CHARACTERIZING SPATIAL LINKAGES BETWEEN INLAND AND COASTAL HABITATS FOR IMPROVED CONSERVATION IN MAUI, HAWAII

By

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ABSTRACT

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Characteristics of inland landscapes draining into the coastal environment influence condition and availability of coastal habitats. While many studies have shown linkages between inland landscapes and coastal regions, few have evaluated such relationships over large spatial extents for the purpose of aiding in efforts to conserve coastal habitats. The research described in this thesis addresses that need by testing spatial relationships between coastal habitat condition and characteristics of proximate draining catchments of Maui, Hawaii. Ecologically meaningful inland natural, inland anthropogenic, and coastal factors that influence coastal habitats were first identified, and relative influences of each group of variables on coastal habitat metrics were quantified. Results indicated that the strength of relationships between catchment characteristics and coastal habitat conditions varied with distance. These findings were then used to inform an assessment of coastal habitats based on intensity of inland anthropogenic disturbances. This step identified coastal areas at varying risk of degradation from inland disturbances, and we combined this result with a map depicting locations of ecosystem services and benefits around the island of Maui including locations for recreation, areas supporting fishing and/or fisheries and habitats for biodiversity. An inventory of those services and benefits most at risk from inland disturbance were provided, and this information may prove useful for resource managers working to conserve Maui's coastal habitats. Outcomes of this research further demonstrate an approach that could be applied in other regions to understand linkages between inland and coastal habitats, improving efforts to conserve coastal habitats from current and future threats.

To my family and friends, you are in all of these pages.

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PREFACE

The research chapters in this thesis have been prepared and formatted for publication. Therefore, there is some repetition in concept, study site descriptions, and methods among chapters.

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OVERVIEW

Coastal habitats offer a diversity of benefits that are ecologically and socially important (Martínez et al. 2007; Barbier et al. 2011), yet their conditions and availability are in decline globally due to anthropogenic disturbances (Myers et al. 2000; Sala and Knowlton 2006; UNEP 2006). While many anthropogenic disturbances result from human activities in and uses of the marine environment (Thrush and Dayton 2002; Waycott et al. 2009; Halpern et al. 2007), another major contributor to the decline of coastal habitats originates from the terrestrial landscape (Crain et al. 2009), including human land use such as urbanization and agriculture. Across the globe, studies have shown links between degradation of coastal habitats and developed inland landscapes. Examples include eutrophication in Chesapeake Bay in the Mid-Atlantic (Boesch 1996), hypoxia in the Gulf of Mexico (Alexander et al. 2008), coral reef bleaching of the Great Barrier Reef of Australia (Wooldridge 2009), and algae blooms of Lake Erie in the Laurentian Great Lakes (Michalak et al. 2013). These studies emphasize consequences of inland landscapes affecting conditions in coastal habitats.

Despite wide acknowledgement of linkages between inland and coastal habitats, an established approach for associating units in the coastal environment with units in proximate terrestrial landscapes to consistently account for spatial relationships has yet to be developed. This is in part due to the lack of defined boundaries in the open water environment that identifies ecologically meaningful units, which hinders efforts to describe relationships between inland systems and the coastal environment. Additionally, drivers of coastal habitat condition are diverse. Different factors may promote or limit linkages between habitats, and important factors may vary by region (i.e., climate, geology, Talley et al. 2006). Understanding spatial relationships between characteristics of inland landscapes, including disturbances, and coastal habitats is integral to identify sources of degradation to coastal ecosystem services (Halpern et al. 2008; Allan et al. 2013). Such information could potentially inform conservation efforts through identification of areas that are highly threatened as well as factors contributing to their decline.

The goal of this thesis is to improve understanding of spatial linkages between inland and coastal systems. Our study was conducted in Maui, Hawaii. The nearshore coastal environment supports a variety of ecosystem services and benefits including recreation, recreational and commercial fisheries, and habitats for biodiversity. Further, landscape characteristics vary across the island's catchments that drain to the coast, ranging from natural to urbanized to agricultural lands. In Chapter 1, we begin by identifying how a set of metrics reflecting reef habitat condition throughout the nearshore region of Maui may be affected by variables in three groupings likely to influence coastal habitat conditions: inland natural landscape variables, inland anthropogenic landscape variables, and coastal variables. We assess the relative contribution of each variable grouping in explaining variation in coastal habitat condition, and we conduct analyses by considering catchment influences varying distances from coastal habitats to determine how proximity affects the strength of relationships. Additionally, we predict specific coastal habitat metrics from a subset of landscape factors to determine important influences on various metrics and to assess the role of hydrology in affecting strength. In Chapter 2, we characterize how inland anthropogenic influences may be expressed in the coastal environment based on findings from Chapter 1. Our analytical approach accounts for inputs from multiple catchments by considering their drainage areas and distances to coastal spatial units. We identify areas in the coastal environment that are at greatest risk of degradation from inland disturbances in relation to coastal ecosystem services and benefits. Then, we assess the coastal ecosystem services and benefits that are the most threatened. Collectively, outcomes of this research increase our understanding of how inland disturbances affect coastal habitats, provide information to support resource management decisions, and demonstrate a potential application for assessment by enabling the characterization of inland influences on coastal habitats.

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CHAPTER 1:

UNDERSTANDING SPATIAL LINKAGES BETWEEN INLAND AND COASTAL SYSTEMS: IDENTIFYING AND QUANTIFYING INLAND INFLUENCES ON COASTAL HABITATS

Abstract

Characteristics of landscapes including catchment area, topography, and land cover draining into coastal habitats influence the condition and availability of those habitats. While linkages between inland landscapes and coastal habitats are widely acknowledged, few studies have evaluated their spatial relationships to aid in conservation. To address this need, we tested for relationships between reef habitat condition and characteristics of proximate draining catchments on Maui, Hawaii, USA. We identified inland natural, inland anthropogenic, and coastal factors that influence coastal habitats and quantified the relative influence of each group of variables. Our findings showed evidence for linkages between inland and coastal systems, as well as how the strength of relationships varied with distance between catchment pour points and reef habitats. Our major findings include that catchment area, annual rainfall, and agricultural land cover having strong effects on multiple reef metrics. We also showed differential associations between reef habitat metrics and measures of catchment characteristics when considering the windward side (wet side) and the leeward side (dry side) of Maui separately. We additionally showed that significant relationships between the landscape variables and reef habitat metrics are more common on the windward side than the leeward side, underscoring the role of hydrology in facilitating linkages. These results illustrate complex relationships between inland systems and coastal habitats. Improved understanding of the drivers of coastal habitat condition have implications for land and coastal management, which can ultimately help inform management decisions that aid in the conservation of nearshore coastal habitats.

Introduction

Condition and availability of coastal habitats are in decline globally (Myers et al. 2000; Sala and Knowlton 2006; UNEP 2006). While human activities worldwide have impacted marine ecosystems, consequences of their cumulative disturbances can be more severe in coastal regions than in the open ocean (Halpern et al. 2008; Lotze 2006). Due to human settlement in landscapes near coastal habitats, average human population density within 100 km of coastlines is approximately three times higher than the global average (Small and Nicholls 2003; UNEP 2006). Intense use of coastal areas can result in generally higher demand for and access to coastal resources as well as specific impacts including shoreline development, shoreline hardening, and other infrastructure (Creel 2003), and these factors can collectively degrade proximate coastal habitats. Additionally, coastal habitats are remotely affected by landscapes far-removed from the coastal environment, with extensively developed watersheds also having negative influences on coastal habitat conditions.

Influences of anthropogenic disturbances in terrestrial landscapes on coastal habitats are driven in part by hydrology. River discharge, surface runoff, and groundwater carry nutrients, sediments, and toxics into receiving coastal waters. Anthropogenic disturbances can disrupt natural hydrological connections between landscapes and the coast, leading to changes in, and potentially degrading, nearshore coastal habitats (Halpern et al. 2008; Wehrly et al. 2013). For example, impervious surfaces such as pavement and roads associated with urban land uses could prevent water from infiltrating into soils, subsequently reducing groundwater input and increasing surface runoff (Paul and Meyer 2001). Such changes in hydrology can have additional changes to nearshore coastal habitats including changing thermal regimes (Allan and Castillo 2007); altering sediment dynamics (Milliman and Meaded 1983); and affecting delivery of nutrients, toxics, and/or woody debris to coastal habitats (Kennedy and Woods 2012). Across the globe, studies have shown links between degradation of coastal habitats and developed inland landscapes, including agricultural and urbanized landscapes. Examples include eutrophication in Chesapeake Bay in the Mid-Atlantic United States (Boesch 1996), hypoxia in the Gulf of Mexico (Alexander et al. 2008), coral reef bleaching of the Great Barrier Reef of Australia (Wooldridge 2009), and algae blooms of Lake Erie in the Laurentian Great Lakes (Michalak et al. 2013). These studies emphasize consequences of inland landscapes affecting conditions in nearshore coastal habitats, in some cases, highlighting mechanisms by which these linkages occur in specific locations. However, as individual, regionally-specific studies, they offer little guidance for extrapolating results to other regions or for describing and comparing such linkages between inland and coastal habitats across large spatial extents (i.e., entire states, ecoregions, continents). These limitations reflect a gap in understanding of relationships between connected inland and coastal habitats and underscore a critical research need to aid in efforts to conserve coastal habitats from anthropogenic disturbances.

While the importance of linkages between inland and nearshore coastal habitats are acknowledged, an approach that characterizes mechanisms by which they connect over large spatial extents has yet to be applied (Gorham 1996; Lamberti et al. 2010; Moser et al. 2012). Such an approach, however, exists for inland aquatic ecosystems. The landscape approach (reviewed in Allan 2004) asserts that conditions of inland lakes and streams are affected by conditions of their catchments, and interrelationships between inland aquatic habitats and landscape features within catchments have been described in many studies (e.g., Richards et al. 1996, Wang et al. 2003, Danz et al. 2007, Infante et al. 2009, Esselman et al. 2011, Schinegger et al. 2016). However, associating specific areas within the coastal environment with landscape characteristics is challenging. For rivers and inland lakes, boundaries of landscape influences can be determined largely through topography, yet the extent over which landscape influences affect coastal habitats is not well-understood. This lack of understanding hinders development of ecologically meaningful spatial units that would account for landscape influences on habitat in the coastal environment. Additionally, drivers of coastal habitat condition are diverse. Different factors may promote or limit linkages between habitats, and important factors may vary by region (Talley et al. 2006). In spite of these challenges, the need for a spatial framework that explicitly associates coastal habitats with inland spatial units is recognized. For example, in 2013, the National Ocean Council released the National Ocean Policy Implementation Plan that emphasized the need for coastal and marine spatial planning, calling for a formalized method to inform and guide decision-making in the coastal and marine environments (NOC 2013). With diverse interests in coastal and marine resources (e.g., shipping, offshore energy, recreation), decision-support spatial planning tools based on a spatial framework would alleviate shortcomings of and complexity related to management decisions that consider conservation (Craig 2015).

This study aids in addressing those challenges by investigating spatial linkages between inland and coastal systems of Maui, Hawaii, USA. Our first objective is to identify factors that most strongly influence coastal habitats in a region with substantial heterogeneity in both inland and coastal characteristics. In support of this objective, we first identify sets of coastal factors and of natural and anthropogenic landscape factors from the inland environment which may be important influences on coastal habitats. Our second objective tests for influences of those three groupings of factors on a set of reef metrics reflecting coastal habitat condition to identify the most influential grouping. Finally, our third objective predicts specific reef metrics from inland

and coastal factors to characterize the importance of different inland influences and identify those that explain the most variance in coastal habitat conditions. In support of this objective, we additionally test for the role of hydrology in affecting influences by conducting analyses on Maui's catchments that receive substantially different amounts of precipitation. Greater understanding of spatial linkages between inland and coastal environments gained through this study can contribute to development of a spatial framework in the coastal environment. In this case, a spatial framework is composed of a set of spatial units that are ecologically-defined with shared characteristics. The explicit characterization of interrelationship of inland catchment characteristics and coastal habitat units can ultimately help inform management decisions and aid in conserving nearshore coastal habitats.

Methods

Study area

This study was conducted in Maui, Hawaii, the second largest island of the Hawaiian archipelago with a land area of 1,884 km^2 (Figure 1.1). The island was formed by the convergence of two volcanoes (West Maui Volcano, formed approximately 1.15 million years ago and East Maui Volcano, formed approximately 0.8 million years ago). Maui's characteristic basalt-based geology is derived from cooled lava flows,which contribute to variability in geologic permeability across the island (Lau and Mink 2006). Due to prevailing trade winds and orographic effects, the windward side of Maui receives substantially more rainfall than the leeward side (Giambelluca et al. 2011), contributing to a higher prevalence of perennial streams on the windward side of the island and more intermittent streams on the leeward side (Timm et al. 2015, Giambelluca et al., 2011). Additionally, Maui exhibits distinct wet seasons (November–April) and dry seasons (May–October).

Approximately 206 km^2 of coral reef habitat occurs in the nearshore region around the coastline of Maui, supporting 12 species of corals (Grigg 1983). These corals provide habitat for a diversity of fish and invertebrates (Randall 1976, Friedlander et al. 2008), including endemic species that utilize the coastal habitats to complete their life cycle (McDowall 2003). Nearshore coastal habitats around Maui are hydrologically linked to the island's landscape and are subject to both natural and anthropogenic influences. Rain events rapidly alter sediment inputs, turbidity, and salinity of coastal receiving waters (Grigg 1995, Lau and Mink 2006). While coastal organisms are adapted to natural extremes in conditions (e.g., Bittler et al. 2014, Moura et al. 2016), anthropogenic activities can result in conditions that may be substantially different than those to which native organisms are adapted (DLNR DAR 2005, Storlazzi and Jaffe 2008). Additionally, both natural and anthropogenic influences originating within the marine environment (i.e., wave impacts, damage from ship anchors) may interact with and compound effects of inland influences on coastal habitats (Chabanet et al. 2005, Buma 2015).

Data collection and variable creation

Inland landscape data

Spatial units

To explore relationships between inland and coastal systems, we identified boundaries of all catchments draining to the coastal environment by perennial and/or intermittent streams and termed these spatial units "pour point catchments" (Figure 1.2). Pour point catchments were derived from a stream layer developed in support of the Hawaii Fish Habitat Partnership (HFHP) by Tingley et al. (In Review). Confluence-to-confluence stream reaches form the basis of the HFHP stream layer, and a local catchment is the topographically-defined land area that drains directly to the stream reach (following Wang et al. 2011). Pour point catchments include the cumulative land area and river network upstream of the pour point draining into the coastal environment.

Inland natural variables

Inland natural variables summarized in pour point catchments were assembled from multiple sources to describe characteristics of the Maui landscape draining into the coastal environment (Table A1.1). Catchment slope was calculated by averaging slopes of stream reaches comprising networks within pour point catchments, and pour point catchment area is the sum of the area of all local catchments comprising a pour point catchment (methods described in Tingley et al., In Review). Mean annual rainfall data were summarized from Frazier et al. (2016), representing the area-weighted average depth of precipitation received across each local catchment comprising a pour point catchment. Soil and geologic characteristics across Maui were sourced from the Soil Survey Geographic Database (SSURGO; USDA 1995). SSURGO hydrologic soil groupings are estimates of relative soil infiltration rates. For this study, we used area-based weighting of values in all local catchments comprising pour point catchments. Values ranged from 1 to 4, where 1 represents the lowest infiltration rate and 4 represents the highest (see Tingley et al., In Review). SSURGO soil erodibility was similarly summarized by area-based weighting of values in local catchments comprising pour point catchments; values ranged from 1 to 3 where 1 is not highly erodible and 3 is highly erodible (Tingley et al., In Review).

Inland anthropogenic variables

To identify potential disturbances to the coastal environment, anthropogenic variables assembled from multiple sources were also summarized in pour point catchments (Table A1.2). Urban landscape influences were characterized by multiple variables sourced from the Coastal Change Analysis Program (CCAP; NOAA 2005). These included high, medium, and low intensity developed urban lands; open urban land; and a composite variable created by summing the above listed subcategories within pour point catchments. Additional urban landscape influences summarized in catchments included impervious surfaces (NOAA 2005); utility pipelines density (Hawaii Office of Planning 1983); percent golf course surface cover (Hawaii OP); population density (United States Census Bureau (USCB) 2002); and road density (USCB 2002). These urban land variables represent potential sources of pollution and may alter hydrologic regimes, contributing to degradation of coastal habitat conditions or habitat loss. Agricultural landscape influences included percent of hay and cultivated crop land cover as well as a composite variable created by summing the two categories in pour point catchments (CCAP 2005); these factors may also alter catchment hydrology or may result in inputs of excess nutrients, sediments, and/or toxics including herbicides and pesticides to coastal receiving waters. Percent of former plantation land cover accounts for pervasiveness of historical pineapple and sugarcane plantations within pour point catchments (Hawaii Office of Planning 1989). This landscape factor was also considered a potential current disturbance that could result in discharges of nutrients, pesticides, and/or herbicides to coastal habitats. An additional disturbance, point-sources, include densities of Superfund National Priority sites (Comprehensive Environmental Response, Compensation and Liability Information System (CERCLIS; USEPA 2010), Permit Compliance System majors (PCS; USEPA 2010), Toxic Release Inventory sites (TRI; USEPA 2010), and Underground Injection Control sites (UIC; Hawaii DOH 2004) in pour point catchments. Stream fragmentation variables include densities of stream and road crossings (USCB 2002), densities of ditch intersections with streams (Hawaii Division of Aquatic Resources (DAR) 2004), and densities of dams (ACOE 2010). Length of ditches characterizes the relative intensity of water diversions within pour point catchments

(Hawaii DAR, 2004). Additionally, the percentage of upstream network classified as 303(d) listed streams (USEPA 2002) characterizes reaches that failed to meet state criteria for water quality, primarily due to sedimentation (Hawaii Department of Health 2012).

Coastal data

Coastal habitat data

Coastal habitat data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Ecosystem Program. Reef characteristics around the coastline of Maui were surveyed between 2005 and 2010. There were 888 benthic segment observations (each approximately 200 m in length) from 92 unique surveys that characterized coastal habitat factors following NOAA's Benthic Towed-diver Survey protocol (Kenyon et al. 2006). These factors include measurements of seafloor cover types throughout segments such as percent coral cover (C), stressed coral cover (SC), sand cover (S), macroalgae cover (MA), and crustose coralline algae cover (CCA). Habitat complexity (H) was also assessed in segments and is a measurement of structural rugosity that potentially reflects amount of refuge for reef organisms. Numbers of crown-of-thorns starfish (COTS) and urchins (U) were estimated to assess their respective densities (count per km^2) in each segment.

Spatial units

Each of the 92 unique reef surveys were composed of multiple benthic segment observations collected within the same survey covering areas that ranged from 0.03 km^2 to 0.59 km^2 around the island of Maui. Individual variables measured (described below) were averaged across observations from individual surveys, with the spatial region assessed by a survey hereinafter referred to as a reef unit. When reef units characterized areas that overlapped 50% or more, we retained information from the most recently-sampled unit. This step left us with 52 unique reef units for analysis (Figure 1.1), encompassing an area of approximately 21.84 km^2 of the nearshore environment around Maui.

Spatial variables

Depth measurements were recorded at 5 minute intervals for each benthic segment. Multiple measurements were averaged for each benthic segment, and segment depths were again averaged to calculate a single measure of average depth for each reef unit. Shortest distances between end points of benthic segments to the shoreline and to the nearest pour point were calculated. Their respective measurements were averaged for each reef unit (Table A1.3).

Natural coastal variables

Natural coastal variables describe physical characteristics of the nearshore environment. Water temperature readings were recorded at 5 minute intervals for each benthic segment. Wave variables representing monthly environmental conditions of waters were assembled from the National Renewal Energy Laboratory (2011) and organized into 5 km by 5 km (25 km^2) grid cells in the coastal environment (Table A1.3). Waves may be natural disturbances on the community structure of coral reefs, and their varying strength and patterns affect morphology and organismal assemblages of coastal habitats (Dollar 1982; Kaandorp and Kübler 2001). We considered multiple metrics to capture different wave characteristics. First, wave significant height is the distance from the trough to crest of waves, and greater wave height may represent greater potential disturbance to reef structures at greater depth (Gourlay 2011). Next, wave energy period is the amount of time it takes two consecutive wave crests to pass a fixed point, and shorter period may reflect more frequent impacts on reef structure (Gourlay 2011). Finally, wave power density measures the amount of energy generated by waves, with greater power potentially acting as a disturbance that may agitate reef communities (Gourlay 2011). We first summarized values of wave measures by annual averages, by dry season (May – October), and by wet season (November – April) (Table A1.3) within each of the grid cells, resulting in a total set of 9 wave variables. Each benthic segment was attributed with the grid cell values in which they occurred, and values for segments were averaged to determine a single value for each reef unit.

Characterizing spatial linkages between inland and coastal data

To test the idea that greater proximity of reef units to pour points leads to greater influence of landscapes drained by rivers on reef units, we created buffers of varying widths around each reef unit and summarized landscape information for pour points in buffers following Jouffray et al. (2014). Pour point catchments were associated with a reef unit when pour points fell within distances defined by 1 km-, 3 km-, 5 km-, and 10 km-wide buffers. Areas drained by all catchments with pour points in buffer distances were summed to yield a total drained area, and other inland metrics were summarized by area-based weighting for further analysis.

Windward and leeward designations

Another idea we tested is that hydrology is a driver of inland and coastal linkages that may affect the extent of potential connections. We expected that influences of landscapes receiving more precipitation around Maui may be stronger and/or more easily detected in coastal environments. To account for varying precipitation levels experienced on windward and leeward sides of Maui, we used a demarcation based on stream discharges developed by the United States Geological Survey (USGS, Yamanaga 1972) that split the island into generally wetter (windward) and drier (leeward) sides (Figure 1.1). Some analyses (described below) were conducted within these regions to identify potential differences across the island.

Analyses

Variable reduction

To select minimally redundant variables that may explain coastal habitat conditions, we assessed groups of inland anthropogenic, inland natural, and coastal natural variables independently. We first assessed minimum, average, and maximum values of variables in each group and eliminated variables that did not vary substantially on Maui. Percentage variables were then arcsine square root transformed, and continuous variables were natural log transformed for additional analyses. For the inland anthropogenic and inland natural variable groups, Pearson pairwise correlations were assessed among remaining variables. When pairs of variables were found to be highly correlated ($|r| \geq 0.65$), one was eliminated based on ecological interpretability. Principal component analysis (PCA, Legendre and Legendre 2012) was performed to identify major variables describing wave characteristics of the natural coastal variables. To aid in interpretation, Varimax rotation was applied to resulting axes. These steps resulted in a subset of variables used for further analysis.

Redundancy analysis (RDA)

To estimate the relative influences of the three variable groups (inland natural, inland anthropogenic, coastal) and to investigate overall inland influences compared to coastal influences on reef habitat metrics, we used redundancy analysis (RDA; e.g., Borcard et al. 1992) with the program CANOCO 5 (Leps and Smilauer 2003). We ran the analysis using summaries of landscape factors in multiple pour points catchments varying distances from reef units (1 km, 3 km, 5 km, 10 km) to characterize how proximity of catchments could influence proportional variance explained by each variable group.

Stepwise multiple linear regression (MLR)

Stepwise multiple linear regression (MLR) was conducted to identify the most important environmental variables and their directionality in predicting each of the coastal habitat metrics. Model selection for each habitat metric was performed using Akaike Information Criterion (AIC) (Burnham and Anderson 2002). A standardized regression coefficient (β) was calculated to evaluate the relative strength of variables selected for inclusion in the models predicting coastal habitat metrics. Regressions were performed for the entire island, the windward (wet) side, and the leeward (dry) side to assess the role of hydrology in establishing linkages between inland and coastal systems.

Results

Description of study region

Inland and coastal variables

Areas of pour point catchments on Maui are relatively small, ranging from 0.08 km^2 to 160.29 km^2 with a mean of 7.64 km^2 (Table A1.4). Catchment slopes on Maui, in contrast, are steep, ranging from 0.27% to 31.20% with a mean of 14.77% (Table A1.4). Higher gradients may contribute to inland inputs being delivered to coastal environments quickly following precipitation events, leading to disturbances of greater magnitude and/or intensity than from streams with lower gradients. Hydrologic soil grouping values for catchments ranged between 1.00 and 3.65 (on a scale of 1 to 4, 1 being the lowest infiltration rate), with a mean of 2.11 (Table A1.4). Annual precipitation also varied across catchments, ranging from 279.63 mm/yr to 8403.95 mm/yr, with a mean of 2497.48 mm/yr (Table A1.4). Means and ranges of inland natural landscape factors were similar between the windward and leeward sides of Maui, except for precipitation. The average value for catchments on the windward side is 3175.64 mm/yr, and the average value for catchments on the leeward side is 1670.46 mm/yr (Table A1.4).

Developed land cover in Maui catchments averaged 4.5% and ranged from 0.00% to 40.07% (Table A1.5), and agricultural land cover in Maui averaged 9.49% and ranged from 0.00% to 84.02% (Table A1.5). These patterns were similar on the windward vs. leeward sides of the islands, as were patterns for road crossing density. Ditch length density varied, however; catchments on the windward side of the island had greater ditch length density (average of 391.74 m/km^2, Table A1.1) than catchments on the leeward side (average of 213.53 m/km^2, Table A1.2). Other inland anthropogenic disturbances were relatively similar in average values and ranges between windward and leeward sides (Table A1.1, Table A1.2).

Reef units around Maui were on average 373.68 m from the shoreline, 1385.52 m from pour points, and 14.16 m deep (Table A1.6). While some coastal factors are similar for reef units on the windward and leeward sides, some metrics differed substantially. Most notably, annual wave power density was much higher on the windward side (11.53 kW/m) vs. the leeward side (4.14 kW/m, Table A1.6). While the differences in average wave power density between the wet season and dry season on the windward side is 9.73 kW/m, seasonal differences are less extreme on the leeward side (1.46 kW/m, Table A1.6). Distance to pour points is on average 858.84 m on the windward side but 1803.23 m on the leeward wide (Table A1.6), and greater distance could influence the strength of influences of inland landscape factors on coastal habitats on the leeward side vs. the windward side of Maui (Figure 1.1).

Reef habitat metrics

Coastal habitat metrics also varied around Maui. Around the entire island, percent coral cover in reef units averaged 14.05%, stressed coral cover averaged 1.46%, macroalgae cover averaged 11.17%, and crustose coralline algae cover averaged 4.55% (Table A1.7). Some metrics also differed on the windward vs. leeward sides. Percent sand cover averaged 30.12% across the island, with less sand cover observed on the windward side than the leeward side (16.19% vs. 41.17% respectively, Table A1.7). Additionally, crown-of-thorns starfish density was higher (0.00014 vs. 0.000028 #/m^2) and urchin density was lower (0.00014 vs. 0.0081 #/m^2) on the windward vs. leeward side of the island (Table A1.7).

Identifying variables important to coastal habitats

Four minimally redundant natural inland variables were selected for further analysis based on investigation of correlations among five natural inland variables: catchment area, catchment slope, mean annual rainfall, and average and minimum hydrological soil grouping (Table A1.3). Minimum hydrological soil grouping was eliminated from further analysis due to its high correlation with average hydrological soil grouping. Investigation of correlations among 14 inland anthropogenic variables also resulted in four minimally redundant anthropogenic variables retained for further analysis: urban land cover, agricultural land cover, ditch length density, and road crossing density (Table A1.4). Urban land cover and agricultural land cover were selected for their potential to alter catchment hydrology and to be sources of pollution and nutrient inputs. Road crossing density (which characterizes stream network fragmentation) and ditch length density (which characterizes water diversions in catchments) were selected for potential influence on hydrology.

In the coastal factor grouping, PCA of nine variables representing multiple aspects of wave characteristics resulted in one axis which explained 86.5% of the total variation (Table A1.8). This outcome shows high redundancy among wave characteristics, and because of this, we selected a single variable, annual wave power density (Ann_wef), for further analyses based on its ecological interpretability. Three other variables were used to characterize coastal conditions including distance from shore, distance from catchment pour point, and bathymetric depth. These variables and annual wave power density were not highly correlated with each other (Table A1.5).

Relationships between environmental variables and coastal habitat metrics

Redundancy analysis results

Redundancy analysis (RDA) showed that inland natural, inland anthropogenic, and coastal groupings of variables explained a substantial amount of variation in coastal habitat metrics. When pour points occurred within 1 km of reef units, 38.7% of total variation in reef metrics was explained; when pour points occurred within 3 km of reef units, 40.2% of total variation was explained; and when pour points occurred within 5 km of reef units, 39.6% was explained. Amount of explained variance dropped when catchments within 10 km of reef units were tested (32.4%), and because of this, regression analyses (described below) were conducted using landscape factors summarized within pour point catchments occurring 5 km from reef units.

Although RDA results showed that coastal variables explained the most variation in coastal habitat metrics of all variable groups tested for all 4 buffer extents (Table A1.9), our findings emphasize the importance of inland influences on reef metrics. Almost six percent of the variance in metrics was explained collectively by inland natural and inland anthropogenic factors for catchments with pour points occurring within 5 km of reef units (Table A1.9). We showed that as distance between the catchment pour points and reef units increased, the contribution of inland natural influences to explained variance increased while the contribution of inland anthropogenic influences decreased (Table A1.9). The greatest inland anthropogenic influence was detected 1 km from reef units; the greatest inland natural influence was detected 5 km from reef units (Table A1.9).

Stepwise multiple linear regression results

Using stepwise multiple linear regression (MLR), individual reef habitat metrics were predicted from environmental factors. For all study sites occurring around Maui, the best predicted habitat metric was habitat complexity ($R^2adj = 0.54$). Other well-predicted metrics ($R^2adj > 0.2$) include: percent sand cover ($R^2adj = 0.44$), crown-of-thorns starfish density ($R^2adj = 0.25$), percent coral cover ($R^2adj = 0.23$), and percent macroalgae cover ($R^2adj = 0.22$, Table 1.10). Reef metrics that were not well-predicted ($R^2adj < 0.2$) include stressed coral cover, crustose coralline algae cover, and urchin density (Table A1.10).

Coastal factors were selected more frequently as significant predictors of reef habitat metrics than inland natural factors and inland anthropogenic factors. Coastal factors significantly ($p<0.1$) predicted 7 metrics, inland natural factors predicted 4 metrics, and inland anthropogenic factors predicted 2 metrics (Table A1.10). Of all coastal factors, annual wave power density significantly predicted the most metrics. It was positively associated with habitat complexity and crown-of-thorns starfish density and negatively associated with percent sand cover (Table A1.10). Other important coastal predictors were depth and average distance from pour points. Depth was negatively associated with habitat complexity and percent coral cover and positively with percent sand cover (Table A1.10). Average distance from pour points was positively associated with percent coral cover (Table A1.10).

Inland natural and anthropogenic factors were associated with several reef habitat metrics at the whole-island scale across Maui. Our best-predicted reef metric, habitat complexity, was negatively associated with rainfall and positively associated with pour point catchment area

(Table A1.10). Rainfall was also negatively associated with urchin density (Table A1.10). Agricultural land cover was a significant and positive predictor of two habitat metrics: percent macroalgae cover and crown-of-thorns starfish density (Table A1.10). In contrast, urban land cover, ditch length density, and road crossing density were never significant predictors of any reef habitat metrics at the whole-island scale (Table A1.10).

We further assessed results for the windward vs. leeward sides of Maui to identify potential differences that may be associated with different amounts of precipitation. Overall, 7 of 8 reef habitat metrics had more variance explained on the windward side than the leeward side of Maui; only percent sand cover was better explained on the leeward side (Table A1.10). Coastal variables significantly predicted 5 metrics on the windward side and 1 metric on the leeward side (Table A1.10), and inland natural variables significantly predicted 4 metrics on the windward side and 1 metric on the leeward side, suggesting that coastal habitat factors may be more strongly influenced by these landscape influences on the windward vs. leeward sides. In contrast to this, inland anthropogenic variables significantly predicted 4 metrics on both sides of Maui (Table A1.10). Agricultural land use was positively associated with coral cover on the windward side, and negatively associated with coral cover on the leeward side (Table A1.10). Agricultural land use was also positively associated with macroalgae cover, crown-of-thorns starfish density, and urchin density on the windward side (Table A1.10). Urban land use significantly predicted 3 reef metrics on the leeward side; it was negatively associated with habitat complexity and positively associated with sand cover and macroalgae cover (Table A1.10).

Discussion

Our results identified factors that contribute to linkages between inland and coastal habitats. We showed how associating a unit in the coastal environment with potential inland influences at various distances alters the strength of relationships, and additionally demonstrated how relationships can vary with amount of precipitation received by catchments. In support of our first objective, we selected a set of minimally redundant and ecologically meaningful variables likely to influence coastal habitats, and we addressed our second objective by quantifying the relative influences of three groupings of those variables (inland natural, inland anthropogenic, and coastal factors) on 8 reef habitat metrics that reflect coastal habitat conditions. Coastal factors explained the most variance in reef habitat metrics, yet inland influences derived from river pour points up to 5 km from reef units also explained substantial amounts of variation in coastal habitats. Inland anthropogenic influences are the greatest 1 km from reef units and decrease with the inclusion of more catchments farther away from reef units, while inland natural influences increased as more catchments were considered up to 5 km. For our final objective, we used multiple linear regression to independently predict reef metrics from inland natural, inland anthropogenic, and coastal variables to identify the most influential predictors and assess how hydrology (as reflected by substantially different amounts of precipitation on windward vs. leeward Maui) may affect associations between reef metrics and predictors. While 5 out of 8 reef habitat metrics were well-predicted across the entire island of Maui, we also observed that more reef habitat metrics were significantly predicted on the windward side than the leeward side of Maui by coastal and inland natural variables. This was not the case for inland anthropogenic variables, which predicted 4 out of 8 reef habitat metrics on both the windward side and leeward side. These findings underscore linkages between inland anthropogenic influences and coastal habitats, which has particular relevance for understanding and managing landscape-derived disturbances on reefs in Hawaii.

Relative influence of coastal, inland natural, and inland anthropogenic groupings

Based on results of the redundancy analysis, coastal factors as a group explained more variance in the full set of reef habitat metrics than the inland factors in our study region. This result is not unexpected given proximity and the role of natural coastal factors, such as wave characteristics and bathymetric depth, in determining benthic habitat characteristics. For example, Dollar (1982) tested for effects of wave energy on coral reef communities throughout Hawaii and showed that physical disturbances from waves are dominant drivers of coral community structure. Additionally, depth is known to affect wave exposure of benthic habitats and light intensity through the water column, thus indirectly influencing morphology and biology of coastal habitats (Kaandorp and Kübler 2001).

We also observed that inland influences explained a portion of reef habitat variation, a finding that also follows those of other studies describing relationship between coastal habitat conditions and inland landscape characteristics. In the US Virgin Islands, Oliver et al. (2011) found that percent impervious surface in watersheds was negatively associated with percent coral cover. In the main Hawaiian Islands, Rodgers et al. (2012) identified a strong, positive correlation between a watershed health index and reef habitat index that were developed separately. Both studies showed how measures of coral reef health are negatively associated with disturbed landscapes in proximate watersheds. Our findings build on that understanding, and we additionally show how distance may influence relationships. We showed that relationship strength between overall inland influences and coastal habitat conditions was largely consistent for pour points within 5 km of reef units, but the importance of different types of influences varied with distance. Most notably, amount of variance explained by inland anthropogenic influences was greatest 1 km from reef units. In contrast, the amount of variance explained by inland natural influences was greatest 5 km from reef units. This could in part be due to inland anthropogenic influences having more localized impacts on habitats that are in close proximity, i.e., within 1 km. To our knowledge, no other studies have explicitly tested for distances in exploring landscape-scale effects of inland influences on coastal habitats for multiple watersheds over a large heterogeneous region.

Influence of landscape factors on individual reef habitat metrics

We used environmental variables to predict each of the reef metrics individually, and the findings illustrate complex interrelationships between landscape factors and coastal habitats. For the 5 best-predicted metrics at the whole-island scale, habitat complexity and macroalgae cover were predicted by inland natural variables, while macroalgae cover and crown-of-thorns starfish density were predicted by inland anthropogenic variables. This result shows the complexity of inland linkages to coastal habitats and highlights greater sensitivity of some metrics over others to inland disturbances. Coastal habitat conditions are often characterized by physical and biological metrics as synthesized by Diaz et al. (2004) in their review of the state-of-knowledge in classifying and evaluating coastal habitat quality. In addition, they emphasize that choice of most effective metrics should vary with research or management interests. In our case, metrics associated most strongly with inland anthropogenic variables are biological (i.e., macroalgae cover and crown-of-thorns starfish density), as opposed to metrics that are largely physical (i.e., habitat complexity, sand cover). Our identified association between biology of coastal habitats and anthropogenic land use follows that of Mallin et al. (1993); they showed increased primary production in coastal habitats with heavily agricultural catchments throughout the Neuse River Estuary in North Carolina, USA. Similarly, Babcock et al. (2016) reported on outbreaks of crown-of-thorns starfish after rain events at Australia’s Great Barrier Reef, with rain events facilitating nutrient inputs from the landscape from various anthropogenic practices including fertilizer application. These results have particular relevance for understanding how reef habitat metrics that represent different aspects of the coastal environment may respond differently to various predictors. Our results highlighted the greatest inland disturbances to Maui's coastal habitats and the most sensitive biological attributes of those habitats, providing useful information for conservation of Maui's coastal habitats as well as guidance for efforts in other regions. Specifically, this result highlights greater sensitivity of some metrics. A manager of coastal habitats may consider those reef metrics associated most strongly with inland anthropogenic variables as indicators of inland disturbances.

Of all variable groupings tested, coastal variables including annual wave power density, depth, and distance to pour point were significant predictors of 4 out of the 5 well-predicted reef habitat metrics across the island of Maui. Jokiel et al. (2004) showed the importance of wave characteristics on the main Hawaiian Islands as major natural factors influencing reef structure, a conclusion that follows our finding at the whole-island scale, where wave power density was associated with habitat complexity. Jokiel et al. (2004) also showed the importance of depth by characterizing how reef communities found at various depths differed in composition and in their response to changes in environmental conditions, which supports our observation of depth being negatively associated with habitat complexity and coral cover. This is explained by depth being a landscape control of the major environmental parameters (i.e., light and hydrodynamics) in determining community structure of coastal benthic organisms (Kaandorp and Kübler 2001). Glynn (1985) suggested that outbreaks of crown-of-thorns starfish in the tropical eastern Pacific region occur with major disturbances such as strong wave events associated with El Niño, which may partially explain the positive relationships we observed between wave power density and crown-of-thorns starfish density. Greater average wave power density could suggest an area of the coastal environment being subjected to greater physical disturbances. Friedlander and Parrish (1998) found that coral community diversity and evenness in Hanalei Bay of Kauai, Hawaii, were related to distance to the river mouth, which is supported by the association we detected between distance to catchment pour points and coral cover.

Inland characteristics also influenced coastal habitats, with rainfall, catchment area, and agricultural land cover identified as significant predictors of select habitat metrics. We showed that rainfall is negatively associated with habitat complexity, a finding that follows Milliman and Meade (1983) who estimated the quantity of inland-sourced sediments delivered to the coast was driven strongly by precipitation and area of the draining catchment. Our results additionally follow those from a synthesis from Fabricius (2005), which describes that runoff associated with agriculture and urbanization affects coral reef population dynamics –specifically, increases in macroalgae and crown-of-thorns starfish.

We saw further evidence for connections between inland and coastal systems by looking at relationships between significant predictors and reef habitat metrics and assessing how findings differed between the windward and leeward sides of Maui. Coastal and inland natural variables were significant predictors of reef habitat metrics much more frequently on the windward side than leeward side, suggesting that reef habitats on the windward side are subjected to more influence from the coastal and inland natural variables that we tested in our study. This could be in part attributed to greater amounts of precipitation on the windward side that flushes potentially more catchment-derived materials into the open water environment (Rodgers et al. 2012). Additionally, all reef metrics were better predicted on the windward side except sand cover. Infrequent precipitation events can be associated with increased concentration of sediments in runoff from rain events (Langbein and Schumm 1958), resulting in rain events on the leeward side transporting greater quantities of sediments to the coast. In addition, we noted that inland anthropogenic variables predicted the same number of reef metrics across the windward and leeward side of Maui. Our finding suggests that agricultural land cover may be the primary disturbance to coastal habitats on the windward side, and urban land cover may be the primary disturbance on the leeward side. Though specific mechanisms by which inland anthropogenic variables influence reef habitats are still unclear, it is worth noting the importance of urban land cover as a significant predictor on the leeward side despite that the windward catchments have greater amounts of urban land cover. The linkage between inland and coastal habitats are complex, but it is evident that the connection is in part driven by hydrology.

Development of a coastal spatial framework

Findings from our research could inform development of a spatial framework, which accounts for how inland influences are expressed in the coastal environment. First, inland natural and inland anthropogenic influences from pour points 5 km from reef units in our study explain the greatest amounts of variation in reef habitat metrics. A hypothetical spatial framework in the coastal environment of our study region could weigh inland natural characteristics of catchments with pour points falling within 5 km of a coastal spatial unit more heavily than catchment pour points that are farther than 5 km. Second, compared to inland natural factors, inland anthropogenic factors are best detected from pour points that fall within 1 km of reef units. Spatial units within 1 km of pour points would be subjected to the strongest inland anthropogenic influences by weighing them more heavily than those more than 1 km away. Lastly, we saw evidence of dominant drivers varying with hydrology, and that more variance was explained on the windward side and the leeward side. Therefore, catchments on the windward side would be assigned greater weight than catchments on the leeward side. The spatial relationships we described would be considered when extrapolating the relative catchment influence in the coastal spatial units. Improved understanding of linkages between inland and coastal systems is the basis that would enable attribution of information to meaningful spatial units (Wang et al. 2016). As coastal and marine spatial planning becomes a growing priority in the United States for structured decision making in coastal resource management (Craig 2015), our study identified elements that would aid in the development of a framework that allows for the inventory and management of spatial information in the coastal environment.

Conclusion

The results of our study show that inland landscapes of Maui influence coastal habitat conditions, as observed in the amount of variance in reef habitat metrics explained by inland variables. In particular, urban and agricultural land cover are the most influential landscape disturbances that we tested. Also, the spatial relationships from our findings can be referenced to develop an ecologically meaningful spatial framework to characterize linkages between inland landscape and the coastal environment. Once established, spatial frameworks would enable the creation of spatial units that allow for the attribution and organization of information in consistent, comparable manners. Our study in Maui demonstrated the potential value of extending the application of the landscape approach from inland systems to the coastal environment, to aid in identifying areas of coastal reef habitats that are threatened by inland disturbances. The differential outcomes in the role of hydrology affecting the strength of relationship between inland characteristics and the various coastal habitat metrics suggest that further research on the relationships between the landscape and the coastal environment is still needed to fully characterize how inland influences affect coastal habitat across large spatial extents. In particular, different regions and other coastal habitat types of the world may have similar or dissimilar trends. This could be due differential levels of sensitivity of the coastal habitat of interest, as well as different environmental conditions such as amount of mean annual rainfall received in proximate catchments. Our study improves understanding of spatial relationships between inland characteristics and coastal habitats in Maui and contributes to the development of a potential spatial framework in the coastal environment by highlighting the factors that could facilitate linkages between inland and coastal systems, and characterizing how that relationship may alter with proximity.

APPENDICES

APPENDIX 1.A:

Tables

Table A1.1. Code, units, date, and source for inland natural variables.

Variable	Code	Units	Date	Source
Catchment area	Area	km^2	2005	Tingley et al., in prep
Catchment slope	Slope	%	2005	Tingley et al., in prep
Mean annual rainfall	Rainfall	mm/yr	2015	Frazier et al. 2015
Average hydrological soil grouping[1]	Soil		1995	SSURGO[2]
Minimum hydrological soil grouping[1]	Soil_min		1995	SSURGO[2]

1. On a scale of 1 to 4, 1 being the lowest infiltration rate
2. SSURGO (Soil Survey Geographic Database, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627)

Table A1.2. Code, units, date, and source for anthropogenic variables.

Variable	Code	Units	Date	Source
Urban landscape influences				
Developed impervious surface	Imperv	%	2005	CCAP[1]
Developed (high intensity)	High	%	2005	CCAP[1]
Developed (medium intensity)	Med	%	2005	CCAP[1]
Developed (low intensity)	Low	%	2005	CCAP[1]
Developed (open)	Open	%	2005	CCAP[1]
Developed (all)	Urban	%	2005	CCAP[1]
Utility pipeline length density	PipesL	m/km^2	1983	Hawaii OP[2]
Percent golf course surface cover	Golf	%	1993	Hawaii OP[2]
Population density	Pop	$\#/km^2$	2010	US Census[3]
Road length density	RoadL	km/km^2	2014	US Census[3]
Agricultural landscape influences				
Cultivated crops	Crops	%	2005	CCAP[1]
Pasture/hay	Pasture	%	2005	CCAP[1]
Agriculture (combined cultivated crops and pasture/hay)	Ag	%	2005	CCAP[1]
Former plantations				
Percent of surface that was once used for pineapple and/or sugarcane production	Ex_ag	%	1989	Hawaii OP[2]
Point source disturbances				
Comprehensive Environmental Response, Compensation, and Liability Information System site density	CERLIS	$\#/km^2$	2014	EPA[4]
Permit Compliance System site density	PCS	$\#/km^2$	2014	EPA[4]
National Pollutant Discharge Elimination System (NPDES) site density	NPDES	$\#/km^2$	2014	EPA[4]
Underground injection well density	UIC	$\#/km^2$	2010	Hawaii DOH[5]
Toxic release inventory site density	TRI	$\#/km^2$	2014	EPA[4]
All EPA site density	EPA	$\#/km^3$	2014	EPA[4]
Stream fragmentation				
Road crossing density	RoadsX	$\#/km^2$	2014	US Census[3]
Ditch intersection density	DitchX	$\#/km^2$	2004	Hawaii DAR[6]
Dam density	Dams	$\#/km^2$	2010	ACOE[7]
Ditch length density				
Ditch length density	DitchL	m/km^2	2004	Hawaii DAR[6]

Table A1.2. (cont'd)

303D listed streams

Percent of upstream network classified as 303D stream with measured TMDL	303d	%	2012	EPA[4]

1. CCAP (Coastal Change Analysis Program, http://www.csc.noaa.gov/digitalcoast/data/ccapregional/)
2. Hawaii OP (Hawaii Office of Planning http://planning.hawaii.gov/)
3. TIGER US Census (Topologically Integrated Geographic Encoding and Referencing, www.census.gov/geo/maps-data/data/tiger-line.html)
4. EPA (US Environmental Protection Agency, http://health.hawaii.gov/cwb/site-map/clean-water-branch-home-page/integrated-report-and-total-maximum-daily-loads/)
5. Hawaii DOH (Hawaii State Department of Health, http://hawaii.gov/health/)
6. Hawaii DAR (State of Hawaii Department of Aquatic Resources, http://dlnr.hawaii.gov/dar/)
7. ACOE (US Army Corps of Engineers, http://www.usace.army.mil/)

Table A1.3. Code, units, date, and source for all compiled coastal variables.

Variable	Code	Units	Date	Source
Spatial variables				
Distance from shore	Dist_shore	m		calculated
Distance from pour point	Dist_pp	m		calculated
Bathymetric depth	Depth	m		TDS; NOAA
Physical characteristics				
Water temperature	Temp	°C		TDS; NOAA
Wave significant height (annual average)	Ann_ssh	m	2011	NREL[1]
Wave significant height (wet season average)	Wet_ssh	m	2011	NREL[1]
Wave significant height (dry season average)	Dry_ssh	m	2011	NREL[1]
Wave energy period (annual average)	Ann_wep	s	2011	NREL[1]
Wave energy period (wet season average)	Wet_wep	s	2011	NREL[1]
Wave energy period (dry season average)	Dry_wep	s	2011	NREL[1]
Wave power density (annual average)	Ann_wef	kW/m	2011	NREL[1]
Wave power density (wet season average)	Wet_wef	kW/m	2011	NREL[1]
Wave power density (dry season average)	Dry_wef	kW/m	2011	NREL[1]

1. NREL (National Renewable Energy Laboratory, http://www.nrel.gov/gis/data_mhk.html)

Table A1.4. Minimum (min.), maximum (max.), mean, and standard deviation (SD) of inland natural variables across all (n = 182), windward side (n = 100), and leeward side (n = 82) pour point catchments draining the Maui landscape. Variable descriptions are included in the Methods section.

Variable (units)	Area[1] (km^2)	Slope[1] (%)	Rainfall[1] (mm/yr)	Soil[12]	Soil_min[12]
All (n = 182)					
Min.	0.08	0.27	279.63	1.00	1.00
Max.	160.29	31.20	8403.95	3.65	3.09
Mean	7.64	14.77	2497.48	2.11	1.60
SD	14.30	7.01	1863.63	0.58	0.61
Windward (n = 100)					
Min.	0.22	3.19	592.62	1.16	1.00
Max.	52.40	23.36	8403.95	3.58	3.00
Mean	6.57	11.54	3175.64	2.10	1.64
SD	8.58	4.63	1925.65	0.50	0.57
Leeward (n = 82)					
Min.	0.08	0.27	279.63	1.00	1.00
Max.	160.29	31.20	7009.57	3.65	3.09
Mean	8.94	18.71	1670.46	2.12	1.54
SD	19.07	7.41	1403.06	0.67	0.65

1. Indicates variables retained for further analysis.
2. On a scale of 1 to 4, 1 being the lowest infiltration rate

Table A1.5. Units, minimum (min.), maximum (max.), mean, and standard deviation (SD) values of inland anthropogenic disturbance variables across all pour point catchments (n = 182) draining the Maui landscape.

Variable	Units	Min.	Max.	Mean	SD
Urban landscape influences					
Developed impervious surface*	%	0.03	13.93	2.10	502.92
Developed (high intensity)*	%	0.00	4.68	0.15	2.68
Developed (medium intensity)*	%	0.00	8.04	0.52	0.58
Developed (low intensity)*	%	0.00	15.07	1.59	1.22
Developed (open)*	%	0.00	23.30	2.23	2.63
Developed (all)*	%	0.00	40.07	4.50	4.13
Utility pipeline length density*	m/km^2	0.00	1066.3	54.00	2.13
Percent golf course surface cover	%	0.00	24.42	0.35	2.13
Population density*	$\#/km^2$	0.00	685.12	34.33	166.36
Road length density*	km/km^2	0.00	42857	5010.51	88.38
Agricultural landscape influences					
Cultivated crops*	%	0.00	81.73	5.08	7.58
Pasture/hay*	%	0.00	56.12	4.40	12.19
Agriculture (combined Cultivated crops & Pasture/hay)*	%	0.00	84.02	9.49	8.45
Former plantations					
Percent of surface that was once used for pineapple and/or sugarcane production	%	0.00	77.75	1.42	15.10
Point source disturbances					
Comprehensive Environmental Response, Compensation, and Liability Information System site density	$\#/km^2$	0.00	0.26	0.00	0.45
Permit Compliance System site density	$\#/km^2$	0.00	2.63	0.07	0.00
National Pollutant Discharge Elimination System (NPDES) site density	$\#/km^2$	0.00	3.24	0.13	0.30
Underground injection well density	$\#/km^2$	0.00	1.00	0.01	0.32
Toxic release inventory site density	$\#/km^2$	0.00	<0.00	<0.00	0.13
All EPA site density	$\#/km^3$	0.00	5.4	0.2	0.02
Stream fragmentation					
Road crossing density*	$\#/km^2$	0.00	5.23	0.96	0.93
Ditch intersection density	$\#/km^2$	0.00	1.99	0.14	0.32
Dam density	$\#/km^2$	0.00	1.38	0.02	0.07
Ditch length density					
Ditch length density*	m/km^2	0.00	2871.80	311.45	486.04
303D listed streams					
Percent of upstream network classified as 303D stream with measured TMDL	%	0.00	100	5.36	0.73

*Indicates variables retained for further analysis.

Table A1.6. Minimum (min.), maximum (max.), mean, and standard deviation (SD) of coastal habitat metrics of the reef units. Variable descriptions are included in the Methods section.

Variable (units)	Dist_shore (m)*	Dist_pp (m)*	Depth (m)*	Temp (°C)	Ann_ssh (m)*	Wet_ssh (m) *	Dry_ssh (m)*	Ann_wep (s)*	Wet_wep (s)*	Dry_wep (s)*	Ann_wef (kW/m)*	Wet_wef (kW/m)*	Dry_wef (kW/m)*
All (n = 52)													
Min.	23.55	156.42	6.16	24.83	0.28	0.26	0.3	7.32	7.43	6.84	0.40	0.35	0.53
Max.	2230.71	8267.57	20.27	26.86	2.02	2.44	1.72	10.42	9.68	11.22	20.1	30.08	11.38
Mean	373.68	1385.52	14.16	25.75	1.14	1.28	1.00	8.42	8.60	8.25	7.41	9.95	4.84
SD	367.08	1721.45	2.60	0.42	0.57	0.69	0.46	0.94	0.63	1.58	5.68	8.26	3.24
Windward (n = 23)													
Min.	121.71	322.48	12.42	24.97	0.86	1.00	0.72	7.69	8.50	6.84	3.80	5.32	2.23
Max.	2230.71	2430.54	20.27	26.07	2.02	2.44	1.61	8.49	9.68	7.30	20.10	30.08	10.13
Mean	431.15	858.84	15.13	25.47	1.53	1.79	1.27	7.92	8.85	6.98	11.53	16.38	6.65
SD	481.86	604.45	1.66	0.25	0.35	0.41	0.30	0.20	0.31	0.12	4.48	6.51	2.58
Leeward (n = 29)													
Min.	23.55	156.42	6.16	24.83	0.28	0.26	0.30	7.32	7.43	7.20	0.40	0.35	0.53
Max.	988.60	8267.57	16.64	26.86	1.99	2.26	1.72	10.42	9.63	11.22	17.20	23.02	11.38
Mean	328.10	1803.23	13.40	25.98	0.83	0.87	0.78	8.83	8.40	9.25	4.14	4.86	3.40
SD	241.12	2168.40	2.96	0.39	0.52	0.59	0.44	1.10	0.75	1.48	4.24	5.50	3.00

*Indicates variables retained for further analysis.

Table A1.7. Minimum (min.), maximum (max.), mean, and standard deviation (SD) of coastal habitat metrics of the reef units. Variable descriptions are included in the Methods section.

Variable (units)	C (%)	SC (%)	S (%)	MA (%)	CCA (%)	H*	COTS (#/m^2)	U (#/m^2)
All (n = 52)								
Min.	0.40	0.00	0.05	0.00	0.00	1.00	0.00000	0.00000
Max.	60.00	13.75	87.50	53.38	27.25	4.60	0.00066	0.15273
Mean	14.05	1.46	30.12	11.17	4.55	2.53	0.00008	0.00461
SD	16.03	2.72	26.03	15.54	5.40	0.82	0.00013	0.02195
Windward (n = 23)								
Min.	0.70	0.00	0.05	0.45	0.00	1.10	0.00000	0.00000
Max.	56.75	8.55	66.50	50.42	15.50	4.60	0.00066	0.00221
Mean	10.97	1.67	16.19	10.29	4.25	2.89	0.00014	0.00014
SD	13.68	2.51	18.48	13.99	4.75	0.74	0.00016	0.00046
Leeward (n = 29)								
Min.	0.40	0.00	6.80	0.00	0.00	1.00	0.00000	0.00000
Max.	60.00	13.75	87.50	53.38	27.25	3.80	0.00022	0.15273
Mean	16.49	1.30	41.17	11.86	4.79	2.25	0.00003	0.00815
SD	17.52	2.91	26.07	16.88	5.95	0.78	0.00006	0.02912

*On a scale of 1 to 6, 1 being the least complex and 6 being the most complex

Table A1.8 Results of the PCA of 9 coastal wave variables. PC1 shows the weight of each variable, and it explains 86.5% of the variation in wave variables. Variable descriptions are included in Table A1.3.

Variable	PC1
Ann_ssh	0.993
Wet_ssh	0.991
Dry_ssh	0.989
Ann_wef	0.988
Wet_wef	0.985
Dry_wef	0.984
Wet_wep	-0.417
Ann_wep	-0.934
Dry_wep	-0.937

Table A1.9. Percent of total explained variance by RDA predicting habitat variables from the 3 groups of variables (inland natural, inland anthropogenic, and coastal). Results include unique contributions from each group as well as their shared variances. Buffer widths indicate the distance between reef units and pour points, and inland factors were summarized for all pour point catchments within specified distances.

Variable Groups	1km buffer	3km buffer	5km buffer	10km buffer
Inland anthropogenic (A)	2.2	0.9	0.2	-0.8*
Inland natural (N)	3.0	3.7	5.6	2.9
Coastal (C)	25.9	21.5	26.0	11.9
A + N	0.6	3.2	1.2	2.0
N + C	3.8	2.4	-0.8*	15.2
A + C	3.0	7.0	2.1	11
A + N + C	0.3	1.6	5.3	-9.8*
Total explained	**38.7**	**40.2**	**39.6**	**32.4**

*Negative values can occur when random normal variables explain more variation than explanatory variables, and are treated as zeros for interpretation (Legendre 2008).

Table A1.10. Stepwise multiple linear regression results of best fit model characterizing relationships between environmental variables (Tables A1.1, A1.2, A1.3) and coastal habitat metrics (Table A1.7). Standardized β is shown in table, and predictor significance is noted for $p<0.05$ (**bolded**) and $p<0.1$ (*italicized*). Results shown are for reef units across the whole island (A), on the windward side (W), and on the leeward side (L) of Maui, Hawaii.

Metric	Extent	Adj. R^2	**Inland anthropogenic variables**				**Inland natural variables**				**Coastal variables**			
			Urban	Ag	DitchL	RoadX	Soil	Rainfall	Area	Slope	Dist_shore	Dist_pp	Depth	Ann_wef
H	A	0.543						**-0.52**	**0.24**				**-0.47**	**1.26**
	W	0.485											*-0.31*	**0.58**
	L	0.438	**-0.68**											
C	A	0.225										**0.37**	**-0.45**	
	W	0.679		**0.79**						**0.46**		*0.28*	**-0.49**	
	L	0.377		**-0.67**				**-0.81**						
SC	A	-												
	W	0.183							**-0.47**					
	L	-												
S	A	0.443											**0.38**	**-0.82**
	W	0.222												**-0.51**
	L	0.305	**0.58**											
MA	A	0.224		**0.50**					*0.23*					
	W	0.386		**0.62**					*0.30*					
	L	0.320	**0.59**											
CCA	A	-												
	W	0.285								*0.38*			**-0.48**	
	L	-												
COTS	A	0.245		**0.37**										**0.50**
	W	0.444		**0.63**									**-0.53**	
	L	0.248												**0.53**
U	A	0.095						**-0.34**						
	W	0.175		**0.46**										
	L	-												
Count of metrics affected	A		0	2	0	0	0	2	2	0	0	1	3	3
	W		0	4	0	0	0	0	2	2	0	1	4	2
	L		3	1	0	0	0	1	0	0	0	0	0	1

APPENDIX 1.B:

Figures

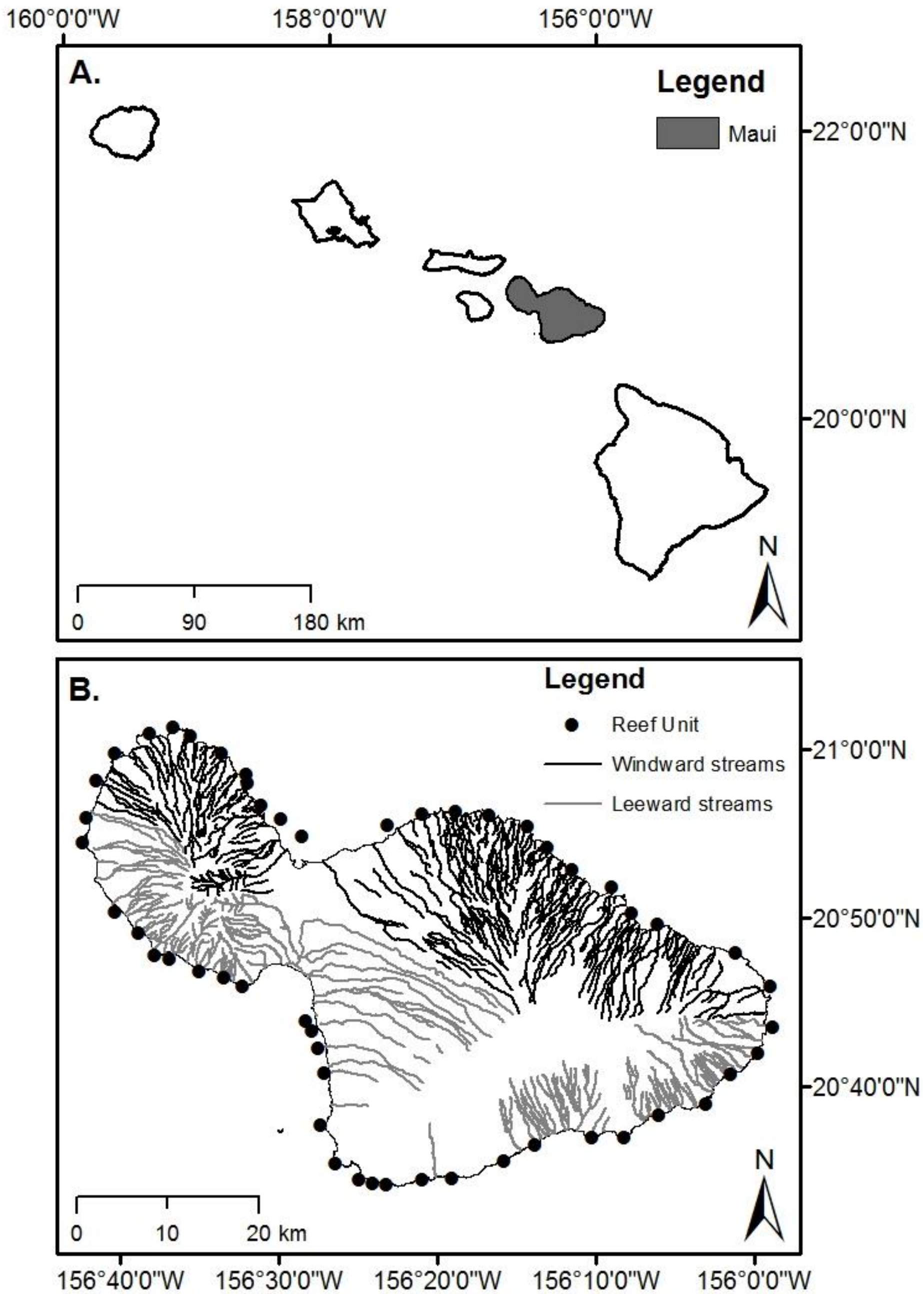

Figure B1.1. Location of Maui in the Hawaii archipelago (A), and location of 52 reef units and streams draining into the coastal environment around Maui (B).

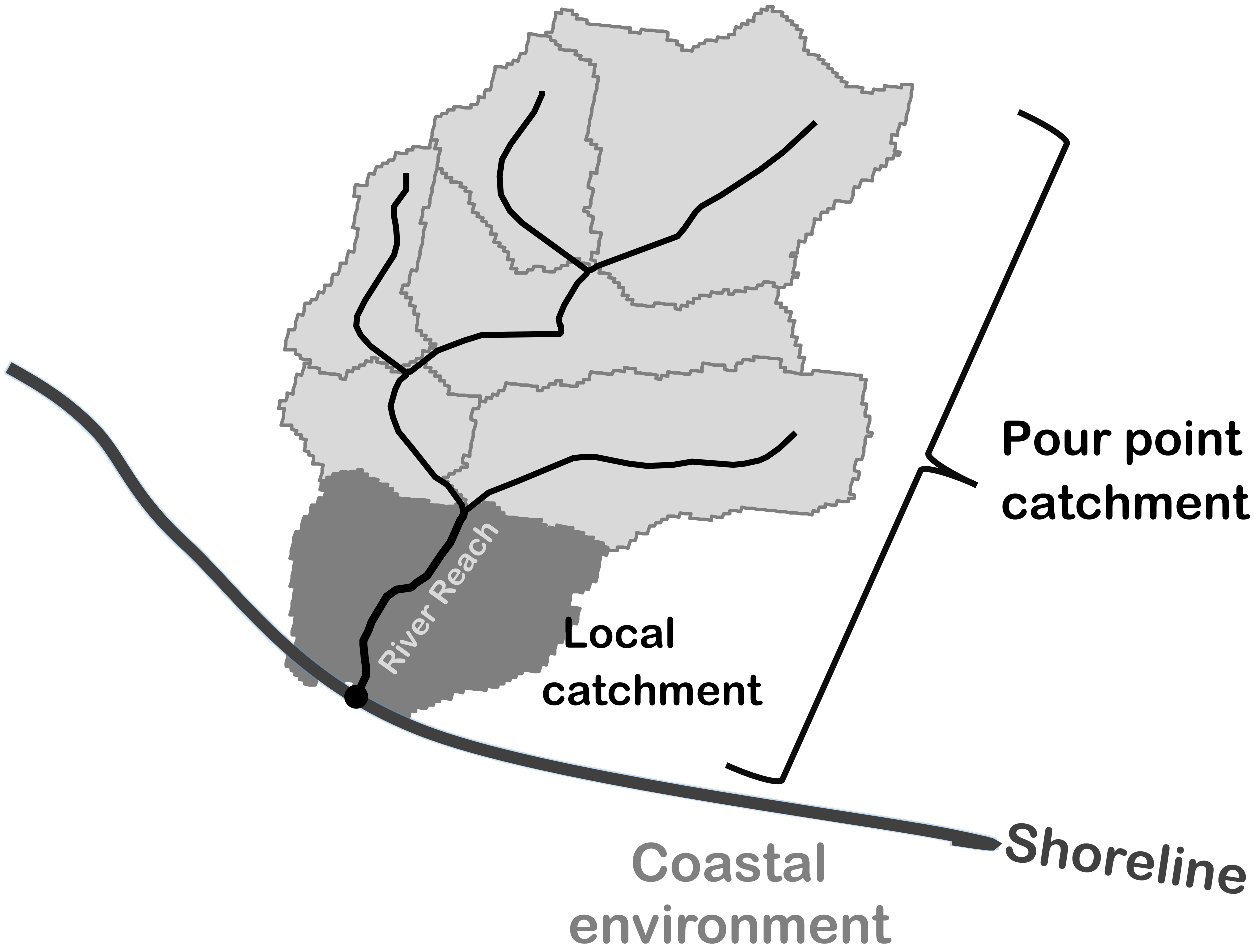

Figure B1.2. The local and network catchments of a river reach draining at a pour point into the coastal environment.

APPENDIX 1.C:

Supplemental tables

Table C1.1. Units, minimum (min.), maximum (max.), mean, and standard deviation (SD) values of inland anthropogenic disturbance variables across windward side pour point catchments (n = 100) draining the Maui landscape.

Variable	Units	Min.	Max.	Mean	SD
Urban landscape influences					
Developed impervious surface	%	0.08	11.06	2.59	2.74
Developed (high intensity)	%	0.00	4.50	0.14	0.54
Developed (medium intensity)	%	0.00	7.09	0.52	1.07
Developed (low intensity)	%	0.03	15.07	2.10	3.07
Developed (open)	%	0.00	23.30	3.18	5.13
Developed (all)	%	0.04	40.07	5.95	8.84
Utility pipeline length density	m/km^2	0.00	594.95	32.10	97.47
Percent golf course surface cover	%	0.00	24.42	0.47	2.74
Population density	$\#/km^2$	0.00	611.90	37.71	82.85
Road length density	km/km^2	69.20	42856	5839	8117
Agricultural landscape influences					
Cultivated crops	%	0.05	81.73	6.86	14.51
Pasture/hay	%	0.06	28.82	3.57	5.41
Agriculture (combined Cultivated crops & Pasture/hay)	%	0.11	84.02	10.43	16.24
Former plantations					
Percent of surface that was once used for pineapple and/or sugarcane production	%	0.00	0.00	0.00	0.00
Point source disturbances					
Comprehensive Environmental Response, Compensation, and Liability Information System site density	$\#/km^2$	0.00	0.00	0.00	0.00
Permit Compliance System site density	$\#/km^2$	0.00	2.63	0.07	0.32
National Pollutant Discharge Elimination System (NPDES) site density	$\#/km^2$	0.00	2.99	0.11	0.43
Underground injection well density	$\#/km^2$	0.00	0.00	0.00	0.00
Toxic release inventory site density	$\#/km^2$	0.00	0.00	0.00	0.00
All EPA site density	$\#/km^3$	0.00	5.26	0.18	0.74
Stream fragmentation					
Road crossing density	$\#/km^2$	0.00	4.86	0.98	0.92
Ditch intersection density	$\#/km^2$	0.00	1.99	0.17	0.36
Dam density	$\#/km^2$	0.00	1.38	0.03	0.15
Ditch length density					
Ditch length density	m/km^2	0.00	2295.25	391.74	469.41
303D listed streams					
Percent of upstream network classified as 303D stream with measured TMDL	%	0.00	100.00	6.87	24.90

Table C1.2. Units, minimum (min.), maximum (max.), mean, and standard deviation (SD) values of inland anthropogenic disturbance variables across leeward side pour point catchments (n = 82) draining the Maui landscape.

Variable	Units	Min.	Max.	Mean	SD
Urban landscape influences					
Developed impervious surface	%	0.03	13.93	1.50	2.48
Developed (high intensity)	%	0.00	4.68	0.17	0.64
Developed (medium intensity)	%	0.00	8.04	0.53	1.40
Developed (low intensity)	%	0.00	11.63	0.97	1.80
Developed (open)	%	0.00	9.86	1.07	1.87
Developed (all)	%	0.00	30.61	2.74	5.20
Utility pipeline length density	m/km^2	0.00	1066.27	80.70	221.18
Percent golf course surface cover	%	0.00	7.32	0.20	0.95
Population density	$\#/km^2$	0.00	685.12	30.20	95.05
Road length density	km/km^2	0.00	38680.79	3999.24	6247.97
Agricultural landscape influences					
Cultivated crops	%	0.00	47.31	2.91	8.11
Pasture/hay	%	0.00	56.12	5.42	11.04
Agriculture (combined Cultivated crops & Pasture/hay)	%	0.00	56.53	8.33	13.59
Former plantations					
Percent of surface that was once used for pineapple and/or sugarcane production	%	0.00	77.75	3.16	11.58
Point source disturbances					
Comprehensive Environmental Response, Compensation, and Liability Information System site density	$\#/km^2$	0.00	0.26	0.00	0.03
Permit Compliance System site density	$\#/km^2$	0.00	2.16	0.07	0.27
National Pollutant Discharge Elimination System (NPDES) site density	$\#/km^2$	0.00	3.24	0.16	0.47
Underground injection well density	$\#/km^2$	0.00	1.00	0.01	0.11
Toxic release inventory site density	$\#/km^2$	0.00	0.00	0.00	0.00
All EPA site density	$\#/km^3$	0.00	5.40	0.23	0.73
Stream fragmentation					
Road crossing density	$\#/km^2$	0.00	5.23	0.94	0.95
Ditch intersection density	$\#/km^2$	0.00	1.56	0.10	0.26
Dam density	$\#/km^2$	0.00	0.81	0.01	0.09
Ditch length density					
Ditch length density	m/km^2	0.00	2871.80	213.53	490.83
303D listed streams					
Percent of upstream network classified as 303D stream with measured TMDL	%	0.00	100.00	3.51	17.54

Table C1.3. Pearson pairwise correlations among inland natural variables. **Bolded** variables were included in the RDA. Variable descriptions are included in Table A1.1.

	Area	Slope	Rainfall	Soil	Soil_min
Area	1.00				
Slope	-0.09	1.00			
Rainfall	0.13	0.07	1.00		
Soil	-0.01	-0.38	-0.27	1.00	
Soil_min	-0.06	-0.52	-0.12	0.68	1.00

Table C1.4. Pearson pairwise correlations of inland anthropogenic variables. The **bolded** variables are included in the RDA. Variable descriptions are included in Table A1.2.

	Imperv	High	Med	Low	Open	Urban	Crops	Pasture	Ag	Pop	RoadL	DitchL	PipesL	RoadX
Imperv	1.00													
High	0.68	1.00												
Med	0.88	0.84	1.00											
Low	0.94	0.52	0.82	1.00										
Open	0.87	0.48	0.74	0.94	1.00									
Urban	0.95	0.61	0.86	0.98	0.97	1.00								
Crops	0.62	0.48	0.55	0.56	0.63	0.62	1.00							
Pasture	0.37	0.17	0.34	0.42	0.44	0.43	0.23	1.00						
Ag	0.59	0.42	0.54	0.56	0.64	0.61	0.82	0.73	1.00					
Pop	0.78	0.67	0.82	0.75	0.70	0.77	0.51	0.33	0.50	1.00				
RoadL	0.57	0.42	0.50	0.53	0.51	0.54	0.52	0.22	0.45	0.44	1.00			
DitchL	0.39	0.27	0.31	0.38	0.41	0.40	0.46	0.06	0.33	0.35	0.56	1.00		
PipesL	-0.02	-0.01	-0.06	-0.04	-0.04	-0.05	0.01	-0.08	-0.05	-0.22	0.17	0.35	1.00	
RoadX	0.22	-0.02	0.11	0.21	0.17	0.18	0.20	0.11	0.19	0.05	0.30	0.11	0.11	1.00

Table C1.5. Pearson pairwise correlations among coastal variables included in the RDA. Variable descriptions are included in Table A1.3.

	Dist_shore	Dist_pp	Depth	Ann_wef
Dist_shore	1.00			
Dist_pp	0.34	1.00		
Depth	0.26	0.23	1.00	
Ann_wef	-0.13	-0.13	0.53	1.00

LITERATURE CITED

LITERATURE CITED

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CHAPTER 2:

ASSESSING INFLUENCES OF INLAND LANDSCAPE FACTORS ON COASTAL HABITATS FOR IMPROVED CONSERVATION

Abstract

Coastal habitats offer a diversity of ecosystem services, but their condition and availability are in decline in part due to anthropogenic disturbances originating from the terrestrial landscape. Improved understanding of how inland anthropogenic disturbances affect coastal habitats is essential for their conservation. This chapter builds on findings from previous work that explores linkages between inland and coastal habitats to assess coastal habitat condition and characterize threats to ecosystem services and benefits around the island of Maui, Hawaii. We first identified catchments associated with discrete areas of the coastal environment (i.e., coastal grid cells) and then assessed the influence of landscape disturbances on grid cells by extending a measure of inland disturbances to coastal habitats. We accounted for catchment drainage area and proximity of multiple catchments to estimate the risk of degradation to coastal habitats, steps that have not been achieved in other studies. We next evaluated locations of ecosystem services and benefits provided by coastal habitats and assessed how they may be affected by the inland disturbances. Our findings show that a majority of coastal ecosystem services and benefits around Maui, including recreation, fishing/fisheries, and habitats for biodiversity are at risk of degradation from inland disturbances. We assessed relative risk of degradation of coastal areas and identified locations of high and low risks that could be used by resource managers for development of conservation actions. The spatially-explicit products (e.g., coastal spatial units and their associated cumulative disturbance scores) and our approach demonstrate a framework for assessing the condition of coastal habitats based on landscape disturbances that may be applicable for other regions.

Introduction

Coastal habitats offer a diversity of benefits that are ecologically and socially important (Martínez et al. 2007; Barbier et al. 2011). Habitat-forming organisms found in coastal areas such as coral, kelp, and mangroves serve as critical habitat for many taxa including fish, sea turtles, marine mammals, and waterfowl, contributing to high biodiversity in areas where these organisms are found (UNEP 2006, Allsopp et al. 2008). Many marine species utilize coastal habitats as foraging, spawning, and nursery areas (e.g., Weng et al. 2007, Erwin 1996), and amphidromous and anadromous fishes require access to coastal habitats to complete their life cycles (e.g., Bell 1999, McDowall et al. 2003). Coastal habitats provide ecosystem services that benefit humans, such as provision of fish for consumption, reduction of sediment erosion from beach fronts through mitigation of wave impacts, support of primary production and nutrient cycling, and creation of multiple recreational opportunities such as diving and surfing to residents of and visitors to coastal areas.

The ability of coastal habitats to provide ecological benefits and ecosystem services are in decline globally because they are increasingly subjected to anthropogenic disturbances (UNEP 2006). Many disturbances result from human activities in the marine environment including dredging and trawling of benthic habitats for commercial fisheries (Thrush and Dayton 2002; Waycott et al. 2009) and degradation of habitats (such as coral reefs) from direct swimmer and diver contact (Halpern et al. 2007; Smith and Edgar 2014). However, another major source of disturbances to coastal habitats originates from the terrestrial landscape (Crain et al. 2009), including human land uses such as urbanization and agriculture.

Influences of anthropogenic disturbances in terrestrial landscapes on coastal habitats are driven in part by hydrology. Natural hydrological connections are maintained by rainfall, but anthropogenic disturbances can disrupt linkages between landscapes and the coast, leading to changes in and potentially degrading nearshore coastal habitats (Halpern et al. 2008; Wehrly et al. 2013). Impervious surfaces like pavement, roads, and building roof tops could prevent water from infiltrating into soils, subsequently reducing groundwater input and increasing surface runoff (Paul and Meyer 2001). Such changes in hydrology as well as other consequences resulting from conversion of natural to developed landscapes can additionally alter coastal habitats. In rivers draining urbanized or agricultural landscapes, studies have documented altered thermal regimes (Allan and Castillo 2007); altered sediment dynamics (Milliman and Meaded 1983); and modified delivery of nutrients, toxics, and/or woody debris (Kennedy and Woods 2012), and these impacts to rivers can be directly transmitted to coastal habitats.

Across the globe, studies have shown links between degradation of coastal habitats and developed inland landscapes. Examples include eutrophication in Chesapeake Bay in the Mid-Atlantic (Boesch 1996), hypoxia in the Gulf of Mexico (Alexander et al. 2008), coral bleaching of the Great Barrier Reef of Australia (Wooldridge 2009), and algae blooms of Lake Erie in the Laurentian Great Lakes (Michalak et al. 2013). These studies show consequences of inland landscapes affecting conditions in nearshore coastal habitats, in some cases, highlighting mechanisms by which these linkages occur. However, as individual, regionally-specific studies, they offer only modest guidance for extrapolating results to other regions or for describing and comparing such linkages between inland and coastal habitats across large spatial extents (i.e., entire states, ecoregions, continents). These limitations reflect a gap in understanding of relationships between connected inland and coastal habitats and underscore a critical research. The explicit characterization of linkages between inland and coastal systems can aid in efforts to conserve coastal habitats from anthropogenic disturbances.

An established approach for associating units in the coastal environment with units in proximate terrestrial landscapes to consistently account for spatial relationships has yet to be developed, though a few recent, regional examples have attempted to do this. Finlayson and Shipman (2003) identified discrete areas throughout Puget Sound based on current patterns and assumed sources of sediments delivered from terrestrial sources. Also, Wang et al. (2015) created units in the Laurentian Great Lakes based on proximity to the shoreline and bathymetric depth. These studies, however, do not explicitly account for how the coastal environment could be affected by inland anthropogenic disturbances, or how that influence could vary from different hydrologic inputs. Additionally, drivers of coastal habitat condition are diverse. While factors such as proximity to inland anthropogenic disturbances may result in fairly similar degrees of influence globally, other factors, such as climate and geology, may promote or limit linkages between draining catchments and coastal habitats and may vary by region (Talley et al. 2006). Better understanding of spatial relationships between inland disturbances and coastal habitats as well as factors that can modify these relationships is integral to fully assess sources of degradation to coastal ecosystems (Halpern et al. 2008; Allan et al. 2013).

This study aids in meeting those needs by characterizing how coastal habitats around the island of Maui, Hawaii may be degraded by inland disturbances delivered by river catchments. Maui is an appropriate study system because it has wide variation in catchment characteristics, including a range in urban and agricultural land use, and its inland and coastal systems are hydrologically linked (Hsiao, this volume a). Additionally, Maui's unique inland and coastal habitats support endemic species that are a focus of conservation efforts. Using our understanding of spatial relationships developed in Hsiao (this volume a), our first objective of this chapter characterizes how discrete areas of the coastal environment may be spatially linked to sets of catchments based on proximity. Next, we characterize the influence of landscape disturbances on coastal habitats by extending a measure of inland river habitat disturbance resulting from anthropogenic land uses into coastal environments. Our final objective evaluates how ecosystem services and other benefits provided by coastal habitats may be affected by the inland-derived disturbances. This study shows an approach for assessing the condition of coastal habitats based on landscape disturbances, providing information that can aid in management and conservation of Maui's coastal resources and potentially those of other regions.

Methods

Study area

This study was conducted in Maui, Hawaii, the second largest island of the Hawaiian archipelago with a land area of 1,884 km^2 (Figure B2.1). The island was formed by the convergence of two volcanoes (West Maui Volcano, formed approximately 1.15 million years ago and East Maui Volcano, formed approximately 0.8 million years ago). Approximately 206 km^2 of coral reef habitat occurs in the nearshore region around the coastline of Maui, supporting 12 species of corals (Grigg 1983). These corals provide habitat for a diversity of fish and invertebrates, including many endemic species (Randall 1976, Friedlander et al. 2008). Nearshore coastal habitats around Maui are hydrologically linked to the island's landscape and are subjected to both natural and anthropogenic influences. Rain events rapidly alter sediment inputs, turbidity, and salinity of coastal receiving waters (Grigg 1995, Lau and Mink 2006). While coastal organisms are adapted to natural extremes in conditions (e.g., Bittler et al. 2014, Moura et al. 2016), anthropogenic activities can result in conditions that may be substantially different than those to which native organisms are adapted (DLNR DAR 2005, Storlazzi and Jaffe 2008). Additionally, both natural and anthropogenic influences originating within the marine environment (i.e., wave impacts, damage from ship anchors) may interact with and compound effects of inland influences on coastal habitats (Chabanet et al. 2005, Buma 2015).

Data collection and variable creation

Inland landscape data

Spatial units

Our inland spatial units are called "pour point catchments," which include all catchments draining from headwaters to the coastal environment by perennial and/or intermittent streams (Figure B2.2). Pour point catchments were derived from a stream layer developed in support of the Hawaii Fish Habitat Partnership (HFHP) by Tingley et al. (In Review). Confluence-to-confluence stream reaches form the basis of the HFHP stream layer, and a local catchment is the topographically-defined land area that drains directly to the stream reach (following Wang et al. 2011). Pour point catchments include the cumulative land area and river network upstream of the pour point draining into the coastal environment.

Inland disturbances

Inland disturbances are characterized by a cumulative habitat condition index (HCI) developed as a part of the 2015 National Assessment of Fish Habitats (http://fishhabitat.org/, Crawford et al. 2016). The HCI incorporates a combination of seven sub-indices that integrate major categories of disturbances to rivers and their catchments including: urban land use, agricultural land use, point source pollution, stream fragmentation, presence of former pineapple and sugarcane plantations, and ditch diversions within catchments. Subindices were composed of a variety of anthropogenic disturbance variables in each category, and the HCI used in this analysis is the linear combination of subindex scores. Specific variables and methods used to create each subindex and the HCI are described in Tingley et al. (In Review). Higher HCI scores indicate greater intensity of anthropogenic disturbance within catchments and to rivers draining catchments (Crawford et al. 2016), and values at catchment pour points were used to reflect potentially greater risk of disturbance to nearshore coastal habitats.

Coastal data

Spatial units

Coastal spatial units used in this analysis are 1 km^2 grid cells that are guided to 18.079° N, 160.89° W. The 1 km x 1 km dimension was a resolution determined from previous work which tested for the strength of associations between metrics reflecting reef habitat condition with inland influences over varied distances (Hsiao, this volume a). These coastal grid cells extend from the coastline of Maui to the 100-fathom depth, an estimate used by National Oceanic and Atmospheric Administration's Office of the Coast Survey as a surrogate for potential coral ecosystem distribution throughout the United States (Rohmann et al. 2005).

Coastal ecosystem services and benefits

Point locations of coastal ecosystem services and benefits observed around the island of Maui were digitized by the Hawaii Office of Planning (1989) from the U.S. Army Corp of Engineers “Maui Resource Atlas.” While some services and benefits provided by coastal habitats may have changed around Maui since 1989, this dataset is the only comprehensive and consistent coverage available to discriminate between different services provided by Maui’s coastal habitats. We grouped all services and benefits into three main categories to aid in interpretation: recreation, fishing/fisheries, and habitats for biodiversity (Table A2.1). Recreational activities include excursion boating, sailing, board surfing, body surfing, canoe paddling, and sport diving (e.g., snorkeling and scuba diving). Types of fishing include gill netting, pole and line fishing, troll and bottom fishing, as well as cultural practices such as torch fishing and spear fishing. Habitats for biodiversity include locations that support organisms including octopus, sea urchin, shark, and opihi –a shellfish that is a staple of the traditional Hawaiian diet. We also identified a subset of ecosystem services and ecological benefits that may be dependent upon coral reefs (Table A2.1), and by dependent, we suggest that the presence and health of coral reefs is very important to providing this service or benefit. These include sport diving, spear fishing, and habitat for octopus and opihi.

Associating pour point catchments with coastal grid cells

For this study, we assigned influences of pour point catchments to coastal grid cells based on proximity, an approach supported by findings from Hsiao (this volume a). We created 1 km, 5 km, and 10 km buffers around centroids of each coastal grid cell (Jouffray et al. 2014). Pour point catchments were associated with a coastal grid cell when they fell within the varied buffer distances, and we used these varied distances to modify the strength of inland disturbances on coastal grid cells (process described below).

Characterizing influences of cumulative inland disturbances on coastal habitats

A cumulative disturbance score was calculated for each coastal grid cell using the HCI scores of pour point catchments falling within 1 km-, 5 km-, and 10 km-buffer distances. This approach follows Halpern et al. (2008), a study that estimated impacts of inland disturbances on marine habitats based on proximity. We enhanced this concept to more directly account for distance between catchments and coastal habitats and for catchment area (i.e., greater catchment area is associated with greater river discharge and potentially greater input of disturbance to coastal habitats, following Wehrly et al. 2013). First, disturbance scores were calculated for coastal grid cells with pour point catchments that fall within 1 km buffers, pour point catchments between 1 km and 5 km buffers, and pour point catchments that fall between the 5 km and 10 km buffers. Scores from pour points within specified distances were combined into single scores based on weighting by catchment areas to yield up to three potential scores for each coastal grid cell. Next, a decay factor was applied to the catchment combined scores more than 1 km away from a coastal grid cell to account for the weakening impact of inland disturbances further away from coastal habitats (following results of Hsiao, this volume a). The decay factor was 0.1 for catchments from 1 km to 5 km away, and 0.01 for catchments greater than 5 km away from a coastal grid cell. Finally, separate scores were combined into the cumulative grid cell score, with influences standardized by area-based weighting. We rescaled the final values to range between 0 and 100, with low values indicating low levels of potential disturbances. We then assigned risk categories to each grid cell, by assigning equal numbers of cell in each of five categories: very low, low, moderate, high, and very high.

Characterizing risk of degradation from inland disturbances to ecosystem services and benefits

Locations of observed ecosystem services and benefits were spatially overlaid with the cumulative inland disturbance scores calculated for coastal grid cells. We then calculated the percentage of each ecosystem service and benefit subjected to the five risk categories of degradation from inland influences. Results were summarized by groups of ecosystem services and benefits (i.e., recreation, fishing/fisheries, and habitats for biodiversity) and by the subset that may be highly dependent on coral reefs. Finally, we calculated percentages of individual and groups of ecosystem services and benefits that fall in each of the five risk categories to assess which are the least and most at risk from inland disturbances.

Results

Pour point catchment areas of Maui range between 0.08 km^2 and 12.89 km^2 (Table A2.2). While the HCI ranges from 0.00 to 1.00 for catchments throughout the five main Hawaiian Islands, the index ranges from 0.00 to 0.41 for Maui catchments, suggesting low to moderate levels of anthropogenic disturbances within these pour point catchments.

Associating pour point catchments with coastal grid cells

A total of 1,461 coastal grid cells were created between the shoreline and 100-fathom depth around Maui (Figure B2.2). There are more grid cells on the west side than the east side of Maui as a result of generally shallower depths on the west and steeper drop offs on the east. Of the grid cells, 239 have catchment pour points within 1 km, 789 have closest catchment pour points within 5 km, and 402 have closest catchment pour points within 10 km (Figure B2.2). Forty coastal grid cells are further than 10 km from the closest pour point catchment (Figure B2.2).

Characterizing influences of cumulative inland disturbances on coastal habitats

Figure B2.3 shows locations of urban and agricultural land use on Maui, as well as the cumulative potential risk of inland disturbances on coastal habitats. Together, these provide insights as to how and why impacts vary throughout Maui's coastal habitats. Most notably, a majority of coastal units subjected to very high risk of degradation from inland influences are located near West Maui, where urban and agricultural land use are concentrated along the shore (Figure B2.3). Grid cells due west of the West Maui landscape range from very high to moderate risk of degradation from inland influences (Figure B2.3). In contrast, more coastal units in the southern and eastern coast of Maui are at low and very low risk of degradation from inland influences, where urban and agricultural land use are less common (Figure B2.3).

Characterizing risk of degradation from inland disturbances to ecosystem services and benefits

Ecosystem services and benefits are widely distributed around the nearshore coastal environment of Maui (Figure B2.4). While fishing and fisheries occur throughout nearshore waters, recreation-related ecosystem services are concentrated on the western vs. eastern side of Maui (Figure B2.5A and B). Locations of habitat for biodiversity, in contrast, are much more spatially disparate. Fewer locations in general occur on the southern vs. northern coast. In terms of specific organisms, octopus are predominantly on the northern and western coast, and opihi are concentrated on the northern and southeastern coast (Figure B2.5C). Services and benefits that may be directly dependent on coral reefs (i.e., sport diving, spear fishing, and habitats for octopus and opihi) are found widely around the island.

Our results also show that most ecosystem services and benefits occurring around Maui are at some risk of degradation from inland disturbances (Table A2.1). Across groups of services and benefits, 74% of locations that support recreation-related ecosystem services, 67% of fishing/fisheries locations, and 72% of habitats for biodiversity are at high or very high risk of degradation (Table A2.1). Within the recreation group, all locations of excursion boating and sailing, more than half of locations for board and body surfing, and half of locations for canoe paddling are in areas of very high risk of degradation (Table A2.1). Shell collecting is the only recreation service that predominately falls in areas of moderate risk (67%, Table A2.1). Within the fishing/fisheries group, all locations for bait fishing and most locations for torch fishing (95%), specialized fisheries (59%), and gill netting (58%) are at very high risk. Nearly half of all spear fishing locations and one-third of throw netting locations are at very high risk from inland disturbances. Most crabbing locations (56%) occur in areas of moderate risk, while troll and bottom fishing locations are distributed across areas of moderate (34%) and high (34%) risk (Table A2.1). Of habitats for biodiversity, those supporting sea urchin and shark, as well as a majority of octopus (94%) and seaweed (87%) habitat locations are at very high risk of degradation (Table A2.1). Opihi habitats are generally distributed across areas of moderate (31%), high (26%), and very high (27%) risk of degradation from inland disturbances (Table A2.1). The subset of ecosystem services and benefits that may be most dependent on coral reefs are largely at high (19%) and very high (47%) risk of degradation from inland disturbances (Table A2.1).

Discussion

In this chapter, risk of degradation to coastal habitats from inland disturbances was assessed around the island of Maui, Hawaii. We first characterized spatial linkages between units on the landscape (pour point catchments) and units in the coastal environment (coastal grid cells). This allowed us to quantify and visualize how influences from inland landscapes may change with distance from coastal regions. Next, we used condition of inland catchments and our understanding of spatial relationships between inland and coastal habitats to characterize risk of disturbances from inland sources on coastal habitats. This step accounted for inputs from multiple catchments and catchment drainage area. By incorporating area, a surrogate for the magnitude of river flows, we accounted for greater influences from larger catchments with more potential to facilitate disturbance to the coast (Wehrly et al. 2013), and we are currently not aware of other studies that have accounted for these factors. Last, we used this information with spatial locations of coastal ecosystem services and benefits around Maui to demonstrate how they may be at risk from inland disturbances. This step is similar to one from a study done throughout the Laurentian Great Lakes to assess sources of anthropogenic stressors in relation to ecosystem services (Allan et al. 2013), but we aren't aware of other efforts in marine systems. Results showed many locations supporting ecosystem services and benefits related to recreation, fisheries, and habitats for biodiversity at risk of degradation from inland influences. Collectively, our results demonstrate a framework for assessing condition of coastal habitats based on inland landscape disturbances as well as an application of the approach. Our outcomes tell us which habitats around Maui are most and least threatened, and by extension, which ecosystem services and benefits are at greatest risk. This knowledge can be used to improve our ability to conserve Maui's coastal habitats into the future.

Associating pour point catchments to coastal grid cells

Development of coastal grid cells from the Maui shoreline to the 100 fathom depth is similar to work done in the Laurentian Great Lakes, where researchers defined the region of the coastal environment that would be most strongly affected by inland influences (i.e., the tidal riverine coastal and tidal riverine open water zones in FGDC 2012; the coastal margin and nearshore zone in Wang et al. 2015). However, our designations are unique in that we subdivided this region to account for coastal habitats that may be variably affected by catchment pour points. Furthermore, pour point catchments associated with coastal grid cells were developed based on findings from Hsiao (this volume a). Specifically, we defined distances to weight catchment influence on grid cells based on the fact that the most variance was explained in coastal habitat metrics by inland anthropogenic influences within 1 km of those habitats while overall variance explained by both natural and anthropogenic inland influences was greatest when catchments were within 5 km of habitats (Hsiao, this volume a).

Characterizing influences of cumulative inland disturbances on coastal habitats

We also showed how the nearshore area of Maui is variably affected by inland influences. Because urban and agricultural land cover are concentrated on the western and northern coast of Maui, coastal grid cells adjacent to those areas are at greater risk of degradation. This outcome follows findings of both Halpern et al. (2008) and Wehrly et al. (2013) who characterize disturbance in coastal habitats from inland sources based on proximate developed landscapes. Our approach differs from these studies by additionally weighing catchment area and pour points at varying distances away from a coastal grid cell based on known relationships derived from Hsiao (this volume a).

We also accounted for magnified risk of degradation by the concentrated input of multiple catchments into the coastal environment, such as the coastal region around West Maui, where many catchments drain into the coast. Currently, we are not aware of another study that explicitly accounts for multiple catchments and weighs their relative influence by catchment area, a surrogate for stream flow that reflects a larger rivers' ability to drain larger areas of the landscape and potentially carry more materials into receiving waters than a smaller river.

Characterizing risk of degradation from inland disturbances to ecosystem services and benefits

We showed that a majority of the ecosystem services and benefits around Maui are at very high risk of degradation from inland disturbances. This finding follows the Millennium Ecosystem Assessment that reported a decline in ecosystem services within coastal habitats across the globe (UNEP 2006). Specifically, we considered three broad groups of ecosystem services and benefits in our assessment: recreation, fishing/fisheries, and habitats for biodiversity. First, regarding recreation, tourism is the largest sector of the Hawaiian economy, and recreation by tourists is heavily dependent on the condition and health of coral reefs. Marine-based recreation is estimated to contribute $304 million annually to the state’s economy (Cesar and van Beukering 2004), with over 80% of visitors participating in some form of recreation that involves the coastal environment such as surfing and snorkeling (Friedlander et al. 2005). Next, commercial fisheries in Hawaii's nearshore environment, which target at least 57 species of fish including multiple species of tuna, mahimahi, and ono, are valuated at approximately $16.4 million annually (Grafeld et al. 2017). Recreational fishing such as throw netting and pole and line fishing are activities also highly-valued by locals and visitors to Hawaii, and it is estimated that more individuals participate in recreational vs. commercial fishing (Smith 1993). Additionally, nearshore fisheries are culturally important in Hawaii, and Native Hawaiians have traditionally relied on catch from torch fishing and spear fishing for subsistence (Carl 2009). Finally, we also found that habitats for biodiversity are at risk of degradation from inland influences, a fact that will challenge the ability to conserve organisms that depend on these habitats from both current and future stressors. Reduced biodiversity infers the possibility of decreased resilience of an ecosystem to recover from disturbances as well as a reduction in their ability to support other services (Worm et al. 2006). With a projected reduction in coral cover expected to occur throughout the Hawaiian Islands (Bruno and Selig 2007), we may also expect a co-occurring reduction in availability of all the ecosystem services and benefits that depend on coral reefs, and this will impact aspect societal well-being unless actions are taken to conserve these systems (UNEP 2006, Barbier et al. 2011).

Our finding suggests that management actions that reduce the impacts of disturbance on the landscape draining to Maui’s coastal habitats could lessen the risk of degradation and protect the ecosystem services and benefits that those habitats provide. Based on results of the characterization of inland influences on coastal habitats, ecosystem services and benefits are disproportionately located in areas that are at risk of degradation from inland disturbances. This is in part due to their locations being near the coast which are more strongly influenced by inland influences due to greater intensity of human settlement. Intense use of coastal areas can result in generally higher demand for and access to coastal resources as well as specific impacts including shoreline development, shoreline hardening, and other infrastructure (Creel 2003).

Study limitations

Our analytical approach was based on findings from Hsiao (this volume a), which tested for spatial associations between inland landscape factors and metrics characterizing coastal habitat condition. Outcomes of that study identified distances over which influences of inland landscape factors on coastal habitats changed, and these findings informed how we chose to associate pour point catchments with coastal grid cells as well as the various distance categories that we used to apply decay functions. This process could be improved with specific discharge estimates for catchments, allowing for more precise estimates of the magnitude of catchment influences based on stream flow vs. catchment area. It would also allow for greater understanding of effects of rain events as drivers that could promote or limits linkages around the island. We also did not have information to account for how currents may affect linkages, and how inland influences dissipate in the coastal environment. Our step to assign a decay factor could be improved with the availability of current information to account for the directionality of how inland influences travel throughout the coastal environment.

Utility of the approach for conserving coastal habitats

The analytical approach highlighted in this chapter demonstrates the utility of the development of consistent spatial units in the coastal environment attributed with information on their linkages to catchments. The outputs yielded from this process enabled our identification of coastal areas that are at greater risk of degradation. This information would support decisions related to identification of target areas, allocation of management resources, and the designation of protection and regulations to consider inland linkages to the coastal environment.

While our particular exercise evaluated the status of ecosystem services and benefits, the coastal spatial units could facilitate assessments of various other factors of interest for improved coastal conservation strategies (i.e., assessment of key fisheries locations, identification of marine protected areas). Other regions could also follow the framework laid out by this approach to test for relationships between inland and coastal systems and to extend inland disturbances into the coastal environment. Conservation efforts are needed to ensure that coastal habitats continue to provide ecosystem services and benefits, but their effectiveness is in part driven by strategic placements. Allan et al. (2013) highlight compelling opportunities in restoration efforts that target areas that offer many ecosystem services at low risk of degradation, as well as those areas at high risk that are affected by just a few stressors (as opposed to multiple stressors). Our analytical approach yields spatially-explicit products that can support decisions related to mitigating inland disturbances for the conservation of coastal habitats. Specifically, the creation of coastal spatial units enables the attribution and organization of information in consistent, comparable manners. Their cumulative disturbance scores disseminates the relative risks from inland disturbances and identifies highly threatened areas and sources of degradation.

APPENDICES

APPENDIX 2.A:

Tables

Table A2.1. Proportion of coastal ecosystem services and benefits at various risk levels of degradation from inland disturbances; the greatest proportion for each group is **bolded**.

	Very Low	Low	Moderate	High	Very High
Recreation	0.06	0.01	0.19	0.20	**0.54**
Excursion Boating	0.00	0.00	0.00	0.00	**1.00**
Sailing	0.00	0.00	0.00	0.00	**1.00**
Aquatic Recreation	0.00	0.00	0.00	0.33	**0.67**
Board Surfing	0.00	0.00	0.12	0.26	**0.62**
Body Surfing	0.11	0.00	0.06	0.33	**0.50**
Canoe Paddling	0.00	0.00	0.33	0.17	**0.50**
Sport Diving*	0.13	0.00	0.26	0.18	**0.44**
Shell Collecting	0.00	0.11	**0.67**	0.00	0.22
Fishing/fisheries	0.05	0.06	0.22	0.20	**0.47**
Bait Fishing	0.00	0.00	0.00	0.00	**1.00**
Torch Fishing	0.00	0.00	0.00	0.05	**0.95**
Specialized Fisheries	0.05	0.00	0.09	0.27	**0.59**
Gill Netting	0.04	0.03	0.13	0.21	**0.58**
Pole and Line Fishing	0.05	0.07	0.23	0.18	**0.47**
Spear Fishing*	0.04	0.07	0.24	0.19	**0.46**
Throw Netting	0.08	0.10	0.25	0.24	**0.34**
Crabbing	0.00	0.00	**0.56**	0.11	0.33
Troll and bottom fishing	0.09	0.11	**0.34**	**0.34**	0.13
Habitats for biodiversity	0.01	0.08	0.19	0.15	**0.57**
Sea Urchin	0.00	0.00	0.00	0.00	**1.00**
Shark	0.00	0.00	0.00	0.00	**1.00**
Octopus*	0.02	0.00	0.02	0.02	**0.94**
Seaweed	0.00	0.00	0.06	0.06	**0.87**
Lobster	0.04	0.04	0.35	0.17	**0.39**
Opihi*	0.00	0.15	**0.31**	0.26	0.27
Services dependent on coral reefs	0.03	0.08	0.23	0.19	**0.47**
Other					
Anchorage	0.00	0.00	0.00	0.00	**1.00**

*Services or benefits included in the subset that may depend directly on coral reefs.

Table A2.2. Units, minimum (min.), maximum (max.), mean, and standard deviation (SD) values of inland variables within pour point catchments (n = 182) draining the Maui landscape.

Variable	Units	Min.	Max.	Mean	SD
Catchment area	km^2	0.08	12.89	1.98	2.34
Habitat condition index*		0.00	0.41	0.08	0.10

*Index ranges from 0 (best condition) to 1 (worst condition) across the five main Hawaiian Islands.

APPENDIX 2.B:

Figures

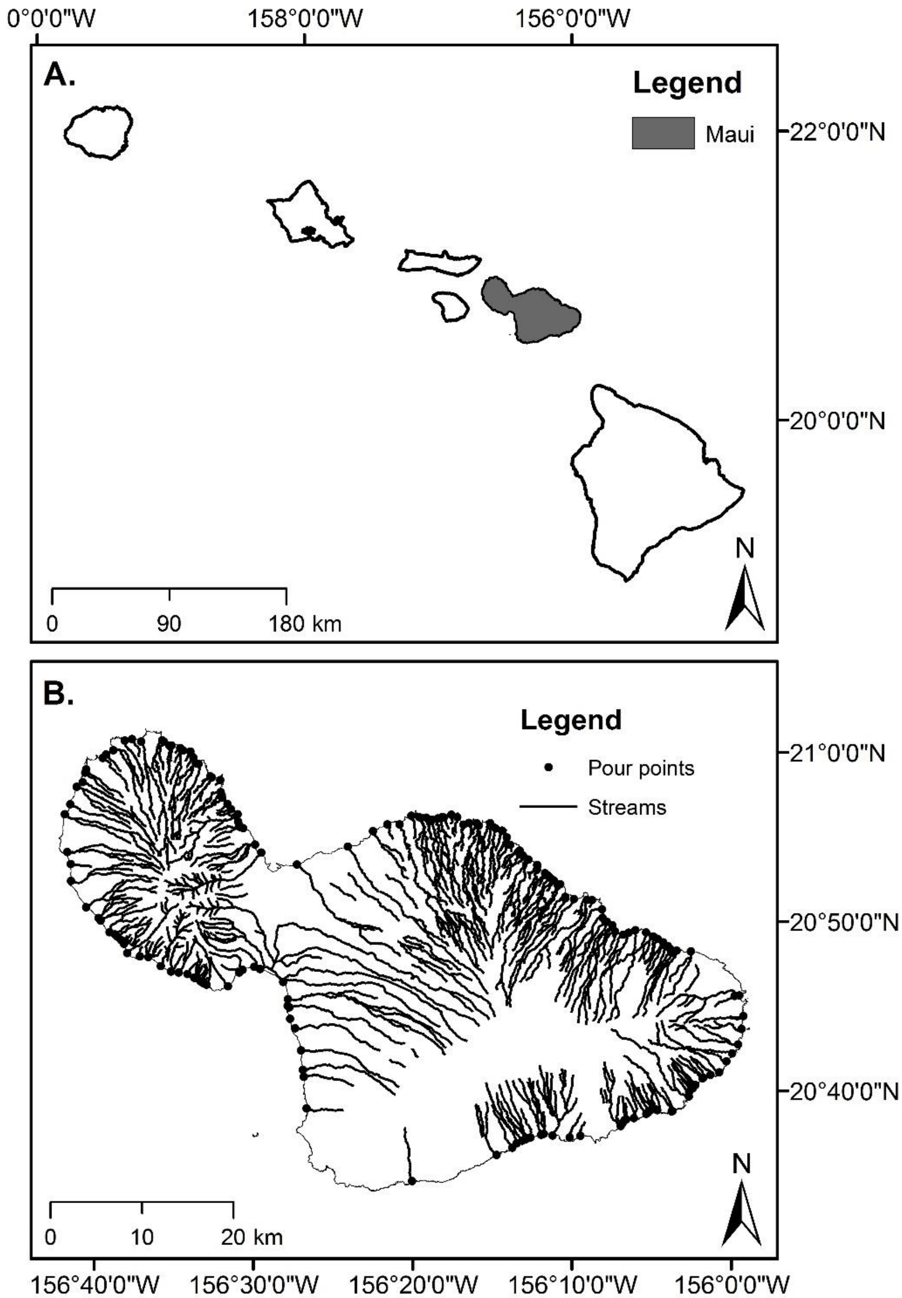

Figure B2.1. Location of Maui in the Hawaiian archipelago (A), and pour points of catchments (n = 182) draining the Maui landscape (B).

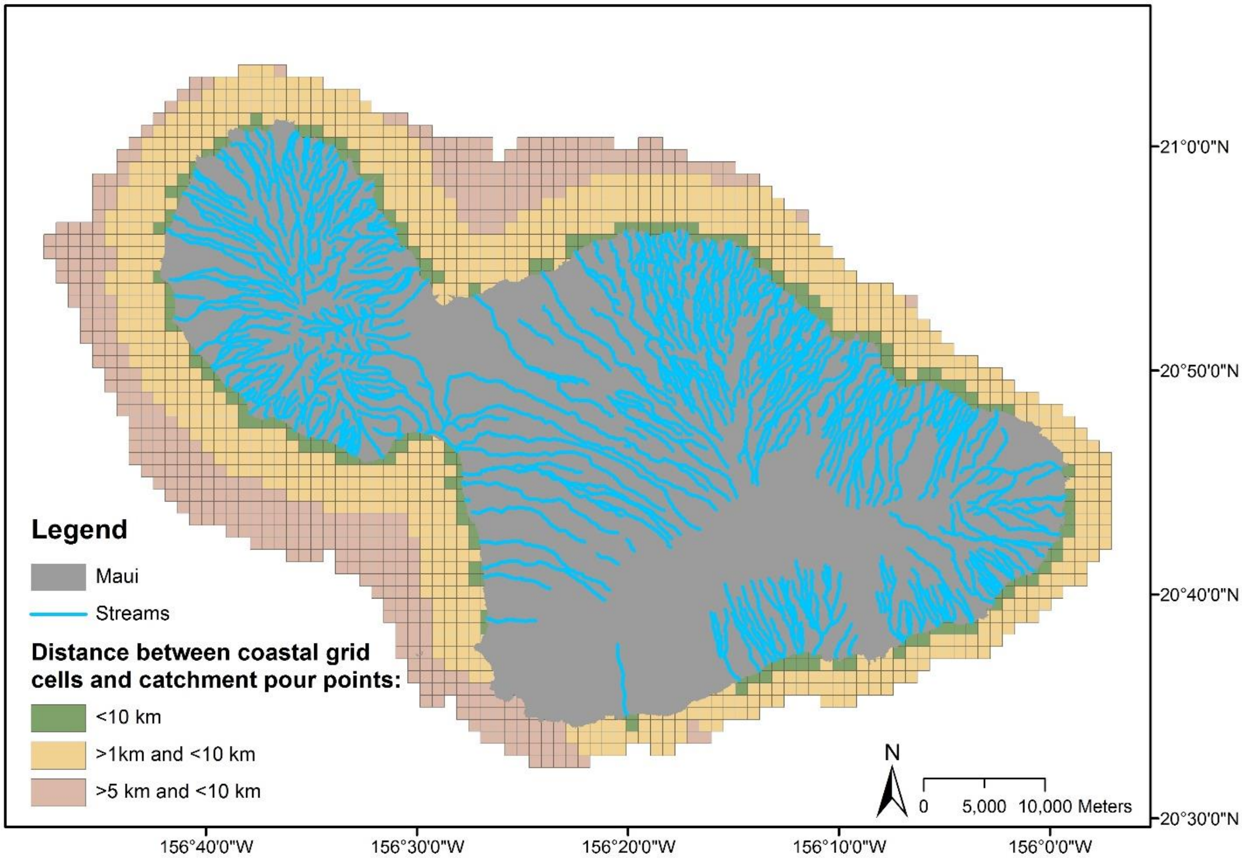

Figure B2.2. Coastal spatial units around Maui, Hawaii, in relation to pour point catchments of the landscape draining into the coastal environment.

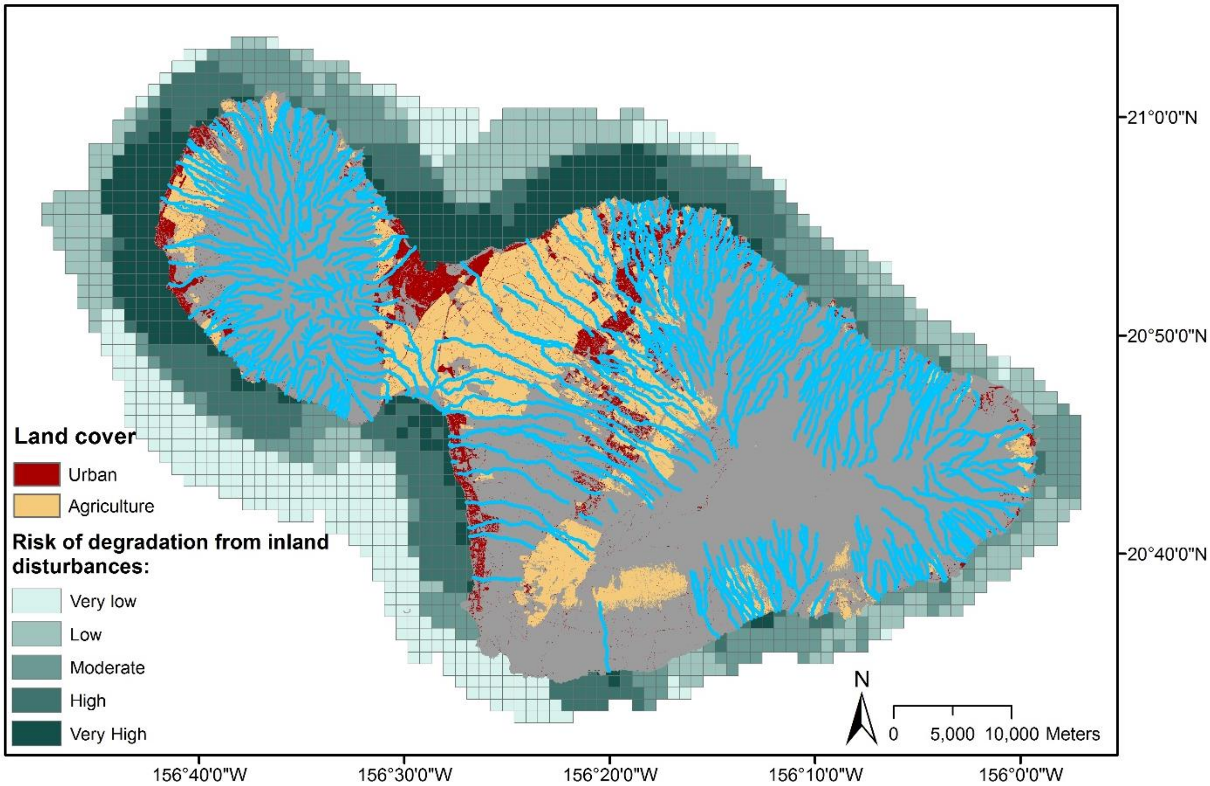

Figure B2.3. Risk of degradation from inland disturbances of coastal units around Maui, Hawaii.

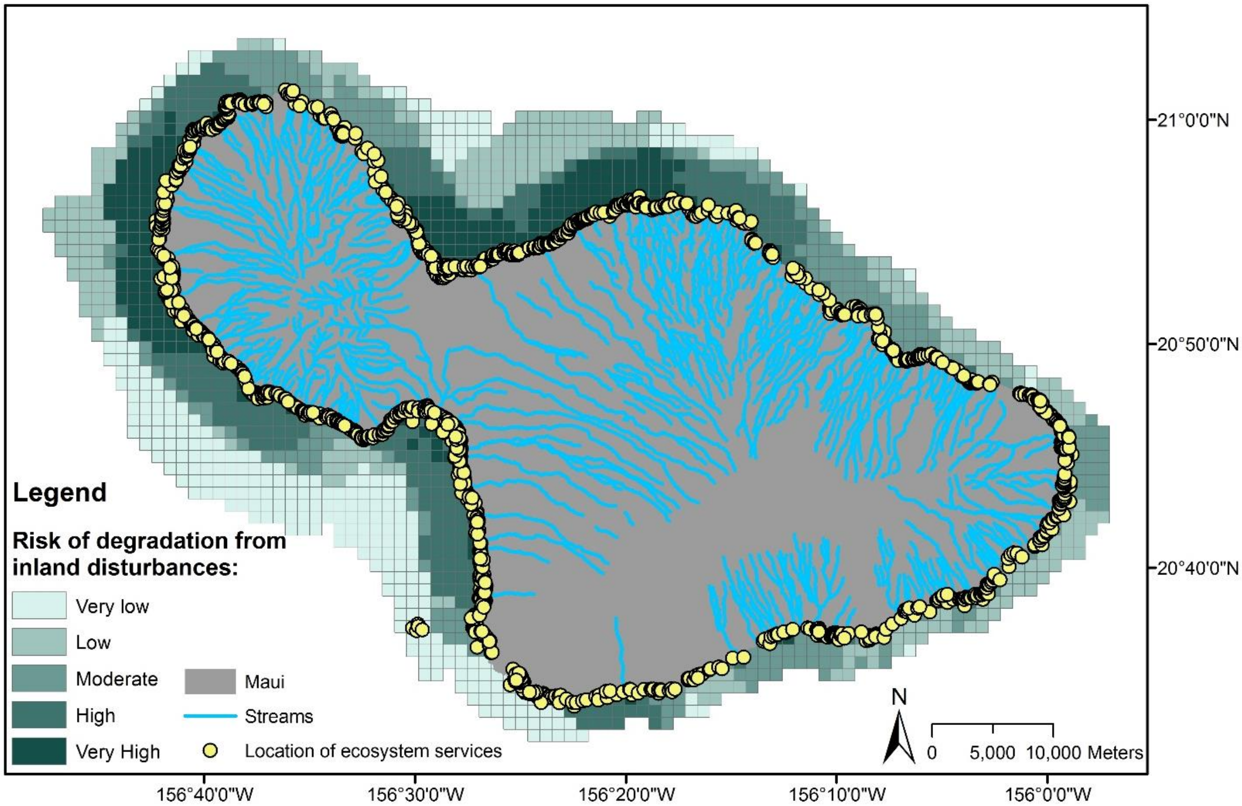

Figure B2.4. Location of all ecosystem services overlaid with characterized inland disturbances in coastal spatial units.

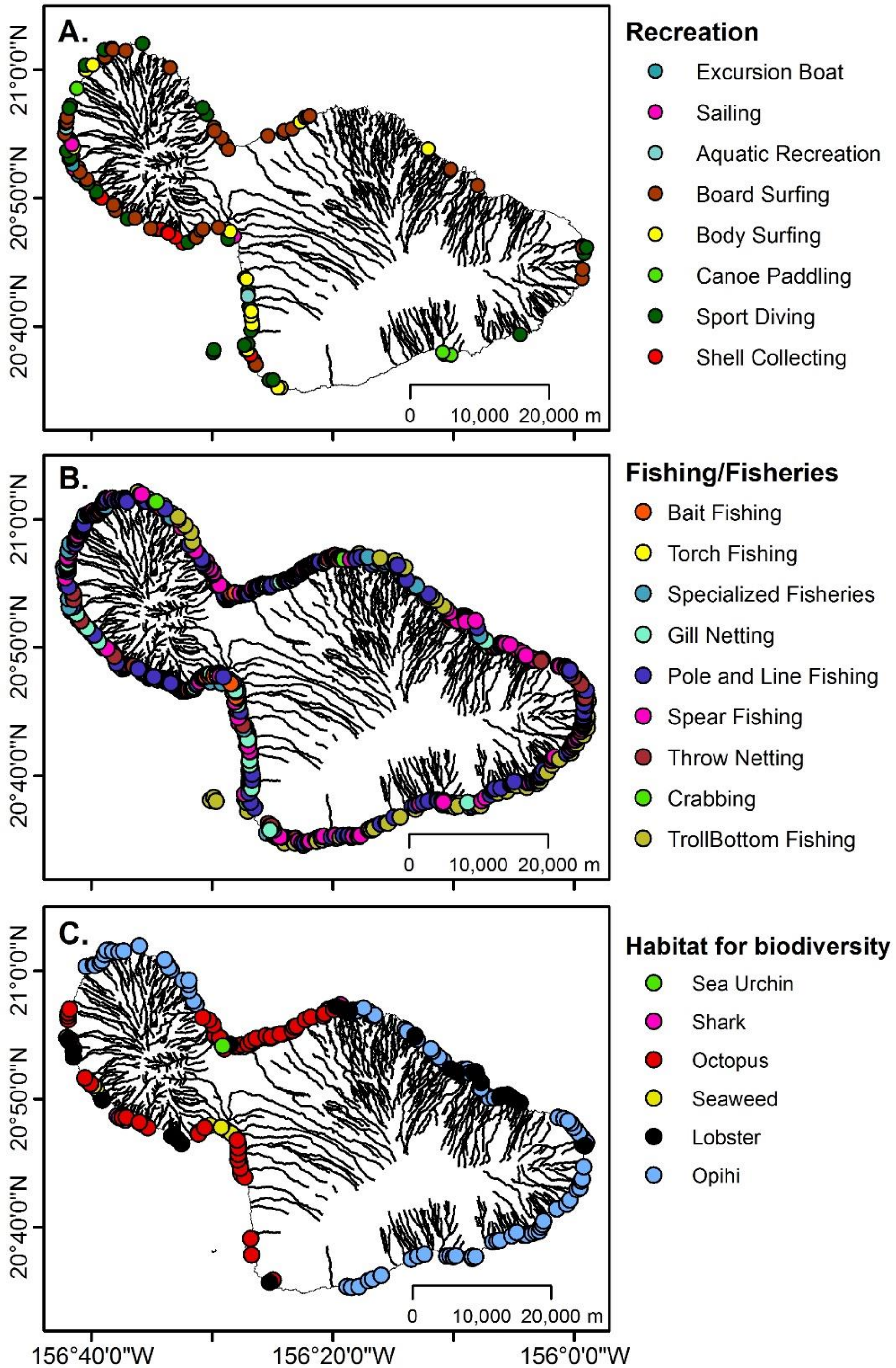

Figure B2.5. Location of ecosystem services by group: Recreation (A), Fishing/Fisheries (B), and Habitats for biodiversity (C).

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MANAGEMENT IMPLICATIONS

Coastal habitats are ecologically and socially important, but their conditions and availability are imperiled due to anthropogenic disturbances (UNEP 2006). While many anthropogenic disturbances result from human activities in and uses of the marine environment (Thrush and Dayton 2002; Waycott et al. 2009; Halpern et al. 2007), another major contributor to the decline of coastal habitats originates from inland landscapes (Crain et al. 2009), including human land use such as urbanization and agriculture. While linkages between inland landscapes and coastal habitats are widely acknowledged, few studies have evaluated their spatial relationships to inform development of a coastal spatial framework that would account for mechanisms by which inland variables influence coastal habitats. This thesis attempts to improve understanding of spatial relationships between inland and coastal systems. Specifically in this section, we highlight the principal findings described in Chapter 1 and Chapter 2, which provide information that could contribute to an approach that associates units in the coastal environment with units in proximate terrestrial landscapes to consistently account for spatial relationships. We then synthesize findings in the context of potential management implications, which can inform decisions that support the conservation of coastal habitats.

Chapter 1

In Chapter 1, we explored how coastal habitat conditions are influenced by landscape factors. The coastal habitat conditions are reflected by a set of reef metrics summarized by locations of reef units that described benthic habitats: habitat complexity, percent coral cover, percent stressed coral cover, percent sand cover, percent macroalgae cover, percent crustose coralline red algae cover, crown-of-thorn-starfish density, and urchin density. The landscape factors are represented by 3 main groupings of variables: inland natural, inland anthropogenic, and coastal. The inland variables are summarized in pour point catchments, and the coastal variables are attributed to their respective reef units.

Results of this chapter indicated that the strength of relationships between inland characteristics and coastal habitat conditions varied with distance between pour point catchments and reef units. In particular, we found that the greatest amount of variance explained by inland anthropogenic variables in coastal habitat condition was observed at 1 km. This suggests that when managing for inland anthropogenic disturbances, decisions should account for influences of catchments with pour points within 1 km of the coastal habitats of interest.

We also noted that the amount of variance explained in coastal habitat conditions decreased when pour point catchments greater that 5 km away from reef units were included in the study. This finding suggests that habitat conditions within 5 km of catchment pour points are sensitive to inland catchment characteristics. Inland natural variables in our analysis included mean annual rainfall. Managers of coastal resources should anticipate the extent to which inland influences may affect coastal habitat conditions to be altered in the face of climate change, depending on whether a draining catchment receives more or less precipitation than its historical annual averages.

Our predictions of individual reef metrics from environmental variables illustrate complex interrelationships between inland factors and coastal habitats. Of the best-predicted reef metrics, habitat complexity and macroalgae cover were predicted by inland natural variables, while macroalgae cover and crown-of-thorns starfish density were predicted by inland anthropogenic variables. This result shows the complexity of inland linkages to coastal habitats and highlights greater sensitivity of some metrics to inland disturbances. A manager of coastal habitats may consider those reef metrics associated most strongly with inland anthropogenic variables (i.e., percent macroalgae cover and crown-of-thorns starfish density), as indicators of inland disturbances from proximate catchments. This is an important step forward with the National Ocean Council setting the need for coastal and marine spatial planning as a national priority in the United States (Craig 2015). The major findings of this chapter contribute to the development of a coastal spatial framework, which characterizes ecologically-meaningful spatial units and their interrelationships with inland influences. This improved understanding would facilitate could guide decision-making in the coastal and marine environment by accounting for disturbances that originate from the landscape.

Chapter 2

In Chapter 2, we characterized spatial relationships between inland pour point catchments and spatial units in the coastal environment based on Chapter 1 findings (Hsiao, this volume a). We first created spatial units consisting of 1 km^2 grid cells and categorized them into 3 major groups: those with closest pour point catchments that fall within 1 km buffers, between 1 km and 5 km buffers, and between the 5 km and 10 km buffers. We calculated a cumulative disturbance score from inland influences that accounts for proximity of the catchment pour points associated with each coastal spatial unit, catchment area, and measures of inland habitat condition. Inland habitat condition is a composite index showing relative risk of inland disturbances to inland habitats (i.e., streams), and we applied the index to evaluate potential risk of inland disturbances to coastal habitats downstream of proximate catchments. We mapped the cumulative disturbance score calculated for each coastal spatial unit to visualize areas of coastal habitats at varying risk of degradation from inland disturbances (Figure B2.3). We additionally mapped locations of ecosystem services to assess those that are most threatened by inland disturbances (Figure B2.4).

The outputs could facilitate decisions that seek to identify areas of concern and for allocation of management resources.

Coastal areas are experiencing rapid ecological changes (Goussard and Ducrocq 2017). Specifically in the context of coral reef management, our findings of relative low and high risk of habitat degradation to inland influences (Hsiao, this volume b) could offer guidance that managers seek. Conservation resources are often limited, and the prioritization of areas with low levels of unmanageable threats or high levels of manageable threats would facilitate effective allocation (Harris et al. 2017). Through the characterization of threats from inland disturbances on coastal habitats, the spatially-explicit maps from this chapter enable the identification of target areas that are at the greatest and least risk of habitat degradation from inland disturbances that accounts for the linkages between inland and coastal systems. Our maps enable the identification of areas that are not degraded, which supports the designation of Marine Protected Areas (MPAs) of habitats that are still intact. The maps also enable the identification of areas that are degraded, as well as their associated catchments, for targeted mitigation of anthropogenic threats that could be remotely influencing the coastal habitats of interest.

The mapped locations of ecosystem services in relation to the relative risk of degradation of coastal habitats from inland disturbances is a proof-of-concept exercise that highlighted the utility of our approach for assessments. For example, the relative risk of degradation of coastal habitats could support existing policies, such as the management of Essential Fish Habitat (EFH) that is a part of the 1996 Magnuson-Stevens Fishery Conservation and Management Act (Rosenberg et al. 2000). EFH are designated habitat areas that are actively managed; they support important fisheries (e.g., serve as spawning grounds and nursery) and warrant special protection. Their locations can be mapped similarly to the ecosystem services, and the analytical process described (Hsiao, this volume b) could be applied, providing information regarding the relative risk of degradation of the designated EFH of interest from inland disturbances.

The results of this chapter additionally highlights the utility of developing consistent and comparable spatial units in the coastal environment. Our attribution of information in the coastal spatial units with their associated inland catchments were enabled by the findings of spatial linkages from an earlier study (Hsiao, this volume a). As improved understanding between inland systems and coastal habitats become available, the process of data attribution can be refined to more accurately reflect inland disturbances in the coastal environment. The extent of linkages between inland and coastal systems may also be altered in the face of climate change (Goussard and Ducrocq 2017), with anticipated shifts in coastal community structure and trophic interactions (Harley et al. 2006). Our study approach allows for the comparison of how inland influences may be expressed on coastal habitats when the parameters that affect linkages changes. Such information would facilitate better assessments of various management metrics of interest (e.g., reef health metric, resilience measures, and ecosystem services) for improved coastal conservation strategies.

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