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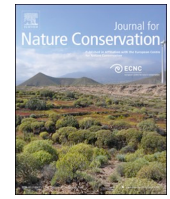

Identifying high value areas for conservation: Accounting for connections among terrestrial, freshwater, and marine habitats in a tropical island system

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ABSTRACT

Functional ecosystems depend on biotic and abiotic connections among different environmental realms, including terrestrial, freshwater, and marine habitats. Accounting for such connections is increasingly recognized as critical for conservation of ecosystems, especially given growing understanding of the way in which anthropogenic landscape disturbances can degrade both freshwater and marine habitats. This need may be paramount in conservation planning for tropical island ecosystems, as habitats across realms are often in close proximity, and because endemic organisms utilize multiple habitats to complete life histories. In this study, we used Marxan analysis to develop conservation planning scenarios across the five largest islands of Hawaii, in one instance accounting for and in another excluding habitat connectivity between inland and coastal habitats. Native vegetation, perennial streams, and areas of biological significance along the coast were used as conservation targets in analysis. Cost, or the amount of effort required for conservation, was estimated using an index that integrated degree and intensity of anthropogenic landscape disturbances. Our results showed that when connectivity is accounted for among terrestrial, freshwater, and marine habitats, areas identified as having high conservation value are substantially different compared to results when connectivity across realms is not considered. We also showed that the trade-off of planning conservation across realms was minimal and that cross-realm planning had the unexpected benefit of selecting areas with less habitat degradation, suggesting less effort for conservation. Our cross-realm planning approach considers biophysical interactions and complexity within and across ecosystems, as well as anthropogenic factors that may influence habitats outside of their physical boundaries, and we recommend implementing similar approaches to achieve integrated conservation efforts.

1. Introduction

Functional ecosystems depend on biotic and abiotic connections among different environmental realms including terrestrial, freshwater, and marine habitats (Beger, Grantham et al., 2010; Lamberti, Chaloner, & Hershey, 2010). Biotic connections can occur via use of different habitats by diverse taxa at different life stages for activities such as foraging and spawning. Diadromous stream organisms, for example, use freshwater habitats for spawning and marine habitats for larval growth and juvenile development (Bauer, 2013; Fitzsimons, Parham, & Nishimoto, 2002). Seabirds forage in marine habitats and return to terrestrial habitats to nest (Hazlitt, Martin, Sampson, & Arcese, 2010), and many amphibians and reptiles migrate between freshwater and terrestrial areas seasonally (Bodie, 2001; Richter, Young, Seigal, & Johnson, 2001). Abiotic connections can occur through transfer of materials across habitats, and hydrological processes (surface runoff, river flows, groundwater discharges) are important mechanisms facilitating such transfers (Melles, Jones, & Schmidt, 2012; Seelbach, Wiley, Baker, & Wehrly, 2006). For example, rivers aggregate and transfer particulate and dissolved organic carbon from headwaters to mainstem

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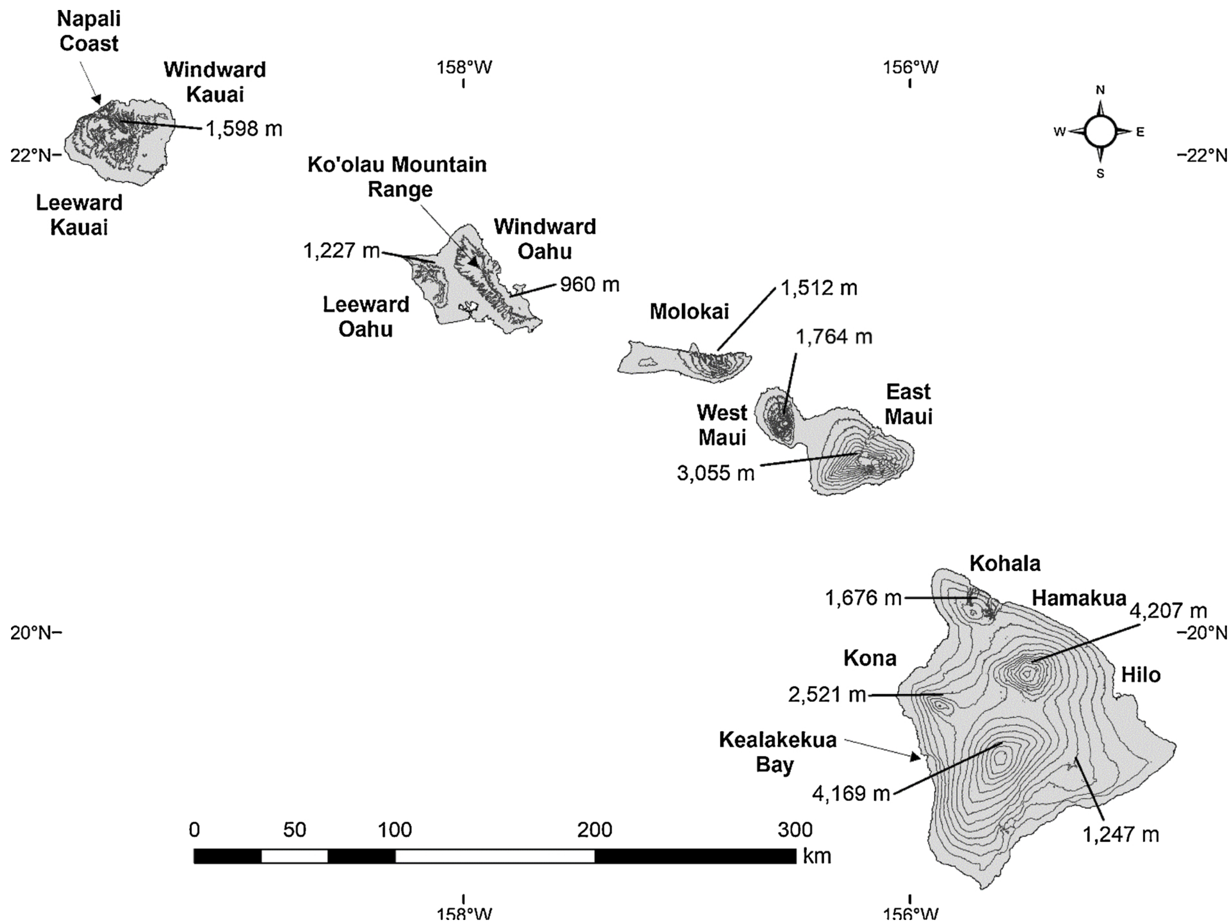

Fig. 1. Study area across the five largest islands of Hawaii. From east to west, islands are Hawaii, Maui, Molokai, Oahu, and Kauai.

river reaches, influencing habitats and ecological processes throughout river networks (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). In addition, discharges of nutrients from rivers and adjacent terrestrial lands into marine habitats can stimulate primary production and affect planktonic communities which support benthic and pelagic food webs (Hoffman, Bronk, & Olney, 2008; Smetacek, 1986).

The aforementioned connections among habitats can also contribute to proliferation of deleterious effects of anthropogenic disturbances, most notably through hydrologic processes. Urbanization and agricultural land use degrade terrestrial habitats, and they can also lead to increased nutrient loading and sedimentation in rivers draining urbanized or agricultural catchments (Allan, 2004; Wang, Lyons, Kanehl, & Bannerman, 2001). Similarly, anthropogenic disturbances in landscapes adjacent to or draining to coastal areas can increase eutrophication and sediment loading to marine habitats in many locations (e.g., Bilkovic & Roggero, 2008; Fabricius, 2005). Such interactions underscore the importance of understanding the potential for anthropogenic disturbances to degrade physical conditions and ultimately alter species assemblages across terrestrial, freshwater, and marine habitats so that disturbances can be mitigated and species may be conserved.

Identifying areas important for species conservation (i.e., high value conservation areas) has historically been conducted independently within terrestrial, freshwater, and marine habitats (Agardy, 1994; Margules & Pressey, 2000; Shafer, 1999). However, anthropogenic disturbances could originate from sources beyond boundaries of the target habitat. Accounting for connections among different habitat types ensures that conservation actions are less likely to be compromised by the failure to consider multiple habitat needs of species with complex life histories (Álvarez-Romero et al., 2011; Stoms et al., 2005). Considering connections among habitat types when selecting areas of high conservation value can also increase cost effectiveness of actions by accounting for proliferation of disturbances across connected habitats. However, compared to planning for individual management goals (e.g., protection of water quality for marine conservation areas vs. protection of catchments and terrestrial organisms), cross-realm planning will require tradeoffs among priorities, and critical assessment of differences in prioritization can indicate whether congruent conservation planning is a useful approach (e.g., Álvarez-Romero, Pressey, Ban, & Brodie, 2015).

Connectivity among habitats on tropical islands is particularly important due to their distinct physical characteristics and unique biological assemblages. Tropical islands are generally small, compact landscapes with high gradients of change in habitat types over short distances. Terrestrial, freshwater, and marine habitats are proximally close on tropical islands, facilitating access by organisms to different habitats (Beger, Grantham et al., 2010). High elevation tropical islands can also have short drainages with steep slopes and areas of high annual rainfall, resulting in surface flows (runoff and/or stream flows) supporting biotic and abiotic connectivity among habitats. Further, isolation from continental systems and inherent vulnerability of streams to drought have contributed to native stream assemblages including amphidromous fish, shrimp, and snails requiring connections between marine and freshwater habitats to complete life histories (McDowall, 2003). While cross-realm conservation planning has recently become more common in temperate regions (Adams et al., 2014; Álvarez-Romero et al., 2011), it is less commonly used in tropical island systems despite the notable importance of accounting for connectivity among freshwater, marine and terrestrial habitats (but see Klein et al., 2012; Makino, Beger, Klein, Jupiter, & Possingham, 2013 for recent examples in Fiji).

In this study, we focus on the Hawaiian Islands, which have strong abiotic and biotic connections across terrestrial, marine, and freshwater habitats. While prioritizing for connectivity among habitats is noted as a valuable management strategy (Kaneshiro et al., 2005; Olds et al., 2016), protected areas and conservation efforts have historically focused on isolated biological realms. The goal of our study is to demonstrate how accounting for connectivity among inland and coastal resources can improve investment efficiency and may only require minimal conservation trade-offs. Our first objective is to identify inland habitats that support native aquatic species and native vegetation that are hydrologically connected to marine habitats of conservation importance (i.e., areas of high cross-realm conservation value). Our second objective is to then determine the magnitude of trade-off required to account for habitat connectivity in comparison to only inland-based prioritizations. Our study serves as an approach for assessing connections among habitats in tropical island ecosystems, and results can aid in efforts to identify priority habitats for conservation that will account for native species with complex life histories in the Hawaiian Islands.

2. Materials and methods

2.1. Study area

The study area includes streams, drainages, and associated nearshore marine habitats of the five largest Hawaiian Islands (Hawaii, Maui, Molokai, Oahu and Kauai; Fig. 1). The islands, formed by lava flows, increase in age from east (Hawaii) to west (Kauai). Perennial streams are most common on the wetter eastern (windward) portions of islands, with intermittent streams more common on their drier western (leeward) portions (Giambelluca, DeLay, Nullet, Scholl, & Gingerich, 2011). In areas where groundwater tables reach elevations high above sea level, baseflow in rivers is maintained through persistent groundwater inputs (Lau, Leung, Mink, & John, 2006). Drainages adjacent to the coast that lack perennial or intermittent streams are also hydrologically connected to nearshore coastal habitats via groundwater delivery and surface runoff. Hawaii's nearshore marine habitats support a diversity of coral reef species and are primary foraging grounds for large predatory marine fishes (Locker et al., 2010; Rohmann, Hayes, Newhall, Monaco, & Grigg, 2005). In addition, these habitats support fishes that move periodically between inland and marine waters (e.g., *Mugil cephalus* and *Kuhlia xenura*; Fitzsimons, McRae, & Nishimoto, 2007; McRae, McRae, & Michael Fitzsimons, 2011) and serve as rearing sites for larval amphidromous stream species (Nishimoto & Ftizsimons, 2006).

2.2. Analysis tools and datasets

We used the spatial planning software Marxan (Ball, Possingham, & Watts, 2009) to identify drainages of high conservation value throughout the five largest Hawaiian Islands. Marxan is an analysis tool to guide spatial decision-making based on the desired objective of minimizing costs of conservation actions. We used drainage areas as the basic spatial planning unit in Marxan. We included three types of habitat datasets – perennial streams, native vegetation, and marine areas of high biological significant – as the conservation features of interests. The cost of conservation effort was represented by the habitat condition within each unit. Each element going into the Marxan analysis in this study is described in the following sections.

2.2.1. Spatial planning units

Local catchments and coastal drainage areas (CDAs) are the two types of drainages characterizing features of the terrestrial environment (Fig. 2) in our spatial planning units. Local catchments are areas of the landscape draining directly into stream reaches and were delineated for the 11,437 perennial and intermittent stream reaches represented by the Hawaii Fish Habitat Partnership's (HFHP) stream layer (Tingley, Infante, MacKenzie, Cooper, & Tsang, 2019), a modified version of the 1:24,000 National Hydrography Dataset (NHD) (US Geological Survey, 2008). Another type of spatial planning unit includes coastal drainage areas (CDAs, also termed interfluves in other regions, e.g., Wang et al., 2015). CDAs are landscapes adjacent to the coast that are not drained by perennial or intermittent streams, and landscape characteristics of these drainages may influence nearshore coastal habitats via hydrological connections occurring through ephemeral stream flows, surface runoff, and/or groundwater discharges. The ArcMap extension ArcHydro 9.0 and a 10 m digital elevation model (DEM) from the National Elevation Dataset (NED; US Geological Survey, 2006) were used to delineate 914 CDAs bound by adjacent local catchments and the coastline (Fig. 2; Table 1).

2.2.2. Conservation features

Three conservation features distributed across the study region were used in analysis (Fig. 3; Table 1). The first feature is total length of perennial stream reaches (km) found in local catchments. This feature represents available fluvial habitat within local catchments, and we used it to prioritize local catchments with greater lengths of perennial flow to emphasize continuous connections among habitats, which are important to Hawaii's native stream species (Nishimoto & Ftizsimons, 2006).

The second conservation feature is the total area of native vegetation cover (km^2) in each planning unit (e.g., local catchments and CDAs). Protection of native vegetation is a priority because native forests in Hawaii are comprised of ecologically- and culturally-valuable plant species more likely to support endemic bird and insect populations. Native vegetation can also have lower evapotranspiration rates and can contribute to stream baseflow via fog drip at high elevations more effectively than nonnative vegetation (Takahashi et al., 2011). Native vegetation cover in this study is characterized by the Hawaii Habitat Quality Dataset, which delineates areas of native forests with limited nonnative vegetation (Price et al., 2012).

The third feature is a metric capturing the connectivity of inland habitat to areas of Hawaii's nearshore marine environment that support high levels of marine biodiversity. Nearshore areas of Hawaii serve as nursery or feeding grounds for many organisms (e.g., finfish, sea turtles, monk seal) and include valued and diverse habitat types (e.g. coral reefs, seagrass beds, salt marshes). Areas of Biological Significance (ABSs) are nearshore regions along each island that are hotspots for high biodiversity and important species' habitats (Weiant, 2009). ABSs were generated in support of The Nature Conservancy's Marine Ecoregional Assessment of the Hawaiian Islands and are represented as polygons adjacent to the shoreline of each island. All local catchments within a stream network with a pour point draining directly to an ABS and CDAs that were directly adjacent to an ABS were designated as hydrologically connected to these important nearshore marine habitats, and they were prioritized in analysis (i.e., these units were assigned a value of “1″ while other drainages were assigned a value of “0″, more information below).

2.2.3. Cost

Cost for each spatial unit was determined from an index characterizing relative condition of stream and terrestrial habitat within drainages. The habitat condition index (HCI) was developed as part of the 2010 National Assessment of Fish Habitats (http://fishhabitat.org/) and followed a landscape approach (Allan, 2004), where more types and greater intensities of anthropogenic activities within catchments and CDAs indicate a greater risk of degradation to stream and terrestrial habitats (following Danz et al., 2007; Esselman & Allan, 2011). The HCI was developed from a combination of 27 variables characterizing anthropogenic landscape disturbances consistently across the study region (Table A1). Variables were first attributed to local catchments and CDAs and were then aggregated throughout entire upstream

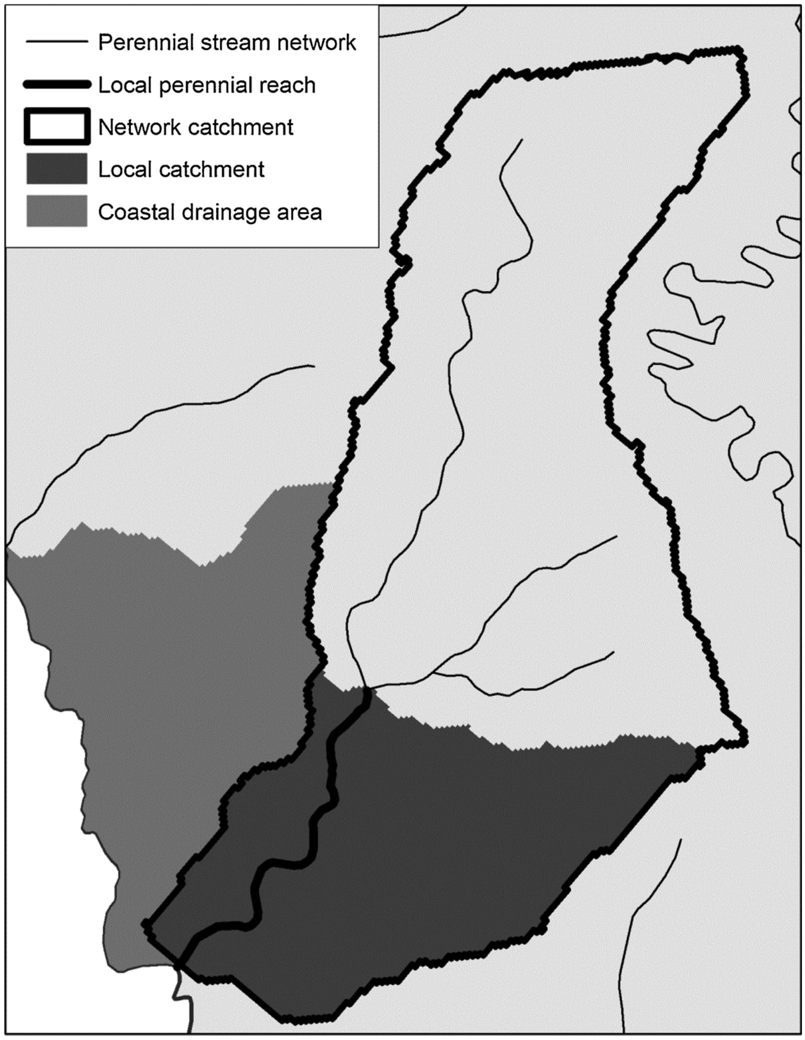

Fig. 2. Local catchments were delineated for each stream reach across the study area. Anthropogenic disturbances were summarized in the local and upstream network catchment. Coastal Drainage Areas (CDAs) were delineated along the coastline to represent areas that do not have a defined channel but are hydrologically connected to the nearshore environment.

Table 1
Counts (and percentages) of planning units in the study region along with total, average, and ranges in areas or length of planning units and conservation features.

	Count (% of total)	Percent of planning units with conservation feature	Total area or length	Mean area or length	10^{th} - 90^{th} percentile	Source
Planning units	12,351 (100.0%)		16,008 km^2	1.3 km^2	< 0.1–1.7 km^2	NFHP database[a]
Local catchments	11,437 (92.6%)		4,843 km^2	1.0 km^2	< 0.1–1.7 km^2	NFHP database[a]
Coastal drainage areas	914 (7.4%)		11,166 km^2	5.3 km^2	< 0.1–1.9 km^2	NFHP database[a]
Units adjacent to coast	1,639 (13.2%)		5,270 km^2	3.2 km^2	< 0.1–1.6 km^2	NFHP database[a]
High elevation (> 200 m)	6289 (51.0%)		7,301 km^2	1.2 km^2	< 0.1–1.9 km^2	NFHP database[a]
Large unit (> 100 km^2)	15 (0.1%)		4,238 km^2	347.1 km^2	112.3– 660.0 km^2	NFHP database[a]
Conservation features						
Perennial reaches		41.0 %	4,814 km	0.4 km	0.0–1.2 km	NHD (2008)
Native vegetation		46.7 %	5,084 km^2	0.4 km^2	0.0–0.4 km^2	Price et al. (2012)
Areas of biological significance		44.8 %				Weiant (2009)

[a] National Fish Habitat Partnership, http://ecosystems.usgs.gov/fishhabitat/.

catchments of perennial and intermittent stream reaches to characterize disturbance in a second spatial extent, the network catchment (Tsang, Wieferich, Fung, Infante, & Cooper, 2014; Wang et al., 2011, Fig. 2), which includes all contributing upstream drainage areas that drain to a given local stream reach. Variables were then grouped into seven categories to describe condition of habitat based on specific stressors (Table A1). The urban category included population density (US Census Bureau, 2001), density of utility pipelines (Hawaii Office of Planning, 1983), and density of roads (US Census Bureau Geography Division, 2002) in units. It also included high, medium, and low intensity urban land uses; open urban land use; and impervious surfaces. These data were assembled from the 2001 National Land Cover Dataset (NLCD, Homer, Huang, Yang, Wylie, & Coan, 2004) with updates in urban land use from the 2005 Coastal Change Analysis Program (C-CAP) for all

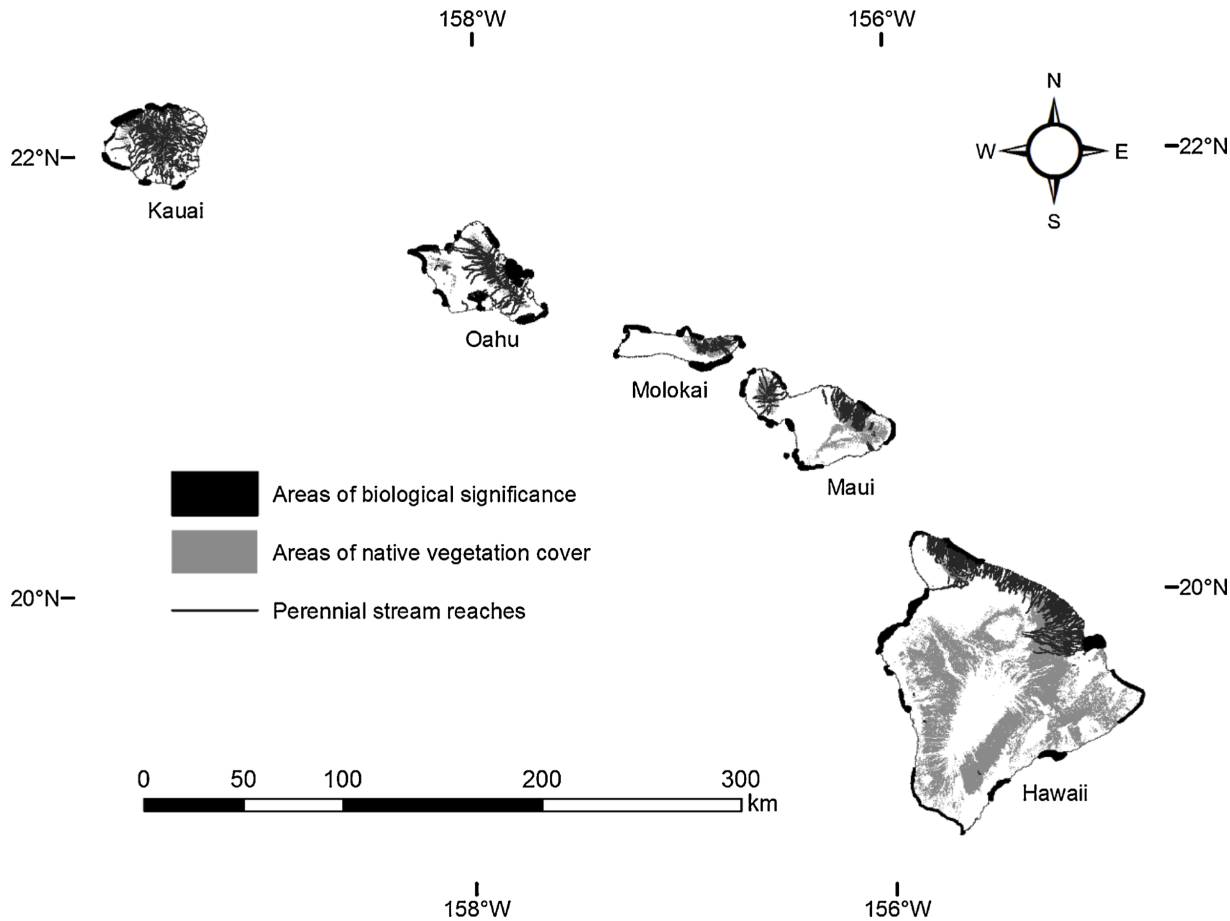

Fig. 3. The three conservation features across the five largest islands of Hawaii.

islands except Hawaii. Agricultural lands included pasture/hay and cultivated crop lands (2001 NLCD, Homer et al., 2004), and former plantations included locations of historical pineapple and sugarcane plantations (Hawaii Office of Planning, 1989). The point source pollution category included densities of Superfund National Priority sites (Comprehensive Environmental Response, Compensation and Liability Information System), Permit Compliance System majors (PCS), Toxic Release Inventory sites (TRI) (US Environmental Protection Agency, 2010), Underground Injection Control sites (UIC, Hawaii Deparment of Health, 2004), and quarries (US Geological Survey, 2003) in planning units. The fifth category, stream fragmentation, included densities of stream and road crossings in catchments (US Census Bureau Geography Division, 2002), ditch intersections with streams (Hawaii Division of Aquatic Resources, 2004), and dams (US Army Corps of Engineers, 2010); this category was not applicable for CDAs as they lack perennial or intermittent streams. Length of ditches, the sixth category, included a single variable to estimate the relative intensity of water diversion within planning units (Hawaii DAR, 2004). Finally, 303(d) listed streams (US Environmental Protection Agency, 2002) characterized reaches that failed to meet state criteria for water quality, primarily due to high levels of turbidity (Hawaii Department of Health, 2012); this disturbance was only summarized at the upstream catchment spatial extent.

For each category, a subindex of disturbance was generated using methods that varied with number of variables in a given category. For categories with a single disturbance variable, variables were standardized from 0 to 1. For categories with two variables, variables were standardized, summed, and rescaled from 0 to 1. For categories with three or more disturbance variables, transformed variables were combined using principal component analysis (PCA) to create the subindex (following Danz et al., 2007; Esselman, Infante, & Wang, 2011). For CDAs, the cumulative index characterizing condition of habitats was calculated from the sum of the disturbance indices; higher scores indicate more disturbed habitats. The cumulative index applied to local catchments was based on conditions in both local and upstream network catchments; the index was created from a weighted average of scores in these two spatial extents. For small streams draining less than 10 km^2, an equal weighting was given to local and upstream network catchments. For larger streams (> 10 km^2 drainage area), local and upstream network catchments were weighted as 30% and 70%, respectively, to account for accumulated disturbance effects from throughout the network vs. locally (Esselman et al., 2011). Additionally, due to high intensity of urbanization along coastlines in Hawaii, the urban index was doubled for creating of the final index to account for relatively greater impacts of urban land use on habitat condition. The final HCI scores ranged from 0 to 1and the higher the HCI score at a given unit represents higher risk of habitat degradation. Jenk's natural breaks (De Smith, Goodchild, & Longley, 2018) were then used to determine five relative levels of habitat condition, very good, good, moderate, poor and very poor (Fig. 4). The five levels of habitat condition were then used to represent the required effort for conservation, with the better the habitat condition suggesting lower cost.

2.3. Scenario 1: Identifying drainages for conservation by accounting for connections among inland and marine habitats

Using Marxan analysis, the first scenario was designed to prioritize drainages of high conservation value based on three factors: 1. extent of conservation features (perennial stream length, area of native

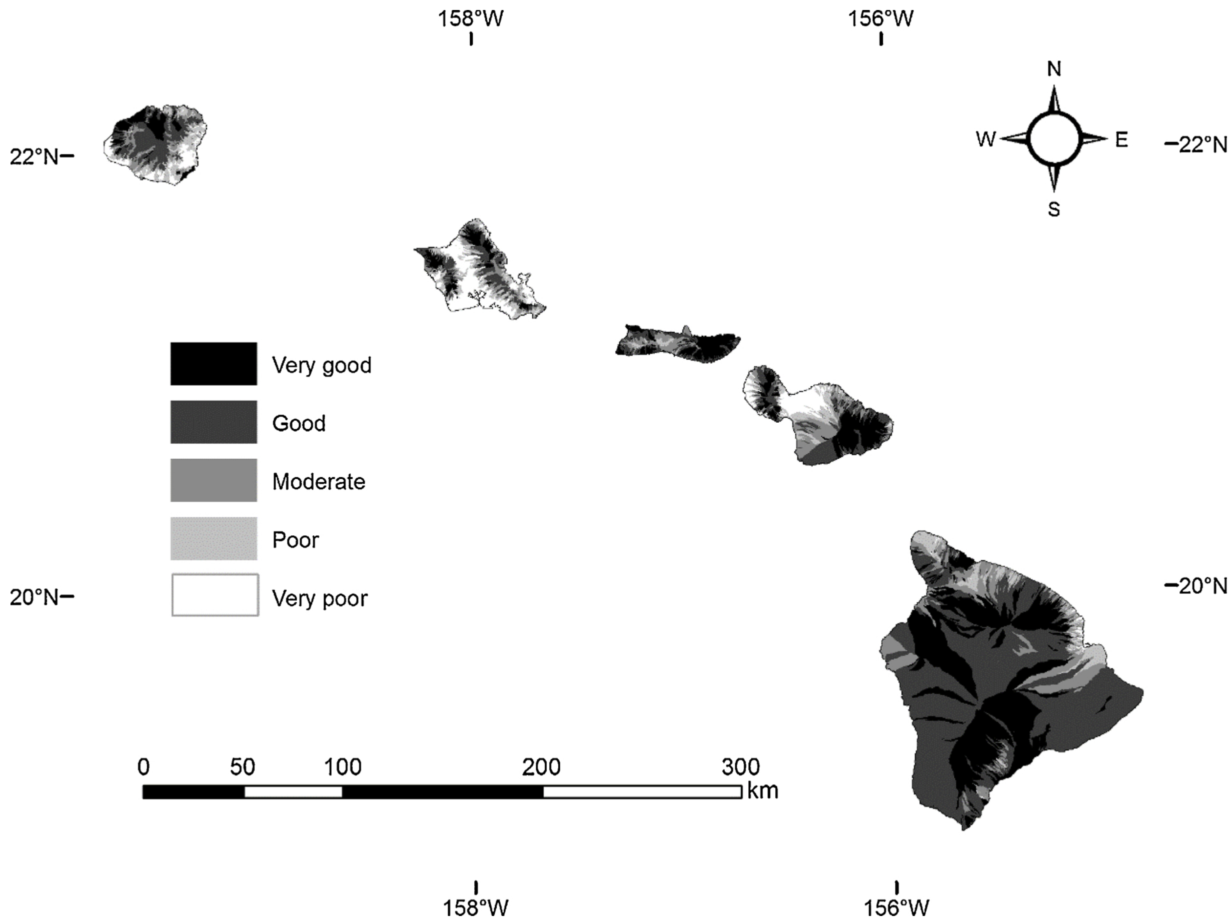

Fig. 4. Relative Habitat Condition Index (HCI) scores across the study region as represented by the National Fish Habitat Partnership 2010 Assessment.

vegetation cover, connectivity to ABSs), 2. their contiguity with other drainages of high conservation value, and 3. their habitat condition. For the first factor, we followed Esselman and Allan (2010) and set target values of 15% for each conservation feature across the study region in meeting prioritization objectives. For the second factor, contiguity among planning units was calculated using the "near as table" tool in ArcMap. For the third factor, we used HCI to represent habitat condition, and higher risk of degradation was used to represent greater cost to conserve habitats. Additionally, following an approach described by Game and Grantham (2008), a sensitivity analysis between boundary length and the cost under different boundary length modifier (BLM) values was performed. A BLM of 0.5 was used to balance increasing the number of selected planning units with minimizing cost. Ultimately, a total of 1000 iterations were completed to select drainages of high conservation value with Marxan, and the selection frequency of planning units from all runs (i.e., summed solution) was used to identify drainages with the highest conservation value.

2.4. Scenario 2: Identifying drainages for conservation by accounting for characteristics of only inland habitats

Scenario 2 was designed to prioritize drainages of high conservation value based on all factors considered in Scenario 1, except for connectivity of drainages to ABSs in the nearshore environment. Scenario 2 represents a conservation planning exercise that does not consider the importance of nearshore marine habitats and connectivity between inland and marine habitats. Results from both scenarios were mapped to represent the top 20% of planning units selected most frequently in the summed solution. We calculated the total percentage of planning units that contained or were hydrologically connected to conservation features, as well as those that occurred at high elevations (> 200 m) and were adjacent to the coast. We summarized the differences and trade-off in the conservation features and cost in these two scenarios. In addition, we mapped the difference between the summed solutions of Scenarios 1 and 2 to assess outcomes of considering adjacency to priority coastal habitats.

3. Results

3.1. Spatial characteristics of planning units, conservation features and costs

The study region includes 12,351 planning units (i.e., local catchments and CDAs) covering a total area of 16,008 km^2 with a mean size of 1.3 km^2 (Table 1). CDAs account for a small percentage of all planning units (7.4%) but are on average larger than local catchments (5.3 vs. 1.0 km^2, respectively). Thirteen percent of all planning units are adjacent to the coast, while over half (51.0%) of all planning units occur above 200 m in elevation. Only 15 planning units greater than 100 km^2 (i.e., large planning units) occur in the study region.

Total length of perennial stream reaches across the study region is 4814 km and perennial reach length within a planning unit is on average 0.4 km. Forty-one percent of planning units contain perennial stream reach habitat. Native vegetation covers 5084 km^2 within planning units. It was present to some extent on all islands but was more common at high elevations (Fig. 3). Less than half (46.7%) of planning units have at least some native vegetation coverage, and 44.8% are either adjacent to an ABS or within a stream network that drains to an ABS (Table 1).

Habitat condition within planning units as represented by the HCI

Table 2
Summarized characteristics of the top 20% most frequently selected planning units for each scenario.

Characteristics of top 20% selected planning units	Scenario 1	Scenario 2
Total area (km^2)	1,855	3754
Average planning unit size (km^2)	0.8	1.5
High elevation (> 200 m) planning units (%)	67	69
Large planning units (> 100 km^2) (%)	< 1	< 1
Units adjacent to coast (%)	12	5
With perennial streams (%)	61	88
With native vegetation (%)	77	77
Connectivity to ABS** (%)	92	49
With both perennial stream and native vegetation (%)	50	67
With perennial streams, native vegetation, and ABSs* (%)	46	37

* ABS: Area of Biological Significance.

ranged from very good to very poor across islands (Fig. 4). Planning units with very poor HCI were most common on Oahu and central Maui, while planning units with very good HCI were common on Hawaii Island. Planning units at low elevations and bordering the coastline were generally in the poorest condition. Higher elevation planning units and those found in hard to access or remote locations (e.g., Napali Coast of Kauai and the northeastern drainages of Molokai) were in very good condition.

3.2. Scenario 1: Identifying drainages for conservation by accounting for connections among inland and marine habitats

The top 20% most frequently selected planning units in Scenario 1 were located across all five islands (Table 2, Fig. 5). The majority (67%) of the top 20% most frequently selected planning units occurred at high elevations, but lower elevation planning units were also frequently selected in regions where HCI scores were good or very good and planning units were hydrologically connected to ABSs. Most (92%) of the top 20% most frequently selected planning units were hydrologically connected to an ABS, and 12% were adjacent to the coast. On Kauai, the majority of planning units frequently selected occurred along the northwest coast (i.e., Napali Coast) and the mountainous regions draining the windward side of the island. Similar areas of frequently selected and contiguous planning units were observed on East Maui (draining to the northeast), along the Kona coast of Hawaii Island, and on the eastern side of Hawaii Island. However, few coastal or low elevation planning units were selected along the shorelines of Hawaii Island and Oahu. Of the top 20% of most frequently selected units, 61% of planning units contained perennial streams and 77% had native vegetation, with 50% containing both perennial streams and native vegetation. Forty-six percent of the top 20% most frequently selected planning units contained all three conservation features.

3.3. Scenario 2: Identifying drainages for conservation by accounting for characteristics of inland habitats

The top 20% of planning units most frequently selected in Scenario 2 were found across all five islands and had a total area of 3754 km^2 (Table 2, Fig. 6). Like Scenario 1, the majority (69%) of the top 20% most frequently selected planning units occurred at high elevations. However, only 49% of the planning units selected in the top 20% were hydrologically connected to an ABS, compared to 92% selected in Scenario 1. Similarly, planning units adjacent to the coast accounted for only 5% of the top 20% most frequently selected planning units in Scenario 2, compared to 12% in Scenario 1. Planning units with high selection frequency were common in regions with numerous perennial reaches, but in some cases, CDAs were also selected in areas with little or no perennial systems, likely an effect of high proportions of native vegetation cover within large planning units (e.g., west of Hawaii Island). Large planning units made up a small percentage (< 1%) of the top 20% of planning units most frequently selected, similar to results of Scenario 1. On Kauai, planning units selected in the top 20% were scattered across the entire island, while on Molokai and Maui, they were more spatially adjacent. Eighty-eight percent of selected planning units contained perennial stream reaches, 77% contained native vegetation, and 67% had both perennial stream reaches and native vegetation cover.

3.4. Trade-off between scenarios 1 and 2 in conservation planning

Many high elevation planning units on islands with greater disturbance along coastal areas (i.e., Oahu and Hawaii Island) were selected in the top 10% of both scenarios (Fig. 7). Commonality in the most frequently selected planning units also occurred in regions with good HCI extending from headwater perennial reaches to the nearshore environment (e.g., Napali coast, windward draining streams of Kohala, windward streams of east Maui) and among large planning units draining drier regions of Hawaii Island. Areas with good to very good HCI but not draining to ABSs, most notably on northeastern Molokai, were in the top 20% most frequently selected in Scenario 1 but not in Scenario 2. A greater number of planning units draining Windward Kauai were also selected in Scenario 1 than Scenario 2.

When considering the conservation features across realms, Scenario 1 included less desirable inland conservation features (i.e., length of perennial streams and area of native vegetation) in top 20% of selected units compared to Scenario 2 (Table 3). However, the sum of HCI scores of top 20% selected units was smaller in Scenario 1 than Scenario 2 (Table 3), which suggested more units with lower HCI scores (i.e., lower risk of degradation, better habitat condition) were selected when considering conservation planning for both inland and coastal conservation features.

4. Discussion

4.1. Overview

Integrated cross-realm planning is needed to promote effective conservation across hydrologically linked terrestrial, freshwater, and marine habitats. Given the potential for hydrology to sustain abiotic and biotic connections as well as its potential to contribute to anthropogenic-induced degradation across habitats (Pringle, 2003), integrated conservation planning across environmental realms is likely most appropriate for conserving ecosystems and species they support in regions with hydrologically linked habitats. Again, organisms in such regions may require multiple habitats to complete their life cycles, and accepted boundaries that distinguish terrestrial from aquatic habitats are not necessarily ecological (e.g., Dixson et al., 2008; Kinzie & Ford, 1977; Mumby et al., 2004). In this study, we identified inland habitats of the Hawaiian Islands supporting aquatic and terrestrial native species connected to high priority marine habitats. We demonstrated that when connectivity among terrestrial, freshwater, and marine habitats is accounted for, areas identified as having high conservation value are generally different vs. when connectivity is not accounted for, underscoring potential advantages of integrated vs. single-realm conservation planning. The trade-off of accounting for connectivity among terrestrial, freshwater, and marine habitats was to select fewer units with perennial streams and native vegetation within the top 20% of the selection. Yet more units with lower HCI scores were in the top 20% selection, i.e., units with lower risk of habitat degradation were prioritized. This unexpected benefit indicates less effort to achieve integrated conservation objectives when accounting connectivity and planning across realms. Further, taking a cross-realm approach and considering hydrological connections in conservation planning in

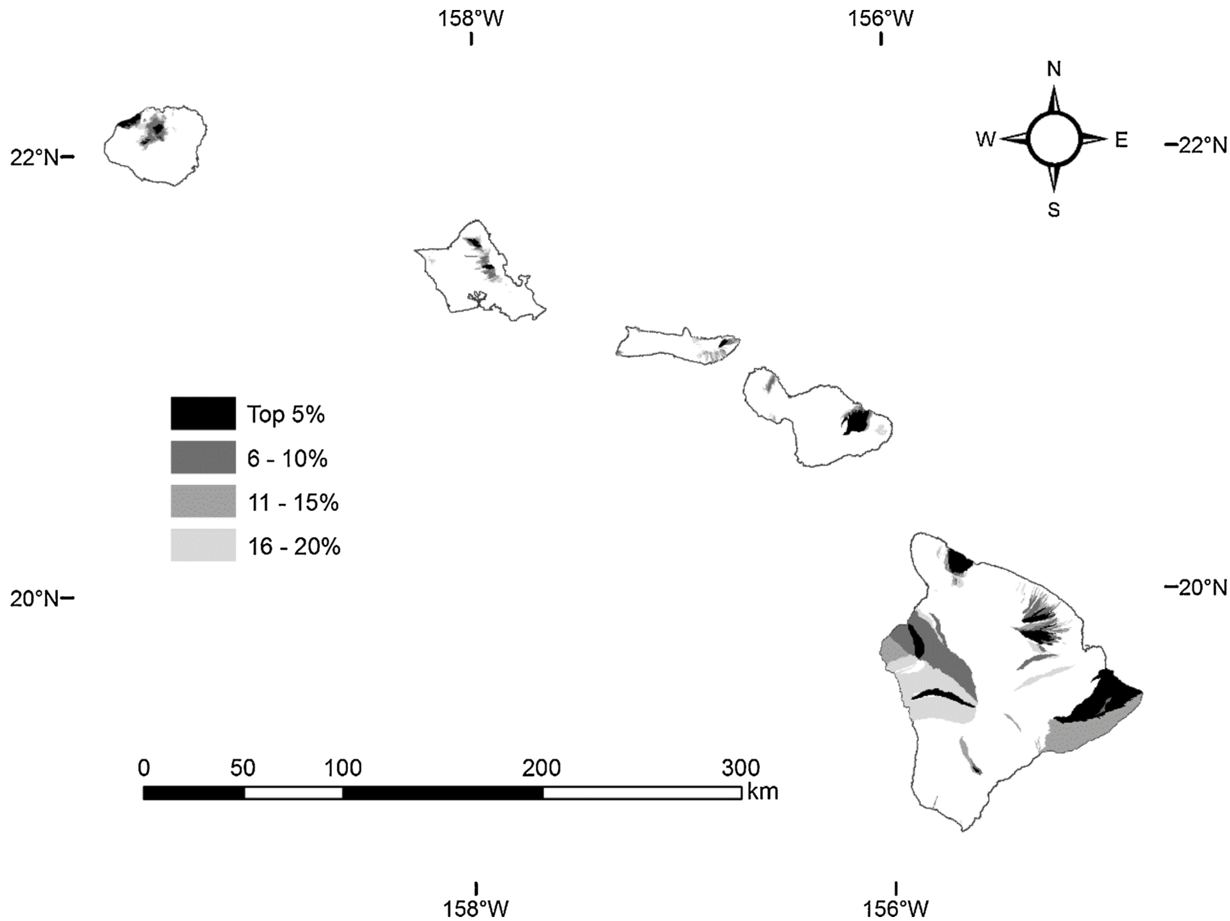

Fig. 5. Planning units selected most frequently across the study region using terrestrial, freshwater and marine conservation features (scenario 1). The top five percent of planning units selected most frequently are found across all five islands, but are more concentrated along coastlines that have very good HCI scores and flow into Areas of Biological Significance (ABSs).

tropical islands like Hawaii will be increasingly relevant given that climate change is expected to alter surface runoff and stream flow patterns beyond historical norms (e.g., Elison Timm, Giambelluca, & Diaz, 2015; Zhang et al., 2016).

4.2. Use of conservation features in prioritization across realms

We chose native vegetation as the conservation feature to assess for terrestrial habitats, perennial streams for freshwater habitats, and areas of biological significance to represent important marine habitats. While our study did not use individual species as conservation features, we instead used the aforementioned habitat targets and connectivity among those habitats as surrogates in each realm because they suggest greater likelihood of supporting multiple native species of interest for conservation. Previous studies have suggested the need to incorporate ecosystem connectivity instead of species-specific connections across realms (Beger, Grantham et al., 2010). Our study similarly aimed to capture connectivity across ecosystems with our broad habitat targets. This approach has several advantages. First, habitats of each realm are represented equally in the conservation planning process. As each realm and habitats within realms could support different numbers of native species, bias is not placed on the realm or habitat with higher species richness. Another advantage of using habitat characteristics in prioritization is that we were not limited by availability of biological data. Extensive biological survey data requires intensive and often expensive monitoring efforts, and data are not commonly available for all areas of conservation interest. We represented conservation features using continuously available information derived with geographic information system (GIS) technologies, an approach that could be applied to any system with limited site-specific biological data, including many tropical island ecosystems. On the other hand, when the ecological linkages are explicit and well understood, connectivity can be formulated, and valuable information could be added to conservation planning (see Beger, Linke et al., 2010).

Similar to previous studies, we found descriptive differences in spatial selection when considering both terrestrial and marine conservation objectives vs. considering them separately (Álvarez-Romero et al., 2015; Klein, Jupiter, Watts, & Possingham, 2014). The trade-off of accounting for connectivity across realms was to select fewer units with perennial streams or native vegetation, which also illustrates the competing objectives in integrated cross-realm planning (Álvarez-Romero et al., 2015). Klein et al. (2010) used cross-realm conservation planning to protect coral reefs, and concluded that in some cases terrestrial conservation is a better investment than marine conservation. We did not do the same comparison (i.e., terrestrial vs. marine conservation), yet our finding highlighted that the cross-realm planning suggested conservation areas with less degradation and therefore less cost (effort) in conserving both terrestrial and marine environments. Our study adds to previous studies in evaluating the trade-off of cross-realm planning, and similarly suggests the differences and benefits of adopting cross-realm conservation are worth considering.

4.3. “Ridge to Reef” conservation

Natural resources managers in Hawaii have increasingly emphasized integrated approaches to conservation, most notably embracing

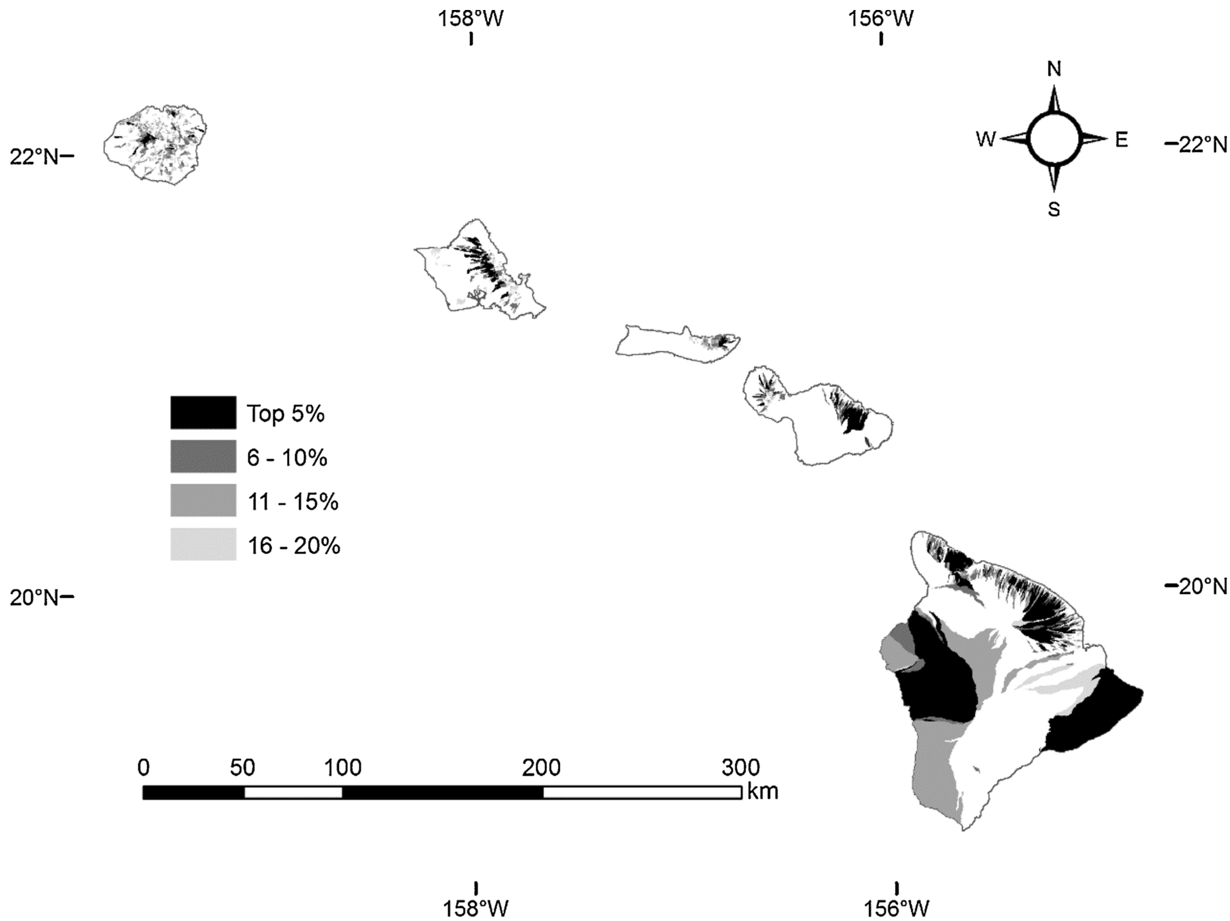

Fig. 6. Planning units selected most frequently across the study region using only terrestrial and freshwater conservation features (scenario 2). The top five percent of planning units selected most frequently are found across all five islands, but are more often at high elevations.

the "Ridge to Reef" concept of conservation. Several agencies with diverse mandates have integrated the Ridge to Reef concept into conservation plans in Hawaii. For example, the U.S. Geological Survey managed soil erosion of a watershed on Molokai to protect the coral reefs (Stock, Cochran, Field, Jacobi, & Tribble, 2011). Similarly, the Coral Reef Conservation Program of National Oceanic and Atmospheric Administration promoted the utility of Ridge to Reef management to protect nearshore habitat (e.g., Pelekane Bay/Puako-Anaeho'omalu Bay on Hawaii Island (Stewart, Michaud, & Donoho, 2011) and American Samoa (Holst-Rice, Messina, Biggs, Vargas-Angel, & Whitall, 2016)). The State of Hawaii Department of Land and Natural Resources and the U.S. Army Corps of Engineers sponsored the West Maui Ridge to Reef Initiative (e.g., Oleson et al., 2017). Local communities have also initiated conservation efforts and developed protection strategies based on the Ridge to Reef concept to protect nearshore marine environment (e.g., Delevaux et al., 2018). All these efforts recognize the hydrological connectivity from mountain to the sea, and therefore protecting nearshore environment by protecting the connected lands.

In contrast to these local and regional efforts, our study implemented the Ridge to Reef concept at a state-wide scale. By incorporating ABSs into conservation planning, we narrowed candidate inland areas of conservation (i.e., catchments with perennial streams and greater amounts of native vegetation) to those with connectivity to these important marine habitats. When the two scenarios are compared, this is especially clear along Northeast Maui, as well as the Kohala and Hamakua coasts on the Island of Hawaii. Those identified areas of high value conservation with connectivity to ABSs include areas that are recognized as distinct ecosystems, such as the areas that have the longest fringing reef (e.g., southern shores of Molokai), and the coast with high diversity of marine life (e.g., Kealakekua Bay Marine Preserve at Kona side of Hawaii Island). This suggests that further conservation efforts that consider connectivity across multiple realms in these regions may be important to protect Hawaiian ecosystems.

Interestingly, even when ABSs were incorporated into the analysis, most areas selected for conservation on the island of Oahu occurred only at high elevations within catchments across the Ko'olau Mountain Ridge and showed little connectivity to the coast (Fig. 5). This isolation of high priority areas may be attributed to two possible reasons. First, conservation features spatially mismatch across realms, such as native vegetation only at high elevations within a catchment, perennial reaches in catchments with little native vegetation, or ABSs adjacent to catchments with few perennial reaches or little native vegetation. Another reason contributing to isolation of priority areas on Oahu is likely due to substantial human disturbance at low elevations and along the coasts, which leads to increased costs in the Marxan analysis and likely inhibited the ridge to reef connectivity in individual catchments. Managers may need to consider how conservation efforts can address these gaps. As the most populated and heavily visited island of Hawaii, the balance between human activities and ecosystem conservation will require natural resource managers to develop strategies that minimize disturbance and promote conservation of connected habitats. For example, we may consider quantifying the "gap" distances between the

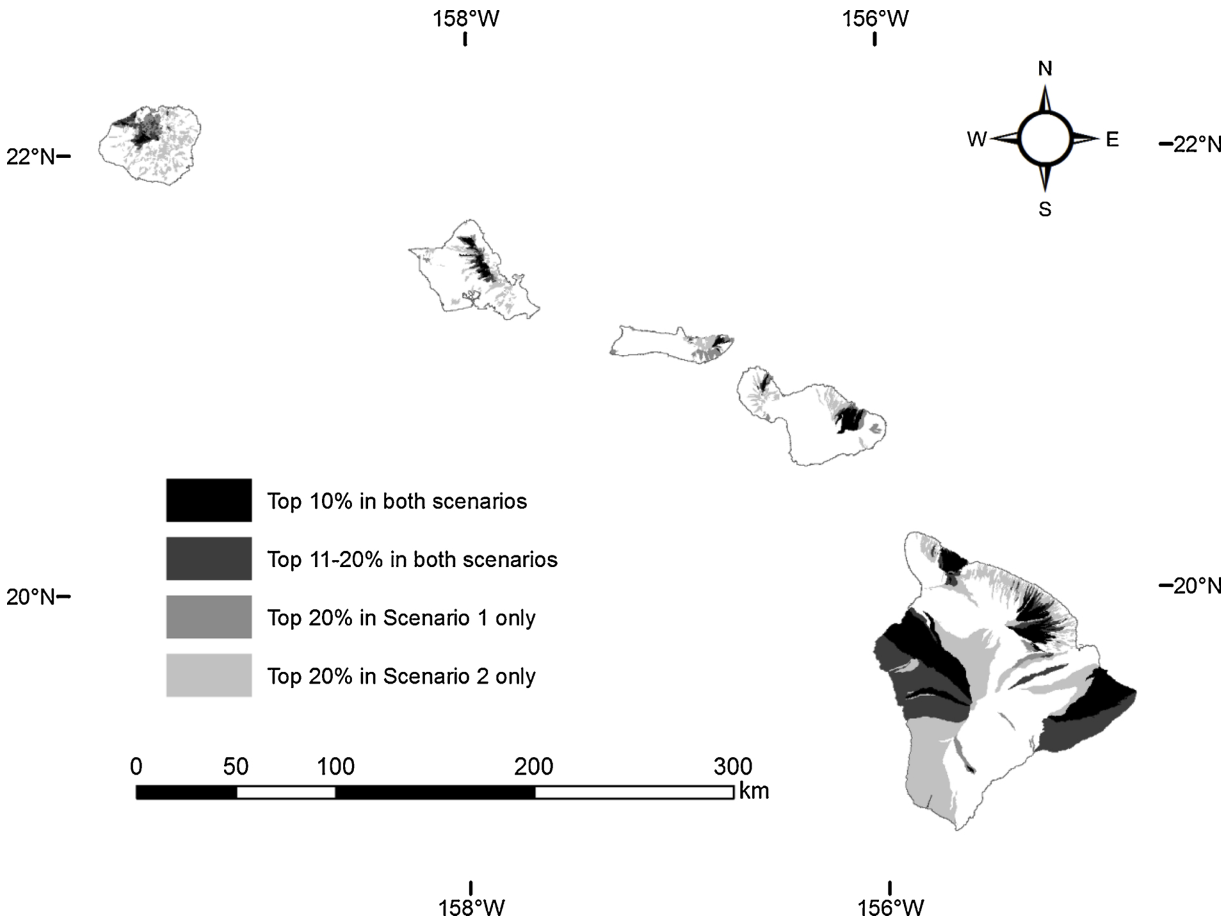

Fig. 7. The most frequently selected planning units (top 10 and top 11–20%) that were selected in both scenarios 1 and 2, as well as planning units that were frequently selected (top 20%) in only scenario 1 or scenario 2.

Table 3
Summarized the statistics of Habitat Condition Index score, perennial stream length, native vegetation areas of the top 20% planning units for each scenario.

	Statistics	Habitat Condition Index (range 0-1)	Perennial stream length (km)	Native vegetation area (km^2)
Scenario 1	Min	0	0.008	0.0001
	Mean	0.054	1.150	1.114
	Max	0.458	17.843	338.958
	Sum	132.551	1719.956	2114.582
Scenario 2	Min	0	0.006	0.0001
	Mean	0.109	1.658	1.612
	Max	0.710	23.552	393.210
	Sum	269.556	3605.875	3069.380

high priority areas in the mountain vs. at the coast. For those catchments with shorter or smaller distances of gaps, we may reestablish the connectivity by limiting development and human activities at the given catchments. Additionally, we may promote connectivity of the stream corridor from ridge to reef by establishing riparian buffers in select catchments. Protection and establishment of riparian buffers has been proven to be effective in protecting water quality and restoring habitats connectivity for fluvial and terrestrial ecosystems (Sweeney & Newbold, 2014). Many urbanized or developed areas have used ecological design to reduce the impact of development (e.g., Marshall et al., 2004). The developed Marxan analysis in this study could be used to examine these potential management strategies.

4.4. The Hawaiian context in conservation

In Hawaii, environmental issues often resonate with the needs and values of the local residents. Many communities are motivated to take care of the land and water resources in their own places and catchments, learning ways of conserving and managing resources sustainably. One example of these community initiatives in Hawaii is the implementation of Traditional Ecological Knowledge, which has been passed on through generations and continues being a part of practices in natural resources management (e.g., Feinstein, 2004; Gon, Tom, & Woodside, 2018). With the same value and context, place-based learning is being promoted and encouraged at all levels of Science, Technology, Engineering, and Math education in Hawaii (Chinn, 2014). This trend of increased effort to understand and address community concerns has garnered local attention and engagement and established successful cases of collaboration (e.g., restoration in He‘eia, Oahu, Bremer et al., 2018). When addressing the gaps and needs in conservation planning in Hawaii, incorporating local community engagement and place-based education could lead to more effective and consequential management decisions.

4.5. Future needs to improve conservation planning

Additional factors may be included in analysis to improve conservation planning. One factor would be information on introduced species. Introduced species are known to threaten native forests (e.g., Moore, 2005), freshwater ecosystems (e.g., Leprieur, Beauchard, Blanchet, Oberdorff, & Brosse, 2008), and estuarine and coastal habitats (e.g., Williams & Grosholz, 2008). They can alter community structure, ecosystem function, and native biodiversity (Holitzki, MacKenzie, Wiegner, & McDermid, 2013). In Hawaii, feral ungulates (i.e., pigs (*Sus scrofa*) and goats (*Capra hircus*)) damaged terrestrial habitats (Sweetapple & Nugent, 2004) and cause landscape erosion (Dunkell, Bruland, Evensen, & Litton, 2011). Additionally, multiple introduced stream species have been described in stream reaches with high percentages of urban land use downstream (Brasher, Luton, Goodbred, & Wolff, 2006), and these species have the potential to compete for the habitat and resources and change stream ecosystem functions. Despite the negative effects of introduced species on ecosystems, current distributions and status of introduced species are not well-described. Improved understanding of their distributions could be incorporated into conservation planning initiatives like the one described in this study to better identify conservation opportunities.

This study had used perennial streams as conservation feature and accounted for upstream influences to downstream habitat by summarizing landscape disturbance factors at a network catchment scale. Both were used to address the hydrologic connectivity among planning units. It would be beneficial and valuable if a hydrological model or a river plume model that is available to directly describe and characterize the upstream catchment influence to the coastal habitat environment. Previously, one river plume model developed for Hawaii is at Kaneohe Bay, Oahu (Ostrander, Mcmanus, Decarlo, & Mackenzie, 2008); another was developed for Mamala Bay, Oahu (Roberts, 1999). However, a comprehensive hydrological assessment or river plume model is not available state-wide. Petus, da Silva, Devlin, Wenger, and Álvarez-Romero (2014) used MODIS data for mapping river plumes in the Great Barrier Reef, Australia, which added river plume spatial information to the assessment of reef and seagrass ecosystems with remote sensing techniques. Being able to describe hydrological connectivity to the coastal environment in such a way would fill a great need for conservation planning in Hawaii.

Locations of culturally-desirable features could also be a valuable addition to cross-realm conservation planning. Desired cultural features like taro plantations (a traditional staple food grown in low-lying reaches of Hawaii) or place-based conservation practices like fish pond restoration (providing nursery habitat for juvenile fishes) could be incorporated as a target conservation features. Such features are increasingly maintained and restored by local stakeholders. These locations could be spatially mapped and integrated into conservation planning approaches, adding valuable fine-resolution information into the conservation planning processes and resulting in a better product for decision-making.

While our study focused on prioritization of Hawaiian ecosystems given current conditions, additional factors to consider in future efforts are effects of climate change on terrestrial, freshwater, and marine habitats. Climate in Hawaii is expected to change in several ways. Windward (northeast) sides of islands are generally projected to be wetter while leeward sides (southwest) will be drier, with variation among islands and with differences in elevation (Elison Timm et al., 2015; Zhang et al., 2016). Increases in air temperature have already been documented at high elevations (Giambelluca, Diaz, & Luke, 2008). Sea level rise is expected to increase groundwater levels at lowlands near coastlines and change hydro-dynamics in estuaries and tidal wetlands (Rotzoll & Fletcher, 2013). These changes could shift distributions of native vegetation (Vorsino et al., 2014), impact streamflow, and decrease habitat availability for stream species in some systems, while also altering condition of nearshore habitats (Rotzoll & Fletcher, 2013). A spatially-explicit identification of areas most susceptible to climate change, including areas with potentially altered hydrologic connections, could add critical information to support conservation planning across realms.

4.6. Conservation prioritization across large landscapes

The value of including connected areas for conservation has been recognized by studies that describe limitations of only protecting isolated natural reserves within larger landscapes (e.g., Noss & Cooperrider, 1994). Identifying conservation areas across a large landscape is now an integral part of many conservation initiatives and is advocated for in natural resources management (Baldwin et al., 2018). To our knowledge, this has not been done in Hawaii. This expansion of scale is a result of a better understanding of the biotic and abiotic interactions and complexities of natural ecosystems, as well as the recognition that the influence of anthropogenic disturbance on an ecosystem goes well beyond that habitat in which it occurs (Halpern et al., 2008). Conservation planning analysis at larger scales encourages natural resources managers within and across agencies and conservation organizations to work together to better achieve broad conservation goals, specifically the intended protection of ecosystems that cross political borders and encompass habitats within multiple realms. A benefit of such an approach is the leveraging of funding and resources to develop more succinct and effective conservation initiatives. Studies like the one described in this manuscript support these efforts by applying a landscape perspective to conservation planning and are valuable as both information and understanding of connectivity among realms grows.

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Appendix A

Table A1
Anthropogenic disturbance variables and categories used in the generation of the 2010 National Fish Habitat Partnership Hawaii Habitat Condition Index scores. Variables were summarized in upstream network catchments (U), local catchments (L) and/or coastal drainage areas (CDA).

Category/variable	Units	Resolution	Currentness	Source	Spatial unit
Urban land/influences					
Open urban	%	2.4/30 m	2001/2005	NLCD[a]/C-CAP[b]	U,L,CDA
Low intensity urban	%	2.4/30 m	2001/2005	NLCD[a]/C-CAP[b]	U,L,CDA
Medium intensity urban	%	2.4/30 m	2001/2005	NLCD[a]/C-CAP[b]	U,L,CDA
High intensity urban	%	2.4/30 m	2001/2005	NLCD[a]/C-CAP[b]	U,L,CDA
Impervious surfaces	%	2.4/30 m	2001/2005	NLCD[a]/C-CAP[b]	U,L,CDA
Population density	#/km^2	12 digit blocks	2000	USCB[c]	U,L,CDA
Length of pipelines	m/km^2	1:24,000	1983	Hawaii OP[d]	U,L,CDA
Length of roads	m/km^2	1:100,000	2000	USCB[c]	U,L,CDA
Agricultural lands					
Pasture/hay	%	2.4/30 m	2001/2005	NLCD[a]/C-CAP[b]	U,L,CDA
Cultivated crops	%	2.4/30 m	2001/2005	NLCD[a]/C-CAP[b]	U,L,CDA
Point source pollution					
Quarries	#/km^2	NA	2003	USGS[e]	U,L,CDA
CERCLIS[f] sites	#/km^2	NA	2007	USEPA[g]	U,L,CDA
PCS[h] majors	#/km^2	NA	2007	USEPA[g]	U,L,CDA
TRI[i] sites	#/km^2	NA	2007	USEPA[g]	U,L,CDA
UIC[j] wells	#/km^2	NA	2004	Hawaii DOH[k]	U,L,CDA
Former plantations					
Pineapple plantation	%	NA	1989	Hawaii OP[d]	U,L,CDA
Sugarcane plantation	%	NA	1989	Hawaii OP[d]	U,L,CDA
Stream fragmentation					
Road crossings	#/km^2	1:100,000	2000	USCB[c]	U,L
Dams	#/km^2	NA	2010	USACE[l]	U,L
Ditch intersections	#/km^2	1:24,000	2004	Hawaii OP[d]	U,L
Length of ditches					
Length of ditches	m/km^2	1:24,000	2004	Hawaii OP[d]	U,L,CDA
303D listed streams					
303D listed streams	%	1:24,000	2002	USEPA[g]	U

[a] National Land Cover Database.
[b] Coastal Change Analysis Program.
[c] U.S. Census Bureau.
[d] Hawaii office of planning.
[e] U.S. Geological Survey.
[f] Comprehensive Environmental Response, Compensation and Liability Information System.
[g] U.S. Environmental Protection Agency.
[h] Permit Compliance System.
[i] Toxic Release Inventory.
[j] Underground Injection Control.
[k] Hawaii department of health.
[l] U.S. Army Corps of Engineers.

References

Adams, V. M., Álvarez-Romero, J. G., Carwardine, J., Cattarino, L., Hermoso, V., Kennard, M. J., ... Stoeckl, N. (2014). Planning across freshwater and terrestrial realms: Cobenefits and tradeoffs between conservation actions. *Conservation Letters, 7*(5), 425–440. https://doi.org/10.1111/conl.12080.

Agardy, M. T. (1994). Advances in marine conservation: The role of marine protected areas. *Trends in Ecology & Evolution, 9*(7), 267–270. https://doi.org/10.1016/0169-5347(94)90297-6.

Allan, J. D. (2004). Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics, 35*(1), 257–284. https://doi.org/10.1146/annurev.ecolsys.35.120202.110122.

Álvarez-Romero, J. G., Pressey, R. L., Ban, N. C., & Brodie, J. (2015). Advancing land-sea conservation planning: Integrating modelling of catchments, land-use change, and river plumes to prioritise catchment management and protection. *PLoS One, 10*(12), 1–26. https://doi.org/10.1371/journal.pone.0145574.

Álvarez-Romero, J. G., Pressey, R. L., Ban, N. C., Vance-Borland, K., Willer, C., Klein, C. J., ... Gaines, S. D. (2011). Integrated land-sea conservation planning: The missing links. *Annual Review of Ecology, Evolution, and Systematics, 42*(1), 381–409. https://doi.org/10.1146/annurev-ecolsys-102209-144702.

Baldwin, R. F., Trombulak, S. C., Leonard, P. B., Noss, R. F., Hilty, J. A., Possingham, H. P., ... Anderson, M. G. (2018). The future of landscape conservation. *BioScience, 68*(2), 60–63. https://doi.org/10.1093/biosci/bix142.

Ball, I. R., Possingham, H. P., & Watts, M. E. (2009). *Marxan and relatives: Software for spatial conservation prioritization.* 185–195.

Bauer, R. T. (2013). Amphidromy in shrimps: A life cycle between rivers and the sea. *Latin American Journal of Aquatic Research, 41*(4), 633–650. https://doi.org/10.3856/vol41-issue4-fulltext-2.

Beger, M., Grantham, H. S., Pressey, R. L., Wilson, K. A., Peterson, E. L., Dorfman, D., ... Possingham, H. P. (2010). Conservation planning for connectivity across marine, freshwater, and terrestrial realms. *Biological Conservation, 143*(3), 565–575. https://doi.org/10.1016/j.biocon.2009.11.006.

Beger, M., Linke, S., Watts, M., Game, E., Treml, E., Ball, I., ... Possingham, H. P. (2010). Incorporating asymmetric connectivity into spatial decision making for conservation. *Conservation Letters, 3*, 359–368. https://doi.org/10.1111/j.1755-263X.2010.00123.x.

Bilkovic, D., & Roggero, M. (2008). Effects of coastal development on nearshore estuarine nekton communities. *Marine Ecology Progress Series, 358*, 27–39. https://doi.org/10.3354/meps07279.

Bodie, J. R. (2001). Stream and riparian management for freshwater turtles. *Journal of Environmental Management, 62*(4), 443–455. https://doi.org/10.1006/jema.2001.0454.

Brasher, A. M. D., Luton, C. D., Goodbred, S. L., & Wolff, R. H. (2006). Invasion patterns

along elevation and urbanization gradients in Hawaiian streams. *Transactions of the American Fisheries Society, 135*(4), 1109–1129. https://doi.org/10.1577/T05-083.1.
Bremer, L. L., Falinski, K., Ching, C., Wada, C. A., Burnett, K. M., Kukea-Shultz, K., ... Ticktin, T. (2018). Biocultural restoration of traditional agriculture: Cultural, environmental, and economic outcomes of Lo'i Kalo restoration in He'eia, O'ahu. *Sustainability, 10*(12), 4502. https://doi.org/10.3390/su10124502.
Chinn, P. W. U. (2014). Place and culture-based professional development: Cross-hybrid learning and the construction of ecological mindfulness. *Cultural Studies of Science Education, 10*(1), 121–134. https://doi.org/10.1007/s11422-014-9585-0.
Danz, N. P., Niemi, G. J., Regal, R. R., Hollenhorst, T., Johnson, L. B., Hanowski, J. M., ... Host, G. E. (2007). Integrated measures of anthropogenic stress in the U.S. Great Lakes Basin. *Environmental Management, 39*(5), 631–647. https://doi.org/10.1007/s00267-005-0293-0.
De Smith, M. J., Goodchild, M. F., & Longley, P.a. (2018). *Geospatial analysis: A comprehensive guide*Hardback ed. Retrieved from(sixth edition). Winchelsea Presshttps://www.amazon.com/Geospatial-Analysis-Comprehensive-Michael-Smith/dp/1912556030/ref=mt_hardcover?_encoding=UTF8&me=&qid=1535856206&dpID=51gX4YTsJFL&preST=_SX218_BO1,204,203,200_QL40_&dpSrc=detail.
Delevaux, J. M. S., Whittier, R., Stamoulis, K. A., Bremer, L. L., Jupiter, S., Friedlander, A. M., ... Ticktin, T. (2018). A linked land-sea modeling framework to inform ridge-to-reef management in high oceanic islands. *PLoS One, 13*(3), e0193230. https://doi.org/10.1371/journal.pone.0193230.
Dixson, D. L., Jones, G. P., Munday, P. L., Planes, S., Pratchett, M. S., Srinivasan, M., ... Thorrold, S. R. (2008). Coral reef fish smell leaves to find island homes. *Proceedings Biological Sciences, 275*(1653), 2831–2839. https://doi.org/10.1098/rspb.2008.0876.
Dunkell, D. O., Bruland, G. L., Evensen, C. I., & Litton, C. M. (2011). Runoff, sediment transport, and effects of feral pig (*Sus scrofa*) exclusion in a forested Hawaiian watershed. *Pacific Science, 65*(2), 175–194. https://doi.org/10.2984/65.2.175.
Elison Timm, O., Giambelluca, T. W., & Diaz, H. F. (2015). Statistical downscaling of rainfall changes in Hawai'i based on the CMIP5 global model projections. *Journal of Geophysical Research Atmospheres, 120*, 92–112. https://doi.org/10.1002/2014JD022059.Received.
Esselman, P. C., & Allan, J. D. (2010). Relative influences of catchment- and reach-scale abiotic factors on freshwater fish communities in rivers of northeastern Mesoamerica. *Ecology of Freshwater Fish, 19*(3), 439–454. https://doi.org/10.1111/j.1600-0633.2010.00430.x.
Esselman, P. C., & Allan, J. D. (2011). Application of species distribution models and conservation planning software to the design of a reserve network for the riverine fishes of northeastern Mesoamerica. *Freshwater Biology, 56*(1), 71–88. https://doi.org/10.1111/j.1365-2427.2010.02417.x.
Esselman, P., Infante, D., & Wang, L. (2011). An index of cumulative disturbance to river fish habitats of the conterminous United States from landscape anthropogenic activities. *Ecological Restoration, 29*(1–2), 134–151. Retrieved from http://er.uwpress.org/content/29/1-2/133.short.
Fabricius, K. E. (2005). Effects of terrestrial runoff on the ecology of corals and coral reefs: Review and synthesis. *Marine Pollution Bulletin, 50*(2), 125–146. https://doi.org/10.1016/j.marpolbul.2004.11.028.
Feinstein, B. C. (2004). Learning and transformation in the context of hawaiian traditional ecological knowledge. *Adult Education Quarterly, 54*(2), 105–120. https://doi.org/10.1177/0741713603260275.
Fitzsimons, J. M., Parham, J. E., & Nishimoto, R. T. (2002). Similarities in behavioral ecology among amphidromous and catadromous fishes on the oceanic islands of Hawai'i and Guam. *Environmental Biology of Fishes, 65*(2), 123–129. https://doi.org/10.1023/A:1020041408248.
Fitzsimons, M. J., McRae, M. G., & Nishimoto, R. T. (2007). Behavioral ecology of indigenous stream fishes in Hawai'i. *Bishop Museum Bulletin in Cultural and Environmental Studies, 3*, 11–21. Retrieved from http://hbs.bishopmuseum.org/pubs-online/strm/bces3r.pdf#page=20.
Game, E. T., & Grantham, H. S. (2008). In J. Ardron, C. Klein, D. Nicolson, H. Possingham, & M. Watts (Eds.). *Marxan user manual for Marxan version 1.8.10*Vancouver, British Columbia, Canada: University of Queensland, St. Lucia, Queensland, Australia, and Pacific Marine Analysis and Research Association. Retrieved from http://marxan.net/downloads/documents/Marxan_User_Manual_2008.pdf.
Giambelluca, T. W., DeLay, J. K., Nullet, M. A., Scholl, M. A., & Gingerich, S. B. (2011). Canopy water balance of windward and leeward Hawaiian cloud forests on Haleakalā, Maui, Hawai'i. *Hydrological Processes, 25*(3), 438–447. https://doi.org/10.1002/hyp.7738.
Giambelluca, T. W., Diaz, H. F., & Luke, M. S. A. (2008). Secular temperature changes in Hawai'i. *Geophysical Research Letters, 35*(12), https://doi.org/10.1029/2008GL034377 n/a-n/a.
Gon, S. M., III, Tom, S. L., & Woodside, U. (2018). 'Āina Momona, Honua Au Loli—productive lands, changing world: Using the Hawaiian footprint to inform biocultural restoration and future sustainability in Hawai'i. *Sustainability, 10*(10), 3420. https://doi.org/10.3390/su10103420.
Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., ... Watson, R. (2008). A global map of human impact on marine ecosystems. *Science, 319*(5865), 948–952. https://doi.org/10.1126/science.1149345.
Hawaii Deparment of Health (2004). *Underground injection control*.
Hawaii Department of Health (2012). *2008/2010 State of Hawaii water quality monitoring and assessment report: Integrated report to the U.S. environmental protection agency and the U.S. congress pursuant to 303(d) and 305(d), Clean Water Act (P.L. 97-117)* Retrieved January 8, 2010, from http://health.hawaii.gov/cwb.
Hawaii Division of Aquatic Resources (2004). *Ditches.* Retrieved January 5, 2010, fromhttp://planning.hawaii.gov/gi.
Hawaii Office of Planning (1983). *DLG pipelines and transmission lines.* Retrieved January 5, 2010, fromhttp://planning.hawaii.gov/gi/.
Hawaii Office of Planning (1989). *Prior agricultural lands.* Retrieved May 1, 2010, fromhttp://planning.hawaii.gov/gi/.
Hazlitt, S. L., Martin, T. G., Sampson, L., & Arcese, P. (2010). The effects of including marine ecological values in terrestrial reserve planning for a forest-nesting seabird. *Biological Conservation, 143*(5), 1299–1303. https://doi.org/10.1016/j.biocon.2010.01.026.
Hoffman, J. C., Bronk, D. A., & Olney, J. E. (2008). Organic matter sources supporting lower food web production in the tidal freshwater portion of the York River Estuary, Virginia. *Estuaries and Coasts, 31*(5), 898–911. https://doi.org/10.1007/s12237-008-9073-4.
Holitzki, T. M., MacKenzie, R. A., Wiegner, T. N., & McDermid, K. J. (2013). Differences in ecological structure, function, and native species abundance between native and invaded Hawaiian streams. *Ecological Applications: A Publication of the Ecological Society of America, 23*(6), 1367–1383. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/24147409.
Holst-Rice, S., Messina, A., Biggs, T. W., Vargas-Angel, B., & Whitall, D. (2016). *Baseline assessment of Faga'alu watershed: A ridge to reef assessment in support of sediment reduction activities and future evaluation of their success.* MD: Silver Springhttps://doi.org/10.7289/V5BK19C3.
Homer, C., Huang, C., Yang, L., Wylie, B., & Coan, M. (2004). Development of a 2001 national land-cover database for the United States. *Photogrammetric Engineering and Remote Sensing, 70*(7), 829–840. https://doi.org/10.14358/PERS.70.7.829.
Kaneshiro, K. Y., Chinn, P., Duin, K. N., Hood, A. P., Maly, K., & Wilcox, B. A. (2005). Hawai'i's mountain-to-sea ecosystems: Social–ecological microcosms for sustainability science and practice. *EcoHealth, 2*(4), 349–360. https://doi.org/10.1007/s10393-005-8779-z.
Kinzie, R. A. I., & Ford, J. I. (1977). *A limnological survey of lower Palikea and Pīpīwai streams, Kīpahulu, Maui.* Retrieved fromCooperative National Park Resources Studies Unit, University of Hawaii at Manoa, Department of Botanyhttps://scholarspace.manoa.hawaii.edu/handle/10125/4028.
Klein, C. J., Ban, N. C., Halpern, B. S., Beger, M., Game, E. T., Grantham, H. S., ... Possingham, H. P. (2010). Prioritizing land and sea conservation investments to protect coral reefs. *PLoS One, 5*(8), 4–11. https://doi.org/10.1371/journal.pone.0012431.
Klein, C. J., Jupiter, S. D., Watts, M., & Possingham, H. P. (2014). Evaluating the influence of candidate terrestrial protected areas on coral reef condition in Fiji. *Marine Policy, 44*, 360–365. https://doi.org/10.1016/j.marpol.2013.10.001.
Klein, C. J., Jupiter, S. D., Selig, E. R., Watts, M. E., Halpern, B. S., Kamal, M., ... Possingham, H. P. (2012). Forest conservation delivers highly variable coral reef conservation outcomes. *Ecological Applications, 22*(4), 1246–1256. https://doi.org/10.1890/11-1718.1.
Lamberti, G. A., Chaloner, D. T., & Hershey, A. E. (2010). Linkages among aquatic ecosystems. *Journal of the North American Benthological Society, 29*(1), 245–263. https://doi.org/10.1899/08-166.1.
Lau, L. S., Leung, K. S., Mink, J. F., & John, F. (2006). *Hydrology of the Hawaiian Islands.* Retrieved fromUniversity of Hawai'i Presshttps://www.jstor.org/stable/j.ctt6wr37p.
Leprieur, F., Beauchard, O., Blanchet, S., Oberdorff, T., & Brosse, S. (2008). Fish invasions in the world's river systems: When natural processes are blurred by human activities. *PLoS Biology, 6*(2), e28. https://doi.org/10.1371/journal.pbio.0060028.
Locker, S. D., Armstrong, R. A., Battista, T., Rooney, J. J., Sherman, C., & Zawada, D. G. (2010). Geomorphology of mesophotic coral ecosystems: Current perspectives on morphology, distribution, and mapping strategies. *Coral Reefs, 29*(2), 329–345. https://doi.org/10.1007/s00338-010-0613-6.
Makino, A., Beger, M., Klein, C. J., Jupiter, S. D., & Possingham, H. P. (2013). Integrated planning for land–sea ecosystem connectivity to protect coral reefs. *Biological Conservation, 165*, 35–42. https://doi.org/10.1016/j.biocon.2013.05.027.
Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature, 405*(6783), 243–253. https://doi.org/10.1038/35012251.
Marshall, B. D., Kreeger, D. A., Velinsky, D. J., Johnson, T. E., Hession, W. C., Horwitz, R. J., ... Charles, D. F. (2004). *Ecological benefits of riparian reforestation in urban watersheds. Protection and restoration of urban and rural streams*373–382. https://doi.org/10.1061/40695(2004)9.
McDowall, R. M. (2003). Hawaiian biogeography and the islands' freshwater fish fauna. *Journal of Biogeography, 30*(5), 703–710. https://doi.org/10.1046/j.1365-2699.2003.00851.x.
McRae, M. G., McRae, L. B., & Michael Fitzsimons, J. (2011). Habitats used by Juvenile Flagtails (Kuhlia spp.; Perciformes: Kuhliidae) on the island of Hawai'i. *Pacific Science, 65*(4), 441–450. https://doi.org/10.2984/65.4.441.
Melles, S. J., Jones, N. E., & Schmidt, B. (2012). Review of theoretical developments in stream ecology and their influence on stream classification and conservation planning. *Freshwater Biology, 57*(3), 415–434. https://doi.org/10.1111/j.1365-2427.2011.02716.x.
Moore, B. A. (2005). Alien invasive species: Impacts on forests and forestry. *Forest resources development service working paper FBS/8E forest resources division FAO,* 62. Retrieved from http://www.fao.org/docrep/008/j6854e/j6854e00.htm.
Mumby, P. J., Edwards, A. J., Ernesto Arias-González, J., Lindeman, K. C., Blackwell, P. G., Gall, A., ... Llewellyn, G. (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature, 427*(6974), 533–536. https://doi.org/10.1038/nature02286.
Nishimoto, R. T., & Ftizsimons, J. M. (2006). *Status of native Hawaiian stream fishes, a unique amphidromous biota. American Fisheries Society Symposium*.
Noss, R. F., & Cooperrider, A. Y. (1994). *Saving nature's legacy: Protecting and restoring biodiversity.* Island Press.
Olds, A. D., Connolly, R. M., Pitt, K. A., Pittman, S. J., Maxwell, P. S., Huijbers, C. M., ... Schlacher, T. A. (2016). Quantifying the conservation value of seascape connectivity: A global synthesis. *Global Ecology and Biogeography, 25*(1), 3–15. https://doi.org/10.

1111/geb.12388.
Oleson, K. L. L., Falinski, K. A., Lecky, J., Rowe, C., Kappel, C. V., Selkoe, K. A., ... White, C. (2017). Upstream solutions to coral reef conservation: The payoffs of smart and cooperative decision-making. *Journal of Environmental Management, 191*, 8–18. https://doi.org/10.1016/J.JENVMAN.2016.12.067.
Petus, C., da Silva, E. T., Devlin, M., Wenger, A. S., & Álvarez-Romero, J. G. (2014). Using MODIS data for mapping of water types within river plumes in the Great Barrier Reef, Australia: Towards the production of river plume risk maps for reef and seagrass ecosystems. *Journal of Environmental Management, 137*, 163–177. https://doi.org/10.1016/j.jenvman.2013.11.050.
Price, J. P., Jacobi, J. D., Gon, S. M., III, Matsuwaki, D., Mehrhoff, L., Wagner, W., ... Rowe, B. (2012). *Mapping plant species ranges in the Hawaiian Islands − Developing a methodology and associated GIS layers*Retrieved from. Hawai'i Cooperative Studies Unit Technical Report HCSU-008https://pubs.usgs.gov/of/2012/1192/.
Pringle, C. (2003). What is hydrologic connectivity and why is it ecologically important? *Hydrological Processes, 17*(13), 2685–2689. https://doi.org/10.1002/hyp.5145.
Richter, S. C., Young, J. E., Seigal, R. A., & Johnson, G. N. (2001). Post breeding movements of the dark gopher frog, *Rana sevosa* go in and netting: Implications for conservation and management. *Journal of Herpetology, 35*(2), 336-321. Retrieved from https://www.fs.usda.gov/treesearch/pubs/9528.
Roberts, P. J. W. (1999). Modeling Mamala Bay Outfall Plumes. II: Far field. *Journal of Hydraulic Engineering, 125*(6), 574.
Rohmann, S. O., Hayes, J. J., Newhall, R. C., Monaco, M. E., & Grigg, R. W. (2005). The area of potential shallow-water tropical and subtropical coral ecosystems in the United States. *Coral Reefs, 24*(3), 370–383. https://doi.org/10.1007/s00338-005-0014-4.
Rotzoll, K., & Fletcher, C. H. (2013). Assessment of groundwater inundation as a consequence of sea-level rise. *Nature Climate Change, 3*(5), 477–481. https://doi.org/10.1038/nclimate1725.
Ostrander, C. E., Mcmanus, M. A., Decarlo, E. H., & Mackenzie, F. T. (2008). Temporal and spatial variability of freshwater plumes in a semienclosed estuarine – Bay system. *Estuaries and Coasts, 31*, 192–203. https://doi.org/10.1007/s12237-007-9001-z.
Seelbach, P., Wiley, M. J., Baker, M. E., & Wehrly, K. E. (2006). Initial classification of river valley segments across Michigan's Lower Peninsula. *American Fisheries Society Symposium, 48*, 25–48. Retrieved from https://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Initial+Classification+of+River+Valley+Segments+across+Michigan+%E2%80%99+s+Lower+Peninsula#0.
Shafer, C. L. (1999). National park and reserve planning to protect biological diversity: Some basic elements. *Landscape and Urban Planning, 44*(2–3), 123–153. https://doi.org/10.1016/S0169-2046(98)00115-7.
Smetacek, V. S. (1986). Impact of freshwater discharge on production and transfer of materials in the marine environment. In S. Skreslet (Ed.). *The role of freshwater outflow in coastal marine ecosystems* (pp. 85–106). Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-70886-2_6 Berlin Heidelberg.
Stewart, C., Michaud, J., & Donoho, M. (2011). *Waiulaula watershed management plan, Mauna kea soil and water conservation district.* Retrieved from http://health.hawaii.gov/cwb/files/2013/05/PRC_319Grant_WaikoloaWatershed-Characterization.pdf.
Stock, J. D., Cochran, S. A., Field, M. E., Jacobi, J. D., & Tribble, G. (2011). From ridge to reef—Linking erosion and changing watersheds to impacts on the coral reef ecosystems of Hawai'i and the Pacific Ocean. *Dela,* (May), 4. Retrieved from https://pubs.usgs.gov/fs/2011/3049/.
Stoms, D. M., Davis, F. W., Andelman, S. J., Carr, M. H., Gaines, S. D., Halpern, B. S., ... Warner, R. R. (2005). Integrated coastal reserve planning: making the land – sea connection In a nutshell. *Frontiers in Ecology and the Environment, 3*(8), 429–436. https://doi.org/10.2307/3868659.
Sweeney, B. W., & Newbold, J. D. (2014). Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: A literature review. *Journal of the American Water Resources Association, 50*(3), 560–584. https://doi.org/10.1111/jawr.12203.
Sweetapple, P. J., & Nugent, G. (2004). Seedling ratios: A simple method for assessing ungulate impacts on forest understories. *Wildlife Society Bulletin, 32*(1), 137–147. https://doi.org/10.2193/0091-7648(2004)32[137:SRASMF]2.0.CO;2.
Takahashi, M., Giambelluca, T. W., Mudd, R. G., DeLay, J. K., Nullet, M. A., & Asner, G. P. (2011). Rainfall partitioning and cloud water interception in native forest and invaded forest in Hawai'i Volcanoes National Park. *Hydrological Processes, 25*(3), 448–464. https://doi.org/10.1002/hyp.7797.
Tingley, R. W., III, Infante, D. M., MacKenzie, R. A., Cooper, A. R., & Tsang, Y.-P. (2019). Identifying natural catchment landscape influences on tropical stream organisms: Classifying stream reaches of the Hawaiian Islands. *Hydrobiologia, 826*(1), 67–83. https://doi.org/10.1007/s10750-018-3726-5.
Tsang, Y.-P., Wieferich, D., Fung, K., Infante, D. M., & Cooper, A. R. (2014). An approach for aggregating upstream catchment information to support research and management of fluvial systems across large landscapes. *SpringerPlus, 3*(1), 589. https://doi.org/10.1186/2193-1801-3-589.
US Army Corps of Engineers (2010). *National inventory of dams.* Retrieved April 1, 2010, fromhttp://nid.usace.army.mil/.
US Census Bureau (2001). *Census 2000 summary file 1: Technical documentation.* Retrieved May 1, 2010, fromW, DC: US. Department of Commerce. http://www.census.gov/2000census/data/.
US Census Bureau Geography Division (2002). *TIGER/line files technical documentation.* Retrieved May 1, 2010, fromWashington, DC: US Department of Commerce. https://www.census.gov/geo/maps-data/data/tiger-line.html/.
US Environmental Protection Agency (2002). *NFH Indexed locations for Selection 303(d) listed water.* Retrieved fromhttp://www.epa.gov/datafinder/.
US Environmental Protection Agency (2010). *CERCLIS, PCS, and TRI sites.* Retrieved May 1, 2010, fromhttp://www.epa.gov/datafinder/.
US Geological Survey (2003). *Active mines and mineral processing plants.* Retrieved fromhttp://ned.usgs.gov/.
US Geological Survey (2006). *National Elevation Dataset.* Retrieved March 1, 2010, fromhttp://ned.usgs.gov/.
US Geological Survey (2008). *National Hydrography Dataset.* Retrieved March 1, 2010, fromhttp://nhd.usgs.gov.
Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences, 37*(1), 130–137. https://doi.org/10.1139/f80-017.
Vorsino, A. E., Fortini, L. B., Amidon, F., Miller, S. E., Jacobi, J. D., Price, J. P., ... Koob, G. A. (2014). Modeling Hawaiian ecosystem degradation due to invasive plants under current and future climates. *PLoS One, 9*(5), https://doi.org/10.1371/journal.pone.0095427.
Wang, L., Infante, D., Esselman, P., Cooper, A., Wu, D., Taylor, W., ... Ostroff, A. (2011). A hierarchical spatial framework and database for the national river fish habitat condition assessment. *Fisheries, 36*(9), 436–449. https://doi.org/10.1080/03632415.2011.607075.
Wang, L., Lyons, J., Kanehl, P., & Bannerman, R. (2001). Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Management, 28*(2), 255–266. https://doi.org/10.1007/s002670010222.
Wang, L., Riseng, C. M., Mason, L. A., Wehrly, K. E., Rutherford, E. S., McKenna, J. E., ... Coscarelli, M. (2015). A spatial classification and database for management, research, and policy making: The Great Lakes aquatic habitat framework. *Journal of Great Lakes Research, 41*(2), 584–596. https://doi.org/10.1016/j.jglr.2015.03.017.
Weiant, P. (2009). *Marine ecoregional assessment for the main Hawaiian Islands. The Nature Conservancy*72 Honolulu, HI.
Williams, S. L., & Grosholz, E. D. (2008). The invasive species challenge in estuarine and coastal environments: Marrying management and science. *Estuaries and Coasts, 31*(1), 3–20. https://doi.org/10.1007/s12237-007-9031-6.
Zhang, C., Wang, Y., Hamilton, K., Lauer, A., Zhang, C., Wang, Y., ... Lauer, A. (2016). Dynamical downscaling of the climate for the Hawaiian islands. Part II: Projection for the late twenty-first century. *Journal of Climate, 29*(23), 8333–8354. https://doi.org/10.1175/JCLI-D-16-0038.1.