Babeldaob Island study area, which, along with a variety of other spatial datasets, were used to feed into the DST for landscape prioritization.

An open-source version of the Nonpoint Source Pollution and Erosion Comparison Tool (OpenNSPECT; Eslinger et al., 2012) was used to estimate overland sediment loads delivered to stream channels across Babeldaob Island catchments. OpenNSPECT is a GIS-based program used to develop relationships between land cover, nonpoint source pollutants, and erosion inputs to stream channels (Oleson et al., 2018). The model was particularly suited to our study as it is sensitive to changes in land cover (Morrison and Kolden, 2015; Oleson et al., 2018), which we vary significantly in our study area to compare sediment loads as a function of changes in the amount of forest and savanna coverage within a catchment.

The OpenNSPECT model requires several spatial datasets to be fully parameterized, including elevation, land cover, rainfall, and soils data. Sediment loads are estimated in the model using the revised universal soil loss equation (RUSLE; Renard et al., 1991):

$$A = R * K * L * S * C * P$$

with A, average annual soil loss, being a function of the parameters: R, rainfall-runoff factor; K, soil erodibility factor; L, length-slope factor; S, slope gradient factor; C, cover management factor; and P, support practice factor. The rainfall-runoff factor (R) quantifies the effect of rainfall on the amount and rate of runoff, and the soil erodibility factor (K) quantifies the susceptibility of soil to erosion, and the amount and rate of runoff. Values were derived from Kuhn et al. (1999) and USDA NRCS (2009).

The model was run for the water years 1984 – 2005, for each of the three vegetation scenarios. OpenNSPECT provided gridded annual accumulation of sediment yield, which was summarized to mean annual sediment yield (tons $\cdot$ km^{-2} $\cdot$ yr^{-1}) at the pour point of each catchment. The effects of road surface and urban and road development were not integrated into our modeling and so are not reflected in the sediment yield estimates. The effects were excluded in our model because their inclusion would have obscured the focus of our effort (understanding benefits of forest protection or restoration) and because spatial data were not available on the very complex network of informal unpaved and often unimproved secondary roads in Palau – data required to accurately model these effects. Given that these sources of sediment are important contributors in other locations (Golbuu et al., 2011b), our modeling underestimates absolute estimates of sediment yields. However, excluding these effects satisfies our objective of directly comparing relative differences in sediment yield as a function of changing forest versus savanna/grassland cover, which the OpenNSPECT model is so designed (Gibbs and West, 2019). Critically, our DST relies fundamentally on relative difference between scenarios to project priorities units for management attention, and so while absolute values of sediment yield should be assessed with caution, the relative differences between modeled land cover scenarios, where other major parameters of climate, soils and topography were held constant, are more robust for interpreting spatial patterns.

2.4. Spatial data

2.4.1. Topography

One arc second DEM data (~30 m native resolution) was acquired for the project area from the USGS National Map (http://nationalmap.gov/). The DEM was conditioned by first clipping the raster to Babeldaob Island, but excluding nearshore areas mapped as mangrove. The resulting DEM was further conditioned to enforce drainage using the methods of Barnes et al. (2014). These DEM files and all subsequent raster files were exported from the GIS in a binary format for input to the DHSVM model.

2.4.2. Stream network development

The DHSVM requires spatially distributed data on the location and characteristics of stream channel types. Stream locations and characteristics influence transitions between surface and subsurface flow, and the rate at which streamflow is routed to downstream locations. The DHSVM model uses a flow routing algorithm to move water through the channel network. A vector stream network was developed from the drainage enforced DEM in a GIS by varying the contributing area required for channel initiation until the resulting channel network approximated the mapped network of the USGS topographic maps, as represented by the Digital Line Graph data. The final contributing area chosen for channel initiation was 200-ha.

Parameters that need to be estimated for each stream segment in the DHSVM include active channel width and depth, and channel gradient and roughness. No data or regional equations were available for estimating values for these parameters for Palau; consequently, quasi-universal equations for gravel bedded rivers were used to estimate these values (Parker et al., 2007). These equations use two-year peak flow and median bed particle size as independent variables. Flood-frequency equations also were not available for Palau. Thus, we calculated the 2-yr recurrence peak flow value for six gaging sites in Palau with available data using the USGS PeakFQ Annual Flood-Frequency Analysis program (Flynn et al., 2006), and then regressed the results against drainage area. We used the resulting equation to estimate the 2-yr peak flow at the midpoint of each channel section, and channel widths and depths using the equations from (Parker et al., 2007). A median bed particle size of 0.05 m was assumed at each channel section. Ten width and depth classes were defined, and each channel segment was assigned to one class. Channel gradients were calculated within the GIS using the DEM and the newly created routed stream network. Roughness (Manning's *n* values) were estimated to be 0.04 for all channel segments.

2.4.3. Soils

DHSVM requires spatially distributed soil texture and depth data. Model parameter values associated with texture class determine the rate at which moisture moves through the soil profile under saturated and non-saturated conditions, while soil depth controls the volume of soil moisture, as well as the interception of soil moisture by stream and road cuts.

The U.S. Department of Agriculture, Natural Resources Conservation Service Soil Survey Geographic (SSURGO) database for the Republic of Palau was used to map soil depth and soil texture classes (USDA NRCS, 2009). Fifty-nine NRCS map units were combined into 8 soil types, based on texture class, and two non-soil types (exposed rock and open water). Soil parameters were derived from the SSURGO database (saturated hydraulic conductivity), Akan (1993; maximum infiltration rate), Rawls et al. (1982; porosity, pore size distribution, bubbling pressure), Saxton and Rawls (2005; field capacity, wilting point, soil density). Soil depths were defined as $>$ 200 cm by the soil survey, therefore a single soil depth of 1.6-m was assumed for the project area - the maximum depth allowed in the SSURGO database.

2.4.4. Climate

Precipitation, wind speed, air temperature, and dew point temperature data were available from a single climate station, Babeldaob/Koror Air (station number 914,080 40309), located approximately three miles south of the modeling area at an elevation of 33.2 m ASL. The period of record for the station was 1947 to present, and we found the data from 01 February 1984 to 01 January 2006 were readily available and complete for the purposes of our work. Data were available in 1- to 3-hr time steps, depending on the year. We summarized the data to a consistent 3-hr time step for the purposes of the DHSVM modeling. Relative humidity was calculated from air and dew point temperatures using the approach of Lawrence (2005). Missing data were estimated by averaging values for preceding and following time steps. Station data were adjusted within DHSVM to every pixel in the model using parameter-specific approaches. Precipitation was adjusted using monthly PRISM precipitation values (Daly and Halbleib, 2006). Air temperature was adjusted based on elevation using a lapse rate of $-0.006^{\circ}\mathrm{C}\cdot\mathrm{m}^{-1}$. Wind speed and solar radiation were adjusted based on position and landform within DHSVM.

Neither short- nor long-wave solar radiation values were available for any station in the vicinity of the project area. Both values were estimated using the approach of Bowling and Lettenmaier (1997). Atmospheric transmittance (Tt) was calculated from daily air temperature extremes using the methodology of Bristow and Campbell (1984). Empirically-derived constants used in the calculation of Tt were unavailable for Palau, thus we supplied values calculated for comparable conditions from the Island of Oahu, Hawai'i. Shortwave radiation was estimated by calculating solar declination and the hourly sun angle for the station location using its latitude and longitude. These values were then used to estimate irradiance at top of atmosphere. Incoming shortwave radiation estimates were then made based on irradiance at top of atmosphere and atmospheric transmittance. Similarly, longwave radiation was estimated from shortwave radiation, air temperatures, relative humidity, and atmospheric transmittance (Bowling and Lettenmaier, 1997).

2.4.5. Vegetation

The DHSVM model requires a wall-to-wall vegetation coverage with enough floristic detail to classify vegetation polygons into a manageable number of vegetation classes and assign the DHSVM-required parameter estimates. We found that vegetation data available for Babeldaob Island during the modeling period of interest varied with respect to quality, coverage extent, and detail. Given these constraints, we acquired a vegetation classification for Palau from the , Geospatial Technology and Applications Center (GTAC). The shapefile was derived from a vegetation map compiled by the Forest Service's Pacific Southwest and Pacific Northwest Research Stations from aerial photographs taken in 1968 and 1971, field checked in 1970, and updated in 1981. The map included information on dominant and subordinate plant species, tree diameter classes, and canopy closure for areas where trees were present. Given the age of the vegetation data, we compared the vegetation classes from the 1981 product with 2006 QuickBird satellite images available from DigitalGlobe, and evaluated the consistency of edges between grassland-savanna and upland forest patches. We found good agreement between the 1981 product and the QuickBird images; correspondence was likely related to an overall low rate of land clearing on the island due to difficult access prior to 2006 completion of the compact road, a strong conservation-focused tourism-based economy, and limited subsistence driven land-use. However, a small population actively used fire to maintain existing savanna patches by slowing forest encroachment into existing savanna, a land-use pattern that is maintained by generally poor soil fertility (Dendy et al., 2015). Nevertheless, we recommend caution when making inferences on current day vegetation patterns from our base map.

Attributes from the original vegetation survey were used in a land cover classification resulting in 11 main land cover types (Table 1). Each land cover class was then further classified based on their canopy interception potential (low, moderate, high), and surface vulnerability to erosion (low, moderate, high), resulting in a total of 99 potential DHSVM vegetation classes, of which only 36 combinations existed on the island. These 36 vegetation classes determined the number of resultant parameter files submitted to DHSVM modeling.

Table 1
Main vegetation and land use classes and their associated DHSVM hydrology model parameters for determining surface vulnerability to erosion and canopy interception potential, as well as their biodiversity ranking used in the EMDS Decision model.

	Surface vulnerability to erosion									
	Low			Mod			High			
	CANOPY INTERCEPTION POTENTIAL									
Vegetation class	Low	Mod	High	Low	Mod	High	Low	Mod	High	Biodiversity class
Bare ground				X			X			1
Urban							X			1
Grassland-savanna	X	X		X	X		X	X		2
Agroforestry	X		X	X	X			X		3
Unknown					X					3
Secondary forest					X		X	X		4
Forest		X	X	X	X	X	X	X		5
Mangrove		X	X		X					5
Marsh		X								5
Water			X							5
Wet forest		X	X	X	X		X	X		5

Canopy interception rankings were categorically assigned as low, moderate and high on the basis of tree canopy fractional cover (higher rankings for higher cover), number of canopy layers (higher rankings for multiple canopy layers versus simple plantation species), and leaf angles (shallow leaf angles ranked higher than steeper angles). Overall this provided a categorical ranking for each vegetation type based on physical interception by leaves, branches and forest structures, with higher canopy inception yielding a reduced amount and physical impact of water that reaches the soil surface. Surface vulnerability reflects the ability of vegetation to impede water and sediment transport, with low vulnerability associated with dense understory vegetation, with a linear estimation of increases in vulnerability as ground cover (vegetation, downed wood, other surface features) decreases.

2.5. Hydrology modeling calibration

Discharge data (both water and sediment) are not needed to run the DHSVM or OpenNSPECT models; however, these data are essential to calibrate the model for the catchments of interest and to validate model output. Stream discharge data were available for seven locations on the island of Babeldaob. Five stations overlapped the climate data period of record (2/1/1984 to 1/1/2006) and were used for calibration of the DHSVM. Given that the hydrological output from the model performed well relative to actual stream gaging data, we expect that hydrological component of calculating sediment delivery to be robust. While important local base layer data needed for parameterizing the model were available for Palau, sediment delivery data are absent for Palau and for much of the tropics, meaning calibration of model was not possible. As a result, the accuracy of our modeled sediment delivery estimates is uncertain. However, while the lack of calibration data clearly affects confidence in absolute delivery rates, our work focused on relative differences in sediment delivery across land-cover scenarios and current (accurately mapped) vegetation cover. In an ideal world these three vegetation scenario model runs would be derived from the same calibrated model. That was not possible. Sediment focused DST work has served important functions in the effective management of temperate watersheds, and so carefully evaluating appropriateness of their application to regions with fewer resources and more limited infrastructure for monitoring sediment fluxes is important. Because the effects of calibration on absolute rates will be much larger than effects on relative differences among simulations, we suggest our goal of better understanding the limits of DST work in understudied tropical areas is reasonable and our modeled scenarios adequately robust for large-scale decision support applications in Palau.

2.6. Statistical analyses

We used Pearson's correlation and linear regression methods to identify the direction and strength of relationships between sediment yields and groundwater recharge depth with the proportion of forest and grassland-savanna coverage across catchments.

2.7. The EMDS application development system

Based on a decade of work in Palau examining impacts of fire on biodiversity and the benefits of restoration management in the Ngrardoc Nature Preserve (Dendy et al. 2015), our team began a dialogue with national environmental leadership about how to scale our work to Babeldaub Island. Our team responded by developing whole island vegetation change maps extending back nearly a century to precisely define the extent and geography of vegetation cover change (J. Dendy, unpublished data). This in turn inspired a collaborative, wall-to-wall fire history mapping effort using both ground-based and remotely sensed methods to precisely define the extent and geography of the fire problem – widely acknowledge as growing since completion of the Compact Road (J. Dendy, unpublished data). The resulting data sources were valuable but difficult for managers to assimilate into coherent recommendations for long-term management of precious biodiversity resources, including near shore environments. For these reasons, our team approached environmental leaders with the concept of collaboratively building a DST for integrating these data sets and linking upland and nearshore environments to support integrated ridge to reef resource management. We selected EMDS as an application development system because it can be used to develop and apply custom logic and decision models to aid in management decision-making (Reynolds and Hessburg, 2014) across biome types including humid tropical systems (Povak et al. 2017). In the current study, EMDS was used to prioritize landscape treatment units across Babeldaob Island based on predicted ecological effects of treatments on sediment yield and groundwater recharge from catchments of the island. The basic workflow of the model is shown in Fig. 2. In EMDS, logic models were designed with NetWeaver® (Miller and Saunders, 2002) to evaluate the ecological status of a particular catchment. The logic model evaluated the strength of evidence (SOE) for the stated propositions described below. Logic model output scores range between −1 (no support for a proposition), and 1 (full support).

Multi-criteria decision models (MCDM) were designed using the Criterium DecisionPlus® software (Murphy, 2014). The utility of incorporating MCDM into environmental management decision-making is the ability to incorporate a variety of logistical, economic, and

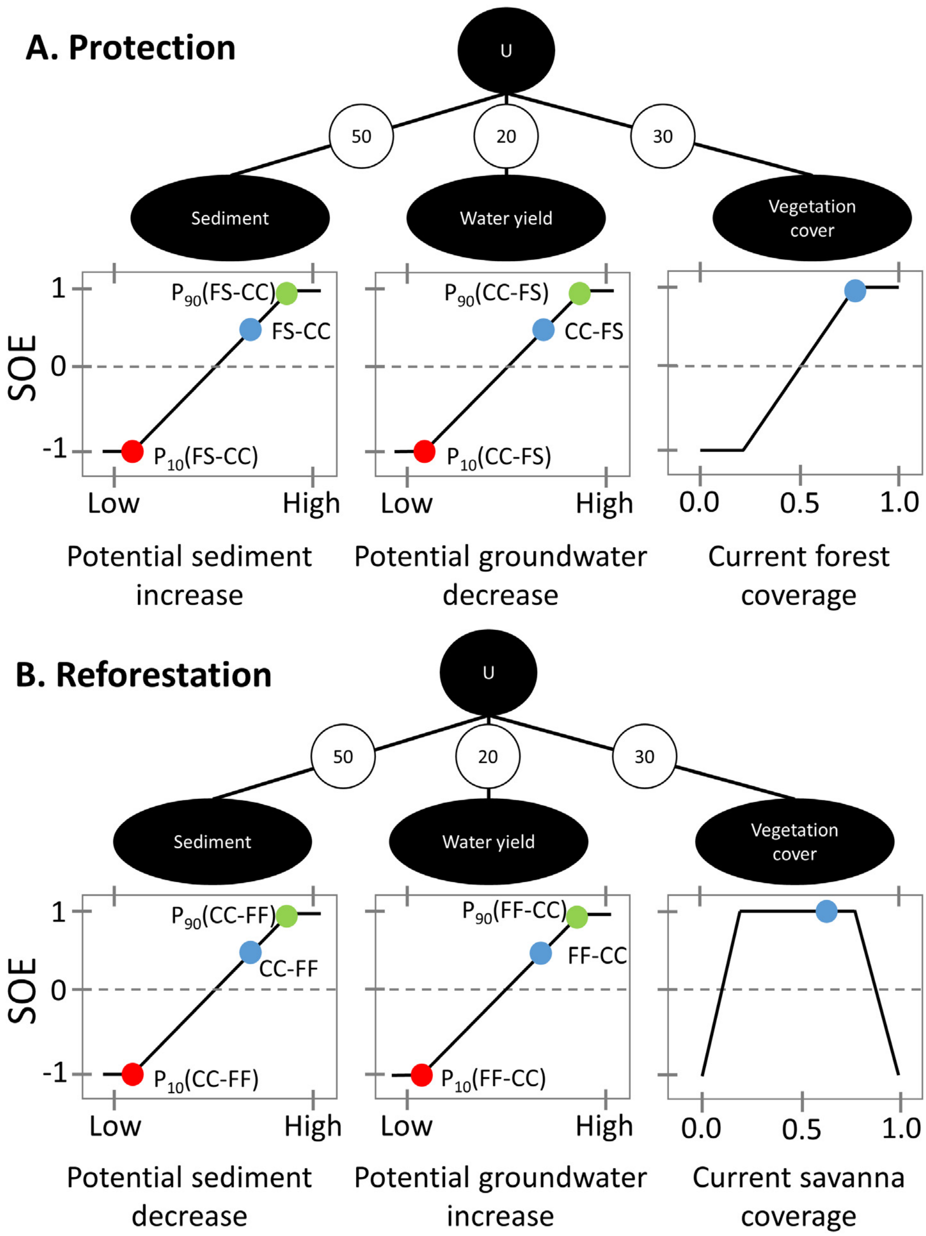

Fig. 3. NetWeaver Logic Model for (A) protection of upland tropical forest and (B) restoration of grassland-savanna vegetation types. Abbreviations are: U, union logic operator; P_{90}, 90th percentile; P_{10}, 10th percentile; CC, current coverage; FS, full savanna; FF, fully forested. Logic model branches were weighted such that sediment yield (50) was emphasized in the logic model calculation, followed by vegetation (30) and water yield (20). Taking the sediment branch of the Reforestation logic model (B) as an example, a high priority catchment (blue dot) would be one which exhibited large declines in sediment yield under the FF condition compared to the CC, and therefore would have a high potential for sediment reduction given an increase in forest coverage. The green and the red dots are calculated as the 90th and 10th percentile values across all catchments and are used as relativize the calculated reductions in sediment for comparisons across catchments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environmental data into the DST, and to vary the influence of individual factors on the final spatial prioritization based on user feedback. MCDM was used here to evaluate results from the NetWeaver logic model (NWLM – see below) together with other data explained to us as being of relevance to Babeldaob land managers including technical and economic feasibility, efficacy, ecological condition, adjacency to priority natural areas, and logistical considerations. Outputs from these models were combined to produce prioritization maps of decision scores related to the model criteria.

2.7.1. The NetWeaver© logic model

The NWLM was used to evaluate the response of each modeled catchment-level sediment output and groundwater recharge to changes in dominant vegetation by calculating two separate SOE scores for:

i. Reforestation – evaluating the proposition that there was high SOE to support reforestation to reduce sediment and enhance groundwater recharge; and
ii. Protection – evaluating the proposition that there was high SOE to support prevention of forest conversion to grassland-savanna types (Fig. 3).

Estimated sediment and water yield under current vegetation conditions (CC) were compared to yields for fully savanna (FS) and fully forested (FF) scenarios. For each proposition, a ramp function was constructed to evaluate groundwater and sediment yields for CC against those for FS and FF. SOE scores near 1 indicated very high support for the proposed treatment (reforestation or protection), scores near -1 indicated very low support for treatment, and scores near 0 indicated neutral support for either treatment.

Logic networks were constructed to evaluate the main goals of reforestation and protection separately (Fig. 3). Each network combined a ramp function relating: 1) sediment loads; 2) groundwater recharge; and 3) the canopy coverage of savanna (reforestation) and forest (protection) using a union logic operator (U), which treats the factors as additive and compensating. We also used factor weighting. The emphasis of the study on the effect of vegetation on sediment transport to nearshore environments lent itself to a logic structure with a weighted Union operator. In this way, all branches of the logic influenced the final logic score, but more weight was given to the main sediment

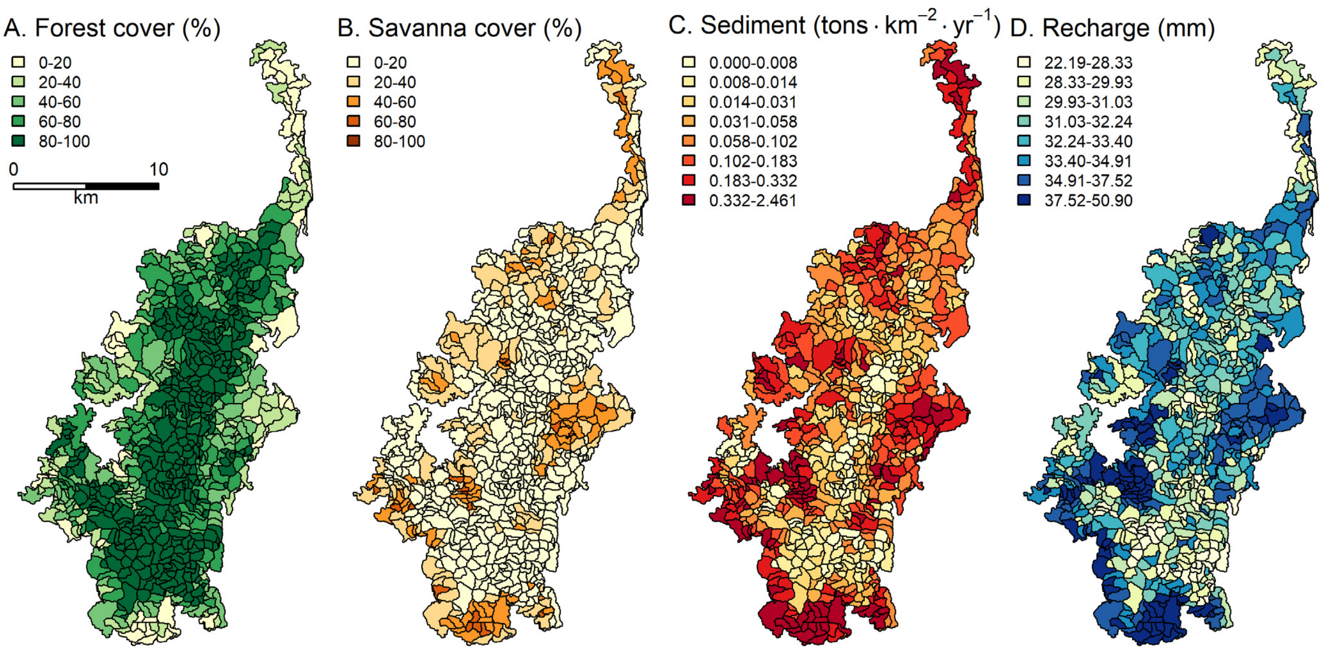

Fig. 4. Maps of current (A) forest coverage and (B) savanna coverage within individual catchments across Babeldaob Island, Republic of Palau. (C) OpenNSPCT-modeled catchment-level sediment load production, and (D) DHSVM-modeled ground water recharge.

delivery process and the vegetation patterns that contribute to sediment delivery.

The sediment yield branch of the logic model utilized a ramp function with break points at the 90th and 10th percentile differences in the CC and FF (Reforestation) and CC and FS scenarios (Protection). Support for the proposition of reforestation occurred when modeled sediment yields under CC was higher than the FF scenario, indicating that restoring forest vegetation would decrease currently high sediment yields (Fig. 3A). Support for protection of upland forest occurred when modeled sediment yield under the FS scenario was much higher than for CC, indicating that loss of forest vegetation would lead to relatively large increases in sediment loads (Fig. 3B).

The second branch of the logic model emphasized groundwater recharge. This branch was also a ramp function with break points at the 90th and 10th percentile differences in the FF and CC (Reforestation) and FS and CC scenarios (Protection). Support for the proposition of reforestation occurred when modeled groundwater under FF was higher than the CC scenario, indicating that restoring forest vegetation would increase currently low groundwater recharge. Support for protection of upland forest occurred when modeled groundwater recharge under the CC scenario was much higher than for FS, indicating that loss of forest vegetation would lead to relatively large decreases in groundwater recharge (Fig. 3).

The final branch of the logic model incorporated vegetation cover. For reforestation, moderate grassland-savanna coverage (20 – 80%) was emphasized under the premise that initial reforestation efforts would be most effective in small savanna patches where recolonization was more likely, and those with interspersed trees or tree clumps throughout. Remnant trees can provide loci from which forest vegetation can expand outwards in the absence of fire (Dendy et al., 2015). For protection, higher forest coverage was emphasized, and breakpoints at 40% and 80% coverage were identified by sediment yield responses to forest coverage (see *4.2 Sediment loads* below).

2.7.2. Multi-criteria decision model (MCDM)

The MCDM incorporated three criteria into the DST: 1) ease of access for management operations (i.e., effort); 2) biodiversity; and 3) the amount of forest-savanna edge. Each criterion was defined with using spatial data layers (see below) and scores standardized between 0 (low priority) and 1 (high) using a linear utility function.

Ease of access was assessed based on the average distance of each 30-m pixel within a catchment to a road, and average slope within a catchment. Relatively flat catchments near a road received higher scores than steep and remote catchments. Linear utility functions were used to scale each metric individually, and scores were averaged together for the final ease of access decision score.

Species biodiversity (richness) was ranked from 1 (low) to 5 (high) based on the vegetation classification in Table 1. High biodiversity rankings were associated with ownerships emphasizing conservation management objectives, whereas low rankings were assigned to urban or highly managed types.

The amount of forest and savanna edge was included in the MCDM because forested catchments with abundant savanna edge have a higher likelihood of being reforested through tree encroachment into open savanna environments, which can be accelerated through planting (Dendy et al., 2015). Such catchments, therefore have a high priority for forest restoration. Conversely, catchments with high forest edge are most susceptible to conversion to grassland-savanna vegetation types with recurrent fires and therefore are a priority for forest protection. Forest/savanna edges were quantified as: 1) the proportion of a unit in a 50-m savanna buffer adjacent to any other vegetation type (Reforestation; median: 0.12, IQR: [0.04, 0.24]); and 2) the proportion of unit in a 50-m forest buffer adjacent to grassland-savanna patches (Protection; median: 0.19, IQR: [0.08, 0.29]).

Within the Criterium DecisionPlus® software, pairwise comparisons were conducted against each criterion to create a complete matrix of weights whose values ranged from 9 (Criteria A is critically more influential than Criteria B) and 1/9 (Criteria B is critically more important than Criteria A) – a value of 1 indicates that Criteria A and B are equally important. We experimented with different MCDM weighting schemes to emphasize each of the four criteria, for example, weighting the ease of access score higher than all other criteria. From these matrices, priority scores were calculated using the analytic hierarchy process (Saaty, 1988), which were used to derive a final decision score for each catchment calculated as a weighted average of all criteria.

3. Results

3.1. Spatial vegetation patterns

Grassland-savanna vegetation exhibited a highly clustered spatial pattern on Babeldaob Island (Fig. 4), and coverage was fairly low overall across affected catchments (median: 12.1%; IQR: [4.3, 27.2]). Only 7% of catchments had > 50% grassland-savanna coverage, most of which occurred in low-lying coastal catchments, often corresponding with populations centers. Upland forest coverage, conversely, was high overall across most of the island, and coverage was highest in the interior of the island. Median forest cover was 78.8% across catchments (IQR: [50.8, 93.6]).

3.2. Sediment loads

OpenNSPECT-estimated sediment loads ranged from 0 to 2.361 tons $\cdot$ $km^{-2} \cdot yr^{-1}$, with the highest concentrations occurring in catchments along the southern coast. Inland catchments generally exhibited low sediment yields, particularly those with high forest coverage (Fig. 4). Sediment yields in the southern state of Airai corresponded with high grassland-savanna coverage and included the town of Airai, the largest city on the island and the Palau International Airport (Figs. 4, 5C). High sediment loads were modeled for the eastern coast of the island in the state of Melekeok, which includes the city of Ngerulmud, the capitol of Palau, as well as Lake Ngerdok, Melekeok's source of drinking water. Both areas correspond with high grassland-savanna coverage (Figs. 4, 5B). To the west, high sediment loads occurred near Ngermeduu Bay (Karamadoo Bay) (Figs. 4, 5D) and corresponded with several larger grassland-savanna patches. To the north, the narrow terminus of the island is characterized by a patchwork of savanna and forest vegetation and was associated with high sediment loads. For the interior of the island, high forest coverage and low population densities corresponded with low grassland-savanna cover and low sediment yields.

Sediment yields were negatively correlated with forest coverage (Fig. 6; Pearson's r = -0.55), with yields decreasing by 0.045 tons $\cdot$ $km^{-2} \cdot yr^{-1}$ with every 10% increase in forest canopy cover. High variability in sediment loads existed for catchments with low forest coverage (< 40%; Fig. 6), suggesting possible additional mechanisms for sediment production within these catchments. Catchments with > 80% coverage generally corresponded with the lowest modeled sediment loads and low uncertainty in estimates.

Sediment yield differences between current and full savanna scenarios were generally much larger than differences between current and fully forested vegetation scenario – an indication of forest condition of Babeldaob Island. Across the island, the median increase in catchment-level sediment when vegetation was converted to full savanna was 0.354 tons $\cdot$ $km^{-2} \cdot yr^{-1}$ (IQR: [0.259, 0.468]). Catchments on the west coast of the island near Ngermeduu Bay incurred the highest increases in sediment yield when converted to savanna vegetation. Large increases in sediment were also observed in interior catchments where upland forest coverage is currently high. Conversely, modeled differences in sediment yield were small overall between the CC and the FF

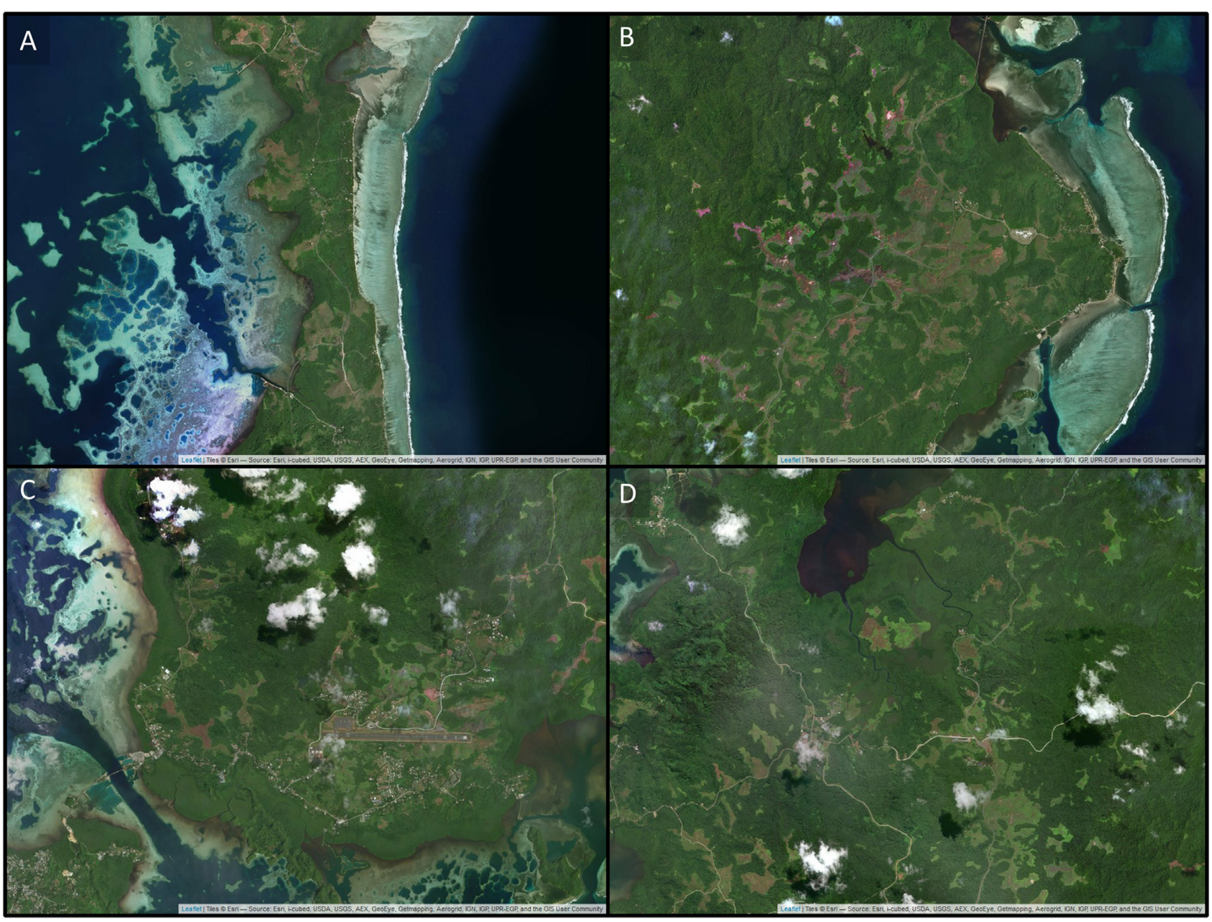

Fig. 5. Aerial photography of Babeldaob Island showing contrasting grassland-savanna (brown) and upland forest habitat (green). A) Northern Ngarchelong and Ngaraard states; B) eastern Melekeok state, featuring the capitol Ngerulmud; C) southern Airai state Palau's population and commercial center, also showing Palau International Airport; and D) western Ngatpang state, also showing Karamado Bay. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

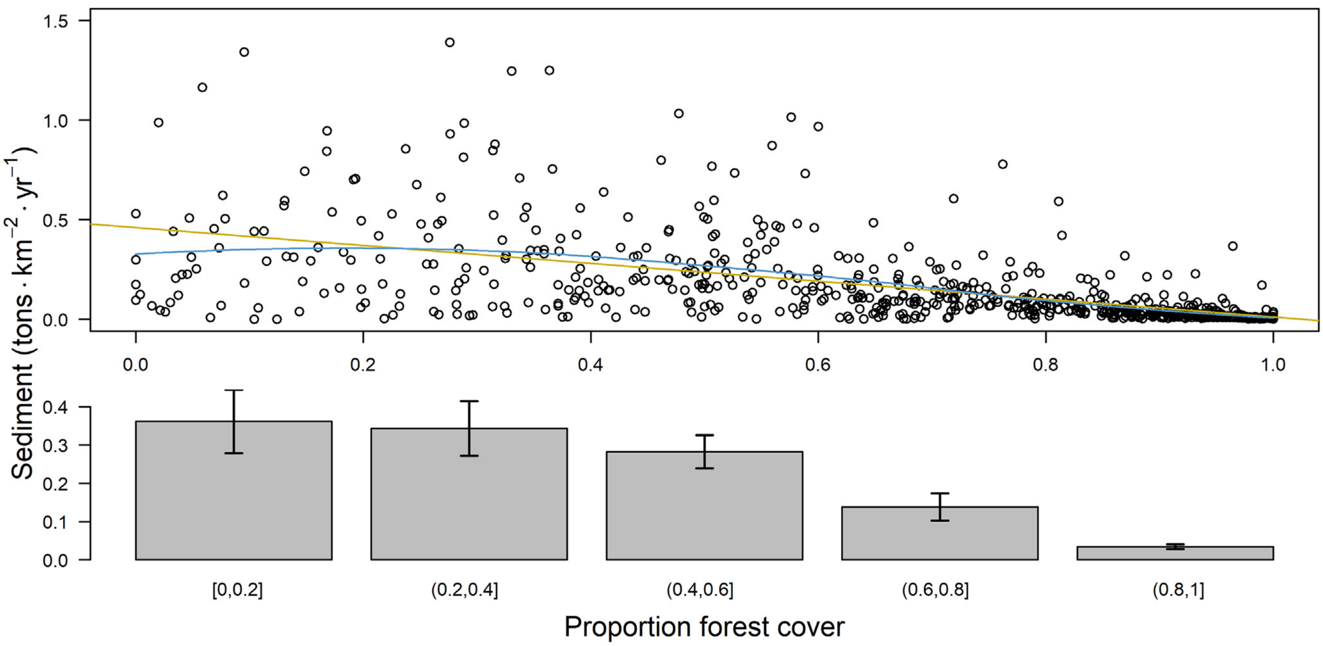

Fig. 6. Relationship between catchment-level forest coverage and sediment yield. Sediment generally declines with expanding forest cover. The yellow line in the top frame is a linear trend line and the blue line is a LOESS trend line. Error bars on barplots indicate standard deviation of sediment yield within each forest coverage class. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scenario, for which the median change in sediment load was 0.050 (IQR: [0.010, 0.161]). Modest changes in sediment yield between these two vegetation conditions likely reflect the high current distribution of forest cover across much of the island (Fig. 4).

3.3. Groundwater recharge depth

Under current vegetation conditions, recharge depths ranged from 22.2 to 50.9-mm across Babeldaob Island. Generally, spatial patterns were similar between groundwater recharge and sediment yields across the island, and these processes exhibited moderate positive correlation ($r = 0.56$). Like sediment yield, groundwater recharge was deepest near the coast, particularly in the south and west.

Relationships between groundwater recharge and forest/savanna coverage were somewhat equivocal. Under current vegetation conditions, groundwater depth increased in catchments with increasing savanna coverage and decreased with increasing forest coverage (Fig. 7), suggesting that additional forest coverage leads to reductions in groundwater depth.

However, when all catchments were converted to upland forest (i.e., fully forested scenario), recharge depth decreased in only 10% of catchments, and on average, catchment-level recharge depths increased by 0.7-m (IQR: [0.3, 1.1]) across the island compared to depths under current vegetation scenario. Similarly, when all catchments were converted to savanna type (i.e., fully savanna), median recharge depths decreased by 3.0-m (IQR: [2.5, 3.5]). Furthermore, the average recharge depth for the fully forested condition across Babeldaob was 33.0-m compared to 29.1 m for the fully savanna condition.

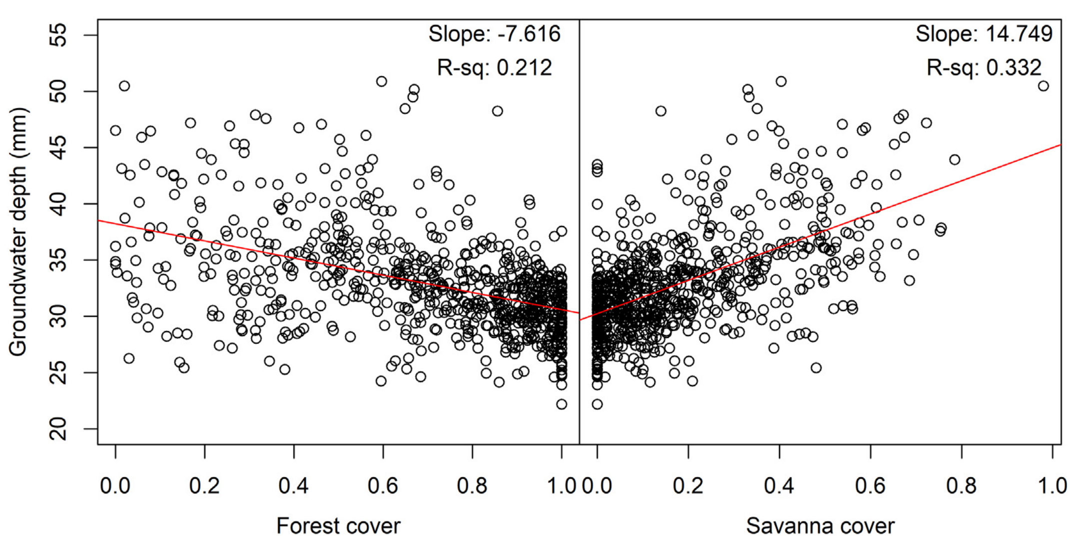

Fig. 7. Relationship between average catchment-level groundwater recharge depth and proportion of forest cover (left-panel) and savanna cover (right-panel). Both linear regressions were significant ($P < 0.0001$).

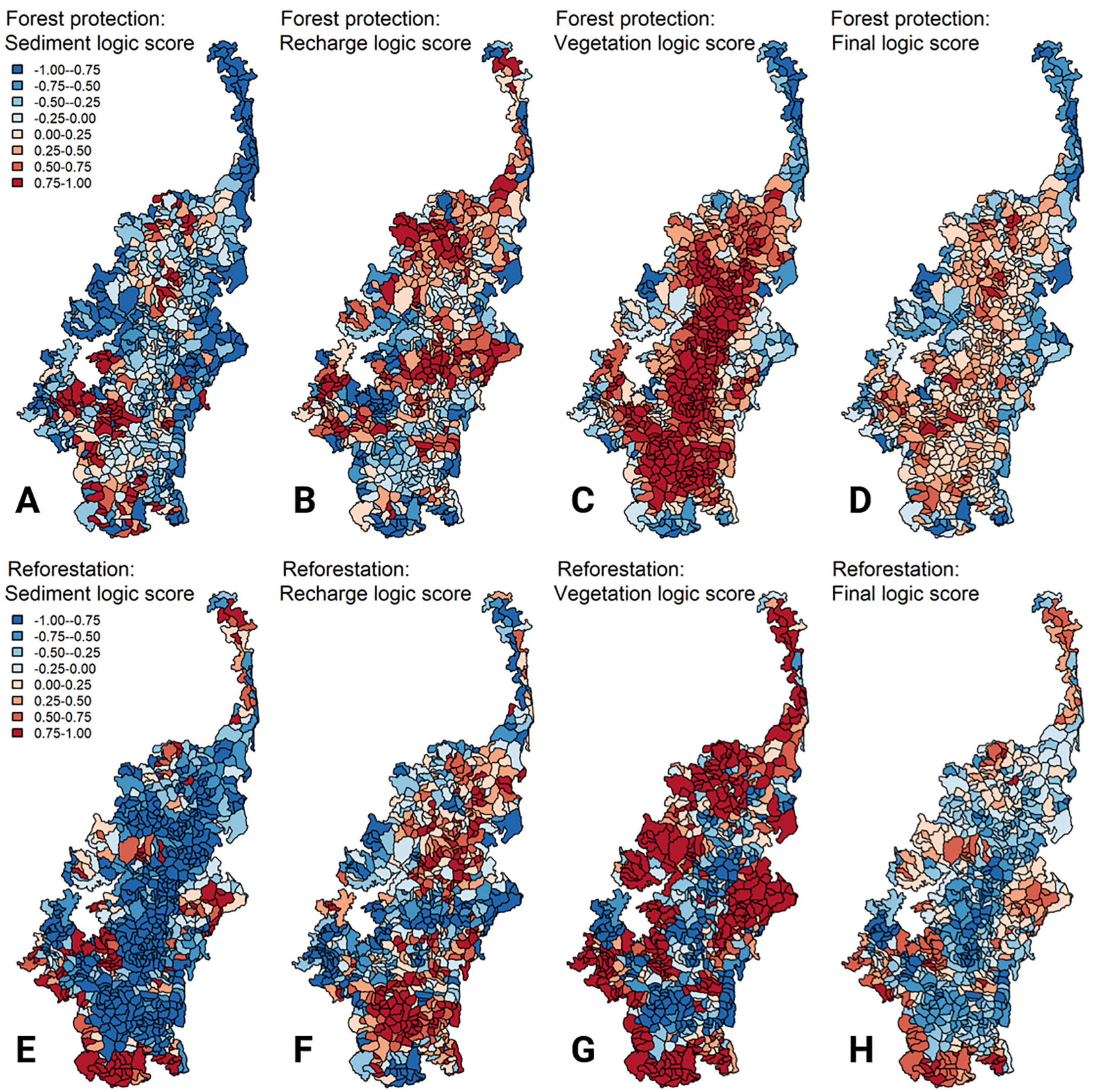

Fig. 8. Catchment-level strength of evidence scores from the EMDS Netweaver Logic Model for reforestation of current grassland-savanna (A-D) and protection of current tropical forest patches (E-H). Dark red colors indicate high support for the proposition for reforestation (top) and protection (bottom), while dark blue colors indicate no support. Maps depict intermediate logic model outputs for sediment (A, E), groundwater recharge (B, F), vegetation (C, G), and the final logic score for each management objective (D, H). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Logic model

3.4.1. Reforestation of grassland-savanna (Reforestation)

Across the study area, 14% of the catchments (17.0% by area) displayed high logic model priority scores (SOE > 0.5) for reforestation (Fig. 8), with 3% of catchments having SOE scores > 0.75. Most high priority reforestation catchments (SOE > 0.75) were located along the coast, particularly in the southern and northern states and Ngermeduu Bay (Fig. 8). Spatial overlap of high priorities across the three logic branches was low overall, which contributed to low incidence of high priority catchments. For example, in the southern state of Airai, catchments along the coast exhibited high priority for vegetation and sediment branches, but SOE scores for groundwater were low (Fig. 8). Conversely, large clusters of high SOE for groundwater were observed in the southern and northern areas of the island that did not correspond to high priority for the other two branches.

Low priority catchments represented 30% of all catchments and were well distributed throughout the island. Many catchments with high priority for the vegetation branch (i.e., high savanna coverage) did not correspond with high priority for sediment, indicating that not all savanna-dominated catchments were high sediment producers.

3.4.2. Protection of upland forest (Protection)

High priority for forest protection was concentrated in the interior of the island (Fig. 8), which supports most of Babeldaob's intact and contiguous forest, with 11% of catchments having SOE scores > 0.5.

Like the reforestation logic, spatial overlap among high priority catchments for the three logic branches was low. The vegetation logic map shows high priority along the interior, corresponding to high forest coverage and low population densities, with over half of the catchments having vegetation SOE scores > 0.5. Logic scores for the sediment branch were low overall (median: -0.288, IQR: [-0.63, 0.13]), and most high priority forest protection catchments were clustered in the southwest portion of the island, again near Ngermeduu Bay (Fig. 8). These results suggest that the drivers of actual (current savanna) or potential (current forest) erosion are being similarly captured by the modeling. High SOE scores for groundwater recharge generally corresponded with moderate to high forest coverage, but the distribution of these catchments was sparse and concentrated in the middle and northwest coast of the island.

3.5. Decision model results

When Decision model scores were calculated with a higher weight given to the Logic model outputs (i.e., emphasizing sediment and groundwater outcomes) this resulted in lower overall scores compared to the Logic model, indicating that high scores for criteria related to biological diversity, savanna-forest edge, and management effort did not correspond with the high SOE scores for either Protection or Reforestation (Fig. 9). When management effort was emphasized, Protection and Reforestation maps yielded similar distributions of decision scores, with high priority catchments restricted to coastal areas given their close proximity to roads and other infrastructure. Overall, decision scores were very low in the central and northwestern portions of the island, indicating that management effort may limit protection and reforestation efforts. Catchments with high decision scores when management effort was emphasized tended to correspond with high reforestation logic scores, indicating that some of the catchments most responsive to reforestation may not be limited by access issues or management costs, as defined in this paper. High decision scores for biodiversity were in the center of the island, corresponding with high SOE scores for Protection and high forest coverage. Finally, when savanna-forest edge criteria were emphasized in the decision model, decision scores for restoration (but not protection) were highest for catchments in the northwest and central portions of the island.

4. Discussion

Pacific Islands contain some of the most biodiverse nearshore and upland ecosystems on the planet and are home to a vast array of endemic species. The remote and isolated nature of these islands results in human populations that rely heavily on nearshore ecosystems to support subsistence lifestyles (Drew et al., 2005; Naylor and Drew, 1998), making them highly vulnerable to global change, especially sea level rise (McGinley et al., 2017; Thaman, 2002). Island ecosystems are influenced by broad-scale changes in global climate (Golbuu et al., 2013) and local changes that connect upland and coastal environments (Fabricius, 2005; McLaughlin et al., 2003). Studies have shown causal linkages between sediment delivery from deforested inland watersheds and increases in mangrove, sea grass, and coral mortality, which often leads to reductions in nearshore ecosystem productivity and diversity (Victor et al., 2006; Golbuu et al., 2011a). This degradation can lead to long-term declines in local shrimp, crab, and fish populations and marine diversity, upon which island community livelihoods depend. In the past few decades, resource managers have accepted that effective management of ridge-to-reef systems requires a deep understanding of the linkages between current land use practices and their potential downstream impacts (Carlson et al., 2019).

We present the results of an island-wide prioritization for Babeldaob Island, Palau, with the main goals of identifying catchments where: 1) reforestation of tropical forest would lead to increased groundwater recharge and reduced sediment yields; and 2) protection of tropical forest would prevent erosion and sedimentation and reduced groundwater recharge conditions. We operated under the premise that conversion of tropical upland forest to grassland-savanna vegetation by conventional burning and mechanical removal practices increases sediment delivery to nearshore environments and can be directly addressed through changes in public policy, advocacy and active reforestation (Golbuu et al., 2011b). This is particularly important in Palau where forest recovery on existing grassland-savanna habitats takes many decades (Dendy et al., 2015). We combined spatial data quantifying vegetation, soils, and climate as inputs to a series of process-based landscape models to estimate groundwater recharge and sediment yields for individual catchments across the island. The use of landscape models allowed for an island-wide assessment of sediment loads resulting from changes in land cover alone. Results were then incorporated into a decision support tool, which provides a science-based communication device to support local, state and national leaders in their efforts to assess the current state of ecosystems across Babeldaob Island and identify potential opportunities and limitations to successful management. This process included a number of in person exchanges to identify criteria used for decisions making, in addition to the modeled hydrological and sediment factors captured here. This work represents an initial step in what continues to be an iterative and adaptive DST development process, and illustrates the potential for applying spatial DST to ridge-to-reef conservation in the Pacific.

To make the DST broadly accessible to a diversity of end users, we developed a web application available at https://northcoast.shinyapps.io/PalauDST/. The application allows access to the spatial data and logic model prioritization maps through an intuitive and well-described user interface with the goal of supporting users in their interaction with the MCDM model. This on-line version of the tool and user interface allows users to change the decision criteria weightings and view resulting changes in the spatial prioritization. While the user cannot engage in the underlying hydrological modeling, the intent of the tool was to use information on somewhat fixed sediment source hotspots, potential and real, and to devise landscape scale management solutions that integrate factors that managers use in daily decision making, which can be weighted differently depending on fluctuations in funding, staffing, agency or organizational priorities, national directives, and trends for the availability of fresh water.

4.1. Sediment yield across Babeldaob

Sediment yield was unevenly distribution across the island and several hotspots were identified in catchments associated with high grassland-savanna cover and coastal population centers. Estimates of sediment loads under current vegetation conditions ranged from 0 to 2.36 tons $\cdot$ km^{-2} $\cdot$ yr^{-1}. We found a non-linear relationship between forest coverage and catchment-level sediment yield, where yield declined sharply, and variability was minimal for catchments with $>$ 80% forest cover. Below this threshold, average yields and variability in yields among catchments was high. Observational evidence of catchments with low upland forest cover suggested that sediment yields were generally lower when grassland-savanna patches were smaller and well dispersed, or where other vegetation types were dominant (e.g., agroforest, mangrove). Furthermore, high variability in sediment yields (Fig. 6) in catchments with low forest cover and high grassland-savanna cover suggest that not all catchments with high grassland-savanna cover are susceptible to high sediment yields, and may indicate that vegetation cover may be less important to sediment production in some catchments, compared to other factors like soils, geology, and topography.

The correspondence of high sediment, high grassland-savanna cover, and high population densities indicates that land clearing for agriculture, hunting, or other land use activity including development are central drivers of erosion and sedimentation, with proximity of these catchments to nearshore environments accentuating impacts on

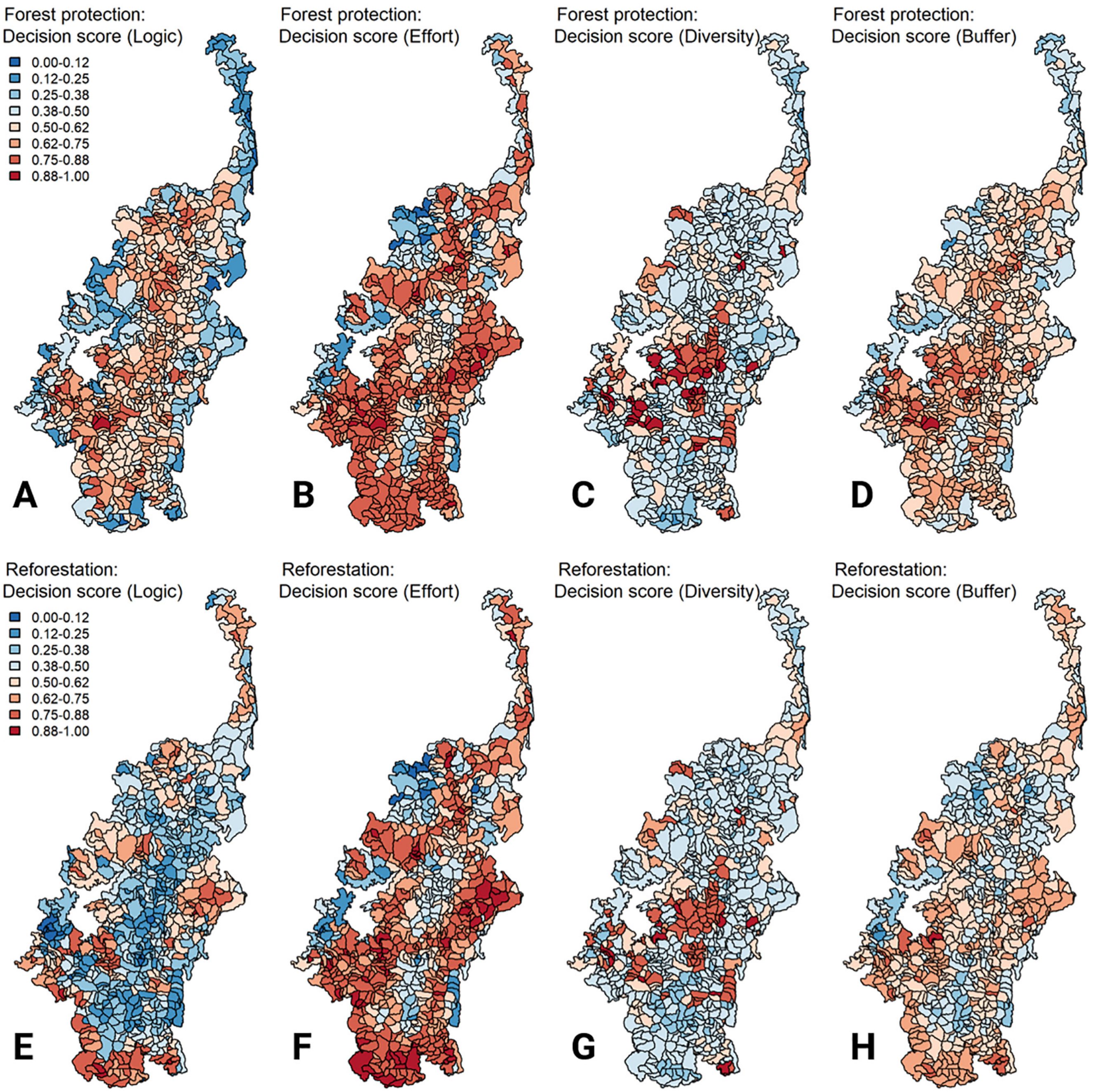

Fig. 9. Catchment-level decision scores from the Multi-Criteria Decision Model within EMDS for reforestation of current grassland-savanna (top row) and protection of current tropical forest patches (bottom row). Management prioritizations were compared across various model weighting schemes that emphasized either the Logic Model score from Netweaver (A, E), management effort (B, F), biodiversity score (C, G), or grassland-savanna and forest edge (D, H). Dark red colors indicate high priority for management, while dark blue colors indicate low priority. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

near-shore coral reef areas. Human caused fires on the island generally follow the same trends in other parts of the world, including Hawaii, where ignition frequency increases by major population centers and roads (Bowman et al., 2011; Krawchuk et al., 2009; Syphard et al., 2007). Fires ignited in the wildland-urban interface are of particularly ecological concern given the proximity of this interface to coastlines. These fires may become more prevalent as climate change leads to increased temperatures and extended periods of drought (Keener et al. 2012).

Our models likely underestimated sediment loads given that the erosional impacts of urban construction, road building and road surfaces were not captured in our modeling. Golbuu et al. (2011b) examined erosion across Babeldaob Island to identify the effect of varying levels of land development on sediment delivery to nearby coral reefs, and found that while variability in sediment yields across watersheds was high (9.7 – 462.4 tons $\cdot$ km^{-2} $\cdot$ yr^{-1}), yields increased with increasing development. Estimates from their study were an order of magnitude or more than modeled estimates from our study. High sediment yields in their study were driven by road construction, and a positive relationship was identified between the number of earth-moving permits and sediment yield. Similarly, Messina and Biggs (2016) observed a nearly 4-fold increase within human-impacted portions of Faga'alu Bay in American Samoa compared with undisturbed portions of the bay. Sediment in that study originated from a rock quarry and a small urbanizing village near the mouth of the watershed. Given that the focus of our study was on quantifying the direct impacts of land cover type changes between tropical forest and grassland-savanna types and given the possibility of this signal being masked by sediment produced by road and urban construction, we eliminated these latter sediment sources from our analysis. However, in doing so, caution should be taken when comparing our estimated loads with other studies.

4.2. Groundwater recharge

Securing a sustainable freshwater supply is a major concern for island nations across the globe, particularly for isolated Pacific Island nations undergoing changes in precipitation and increasing pressures on local water supply systems with expanding populations (Frazier et al., 2019). Access to freshwater in Palau is generally not a concern given their relatively low population and generally high annual precipitation, however, during severe droughts, Palau has experienced severe water deficits requiring country wide rationing. For example, El Niño events in the Western Pacific result in strong droughts in Palau, the most recent revealing that current infrastructure was inadequate for maintaining an adequate freshwater supply to residents (Besebes, 2018). For example, in March 2016, monthly rainfall fell below the minimum required to meet municipal water needs in Koror, Palau's commercial center. These drought events can also compromise water supplies for agriculture, wildfire prevention, and other public uses (Keener et al., 2012). As climate change progresses, such incidents may become more frequent (Frazier et al., 2019). Identifying ways to enhance water supplies will be critical to building socio-ecological resiliency in Palau. Understanding the landscape scale consequences of fire and forest management, with know and modeled impacts on water balance, is a critical piece of building this resilience.

At the island level, we found that groundwater depths were deeper for the fully forested (FF) versus fully savanna (FS) scenarios, indicating that larger area under forest cover across Babeldaob could lead to overall increases in groundwater recharge. However, at the level of the catchment, the relationship between forest cover and freshwater retention varied with local site conditions, with some evidence that catchment-level groundwater recharge depth increased with increasing grassland-savanna coverage – complicating efforts to predict groundwater responses to reforestation. However, island-wide, the deepest groundwater recharge depths on average were found for the fully forested scenario (33.6 mm), followed by the current vegetation (32.9 mm), and then the fully grassland-savanna scenario (29.9 mm). A possible explanation for this trend is that reforesting upland, interior catchments in the fully forested scenario reduces runoff otherwise caused by grassland-savanna types in the other two scenarios and increases diffuse recharge from precipitation in those and other downstream catchments. These gains are somewhat counteracted by uptake from intact forest through high rates of evapotranspiration. Groundwater recharge is only one piece of the greater hydrologic cycle for the island and a more comprehensive study of these dynamics is warranted to help make predictions on the interactions between vegetation and climate in the future.

4.3. Hydrology and sediment model limitations

A lack of sediment data from stream gauges on Babeldaob prevented us from calibrating the sediment model, and thus sediment estimates presented here are uncertain and should be noted only for their relative differences. Furthermore, estimated sediment yields did not include the influences of roads, road construction and urban development, because reliable data did not exist to adequately represent these processes in our models. While major sources of terrigenous sediment in Palau can include road construction, urban development and land clearing (Golbuu et al., 2011b), excluding these sources allowed us to more robustly examine and isolate the role of reforestation and forest protection on sediment delivery to streams and near shore areas.

The OpenNSPECT model does not account for landslides or mass wasting events, which can be large contributors to total sediment yields. Furthermore, we present mean sediment yields for a 20 + year period. Subsequent analyses could incorporate pulse events that contribute large quantities of sediment to streams and coral environments during a single event or a particularly wet year. While the OpenNSPECT model used here likely underestimated real sediment yields, the model does not include redeposition or instream dynamics; without this time stepping, sediment delivery to near shore areas represent worst-case scenarios. For example, sediment can be deposited higher up in a watershed, and our modeling does not include budget calculations that capture these gains and losses (Walling and Collins, 2008).

Our sediment modeling also did not assess the fate of sediment delivered to nearshore environments. Sediment deposition on mangroves, seagrass beds, and coral reefs is a function of sediment input amount from inland watersheds, but also ocean currents and the size and shape of shoreline features (Fabricius, 2005; Golbuu et al., 2011b; Messina and Biggs, 2016; Storlazzi et al., 2009). Coastal vegetation such as mangrove forests can also reduce the amount of sediments that reach other nearshore ecosystems, though this varies with forest structure and condition, above ground root type, and suspended sediment loads (Carlson et al., 2019; Golbuu et al., 2003; Krauss et al., 2003), and this driver of coral health needs to be incorporated into future modeling (Victor et al., 2004). To understand the impact of sediments on near shore environments, terrestrial modeling efforts such as ours will need to be coupled to marine focused process models.

The vegetation layer used to characterize current vegetation cover types was derived from aerial photography taken > 30 years prior to this study and therefore may not represent vegetation conditions during the study. At the time of this study, this was the most detailed description of vegetation cover for Babeldaob Island. As mentioned, more recent satellite imagery was used to assess temporal differences in vegetation, and we found reasonable coherence between grassland-savanna and forest extent among the layers. We attribute this to the fact that most human ignited fires occur within grassland-savanna patches (i.e., reburns) and the slow natural encroachment of forest into grassland-savanna types. However, given the linkages between inland vegetation and nearshore habitats, there is a clear need for future work to develop updated vegetation maps. Access to high resolution and timely ecological data is a hindrance across many areas of the world, and a major goal of applied research is to develop science-based inferences from limited data sources, while assessing how filling key data gaps can improve future iterations of the research.

4.4. Decision support modeling

The DST developed here is an example of an adaptable, scalable, and data-driven decision making framework that can be applied to a variety of environmental issues (Reynolds and Hessburg, 2014). Most example applications come from the conterminous US and include prioritizing Regional and National Forest reforestation treatments in the USA to reduce fire hazard (Reynolds and Hessburg, 2005; Hessburg et al., 2004, 2013), assessing stream degradation in headwater streams due to atmospheric sulfur deposition from coal-fired power plants (Reynolds et al., 2012), or mapping conservation values for forest planning (Hessburg et al., 2007; Reynolds et al., 2000). More recently, a DST was developed for the windward coast of Hawaii Island aimed at prioritizing catchments for invasive species removal to increase freshwater production (Povak et al., 2017, https://www.fs.fed.us/psw/tools/watershedexplorer/). The Hawaii work also integrated DHSVM hydrology modeling with several plant invasion and climate change scenarios. While hydrology modeling helped identify opportunities to sustain increases in freshwater under climate change, the DST prioritization in Hawaii was most influenced by access limitations in rural areas where road and trail networks were lacking, requiring long travel times which increased costs per unit area treated and so reduced efficiency of management investments. These catchments often also corresponded with areas of highest freshwater production, highest levels of invasion, but because of access and costs, were not consistently assigned highest management priority.

Similarly, results from the Palau DST presented here show the importance of effectively integrating the various drivers of decision making into resource planning. Overall, the catchments with highest reforestation scores corresponded with coastal catchments near population centers with moderate grassland-savanna coverage and high sediment loads that could be mitigated by reforestation (Fig. 8). Conversely, high logic model scores for upland forest protection were located towards the rural center of the island with high forest coverage and where conversion to grassland-savanna vegetation would lead to high sediment yields and a reduction in groundwater recharge depths (Fig. 8). Ngermeduu Bay on the southwestern coast of the island was identified as a high priority reforestation area by our logic model. This area is characterized by a high concentration of grassland-savanna vegetation, farms, and unpaved roads (Golbuu et al., 2011b). Ngermeduu Bay itself houses a high level of marine biodiversity and coral reef communities near its mouth, and thus is an important area of conservation concern. Golbuu et al. (2011b) looked at a much broader contributing area to Ngermeduu Bay (86 km^2), and within this area our logic model identified four key catchments (~100 ha) near the main contributing rivers flowing into Ngermeduu Bay as high priority (SOE > 0.5) for reforestation. High priority catchments on the southern and eastern coasts of the island corresponded with the states of Airai and Melekeok, respectively. The former is the island's population center, while the latter houses the capital city as well as a RAMSAR site (a wetland site of international importance under the Ramsar Convention; Gardner and Davidson, 2011) that is the main source of drinking water for Melekeok. Land conversions from tropical forest to grassland-savanna and other agricultural types increased in the early 20th century under Japanese occupation, which saw a switch from subsistence agriculture to large-scale plantations. Following this era, abandonment of these plantations following World War II led to an increase in forest cover by ~ 8% in the 30 years after the war but has remained stable since the mid-1970s (Iida, 2012). This suggests that non-forest patches near population centers have likely persisted for some time and conversions back to forest, where warranted, will require both ecological solutions to facilitate forest recovery and social solutions to address intentional reburning.

The DST presented here does not include tactical planning strategies to suggest specific management practices (e.g., site preparation, planting, weeding) for candidate catchments. Forest patches in degraded areas recover slowly; even inside protected areas without fire (Dendy et al, 2015). Periodic fertilizer applications to patch interiors, with or without native seedling plantings, have been shown to increase the rate of forest recolonization while preventing nutrient runoff from treatments (Dendy et al., 2015). Fertilization also can increase tree flowering and fruit production, which increases seed rain and enhances visitation from pollinators and dispersers. Finally, growth of forested patches within savannas is enhanced by active planting at patch boundaries.

Critically, restoration actions will not be effective if burning is not managed. Altering the timing or location of burning and especially preventing accidental or arson fires will require increased cooperation by residents with local, state, and national agency and organization leadership. This is being achieved by expanded outreach to private landowners resulting in increased public awareness of the impacts of unwanted fire. This awareness is also being achieved by non-governmental organizations, such as the Ebiil Society (www.ebiilsociety.org/), which is leading community-based inreach focused on fire awareness and prevention education and post-fire biocultural restoration. Providing educators and outreach specialists with concrete information about the downstream effects of continued land clearing on highly valued coral reef areas will enhance the specificity of outreach materials and help leaders target fire prevention actions to the highest priority areas. In Saipan, major sediment contributions originated from a small handful of land parcels, and successful reforestation of degraded forest and road improvements were driven by multi-agency efforts to target these land owners (Montambault et al., 2015; SeaWeb, 2014). In Palau, local government support for conservation efforts drove the recovery of the remote Helen Reef following a massive coral bleaching event combined with overharvesting and illegal fishing. Successful conservation management here resulted from long-term monitoring, data-driven policy shifts and law enforcement actions to foster the recovery of the reef.

Top-down governmental efforts have also led to major policy changes in Palau. For instance, the Palauan government has placed bans on commercial fishing and "reef-toxic" sunscreens for the benefit of marine health and ecotourism. From these experiences, government and community support can effectively align with priorities to overcome challenges to conservation efforts in Palau. Successful environmental management in Palau has resulted from effective ecological monitoring engagement of ecological data, reliance on best available science, local community support and government leadership, and adaptive policy decision making that responds to the needs of the citizens of Palau as well as the ecology of the island. This tool seeks to provide a similar data portal and nexus for effective and aligned decision making and implementation in the realm of fire prevention, forest protection and forest restoration.

The DST presented here represents a mechanism to apply adaptive management to address economic and ecological impacts of certain land use practices on coral reef health. This model provides a transparent and data driven process to assist stakeholders in assessing the current state of the ecosystem, and in identifying opportunities and barriers to management through an iterative and adaptive dialogue. The model presented here represents a first approximation of a DST; future advancements to the DST include: 1) updating spatial vegetation data to better inform the hydrology models; 2) systematic monitoring of sediment yields within streams across the island to better calibrate the sediment model; and 3) meetings with local community members, stakeholders, policy makers, government officials, scientists and professionals to identify opportunities and limitations to management on the island, and interactively build upon the logic and decision models to best reflect the needs of Palau.

CRediT authorship contribution statement

Nicholas A. Povak: Conceptualization, Methodology, Software, Formal analysis, Visualization, Supervision, Writing - original draft, Writing - review & editing. **Christian P. Giardina:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing. **Paul F. Hessburg:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing. **Keith M. Reynolds:** Conceptualization, Methodology, Supervision. **R. Brion Salter:** Methodology, Visualization. **Chris Heider:** Methodology, Formal analysis, Writing - original draft. **Ed Salminen:** Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. **Richard MacKenzie:** Conceptualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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