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Research article

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

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A B S T R A C T :

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),