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Research article

Upstream solutions to coral reef conservation: The payoffs of smart and cooperative decision-making

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ABSTRACT

Land-based source pollutants (LBSP) actively threaten coral reef ecosystems globally. To achieve the greatest conservation outcome at the lowest cost, managers could benefit from appropriate tools that evaluate the benefits (in terms of LBSP reduction) and costs of implementing alternative land management strategies. Here we use a spatially explicit predictive model (InVEST-SDR) that quantifies change in sediment reaching the coast for evaluating the costs and benefits of alternative threat-abatement scenarios. We specifically use the model to examine trade-offs among possible agricultural road repair management actions (water bars to divert runoff and gravel to protect the road surface) across the landscape in West Maui, Hawaii, USA. We investigated changes in sediment delivery to coasts and costs incurred from management decision-making that is (1) cooperative or independent among landowners, and focused on (2) minimizing costs, reducing sediment, or both. The results illuminate which management scenarios most effectively minimize sediment while also minimizing the cost of mitigation efforts. We find targeting specific "hotspots" within all individual parcels is more cost-effective than targeting all road segments. The best outcomes are achieved when landowners cooperate and target cost-effective road repairs, however, a cooperative strategy can be counter-productive in some instances when cost-effectiveness is ignored. Simple models, such as the one developed here, have the potential to help managers make better choices about how to use limited resources.

1. Introduction

Coral reefs around the world are under threat by land-based source pollutants (LBSP) (Burke et al., 2011; Fabricius, 2005; Halpern et al., 2008). Human activities on land have significantly increased concentrations of sediment, nitrogen, phosphorus, organic pollutants, heavy metals, and pathogens in coastal environments, causing major disruptions in reef ecological processes (Dachs and Méjanelle, 2010; Fabricius, 2005; Foley et al., 2005; McClanahan and Obura, 1997; Syvitski et al., 2005). Degradation of coastal ecosystems undermines the production of ecosystem goods and services critical to the food security and livelihoods of billions of people worldwide (Moberg and Folke, 1999; United Nations Environment Programme, 2006).

Land use and management practices can directly affect the export of sediments and nutrients to reefs (Correll et al., 1992; McCulloch et al., 2003; Messina and Biggs, 2016; Young et al., 1996). Land managers can mitigate LBSP in a variety of ways, from restoring ecological processes that regulate runoff and erosion (e.g., revegetating to hold soil on the landscape and enhance infiltration), to modifying ecohydrological systems to retain sediment (e.g., riparian buffers, instream wetlands. or rain gardens) (Gumiere et al., 2011), to directly managing fluxes via structural engineering (e.g., sediment retention reservoirs, channel armoring) (Daniels

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and Gilliam, 1996; Zeimen et al., 2006), to improving drainage design to slow down sediment production from roads (Ramos-Scharrón, 2012), to protecting eroding surfaces with pavement or gravel (Ziegler and Sutherland, 2006).

This variety of strategies for mitigating LBSP provides options for managers and impels thoughtful decision-making about the costs and benefits of alternative approaches. Additionally, because watersheds are often a mosaic of landownership, landscape-scale decision-making must also consider the costs of cooperative versus independent management actions relative to their effectiveness in reducing LBSP. Quantitatively comparing alternative mitigation strategies in terms of efficacy, overall cost, and costs to individual stakeholders can inform debate and provide a suite of effective options that maximize ecological value and/or minimize management cost. Furthermore, this information can provide a politically neutral approach to identifying the landowners who are most critical to engage in order to reach mitigation targets, thus helping managers tune their outreach and coordination efforts. This complex challenge can be informed by trade-off analysis, a formal decision analysis tool that accounts for multiple objectives (e.g., minimize cost, maximize impact) in evaluating the efficacy of alternative management strategies for achieving a policy goal (for a detailed discussion of tradeoff analysis see (Lester et al., 2013)). Numerous models exist to predict the physical impacts of alternative land management or LBSP mitigation practices (Merritt et al., 2003), and coupling of trade-off analysis to these models can be insightful.

Using a case study of mitigating sedimentation on reefs by abating erosion from agricultural dirt roads, we demonstrate the benefits of quantitative trade-off analyses to aid management decision-making. Erosion from dirt roads is a concern in many coastal areas because roads act as both an active source of sediment, a runoff amplifier, and a rapid conduit towards the ocean (Nagle et al., 1999; Ramos Scharrón and MacDonald, 2005; Sidle et al., 2004; Ziegler and Giambelluca, 1997). In many tropical mountainous environments, erosion from unpaved roads can be disproportionately high compared with other sources of sediment, and even low density road networks can increase runoff response, degrading nearby streams and receiving water bodies (Ramos Scharrón and LaFevor, 2016; Ziegler et al., 2004). We focus our analysis on watersheds along the western slope of Maui Island, Hawai'i, USA, and evaluate the cost and efficacy of reducing LBSP from alternative dirt road repair plans. Watershed characterizations identified poorly maintained agricultural roads as a key potential source of sediment (Group 70 International, 2015; Sustainable Resources Group International, 2012a). Recent fieldwork confirmed significant gullying on the roads that run perpendicular to the coast, and that many of the agricultural roads, including their former sediment mitigation measures, have fallen into disrepair (Fig. 1).

The overall policy objective in these watersheds is to achieve comprehensive reduction of sediment runoff from the landscape at minimal cost. However, in practice, the management objective can vary between cost effective (i.e., most sediment reduction per dollar spent) and solely cost-based (i.e., lowest cost per road segment) road repair. We use trade-off analysis to assess the efficacy of these alternative management objectives, under an individual or collective action, for achieving the overall policy objective. Roads are a useful study system; they vary both in their current contribution to sediment and in the costs required to mitigate erosion. They are therefore an illustrative example of a wide array of geographically dispersed landscape features whose management can be improved through decision analysis.

Fig. 1. Evidence of gullying in former agricultural roads, West Maui, Hawai'i.

2. Methods

2.1. Study site

The West Maui region in the Hawaiian Islands (20.93° N, 156.68° W) includes five watersheds designated by the U.S. National Oceanic and Atmospheric Administration (NOAA) as priority watersheds, encompassing a total area of 97 km^2 (Fig. 2). There are four state-designated land use zones – urban, agriculture, rural, and conservation – which exist along steep spatial gradients of elevation (0–1764 m), rainfall (406–9296 mm/yr) and soil orders (Mollisols to Oxisols) from the coast to the summit (Cheng, 2014). Rainfall also increases from south to north, from the Wahikuli watershed to Honolua watershed. Topographically, drainage density increases and watersheds narrow along this same gradient. According to the United States Geological Survey (USGS) National Hydrography Dataset, of the 19 streams in West Maui, only one is perennial (Honokahua) all the way to the coast, two are perennial in their upper reaches (Honolua and Kapaloa), while the rest are intermittent or ephemeral. Offshore of the study area is approximately 9 km^2 (or 900 ha) of hardbottom reef habitat, and a little over 0.5 km^2 (or 53 ha) of it is coral dominated, predominantly *Porites*, *Montipora*, and *Pocillopora* spp.. The northern reefs declined from 30% coral cover to 10% between 2000 and 2015, while areas in the south have remained relatively steady during the same period, with coral coverage between 20 and 40% (Sparks et al., 2015). The declines have been blamed on heavy, periodic sedimentation events (Sparks et al., 2015), although a recent scientific report highlighted the role of lighter, more frequent rain events in causing sediment plumes (Stock et al., 2016).

The West Maui Ridge to Reef (WMR2R) consortium is a group formed to protect one of the most vulnerable and economically valuable coral reefs in the United States (The State of Hawaii, 2010). The reef is threatened by land-based source pollutants (LBSP),

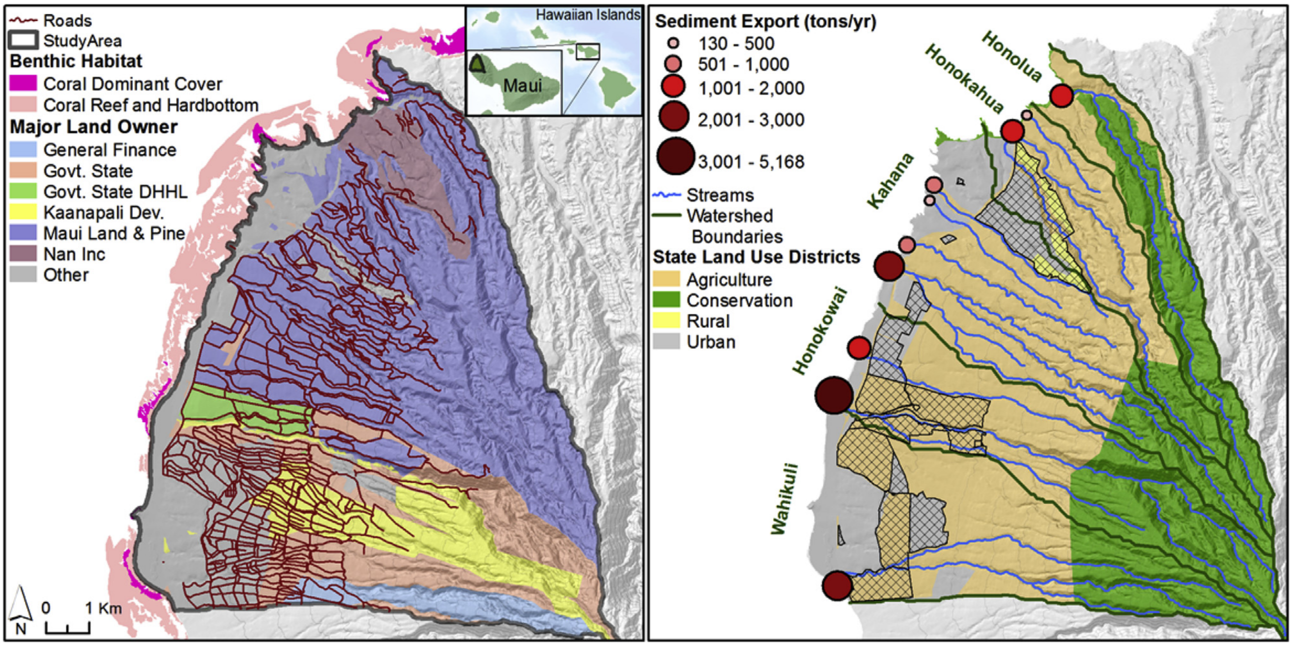

Fig. 2. Study site. A. Study site including the location of agricultural roads, benthic habitat, large landowners. B. Major streams connecting watershed to coast, with baseline (i.e., total) sediment export at coastal pour points, land use zones, and (in black hash) areas slated for development according to the Maui County Department of Planning, May 2016 (Maui County, 2016).

including sediments and nutrients (Group 70 International, 2015; Sustainable Resources Group International, 2012b). In the watersheds above the West Maui coral reef, changing land use from sugarcane and pineapple production (in years 1840–2009) to a tourism-based economy and planned development of over 6000 new homes has the potential to exacerbate sediment export problems. What was once active agricultural land today lies mostly fallow, and most former agricultural roads (~360 km total) have fallen into disrepair, although some are still used for occasional access, e.g., upper watershed management and fire suppression. Six main landowners, including the State of Hawaii, manage these former agricultural lands. Conservation lands in the upper reaches of the watersheds preserve some of the last remaining native forests in the islands, and are managed by a watershed partnership.

2.2. Input layers

To estimate the contribution of sediments from eroding agricultural roads, we first created a fine resolution (2.4 m) land use map that differentiated between agricultural and urban roads. The map was based on NOAA's C-CAP (Coastal Change Analysis Program) 2.4 m land use map from 2005 (https://coast.noaa.gov/ccapatlas/). Agricultural roads were merged from two sources, the State of Hawai'i Office of Planning, and bare land areas detected using WorldView-2 imagery (0.46 m resolution). Polygons of bare land were visually classified from WorldView-2 data and used as a training class for a supervised classification using Maximum Likelihood classification in the ArcGIS 10.3 Image Classification toolset. Bare agricultural roads were then identified, digitized to polylines by hand, verified using the original imagery, and rasterized at 2.4 m resolution for incorporation into the land use map. We manually adjusted the roads using surveys for Wahikuli, Honokōwai, and Honolua watersheds that estimated the hydrologic connectivity to the stream network of road-derived sediments (Stock et al., 2016). A 10 m digital elevation model was downloaded from University of Hawai'i Coastal Geology Group (http://www.soest.hawaii.edu/coasts/data/hawaii/dem.html). Table SI-1 catalogs all model input layers.

2.3. Management units and road segments

We created spatial management units for analysis based on the intersection of hydrologic units, major landowner property boundaries, and state land use districts. We used a threshold flow accumulation of 3000 cells (where cells are defined by the DEM) in ArcHydro to define the size of hydrologic units. Land ownership boundaries came from publically available state tax maps, maps from the watershed management plans, and updates based on interviews. Intersecting management units and roads resulted in 157 road segments, which were each considered individually for potential repair in the analysis.

2.4. Sediment loads

Guided by Fu et al.'s (2010) review of road erosion models and similar to Ramos-Scharrón and MacDonald (2007), we modeled sediment export from unpaved roads using a sediment delivery model approach, drawing on the Natural Capital Project's InVEST toolkit (InVEST SDR version 3.2) (Hamel et al., 2015; Tallis and Polasky, 2009). Operating at the resolution of the digital elevation model input, the InVEST sediment delivery model quantifies sediment yield by coupling the revised universal soil loss equation (RUSLE), which estimates sediment eroded, with a sediment delivery ratio (SDR) to estimate the proportion of sediment eroded on a given area that will travel to the stream (Hamel et al., 2015).

RUSLE is a rough approximation for estimating soil loss from roads, yet it provides a simple framework for estimating erosion rates, and has been modified in other cases to apply to roads (Fu et al., 2010). It estimates erosion based on a handful of empirical variables: rainfall erosivity, surface material erodibility, slope, area, cover, and management; traffic, maintenance, and potentially surface characteristics may be handled by adjusting the latter two, although RUSLE likely poorly estimates some processes of road erosion (Fu et al., 2010). A number of alternative empirical models for road erosion exist (as reviewed in (Fu et al., 2010)), however, with the available data, we calibrated RUSLE's annual soil loss to field-assessed lowering rates (Stock et al., 2016), a fine resolution land use map that designated roads, assuming that each was equal width. Table SI-2 enumerates all input parameters.

To assess delivery, the model calculates SDR for each pixel, as explained in Hamel et al. (2015). The SDR reflects landscape connectivity, or internal linkages between runoff, sediment sources, and sinks, by modeling hydrological connectivity. Each pixel's hydrological connectivity is assessed, based on characteristics of the upslope area (i.e., cover factor, area, and slope, which affect the contribution of the upslope area) and the flow path to the stream (i.e., length, cover factor, slope, which affect the sink capacity of the downslope area). The SDR for a given pixel is then a function of this pixel-specific hydrological connectivity, a theoretical maximum SDR (set at 0.8 per (Hamel et al., 2015)), and calibration factors that set the relationship between SDR and hydrological connectivity (Borselli et al., 2008). This method accounts for hydrological connectivity of the distance and conditions between the roads' drainage points and the streams (Croke et al., 2005).

To calculate the baseline erosion from the entire watershed, we used InVEST SDR, the land cover maps, annual rainfall data from the Hawaii Rainfall Atlas (Giambelluca et al., 2012), and a parameter table reflecting land covers in Maui (Table SI-2). To set the connectivity of the hydrological network, we modeled the stream network in InVEST using a stream accumulation parameter of 2,000, which we set based on visual assessments of the stream network and concurrence between the generated stream layer and Hawai'i Department of Aquatic Resources' stream dataset (http://planning.hawaii.gov/gis/download-gis-data/). USDA-NRCS C-factor values were adopted for each of the land use classes. Fallow agricultural land (dry grassland) and grassland (grassland) were assigned 0.12 per the work of Lianes et al. (2009) whose research in Costa Rica matched West Maui conditions. Further justification for the specific parameterization is detailed in Falinski (2016); as no calibration data were available for West Maui, parameters were chosen based on literature and data from other Hawaiian watersheds.

Following Sheridan et al. (2006), to simulate repair of agricultural roads, we adjusted the cover management (C) factor within the RUSLE equation, which captures the effect of land use and management (Dissmeyer and Foster, 1981). While tuning the C-factor to approximate road maintenance has been suggested as a possible, though inexact, approach (Fu et al., 2010), the lack of published studies led us to select best approximations, based on our best judgment. Specifically, we modeled current road segments either as repaired (minimizing sediment loss through drainage modifications, i.e., water bars and in some reaches gravel) – designated by a C-factor of 0.03 (which corresponds to C-factors used for high density urban zones or impervious surfaces), or as unimproved (lacking drainage modifications to reduce sediment, i.e., bare surface) – with a C-factor of 0.8 (a value typical of bare, exposed land). The 0.8 C-factor value reflected the fact that most roads in our area are bare, exposed soil, where gullying is evident. A 0.8 C-factor corresponded to an average of 113 tons/hectare/yr of erosion (or 1.19 cm/yr lowering rate), which are lower than reported for other tropical roads (Sidle et al., 2004), and within the range of locally estimated lowering rates for agricultural fields (Stock et al., 2016). The 0.03 C-factor was selected based on the logic that some erosion is likely even on repaired roads (i.e., water bars and gravel are not 100% effective). Our estimate that erosion would be reduced by about 96% is supported by findings in the literature, e.g., soil loss from bare, newly constructed roads was eight times greater compared to graveled roads (Swift, 1984), graveling of 10 and 20 mm initially reduced sediment loss by 75% and 95% on Oahu roads without traffic (Ziegler and Sutherland, 2006), 15 cm of gravel reduced erosion by 79% on traveled ways of mountain forest roads (Burroughs and King, 1989), and water bars can reduce sediment load by an average 60% (Wallbrink and Croke, 2002). Further justification for this level of reduction is that most roads in the fallow agricultural zone of West Maui are rarely, if ever, traveled by vehicles.

2.5. Costs – cost function

After examining the watershed management plan (Sustainable Resources Group International, 2012a), technical guidance from the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) (https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/fotg/), literature on mitigation options (Burroughs and King, 1989; Ramos-Scharrón, 2012; Ramos-Scharrón et al., 2012) as well as several local proposals for road repair and talking with local land managers, we decided that the most realistic road repair scenario for West Maui involved: (1) inserting water bars to divert runoff and sediment, and (2) graveling roads that receive high annual precipitation. Summing the water bar costs and the graveling costs, each road segment was assigned a unique repair cost.

We determined water bar spacing on roads using USDA Forest Service guidelines, which outline recommendations for the maximum distance between cross drains based on road grade and soil type (Copstead et al., 1998). According to these guidelines, water bars can be expected to last ten years if maintained properly. The mean slope for each road segment and road length were calculated using USGS 10 m DEM and the Add Surface Information tool in ArcGIS to estimate the number of water bars required to achieve adequate drainage and reduce sediment loss. The cost of one water bar installation ($373) and maintenance ($1776/bar present value over 10 years at 3% discount rate) was based on consultation with local contractors and includes equipment rental and fuel, hired labor, and insurance.

Graveling costs were extrapolated to a per unit length value from an existing contractor proposal and expert opinion of the West Maui Soil and Water Conservation District Director. Roads in higher rainfall zones are exposed to more rain, and are therefore more likely to need maintenance and are more prone to washout (Ziegler et al., 2001). We estimated that graveling was necessary for areas with precipitation greater than 1524 mm/yr (Wes Nohara, West Maui Soil and Water Conservation District Director, pers. comm.). Average annual rainfall data from the Hawai'i Rainfall Atlas (Giambelluca et al., 2012) was used to calculate, for each management unit, the length of road (if any) receiving greater than 1524 mm/yr of rainfall; 42 of 156 management units had some portion of road that required gravelling. This length was then used to calculate the graveling cost ($0.945/m for an average of 10 cm of gravel laid).

2.6. Management scenarios

We considered seven different management scenarios defined by their decision-making scope and approach to road repair: one where road repair decisions are random, one achieving an optimal reduction in sediment delivery per dollar spent, and five sub-optimal scenarios that are either not cost-effective or cooperative. The optimal scenario requires that landowners cooperate in their decision-making and focus on repairing roads that are both the least expensive to repair and with the most sediment reduction from being repaired. For the scenarios where cost of road repair factors into the decision-making, we considered a management budget ranging from zero to the maximum value required to repair all roads in the study domain. The seven scenarios are outlined in Table 1, and explained in detail below.

Under *random management* roads are chosen for repair randomly across the entire study domain. This solution was determined by replicating 1000 times the process of randomly selecting $n = 1,2, \ldots, 157$ road segments for repair (i.e., one to all), producing a total 157,000 random road repair strategies.

Under *independent, cost-based management* the budget is divided evenly among the landowners and they individually select roads to repair within their jurisdiction based on their affordability. This solution was determined by ranking each landowner's roads in ascending order by the cost of repair (i.e., cheapest roads first); then selecting roads to repair for each landowner in the order of their ranking until each landowner's budget is spent. The analysis was then replicated across the range of budget levels.

Cooperative, cost-based management is the same as the above scenario except that the budget is pooled among the landowners, who then collectively select for repair roads from across the study domain. This solution was determined by ranking all roads in ascending order by the cost of repair, then selecting for repair roads in the order of their ranking (the higher the given budget, the more roads repaired).

Under *independent, sediment-based management* the landowners individually select roads to repair within their jurisdiction based on the reduction in sediment export if fixed. This solution was determined by ranking each landowner's roads by their potential sediment reduction (if fixed), then for each landowner selecting for repair $n = 1,2,\ldots,$ maximum number of roads in their jurisdiction.

Cooperative, sediment-based management is the same as the above scenario except that the landowners collectively select for repair roads from across the study domain. This solution was determined by ranking all roads by their potential sediment reduction (if fixed), then selecting for repair $n = 1,2,\ldots, 157$ roads in the order of their ranking.

Under *independent, cost-effective management* the budget is divided evenly among the landowners and they individually select roads to repair within their jurisdiction based on their cost-effectiveness, which is defined as the reduction in sediment export if a road is repaired divided by the cost of the road's repair. This solution was determined by ranking each landowner's roads by their cost-effectiveness, then selecting roads to repair for each landowner in the order of their ranking until each landowner's budget is spent. The analysis was then replicated across the range of budget levels.

Cooperative, cost-effective management represents the most objective approach to decision-making that seeks to solve the problem as efficiently as possible. It is the same as the above scenario except that the budget is pooled among the landowners, who then collectively select for repair roads from across the entire study domain. This solution was determined by ranking all road by their cost-effectiveness, then selecting for repair roads in the order of their ranking (the higher the given budget, the more roads repaired).

2.7. Trade-off analysis

We conducted trade-off analysis (Lester et al., 2010) to compare the efficacy of the management scenarios in achieving comprehensive reduction of sediment runoff from the landscape at minimal cost (i.e., the policy objective). 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). 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., 2010). Differences between these outcomes in the tradeoff plot indicate changes in efficacy in achieving the policy objective. Specifically, we compared management scenarios by quantifying changes in their outcomes along two dimensions defined by the axes in the trade-off plot: given a finite management budget, the extra erosion control achieved from improved decision-making; and, given a target erosion control level, the cost savings achieved from improved decision-making.

3. Results

3.1. Sediment reductions achieved

The annual sediment load reaching the coastline according to the InVEST model is ~18,900 tons/yr (Fig. 2b). 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%. These relatively low values indicate that only a portion of the eroded sediment will be exported to the coast annually (Anderson and MacDonald, 1998; Calhoun and Fletcher, 1999; López et al., 1998).

Table 1
Seven management scenarios.

Management scenario	Landowner budgets and road repair jurisdiction		Priority roads to repair		
	Separate and local for each landowner	Pooled among landowners, and domain-wide	Least expensive to repair	Most sediment reduction from repair	Most sediment reduction per $ spent
Random		X			
Independent, cost-based	X		X		
Cooperative, cost-based		X	X		
Independent, sediment-based	X			X	
Cooperative, sediment-based		X		X	
Independent, cost-effective	X				X
Cooperative, cost-effective		X			X

3.2. Efficiency of alternative management scenarios

The alternative management scenarios vary in their efficacy at achieving comprehensive reduction of sediment runoff from the landscape at minimal cost (the policy objective; Fig. 3). The two cost-based approaches, where roads are selected for repair based solely on their affordability, either cooperatively (blue) or independently (red) among the landowners, perform poorly and no better than random management. A significant improvement in efficacy is achieved when landowners instead select roads for repair based on their cost-effectiveness (tons sediment mitigated per dollar spent; green and black lines). The greatest benefits arise when landowners also act cooperatively across the entire study domain (not just within their individual jurisdictions; black line, representing the efficiency frontier).

Somewhat counter-intuitively, in some situations a cooperative cost-based approach is less optimal than an independent cost-based approach (i.e., the blue line is interior to the red line). The result arises because, in the independent strategy, landowners will more often run out of cheap roads to repair, and be forced to repair expensive, but *more cost effective* road segments. A cooperative approach provides a far larger set of low-cost options to choose from, most of which are not cost-effective. Said another way, when coupled with cost-based decision-making, cooperation provides more options to focus only on cheap repairs, allowing the group to avoid expensive but cost-effective roads. In essence, the landowners are working together implementing a poor decision-making strategy.

Differences between the trade-off lines in either the x- or y-axis dimension in Fig. 4 indicate the value from improved decision-making (or, viewed differently, loss from suboptimal decision-making). For example, with a budget of $8 million, cost-effective and cooperative management (Fig. 4A, black line on x-axis) results in ~650 tons/year less sediment reaching the coast when compared to the next best option (independent and cost-effective; Fig. 4A, green dashed line), and ~1700 tons/year less sediment than the least optimal strategy (cooperative, cost-based; Fig. 4A, blue dotted line). Put another way, the optimal strategy achieves 12% more reduction than the second-best strategy and 31% more reduction than the least optimal strategy for the same cost. These suboptimal strategies result in different roads being repaired (Fig. SI-1). Similarly, if a certain sediment reduction goal is set (at, say, 4000 tons/year sediment reduced), annual cost savings into the several millions of dollars can accrue from adopting more optimal strategies (Fig. 4B). The broad shape of the humped curves in Fig. 3 indicates there is a wide range of budgets and target sediment levels over which substantial gains can be accrued from optimal decision-making, particularly when optimal management is compared with the two cost-based management scenarios.

Prioritizing and fixing roads based on their sediment reduction potential offers a similar outcome (Fig. SI-2). The sediment-focused strategy results in more sediment reduction than the cost-based strategy, and less than the optimal strategy. Also, similar to that found for the cost-based strategies, cooperation under the sediment-based strategy can result in less effective outcomes relative to those under independent action. However, at high budget levels this pattern dissolves and the sediment-based strategy (cooperative or independent) delivers outcomes better than even that by independent, cost-effective management.

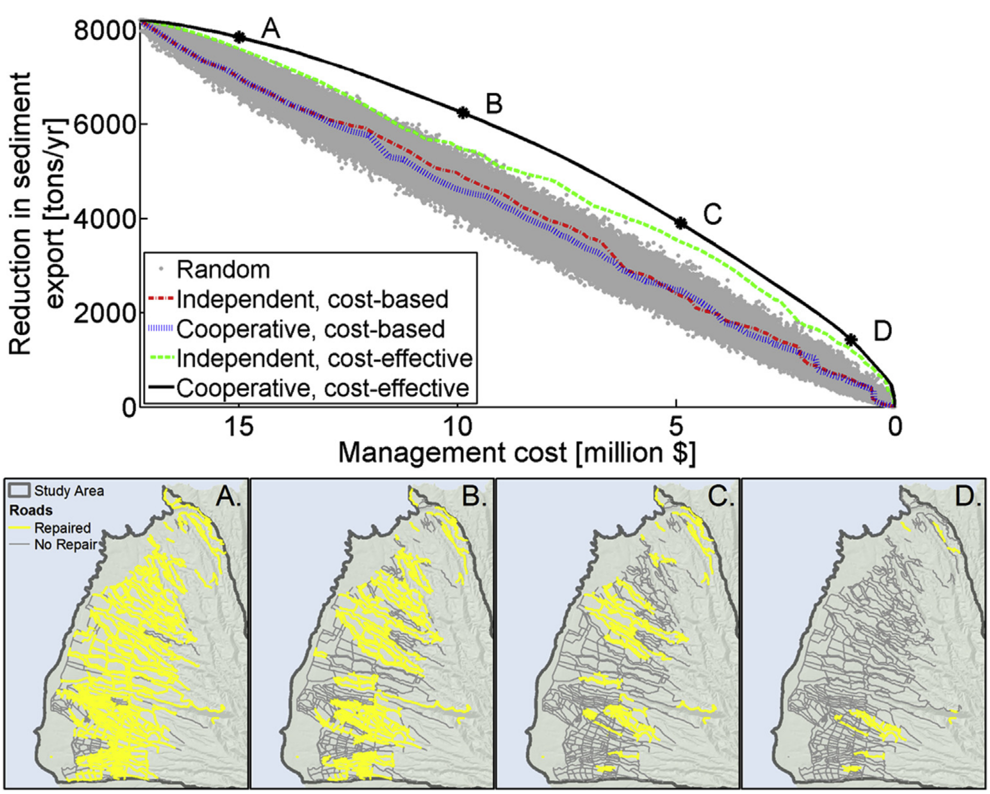

Fig. 3. Comparison of different distributed solution strategies for mitigating erosion of sediment from agricultural roads. A. Each point on the graph represents a set of road segments that can be repaired at a given cost and reduction in sediment export. Landowners can choose to make decisions independently (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.

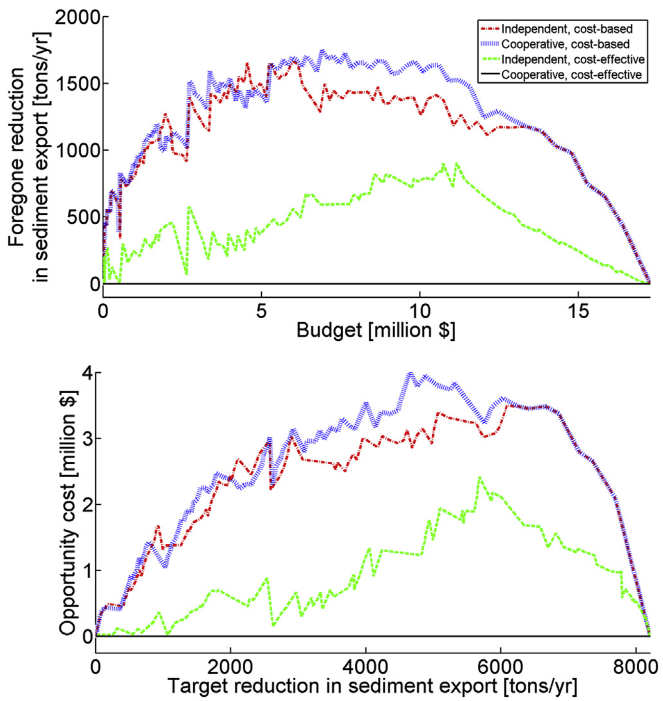

Fig. 4. Lost value from poor decision-making. A. Foregone (i.e., no generated) reduction in sediment export (tons/year) from each strategy compared to the optimal (black, on x-axis). B. Opportunity cost (the loss of potential gain; million $) of adopting a strategy other than the optimal one, given a sediment reduction target.

4. Discussion

Resources for management are limited, thus it is important to put funds to their most effective use. This study shows the benefits of using a decision analysis approach to identify solutions that have the best outcome for the cost. We used relatively simple and accessible models to estimate the effect and cost of management, then analyzed how different management strategies affected the overall economic outcomes. We reveal significant benefits from making good decisions.

First of all, using our model to select priority road segments appears to generate more cost-effective erosion mitigation. Regardless of whether land-owners are acting independently or in concert, managers should target roads that are more cost effective to repair.

Secondly, we show that cooperative management (i.e., landowners consider all roads across the entire landscape regardless of watershed and ownership) is more efficient than independent management when coupled with cost-effective decision-making, as it enables the landowners to collectively focus on the most cost effective road repairs across the entire landscape. In our case, one landowner holds 48% of the land, and 46% of the roads that need repairing. In a situation with more, smaller landowners, the benefits from cooperation would be even more pronounced. Whether these efficiency gains from collective action exceed the broader transaction costs of cooperative decision-making is still an open question.

Finally, our results also present a warning: cooperation, when coupled with poor decision-making (i.e., choosing solutions that are the cheapest, or which reduce the most sediment), can substantially limit the value of management and prevent achievement of the policy goal (i.e., comprehensive, cost-effective sediment reduction). In this case, working together is counter-productive because the decision-making process is missing a non-economic factor (sediment reduction) important to the valuation of alternative management actions.

4.1. Benefits and limits of collective action

Conservation management strategies benefit from cost-effective decision-making that strategically compares the economic costs and environmental benefits or impacts of alternative options (De Groot et al., 2010; Naidoo et al., 2006; Pullin and Knight, 2001; Ramos Scharrón and MacDonald, 2005; Ramos-Scharrón et al., 2012). Coordinating decision-making and actions among interacting stakeholders (e.g., landowners, water users, resource managers) can enhance management outcomes economically, socially, and ecologically (Baland and Platteau, 1997; Leopold, 1933; Smith, 1986; C. White et al., 2012a). These principles underlie ecosystem-based approaches to management that seek to comprehensively account for and manage biophysical and socioeconomic factors for increasing the joint value of an ecosystem to society (Slocombe, 1998; Tallis et al., 2012).

In regions like West Maui, with multiple landowners distributed within and across watersheds, collective action may seem critical to management success. However, we show that substantial (though not maximum) economic and environmental benefits can be gained through smart (i.e., cost-effective) decision-making alone without cooperative action. The result is in part dependent on the scale of landowner properties relative to the study region. At one extreme, one large landowner can manage optimally via independent, cost-effective decision-making, and at the other extreme, land divided among many small landowners can lead to sub-optimal results because much of the budget likely will be spent on roads that are cost-effective at the scale of an individual landowners' holdings, while missing opportunities to target the roads that are most cost-effective to fix at the landscape scale. Thus, the value of cost-effective decision-making increases with the relative scale of the landowner parcel size to the problem domain size.

This result underscores the importance in decision analysis of matching the scales of management action with their social-ecological systems (Eaton et al., 2016). The relative value of independent and collective action we see in West Maui accords with other studies indicating a positive correlation between management capacity to scale to the size of a problem and management success (Sanchirico and Wilen, 2005; C. White et al., 2012a). It also parallels the "problem of institutional fit" literature, which suggests management must match spatially, temporally, and functionally the underlying social-ecological system (Cumming et al., 2006).

In our case, five large landowners hold parcels approaching the size of the study area (86%), with many road segments within each (92% of total road length), resulting in substantial (though not maximal) benefits from smart decision-making even without cooperation. In a case where land was more diversely owned, the policy objective of cost-effective management across the landscape would be more starkly confronted with decision-making at the plot scale, and our result of "pursue cost-effective management before all else" may underestimate the importance of collective action.

When a single manager or landowner does not control decision-making across the entire scale of the problem, but rather control is distributed across multiple entities, cooperative action (coupled with smart decision-making) becomes critical for achieving optimal outcomes (E. W. Anderson and Baum, 1988). In this case, sub-optimal outcomes are overcome by coordinated actions among the stakeholders for their collective benefit (Bouwen and Taillieu, 2004; C. White et al., 2012a, 2012b). Note, however, that cooperation in our study unevenly distributes the burden of road repairs amongst landowner parcels, and could require some landowners to fund repairs on another's parcels. Moreover, some landowners operate resorts at the base of their watersheds, so coastal water quality is an immediate business concern, thus they might strongly prefer fixing roads in their watersheds. Such asymmetry in private costs or gains to individual stakeholders can present hurdles to cooperative management (Bouwen and Taillieu, 2004; Hardin, 1982; C. White et al., 2012a). Successful coordinated management in West Maui thus may require reconciling the increase in overall cost-effectiveness of road repair across the entire study domain with grievances by individual landowners expected to shoulder more road repairs or see fewer benefits than others, e.g., with transfer payments or other ways of sharing the overall collective gains among the landowners (Sumaila, 2005).

Collective action is not unequivocally beneficial, however, and can even produce counterproductive outcomes when coordinated decision-making is misguided by a poorly defined management objective (i.e., cost-based or sediment-based, instead of cost-effective use of the budget). When the management objective does not align well with the policy goal (e.g., management repairs the cheapest or most egregious roads, compared with the policy goal of reducing sediment at the lowest possible cost), cooperation may lead to little benefit or even substantial cost, relative to acting independently (Fig. 2; Fig. SI-2). Conversely, when the management objective does align with the policy goal (repair the most cost-effective roads), cooperating has substantial value.

Simply put, collective action can be more powerful than individual actions, and as such highlights the importance of aligning management objectives and the policy goal. If coordinated action is poorly directed through ill-informed or misguided management objectives, it can produce counterproductive outcomes (Hardin, 1982; Ostrom, 1994). This is true in our cost or sediment driven cases where the objective was poorly aligned with policy at the outset, but can also be the case generally when externalities (i.e., unintended side-effects of an action) are ignored. These findings highlight the importance of carefully defining the management objective in order to make the most out of cooperative action and avoid it leading to perverse outcomes (Degnbol and McCay, 2007).

4.2. Incorporating multiple trade-offs

The trade-off approach demonstrated here can be expanded to multiple competing objectives to reduce conflict and focus debate on optimal strategies. The utility of estimating a efficiency frontier in trade-off analysis has been demonstrated in balancing competing uses of Massachusetts coastal waters (C. White et al., 2012b), designing MPAs in the Caribbean (Brown et al., 2001), balancing ecosystem service provisioning in a California floodplain (Garnache, 2015), assessing trade-offs in ecosystem services across European landscapes (Ruijs et al., 2013) and biological and economic objectives in Willamette Basin (Nelson et al., 2009; Polasky et al., 2005), and in siting MPAs in California (J. W. White et al., 2013).

In West Maui, the approach could be expanded to evaluate other sources of sediment, broader LBSPs, or other stressors (e.g., fisheries). Our approach identified the most optimal actions given one mitigation action, but roads are not the only source of sediment in West Maui. The bioeconomic modeling and trade-off analysis approach used here could be expanded to account for other forms of sediment control under consideration, e.g., rain gardens, lo'i (wetland taro), feral ungulate extermination and fencing, and stream restoration. There are two potential approaches to adding these other forms of sediment control. One could maintain the two-axis approach, integrating all the sediment control actions into an aggregate sediment export metric to be compared with management costs (e.g., as done for total economic value by Lester et al. (2013)). Alternatively, each form of sediment control could be assessed on a separate axis (e.g., roads to repair and fences to construct) in relation to an objective function defined by sediment export, cost of management, and other metrics (C. White et al., 2012b).

In West Maui, the overarching five-watershed policy goal is to preserve the health of coral reefs; limiting sediment (and from roads specifically) is but one piece of the management puzzle. Multiple stressors impact coral reefs (e.g., nutrient addition, sedimentation and fishing) (Granek et al., 2010). Actions to mitigate each stressor in a suite (e.g., alternatives to mitigating sediment, controlling nutrients, and managing fisheries) can be defined and traded-off, and/or multiple desired ecological outcomes (e.g., coral reef health, beach quality, fish biomass) or ecosystem services (e.g., snorkeling quality, resource fish abundance) can be compared. Notably, the latter would require an ecosystem model capable of capturing the behavior of the complex system, including interactions and feedbacks among stressors and ecological components, as multi-stressor interactions can produce dramatic and surprising ecological reactions and changes (Ban et al., 2014; Graham et al., 2013; Jouffray et al., 2015; Szmant, 2002). The trade-off analysis process would nevertheless follow the same steps: (1) collectively and inclusively agree upon the management objectives; (2) creatively define possible management actions; (3) assess each action's outcomes and evaluate against each objective; and (4) identify the optimal set of management actions that represent win-win outcomes (those along the efficiency frontier). Decision-makers could then collectively choose actions to take.

4.3. Limitations to our modeling approach

Our results present a framework for evaluating tradeoffs implicit in management and highlight the importance of working with well-defined management objectives. However, there are important caveats to our modeling that may impact the on-going management choices we are attempting to inform.

The InVEST-SDR model is not a model built specifically for roads (Hamel et al., 2015), there are serious limitations to using RUSLE to estimate erosion from roads, although coupling of a source model with an SDR is common practice (Fu et al., 2010). Our simple modeling approach ignores that roads can fundamentally alter the hydrology of landscapes (Nagle et al., 1999; Ramos Scharrón and LaFevor, 2016; Sidle et al., 2004; Ziegler and Giambelluca, 1997). By focusing exclusively on erosion from road surfaces, our approach partially handles the direct increase of connectivity due to roads (i.e., the model generally returns results where roads near/connected to streams have higher sediment delivery ratios than those that do not) (Croke et al., 2005). One caveat is that we do not explicitly consider how fixing downstream segments may alter the connectivity of uphill segments, although the SDR partially handles this (Croke and Mockler, 2001; Gumiere et al., 2011). Our approach also neglects roads' role in connecting overland flow processes to the stream network and amplifying runoff (Ramos Scharrón and LaFevor, 2016), which may increase sediment yield (Bracken and Croke, 2007; Croke et al., 2005; Ramos-Scharrón, 2012).

As no calibration data are available for these watersheds for either daily discharge or suspended sediment concentration, and it is likely that key processes are missing, our results should be interpreted as relative values. That said, their orders of magnitude are robust. A recent modeling effort in West Maui, which used a different model (GSSHA) that relied on historical rainfall data, estimated that Honokowai watershed, one of the five watersheds in the study area, would export 938 tons for each two-year storm, and 8348 tons for each 10-year storm (Babcock et al., 2016). Other watersheds in Hawai'i with long-term suspended sediment datasets have found similar orders of magnitude. Kawela on Molokai exported an average of 6652 tons per year (4.82 tons/ha/yr) (Stock et al., 2010), Hanalei on Kauai exported 14,530 tons per year (2.42 tons/ha/yr) (Ferrier et al., 2011), and Halawa on Oahu documented an average of 4310 tons per year (4.17 tons/ha/yr) (Matsuoka et al., 1993). The total sediment export values from the West Maui study area and the yields (1.94 tons/ha/year), therefore, are conservative compared to other watersheds in Hawai'i. The estimates of sediment erosion and delivery offer a relative measure of road sediment production that is useful for our study's purpose (Fu et al., 2010), i.e., to use trade-off analysis to assess the efficacy of alternative management decision-making, under an individual or collective action, for achieving the overall policy objective. Even if the sediment model estimates are coarse, our analysis of the relative benefits of one management strategy over another will remain sound, as long as the relative ranking of road segments is correct.

Our model focuses on the landscape scale policy objective, and thus does not differentiate sediment by location; any sediment that reaches the coast across the entire study region is considered equally undesirable, and any sediment reductions achieved are similarly equally desirable, regardless of their relative magnitude, proximity to coral reefs, or state of those reefs (Fig. 1B). A logical next step would be to spatially prioritize sediment reductions by watershed, depending upon some simple evaluation (e.g., of the effect on, relative vulnerability of, or societal importance of the coral reef) (Ramos-Scharrón et al., 2012; Tulloch et al., 2016). More advanced ecological modeling would be needed to connect reductions in sediment or other LBSPs with the fundamental objective of the watershed management plan in West Maui – preserving and restoring reef health (Sustainable Resources Group International, 2012b).

Turning to costs, we assessed costs for one sediment mitigation action that was actively being funded at the time, but our cost function does not consider costs of moving equipment or challenges to road access, which have real cost implications. Lastly, it is important to stress that the likelihood is low of roads being repaired at this scale, given budget constraints. Moreover, recent watershed reconnaissance work by USGS suggests that roads, at least for small storms, represent a small portion of sediment runoff from the landscape, and that in-stream erosion of legacy agricultural sediment is likely the largest source of fines during frequent rain events (John Stock, USGS, personal communication). Though some roads will be maintained for fire control and other access, particularly as the landscape is slated for massive development over the coming decades, the benefits are uncertain from repairing roads that may be sources only in large, infrequent rainfall events, and which future development might modify anyway (Tova Callender, personal communication).

4.4. Conclusion

West Maui landowners and managers set a policy objective of comprehensive reduction of sediment runoff from the landscape at minimal cost. We used simple modeling of erosion and costs to assess the cost-effectiveness of repairing agricultural roads, with seven scenarios. Our results point to three main conclusions: (1) an evaluation of cost-effectiveness, even done with simple models, can guide maximally effective management interventions. (2) Collective action is important, but there is value to acting alone in cases where a single actor is big enough. (3) Collective action is not a panacea, and can lead to counter-productive outcomes if poorly targeted, i.e., towards goals that neglect cost-effectiveness.

Coral reefs are critical ecosystems, playing a fundamental ecological role, while providing countless goods and services to humans. In an era where anthropogenic activity constitutes an existential threat to coral reefs and conservation budgets are a fraction of what is likely needed for protection, action must hone in on mitigating the most damaging activities in the most cost-effective manner possible. Trade-off analysis, coupled with simple modeling tools, can be insightful and help achieve the best environmental and economic outcomes.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.12.067.

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