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Abstract A linkage between the condition of watersheds and adjacent nearshore coral reef communities is an assumed paradigm in the concept of integrated coastal management. However, quantitative evidence for this "catchment to sea" or "ridge to reef" relationship on oceanic islands is lacking and would benefit from the use of appropriate marine and terrestrial landscape indicators to quantify and evaluate ecological status on a large spatial scale. To address this need, our study compared the Hawai'i Watershed Health Index (HI-WHI) and Reef Health Index (HI-RHI) derived independently of each other over the past decade. Comparisons were made across 170 coral reef stations at 52 reef sites adjacent to 42 watersheds throughout the main Hawaiian Islands. A significant positive relationship was shown between the health of watersheds and that of adjacent reef environments when all sites and depths were considered. This relationship was strongest for sites facing in a southerly direction, but diminished for north facing coasts exposed to persistent high surf. High surf conditions along the north shore increase local wave driven currents and flush watershed-derived materials away from nearshore waters. Consequently, reefs in these locales are less vulnerable to the deposition of land derived sediments, nutrients and pollutants transported from watersheds to ocean. Use of integrated landscape health indices can be applied to improve regional-scale conservation and resource management.

Keywords Landscape ecology · Ecosystem health · Biotic indicators · GIS analyses · Index

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Introduction

Ecological studies which evaluate the integrity and health of whole ecological systems are of increasing importance in resource management (e.g., Westra and others 2000). Undisturbed systems maintain vigor, organization, and resilience (Ulanowicz 2000) created by the "evolutionary and biogeographical processes of that place" (Angermeier and Karr 1994). Humans can degrade the health of ecosystems through various activities (e.g., Westra and others 2000). Landscape ecology focuses on the interaction of ecological processes and spatial patterns to evaluate the characteristics of this interaction in relation to human activity (e.g., Turner and others 2001). For such an assessment, tools such as "landscape indicators" can be used to quantify human impact by examining the extent of land use change occurring spatiotemporally (e.g. Meyer and Turner 1994). In continental systems upland land use influences riverine ecosystems lower in the watershed (e.g., Omernik and others 1981; Williams and others 1997); however, we know of only one recent study that has attempted to apply landscape indicators to examine human influence on whole ecological systems from catchment-to-sea. Oliver and others (2011) using a landscape development intensity index found a negative relationship between coral and human activity in St. Croix (US Virgin Islands) where regions of higher human activity had poorer coral condition. Whole-system studies are difficult to conduct on continents, but are possible on oceanic islands which can be viewed as unique microcosms of continental systems (Kaneshiro and others 2005). Results from such whole-ecosystem studies may be integrated into management efforts to sustain ecosystem health and services in entire catchment-to-sea (or ridge-to-reef) environments. The "ridge to reef" paradigm has become a familiar management theme throughout the Pacific (USGS 2008, Richmond and others 2007) and for centuries has been a central element in the native Hawaiian management scheme known as the "*ahupua'a* system" (e.g., Handy and Handy 1978). This traditional and integrated view of Hawaiian land division and resource management combined watersheds, streams and coastal regions as integral interacting components of an ecosystem (Williams 1992, Jokiel and others 2011). In this holistic view, the sustainability of watershed and nearshore resources (e.g., coral reefs) were recognized as being related to human practices on land (Handy and Handy 1978) which today is a central premise in ecological science (e.g., Gergel and others 2002).

Both natural and anthropogenic factors are influential in structuring coral and fish populations. Many natural factors influence coral reef communities including wave energy (Grigg 1983), spatial complexity and depth (Rodgers 2005) competition, predation (Vermeij and others 2010), and disease (Vargas-Ángel and Wheeler 2009). Anthropogenic factors also influence ecological structuring of coral reefs including human population, distance from streams (Rodgers 2005), sedimentation (Rogers 1990), overfishing, (Williams and others 2008) invasive species (Godwin and others 2006), coastal construction, and climate change (Kleypas and others1999). The watershed impacts the adjacent reef primarily through ground- and surface water flows that form a "geomorphic-hydrologic continua (Vannote and others 1980), transporting nutrients, sediments, organic matter, and other materials from the watershed to the ocean (Kido 2008). Groundwater seepage alters reef salinity and temperature and is a major source of nutrient delivery to reefs. Under natural conditions, streams and sheet runoff interact with watersheds, riparian zones, and flood plains in the transfer of fresh water, sediments, organic matter and other materials from catchment-to-sea. However, human-induced alterations in watersheds caused by clearing of forests, increased agriculture, overgrazing, urbanization and modification of stream channels can profoundly disrupt natural function, transport massive quantities of material downstream (Ward 1998), and deliver increasing amounts of pollutants to the reef.

Landscape indicators have been used successfully to quantify the condition of terrestrial ecosystems (e.g., Gergel and others 2002). For example, indicators have been used to evaluate the physical structure of vegetation (Meyer and Turner 1994), relate human uses in catchments to stream water chemistry (Osborne and Wiley 1988) and relate spatial patterns in riparian zones to nutrient loads in ground- and surface-waters (Detenbeck and others 1993). Such studies demonstrate the importance of using characteristics of the landscape to explain ecological processes (Karr and Chu 1999). Karr and Dudley's (1981) Index of Biological Integrity (IBI), for example, integrated information on fish communities from individual, population, and community levels into a single, ecological-based index that is responsive to water resource quality. IBIs applied in this manner reflect the condition of land–water linkages, physical habitat quality, hydrological regime, energy inputs, and biological interactions in whole ecosystems (Ganasan and Hughes 1998). For regional-scale monitoring applications, landscape indicators can summarize the ecological status of ecosystems over broad geographic regions (e.g., Jones and others 2000). However, the scientific challenge is to more effectively relate spatial patterns observed in the landscape to ecological processes occurring in the environment (Gergel and others 2002). Ecological assessment protocols have been developed that can evaluate the impact of anthropogenic influence on biophysical environments with protocols that serve to link landscape indicators to ecological processes. For example, a hydrogeomorphic model (HGM) has been widely applied to quantify the functional aspects of wetlands (Brinson 1993; Magee 1996, Smith and others 1995). Ben-Tzvi and others (2004) developed a "coral reef deterioration index" which can identify disturbed coral reef communities. A standardized coral reef monitoring and assessment protocol designed to evaluate the overall condition of Hawai'i's reefs and track temporal changes (Brown and others 2004) has been in use in Hawai'i for over a decade. For stream environments, Kido (2001) developed a multimetric IBI which utilizes attributes of the native fresh water fish and macroinvertebrate assemblage to evaluate the impact of human influence on Hawaiian stream health, while Jameson and others (2001) developed a strategy for creating IBI's for coral reefs. These approaches synthesize results of complex ecological research programs into a framework that can be easily communicated to a broad audience in a straightforward manner. Linking landscape indicators to biological metrics can provide insights into the influence of human activities on biophysical systems.

In this study we evaluate the usefulness of integrating a landscape index for Hawaiian watersheds and their adjacent coral reef environments using both coral and fish population indicators in order to provide a holistic catchment-to-sea landscape perspective of the impact of humans on the health of whole ecological systems on a large scale. Furthermore, we evaluate and discuss linkages of spatial land-use patterns to various ecological processes in relation to the nearshore marine biota.

Materials and Methods

Hawai'i Watershed Health Index (HI-WHI)

The State of Hawai'i GIS database watershed layer covers the eight main Hawaiian Islands (Fig. 1). These watershed delineations provide relative drainage and management units from mountain-to-sea which include all terrestrial, freshwater, and marine resources. The Hawai'i Watershed Health Index (HI-WHI) (Kido 2006) was developed as a landscape indicator that quantifies levels of human impact across a basic set of land cover classes and thereby evaluates the overall health (Westra and others 2000) of watershed delineated units. For the main eight high islands in the State of Hawai'i, 571 watersheds (O'ahu = 106, Ni'ihau = 14, Moloka'i = 50, Maui = 112, Lāna'i = 32, Kaua'i = 74, Kaho'olawe = 24, Hawai'i = 159) have been delineated (www.state.hi.us/dbedt/gis). These watersheds roughly follow ancient Hawaiian *ahupua'a* boundaries from ridge-to-reef. The method to calculate HI-WHI uses a GIS-based analysis (ArcGIS 9.2) to create a number of basic land cover classes from existing datasets, extract percent cover for each class within a watershed, then weight percent cover data to calculate an "index of watershed health". Weightings are assigned relative positive or negative values of various magnitudes based on expert knowledge, and by searching for trends between existing field data values and percent land cover within watersheds.

Land cover classifications used in the analyses were developed for all islands as part of the HI-GAP Project (Gon and others 2006) and were extracted from analyses of Landsat 7 imagery. Land cover classes that varied between islands were simplified into a basic set of metrics that could be applied in watershed delineated units statewide to quantify levels of human impact. Nineteen classes were described (Table 1) and percent cover per watershed unit was calculated using standard GIS procedures in ARCMAP (ArcGIS 9.2).

WHI scores were calculated using an initial rating scheme for metrics which were compared to IBI scores

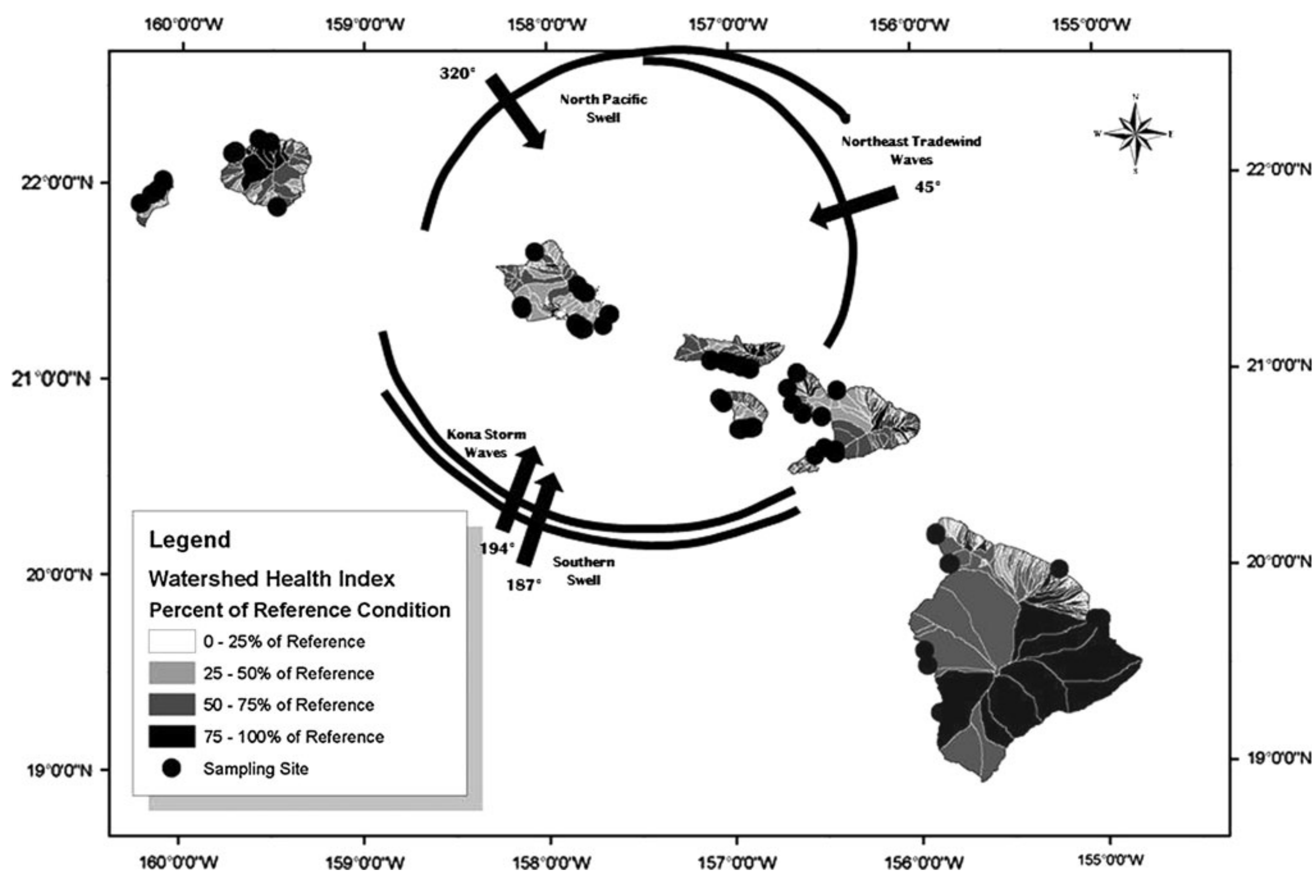

Fig. 1 Map of the main eight Hawaiian Islands depicting the 571 watersheds and the 52 nearshore sites used in the comparison of the Watershed Health Index with the Reef Health Index. Watershed delineations depict four index reference conditions ranging from poor (0–25%) to good watershed health (75–100%). Dominant wave directions and extent are provided

Table 1 Weighting metrics developed from land cover classes that were applied in watershed delineated units statewide to quantify levels of human impact

Metric No.	Metric	Input Weightings
1	Native Forest	2
2	Unclassified Forest	1
3	Alien Forest	−1
4	Native Shrubs	2
5	Alien Shrubs	0.5
6	Unclassified Shrubs	1
7	Grasslands	−1
8	Open Sparse Vegetation	−0.25
9	Very Sparse Unvegetated	−1
10	Agriculture	−1.5
11	High Intensity Developed	−2
12	Low Intensity Developed	−1.5
13	Major Roads	−0.5
14	Other Roads	−1
15	Water Bodies	−1
16	Ditches	−1
17	Natural Open Sparse Veg	0.25
18	Natural Very Sparse Unveg	1
19	Natural Grassland	1

obtained by sampling streams in the corresponding watershed based on the idea that catchment health and stream health are highly correlated. Strong validation of metric scoring was provided as additional data became available. This iterative process was used to develop a system of weightings for metrics that would account for the polarity and magnitude of the impact of each variable on watershed health. For example, roads and modified streams (artificial paths, drainage ditches, aqueducts, siphons, canals, pipes etc.) reduce stream habitat quality and degrade ecological health so they were assigned negative weighting scores. Total feet per acre per watershed unit for such human modified structures were calculated from existing vector datasets using standard GIS procedures. A higher score was given to 'Native Forest' than to 'Alien Forest' and to 'Natural Grassland' than to 'Grassland' although both provide protection from erosion because the natural state indicates a more intact watershed with reduced human disturbance and enhanced control of water, nutrient, and sediment movement in Hawaiian watersheds. Similarly, 'Water Bodies' are scored negatively because the overwhelming majority of water bodies in Hawai'i have been dewatered, channelized, and diverted for irrigation purposes often causing a disconnect from the watershed to adjacent nearshore regions, creating a significant detrimental influence on the watershed's overall ecological health and integrity.

The watershed health index (HI-WHI) is equal to the sum of the products of each metric and its corresponding weighting value and is calculated as:

$$\mathrm{HI-WHI} = \Sigma(L_i W_i)_i$$

where i = metrics 1-19; L = percent land cover (inclusive of length per unit area of roads and ditches for a watershed); W = metric weighting (Kido 2006).

HI-WHI scores were calculated for all 571 watersheds in the state and rescaled to a percentage to ease interpretation. Consequently, values ranged from 0% -100% with increasing magnitude indicating better watershed health. Linear regression analysis was used to test the relationship between watershed characteristics and corresponding stream habitat/biotic integrity ratings (Kido 2001) for 22 watersheds on Kaua'i, O'ahu, Maui, Moloka'i, and Hawai'i Islands (e.g., Kido 2000a; Kido 2000b). Watershed health as determined by the HI-WHI showed a statistically significant positive relationship with stream health as measured by field assessments of habitat condition ($R^2 = 0.62$, $P < 0.0001$) and biotic integrity ($R^2 = 0.68$, $P < 0.001$) using metrics developed by Kido (2001). Therefore, the HI-WHI as a landscape indicator was able to characterize the impact of humans on Hawaiian watershed units and relate this condition to its ecological health as reflected in the biological integrity of its stream environment.

Reef Health Index (HI-RHI): Information Database Development

The data used to develop the HI-RHI came from 170 stations at 52 sites sampled from 2000 to 2004 within the main Hawaiian Islands (Fig. 1) (Rodgers and others 2010). Expert knowledge and governmental resource management priorities were used to select a wide range of sites with randomly generated stations within each site. The sites encompassed an array of longitudinal gradients, environmental degradation, levels of management protection, human population level, and extent and direction of wave exposure. These sites represent a subset that characterizes the full range of Hawaiian coral reef communities. Watershed boundaries were determined as previously described and independently used to develop the HI-RHI.

Metrics used in the Reef Health Index (coral cover, coral richness, fish diversity, numerical abundance, and the biomass of fishes) were developed from standard methodologies used in the assessment of benthic populations on reef substrate (e.g., Rodgers and others 2010). High resolution digital images were taken every meter along 10 randomly selected 10 m transects using an Olympus 5050 zoom digital camera and PT050 underwater housing mounted to an aluminum monopod frame. The camera was 1.7 m from the substrate generating a 50 × 69 cm image representing 0.35 m^2 of reef area. The PhotoGrid software package (Bird 2001) was used to quantify percent cover and species richness of corals from the images. Fish populations were quantified using standard visual belt transects (Brock 1954). SCUBA divers swam along one 25 m × 5 m transect (125 m^2) at each station recording species, quantity and total fish length. Fish numerical abundance, biomass, and diversity were calculated in a Microsoft ACCESS ®database from fish numbers and total lengths.

A precursor to the RHI was the Ecological Gradient Model (EGM) (Rodgers and others 2010) which described coral reef condition using 45 biological, physical and environmental factors. Initially, all factors were included in the EGM to describe reef condition and are appropriate when modeling reef condition alone, however, possible spurious relationships can occur due to overlapping dependent factors causing autocorrelation when examining both watershed and reef indices together. For this reason the original factors were narrowed down to five key biological factors that simplified the characterization of the biological integrity of coral reefs yet still provided sufficient resolution to differentiate reef health and maintain the relationship among sites. This analysis excluded any abiotic factors and factors that were a function of human population and correlated with watershed factors such as roads and agriculture. Therefore, we are testing the biological response of reefs to the watershed. The key metrics selected and measured to compare to the HI-WHI were coral cover, coral richness, fish diversity, numerical abundance and the biomass of fishes. Coral diversity was not used as a response variable since coral diversity among sites is low in the Hawaiian Islands (Jokiel 2008) and may not be an appropriate indicator of environmental conditions in this region (Jokiel and others 2004). These five biological parameters were given equal weight and used to calculate the Reef Health Index (RHI) using calculations developed for the EGM (Rodgers and others 2010) (available at www.cramp.wcc.hawaii.edu). RHI values ranged from 0 (poor reef health) to 10 (good reef health).

Statistical Analysis

To compare the Reef Health Index and the Watershed Health Index (HI-WHI), index values were grouped according to physically adjacent watershed — reef locations across the main Hawaiian Islands. A general linear regression model in STATISTICA 9.0 (Statsoft 2009) was used to evaluate the relationship between the RHI (dependent variable) and the HI-WHI as a continuous predictor with wave exposure direction (North [$n = 36$], South [$n = 26$], Sheltered [$n = 108$]) and water depth (5 m [$n = 74$], 10 m [$n = 55$], 15 m [$n = 41$]) as categorical factors. Wave exposure was defined as the orientation of the site to prevailing swell directions as outlined in Moberly and Chamberlain (1964). Sites protected from direct swells, either within an embayment or in an island shadow were classified as sheltered. The small sample size for directly north facing stations ($n = 6$) necessitated combining stations facing all northerly directions (N, NE, NW) into the north category (N). A Tukey's multiple comparison test for unequal N was used to examine differences among means at $\alpha = 0.05$. The original watershed and reef index values were used in the statistical analysis because these data met the assumptions of normality and homogeneity of variances (Zar 1999).

Results

The overall model including all of the factors explained a small yet highly significant proportion of the variation for the RHI ($F9, 160 = 3.48$, $p < 0.001$, $r2 = 0.18$). The relationship between the RHI and HI-WHI was significant and positive ($F1, 160 = 8.78$, $p = 0.003$). Therefore, "healthy" watersheds were generally associated with "healthy" adjacent reef environments with correspondingly high index scores (Fig. 2). The wave exposure direction was also significant ($F2, 160 = 3.75$, $p = 0.03$) with sheltered sites having significantly higher RHI values ($p = 0.02$) than either reef sites facing directly north or south (Fig. 3, Table 2).

The RHI values were undifferentiated among the three depths ($F2, 160 = 2.92$, $p = 0.06$), but the general pattern showed that the RHI values were lower at the 15 m reef compared to the 5 and 10 m reefs. This pattern in the RHI

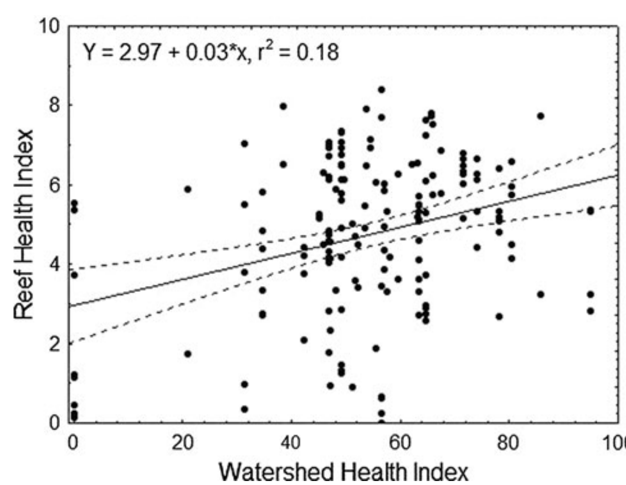

Fig. 2 The relationship between the Watershed Index and the Reef Index for 170 stations at 52 sites around the main eight Hawaiian Islands. Dashed lines represent the 95% confidence intervals around the fitted regression line

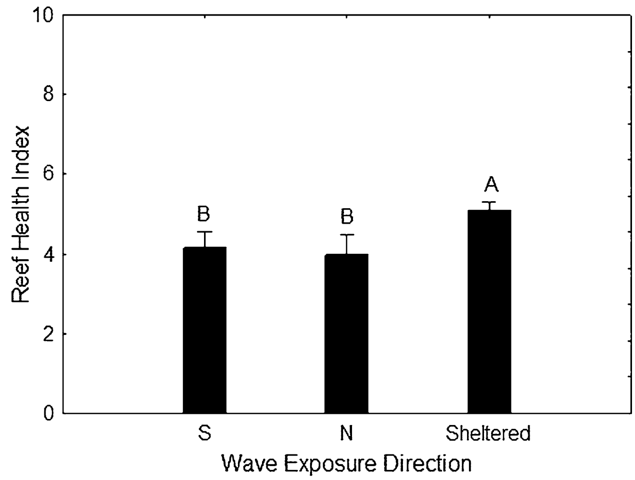

Fig. 3 The mean Reef Health Index (RHI) for sites with different wave exposure directions of South (S), North (N), and protected embayments (Sheltered). Sample sizes were $n = 26$ for S, $n = 36$ for N, and $n = 108$ for Sheltered. Error bars are $\pm$ 1 SE of the mean with plot values computed for covariates at their means. The same letter above the bar denotes homogenous means using an Unequal HSD post hoc test at $\alpha = 0.05$

values among depths was also consistent regardless of wave exposure ($F4, 160 = 2.18$, $p = 0.07$) with north and south facing reefs having lower RHI values at the 15 m depth than at shallower depths. Only sheltered reefs had virtually indistinguishable RHI values among all three depths.

Subsequent partial correlation analysis found a low positive partial correlation of 0.18 ($p = 0.02$) between RHI values at 10 m reefs and 15 m when controlling for the 5 m reefs. When wave exposure was also controlled for, then a strong positive partial correlation of 0.95 ($p < 0.001$) was documented between the RHI and WHI values at the 5 m sites with a southern exposure. These shallow sites had the most pronounced relationship between the two indicators and supported the overall relationship between the RHI and WHI. There was also a low positive partial correlation of 0.19 ($p = 0.02$) found between the RHI and WHI values for south facing 10 m reefs and sheltered 15 m reefs. These results indicated that the positive relationship between the RHI and WHI values was collinear at these reefs. The other combinations of wave exposure and depth did not have any significant relationship with the RHI.

Discussion

Results of this investigation provide evidence to support the long standing assumption that there is a significant overall relationship between the condition of watersheds and the condition of adjacent coral reef communities in Hawai'i. The key to relating watershed and reef condition indices was the development of relevant metrics and landscape indices. Though serendipitous circumstances over the past decade a terrestrial group led by M. Kido was developing a state-wide watershed index while at the same time a marine group headed by K. Rodgers was developing a state-wide coral reef index. The first group developed indicators for watershed health (HI-WHI), with an emphasis on the relationship between watershed health and stream condition. The second group developed a model (EGM) that was used to rank relative reef condition throughout Hawai'i. Upon completion of these indices the question arose as to whether or not there was a relationship between these two indices, each of which are based on very different metrics. The relationship was found to be statistically significant. However, in order to eliminate the possibility of covariance, the ranking of the EGM was modified into the HI-RHI, which uses only biological metrics in the marine environment to calculate an index. The HI-WHI shows a significant correlation with the HI-RHI.

The significant ($p < 0.001$) relationship between HI-WHI and HI-RHI can be teased apart in order to determine the contribution of the various major reef communities to the overall pattern. Depth and wave exposure are highly influential and dominate in determining biotic community structure on reefs in most environments (Friedlander and others 2003, Jokiel and others 2004,

Table 2 General Linear Regression Model results for the Reef Health Index with the Watershed Health Index as a continuous predictor and Direction and Depth as categorical factors

Source	df	SS	MS	F	p	Non-centrality φ	Observed power
Intercept	1	135.96	135.96	39.08	**0.000**	39.08	1.00
Watershed Health Index	1	30.55	30.55	8.78	**0.004**	8.78	0.84
Direction	2	26.12	13.06	3.75	**0.026**	7.51	0.68
Depth	2	20.35	10.17	2.92	0.057	5.85	0.56
Direction*Depth	4	30.37	7.59	2.18	0.073	8.73	0.63
Error	160	556.61	3.48				

Statistical significance ($p < 0.05$) is indicated by the *bold* font

Storlazzi and others 2005). In relation to water motion, watersheds on the south-facing sides of islands that receive low to moderate wave energy were found to be a significant predictor of reef health. This relationship diminished along north facing coasts exposed to the strongest and most persistent wave regimes of the North Pacific Swell and the Northeast Trade Wind Swell (Jokiel 2008). Reef sites in such high wave energy locales are flushed by strong waves and currents. They appear to be less vulnerable to the build-up of land derived pollutants and thus less influenced by the condition of adjacent watersheds. Sheltered reef sites represented a combination of highly variable HI-RHI and HI-WHI values that often included factors such as overfishing which only impacted one index and not the other. For example, several of the reef sites such as Honolua Bay, Hakioawa, and Kanahena Bay with high HI-RHI values are in marine protected areas with excellent resource conditions yet the adjacent watersheds have been impacted to varying degrees by anthropogenic activities. In the case of Honolua Bay, the watershed has changed dramatically over the last century due to the diversion of Honolua stream in 1902 (Wilcox 1996), initiation of the pineapple industry around 1910, and development of the Kapalua resort area since the 1990 s (Brown 2004). Hakioawa on Kaho'olawe, was a military target range until 1990 so the watershed was decimated, while at the same time the reef resources were protected and continue to be to this day (http://kahoolawe.hawaii.gov/history.shtml). In contrast, other sheltered reef sites such as Kamalō and Kamiloloa on Moloka'i with low HI-RHI values are adjacent to watersheds in relatively good condition. The Kamalō reefs scored poorly due to the depauparate fish assemblage which could be the result of overfishing and the close proximity (0.5 km) of these sites to a boat ramp. In comparison, the Kamiloloa reefs were degraded by chronic sedimentation that restricted coral cover (Field and others 2008). At these sites, the sediment was actually transported down the reef flat from watersheds 2-3 km upcurrent and resuspended. Resuspension of land derived sediments have been well documented (Ogston and others 2004; Storlazzi and others 2005; Presto and others 2006) along this reef flat and linked to the condition of coral reefs (Brown and others 2007).

This disconnect between the reef health and condition of the adjacent watershed was most apparent for the sheltered sites and resulted in the low predictive value of these sites.

Depth was not found to be a strong predictor of reef health when compared against the watershed index, although shallow (5 m), south facing reefs did exhibit a strong positive correlation between the two indices. Lower HI-RHI values were also documented at the deepest sites at a depth of 15 m, but the relationship was not significant and relatively consistent among wave exposures. This result was surprising given the influence of depth on coral reef community structure in Hawai'i (Jokiel and other 2004). Jokiel and others (2004) found that deeper reefs (>5 m) generally had higher coral cover that shallower reefs. Deep sites, however, experienced a decline at a larger proportion of sites compared to shallow reefs (64% vs. 50%) during their study. In the Caribbean, Nowlis and others (1997) found that sedimentation and coral mortality increased with depth and proximity to river mouths, but this was immediately following tropical storm Debbie. Therefore, depending on the time that the actual surveys took place, depth may or may not be a useful indicator of reef health. Most of the sites included in this study were sampled once without incorporating a temporal component in the HI-RHI so it is possible that depth could emerge as an important variable in the future. It is also possible that the reef sites chosen for this study were close enough to each other with similar enough metrics at the various depths that any differences were masked at the scale of the watershed.

The finding that the HI-WHI and HI-RHI showed an overall significant relationship gives credibility to the use of landscape indicators to predict the condition of reef environments suggesting appropriate metrics were selected for each index. Furthermore, the exceptions to the pattern seen at heavily wave exposed sites fit what is known about the relative vulnerability of reefs caused by differences in flushing rate and the physical forcing function of strong waves (Storlazzi and others 2005). Friedlander and Brown (2006) monitored north shore reefs in Hanalei Bay, Kaua'i from1992 to 2006 and found that coral cover along with the fish assemblage were virtually unchanged. These patterns were remarkable given the agricultural land use activities, lack of sewage treatment facilities, and stream discharge levels from the four adjacent watersheds. They hypothesized that these north shore reefs were structured more by natural factors than anthropogenic factors (Friedlander and Brown 2006). Coral, fish and algal assemblage characteristics are known to be strongly influenced by environmental stress responding consistently to a wide range of impacts and exhibit high, yet quantifiable levels of ecological variability (Rodgers 2005).

Excessive sediment transport from watersheds via streams to the ocean is one of the key factors which contribute to the degradation of adjacent reef environments (Kido 2001; Fabricius 2005, Brown and others 2007). When terrestrial sediment overwhelms the nearshore reef system it becomes the dominant forcing function affecting community structure (Rodgers 2005). Sediment impacts are amplified in embayments, harbors and sheltered areas where longer residency times and poor water circulation result in a larger percentages of organics and fine grain-sizes being deposited on nearshore reefs (Dollar and

Grigg 2004). These types of watershed derived disturbances have been found to be highly influential in defining reef condition (Rodgers 2005) and disruption in the serial pattern along the natural gradient of stream distance from a reef can characterize anthropogenic influence (Clarke and Gorley 2001). However, strong currents and high waves impacting coastlines can increase local circulation which can flush and remove fine sediments from nearshore waters and effectively mask the links between watershed and adjacent reef communities. This appeared to be the case at Hanalei Bay, which is one of the best studied north shore reef systems in Hawaiʻi (Friedlander and Brown 2006; Storlazzi and others 2006; Draut and others 2006; Derse and others 2007). For predicting reef health in regions outside of Hawaiʻi, where watershed information is not available we advocate using a reef index that measures both biotic and abiotic factors since we have shown that either can predict reef health in regions not heavily impacted by wave energy.

Conclusions

Our overall results are in concert with the results of the only other large scale study linking watershed indicators with coral reef condition, conducted in St. Croix (US Virgin Islands) (Oliver and others 2011). In addition to the Landscape Development Intensity index variables ($n = 17$), contributing to the overall negative relationship of human modified watersheds to reef condition, Oliver and others (2011) found that depth (distance from shore) was an influencing factor that has also been described by Smith and others (1995). Both studies show a negative impact from human modified watersheds to adjacent coral reefs regardless of the major differences between these two regions (e.g., watershed number and area), and despite being located in different oceans with dissimilar coral species. The link between the HI-WHI and the HI-RHI demonstrates the watershed influence on adjacent reefs on a large spatial scale providing predictive value on reef health based on landscape indicators.

Multimetric indices applied as landscape indicators (e.g., Gergel and others 2002) have been successfully used to evaluate the ecological condition of freshwater streams (Karr and Chu 1999; Kido 2001), wetlands (Brinson 1993; Magee 1996; Smith and others 1995), and coral reefs (Ben-Tzvi and others 2004; Wolanski and others 2004; Rodgers and others 2010). Our study extends this paradigm by applying a watershed health index (HI-WHI) to predict coral reef health index (HI-RHI) values. Our results indicate that watershed impacts in tropical Pacific islands are linked to adjacent coral reefs through transport processes that deliver sediments, nutrients and pollutants to nearshore areas via surface flow and submarine groundwater discharge. However, external biophysical factors such as wave energy regimes (e.g., wave height, wave direction, nearshore currents, etc.) and coastal human impacts (e.g., overfishing, invasive species introductions, etc.) can obscure the direct links between watersheds and coastal ecosystems. Nevertheless, we find that integrated landscape indicators are useful tools with which to quantify and evaluate ecological status on whole-systems at regional spatial scales. Watershed use in Hawaiʻi has historically been well documented and sub-catchments contributing to the poor condition of a watershed (e.g., nutrients and sediment) are recognized in most areas. The difficulty is that there is little culpability. A quantitative link between land use practices and reef condition will give policymakers the evidence needed to enact stronger legislation. Moreover, if developed properly they can be used to predict the condition of related sites within a region that has not yet been sampled. The predictive ability to characterize and relate watershed health to coral reef health on regional scales can provide a viable management alternative where budget and manpower for extensive reef surveys are limited. Resources can be more efficiently directed at identifying healthy reefs, restoring degraded reefs, establishing marine protected areas, and acquiring the political, community and industry support needed to develop an integrated set of management strategies. The data found in this study can serve as a guide for mitigation efforts to protect reef resources downstream from watersheds. The spatial connection of a stronger direct link of south facing watersheds to their adjacent reefs can allow a more focused effort for planning future patterns of urban growth, instituting best management practices, amending zoning, and determining development priorities. The use of integrated landscape indicators can help to optimize management efforts and resources on the ground so as to mobilize effective coordinated watershed and coral reef conservation programs. The next phase of this research would be to test the validity of this model using field verification of various reefs along a gradient of watershed degradation and use sensitivity analysis to examine the impact of individual factors in a region to concentrate management strategy and reduce spatial efforts.

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