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A native species-based index of biological integrity for Hawaiian stream environments

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Abstract Based upon ecological data provided by a 6-year study of native species assemblage structure and function in near-pristine Limahuli Stream (Kauai), The Hawaii Stream Index of Biological Integrity (HS-IBI) incorporates 11 metrics covering five ecological categories (taxonomic richness, sensitive species, reproductive capacity, trophic–habitat capacity, and tolerance capacity). The HS-IBI was shown to effectively distinguish stream biological condition on a continuum from undisturbed (near-pristine) to severely impaired in sampling of 39 sites (6 estuarine reaches) on 18 Hawaiian streams located on all major islands. A significant relationship was validated between relative levels of human impact occurring within-watersheds (determined through use of a landscape indicator) and IBI ratings with metrics responding predictably to gradients of human influence. For management interpretation of HS-IBI results, a framework comprised of five "integrity classes" (excellent–good–fair–poor–impaired) is provided which can be used to operationalize HS-IBI results obtained through standardized sampling of stream sites that "…translates into a verbal and visual portrait of biological condition." Through its focus on native species, the HS-IBI incorporates evolutionary and biogeographic variation for the region with biological expectations based upon reference condition benchmarks established in near-pristine stream environments where ecological functioning is naturally self-sustaining and resilient to normal environmental variation. The methods and tools described in this study are appropriate for application in all perennial streams in Hawaii and may be adapted for use in streams on other tropical Pacific islands where native species assemblages persist in near-pristine stream environments.

Keywords Functional ecological guilds · Bioassessment · Landscape indicators · Tropical Pacific islands · Land use in watershed catchments

Introduction

Humans through their degradative impacts on ecosystems and non-sustainable use of natural resources have created serious environmental challenges for social–ecological systems globally. Miller and Rees (2000) argue that at the heart of the problem is our inability to understand, value, and measure "ecological integrity" within the environments that we exploit. Integrity and health are terms useful in understanding the relationship of humans to surrounding ecological systems (Haskell et al. 1992; Karr and Chu 1999) and refer to the qualities best observed ecologically in "wild nature" or at least in environments minimally impacted

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by humans (e.g., Westra 1995). Within such natural environments, species in functional ecological guilds exploit environmental resources in similar ways depending upon habitat diversity exhibiting characteristic tolerances, preferences, assemblage features, etc. (Noble et al. 2007). The ecological guild approach, developed conceptually to simplify community analysis and assist in predicting community change (e.g., Austen et al. 1994), is a basic element in the widely applied Index of Biological Integrity (IBI) used to evaluate the ecological status of aquatic ecosystems (e.g., Karr and Chu 1999). Metrics used in IBIs are designed to measure responses of species within ecological guilds which react in predictable ways to human disturbance with a given metric being a unit-specific measure of an explicit group of species within a community (Noble et al. 2007). Developed in "reference conditions" that are minimally disturbed by humans, metrics operationally define ecological conditions that are "able to support and maintain a balanced, integrated, and adaptive biological system having the full range of elements and processes expected for a region" (Karr 1999).

Reference sites (referring here to "near-pristine" environments), therefore, that contain native species assemblages provide an ideal basis to define a condition of "integrity" within an evolutionary and biogeographic context for a particular region. Operationalized within the logistical framework provided by the multi-metric IBI (Karr 1981), native ecological guild/assemblage features can provide a basis for comparisons of present vs. expected baseline biological condition within a particular region. Divergence from the defined baseline would indicate a move away from "integrity" in response to anthropogenic influence (Karr and Chu 1999) and associated impairment in the inherent qualities of "healthy" biological systems described by Karr (1999) as being naturally self-sustaining and exhibiting maximal production/vitality and resilience to normal environmental variation. Therefore, reference sites where native species remain dominant are prime locations for IBI development, which, if designed properly, can provide effective benchmarks and comparable standards for stream conservation and management programs tailored to specific biogeographical regions.

In this paper, I document the development of an IBI for Hawaiian stream environments developed in near-pristine streams in which natural assemblages of native stream animals persist (e.g., Kido 2008). Streams in the islands are typically confined within steep-sided amphitheater-headed valleys that flow to the ocean from high rainfall zones located on their formative volcanoes between 610 and 1,829 m (2,000 and 6,000 ft) elevation, over distances of generally much less than 32 km (20 miles) (Stearns 1985). Natural stream channels are filled with basalt substrate weathered from igneous volcanics, and structural variability among streams is dependent upon island-specific age, rainfall regime, and elevation origin. A native freshwater macrofauna (Table 1) inhabits the entire continuum of near-pristine Hawaiian streams from "mountain-to-sea," and they are all amphidromous species (McDowall 1992) that retain marine larval phases but complete their juvenile and adult phases restricted to fresh water (e.g., Fitzsimons et al. 2002). They serve as effective biological indicators as they are taxonomically unique, readily identifiable, specifically adapted to Hawaiian stream environments, known to be sensitive to environmental degradation, and found in streams on all islands due to their amphidromous life histories (e.g., Kinzie 1990; Fitzsimons et al. 2002). In high-quality streams, native species are expected to partition habitat similarly from mountain-to-sea, forming functional ecological guilds

Table 1 Native Hawaiian amphidromous stream fish and macroinvertebrate species expected in near-pristine perennial streams

Taxa	Status
Fishes (Teleostei; Perciformes)	
Gobioidei	
Eleotridae—*Eleotris sandwicensis* (Vaillant and Sauvage)	Endemic
Gobiidae—*Awaous guamensis* (Edoux and Souleyet)	Indigenous
Lentipes concolor (Gill)	Endemic
Sicyopterous stimpsoni (Gill)	Endemic
Stenogobius hawaiiensis (Cuvier and Valenciennes)	Endemic
Percoidei; Kuhliidae—*Kuhlia xenura* (Jordan and Gilbert)	Endemic
Macroinvertebrates	
Arthropoda; Crustacea; Decapoda;	
Atyidae—*Atyoida bisulcata* (Randall)	Endemic
Palaemonidae—*Macrobrachium grandimanus* (Randall)	Indigenous
Mollusca; Gastropoda; Neritidae	
Neritina granosa (Sowerby)	Endemic

with distinct species-specific assemblages characterizing five ecological zones (i.e., estuarine/low–mid–upper reaches/headwaters) (Kido 2008). The distinct ecological guild/assemblage features identified were incorporated into a suite of metrics which provided the foundation for the Hawaii Stream Index of Biological Integrity (HS-IBI) which has proven to be a useful tool in statewide stream ecological assessment and monitoring applications.

Methods

IBI metric development, testing, and evaluation

The metrics for the HS-IBI were developed initially from the analyses of species abundance data collected with underwater visual census (UVC) in a 6-year study (Jan 1998 to Dec 2003) of assemblage structure in Limahuli Stream located in a relatively remote region of North Kauai (Fig. 1) (Kido 2008). In this study, a persistent ecological guild/assemblage structure was identified in Limahuli Stream in which native stream animals partitioned the entire stream system into distinct ecological zones. In specific zones from mountain-to-sea, native fish and macroinvertebrates were found in their highest densities with overlapping distributions of syntopic species; species diversity was highest at the midpoint of the continuum; numbers of species and their abundances declined with increasing elevation; and reciprocal fluctuations in species abundances limited overall variation in species diversity to a 22 % range (Kido 2008).

Using this persistent assemblage pattern as a template and information from published studies (e.g., Kido et al. 1993; Ha and Kinzie 1996; Kido 1996a, b) to incorporate ecological features, candidate IBI metrics were developed following general guidelines in Karr (1981)/Hughes et al. (1998) with overall scoring following Karr's (1981) original 5–3–1 criteria and standardization to a 0–100 % scale to ease interpretation. Metrics were designed to quantify measurable

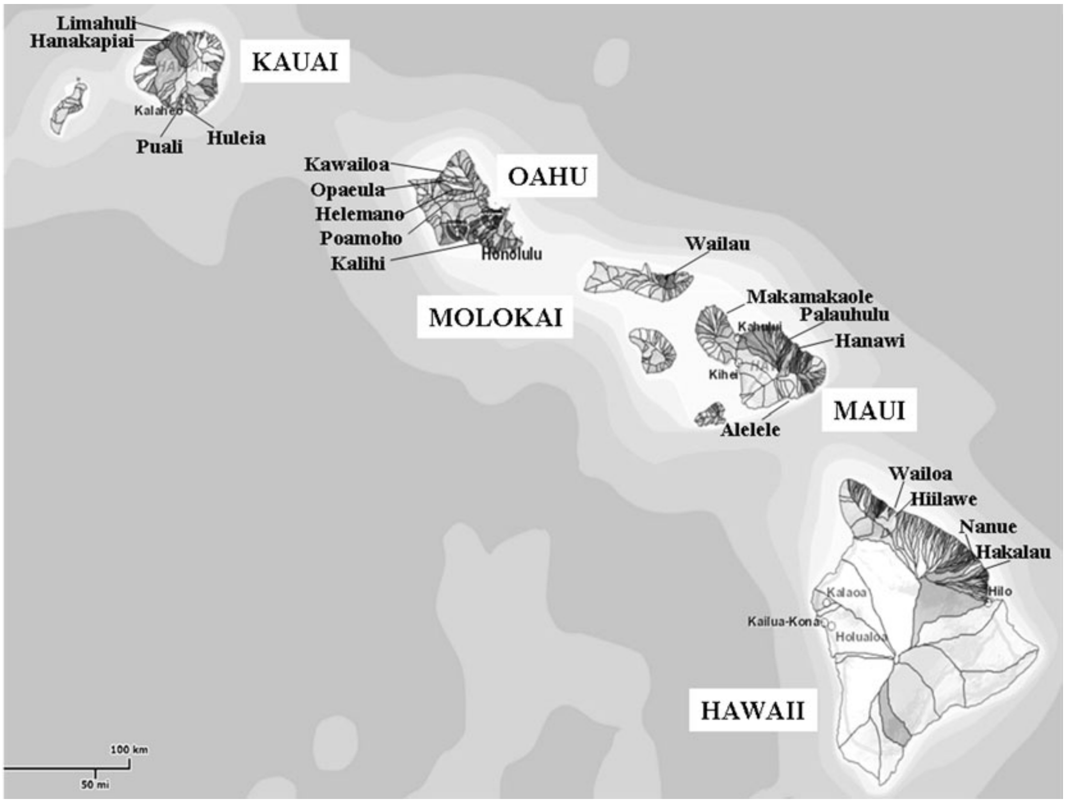

Fig. 1 Designated watershed units (*solid lines* are boundaries) and approximate locations of HS-IBI study streams in the main Hawaiian Islands

spatiotemporal characteristics of assemblage features, trophic ecological guilds, taxonomic richness, reproductive potential, species abundances, and individual health (Noble et al. 2007). These attributes are known to be sensitive to human influence and degrade with increasing levels of human impact (e.g., Barbour and Karr 1996; Lyons 2006).

Spatial–temporal performance of HS-IBI metrics

In order to evaluate the functional performance of the HS-IBI over time in a "whole" Hawaiian stream system from mountain-to-sea, metrics were tabulated from UVC data previously collected in lower–middle–upper elevations in Limahuli Stream (Kido 2008) and adjacent Hanakapiai Stream (Sherwood and Kido 2002) located in the relatively pristine northern quadrant of Kauai Island (Fig. 1). Standardized study site lengths were 20 times mean stream width (100 m minimum) and for Limahuli Stream sampled monthly from Jan 1998 to Jan 2002 and bi-monthly thereafter until Dec 2003 (Kido 2008). Hanakapiai Stream surveys were conducted in Sep 1998, Feb 1999, and June 1999 (Sherwood and Kido 2002). These proximate North Kauai streams exhibit subtle quality differences with Hanakapiai Stream being more remote/inaccessible and thus less influenced by humans than Limahuli Stream. Using this comparison, HS-IBI metrics were evaluated for their ability to effectively detect subtle human-induced ecological differences occurring spatiotemporally in the native species assemblage of the stream system from mountain-to-sea.

The HS-IBI was also tested for its ability to distinguish ecological impairment along practical gradients of human-induced disturbance in stream sites found on all islands which may differ along major gradients of island-specific age, rainfall regimes, and elevation. In this second round of HS-IBI testing, site surveys were conducted from Dec 1998 to Oct 2000 with sampling of 39 sites (6 estuarine reaches) on 16 Hawaiian streams located on all islands across gradients of human use from near-pristine to heavily urbanized (Fig. 1). At the time, site selection and levels of human impact within watersheds were determined by experience and expert judgment; however, a posteriori watershed condition was verified using the Hawaii Watershed Health Index (Kido 2006) (explained briefly below).

Statistical analyses

Species abundance and diversity analyses (Ludwig and Reynolds 1988) of assemblage features within and among elevational study sites in Limahuli Stream for the 6-year study period (Dec 1998 to Dec 2003) were used in the initial conceptual design of HS-IBI metrics. Specific details of statistical procedures for these analyses are provided in Kido (2008). For the HS-IBI, Pearson's correlation coefficient was used to determine if ratings were independent or covaried within and among sites. A coefficient of variation (CV=%) was also calculated to evaluate HS-IBI performance within and among sites in Limahuli Stream over the 6-year study period. Linear regression applied to statewide HS-IBI datasets was used to evaluate the degree to which stream integrity ratings were related to levels of human impact in their surrounding watershed environments as quantified by the Watershed Health Index (explained below). For these analyses, data were imported into a SAS version 9.13 project (SAS Institute, Inc. 2000) which was also used to produce general summary statistics (mean, median, ranges, standard errors, etc.).

The Hawaii Watershed Health Index

Initially, expert judgment and field experience were used to select study sites in watershed environments across the Hawaiian islands that could test the HS-IBI's ability to discern the full range of human-induced impacts on stream environments from near-pristine to severely impaired. Subsequently, the Hawaii Watershed Health Index (HI-WHI) (Kido 2006; Rodgers et al. 2012) was developed as a landscape indicator (Gergel et al. 2002) to quantify levels of human impact across a basic set of land cover classes which considered the amount and arrangement of human-altered land within catchments. For the eight main Hawaiian islands, 571 watersheds (Oahu=106, Niihau=14, Molokai=50, Maui=112, Lanai=32, Kauai=74, Kahoolawe=24, Hawaii=159) have been officially delineated (www.state.hi.us/dbedt/gis) by the State of Hawaii (Fig. 1). Explained only briefly here (with specifics provided in a subsequent paper), the HI-WHI used Geographical Information System (GIS)-based land cover classifications extracted from Landsat 7 imagery as part of Hawaii GAP (Gon et al. 2006) that were simplified to a basic set of land use classes. These classes were overlaid upon the state's designated watersheds which are typically contained within steep-sided valleys, within which flow complete stream systems from mountain-to-sea (Fig. 1). Nineteen land cover/land use classifications representative of human impacts within watersheds were extracted from GAP GIS coverages, and the percentage of coverage within watersheds was calculated using standard GIS procedures in ARCMAP (ESRI, Inc.). Infrastructure such as roads and irrigation ditches that were anticipated to reduce stream biological quality were calculated in units of feet per acre for each watershed from existing statewide vector datasets. Weightings for each metric were assigned positive or negative values of various magnitudes using expert knowledge and trend analyses used to estimate levels of human impact within watersheds. For example, native forest cover was given a high weighting value and thus high percent coverages within watersheds corresponded to lowered human-induced disturbance overall and higher scores for watershed health. For each of the 19 metrics, percent land cover per watershed unit was multiplied by weighting values and standardized to a 0 to 100 % scale to calculate the Hawaii Index of Watershed Health (HI-WHI) which is used in this paper to verify the ability of the HS-IBI to discern overall levels of human-induced disturbance to streams within-watershed environments.

Standarized rapid assessment protocol for the HS-IBI

Stream sampling procedures originally developed for use in the 6-year monitoring study of Limahuli Stream (Kido 2008) were abbreviated for use as a Rapid Assessment Protocol (RAP) (e.g., Resh and Jackson 1993) designed to minimize labor costs and optimize sampling effort integrated into a multimetric IBI framework. As a standard procedure, study site length is measured to be 20 times the mean stream width (100 m minimum) to ensure sampling of all major habitat types (Leopold et al. 1964). Study sites are partitioned into approximate fourths and flagged from downstream-to-upstream points at 0, 25, 50, 75, and 100 % intervals to provide a grid framework clearly visible by the assessment team. Within the grid, eight transect lines (two in each quadrant) are carefully secured at randomly chosen locations on stream banks so as to maintain a 6–12 cm (2.5–5 in.) vertical height above the water line which makes the line easily viewable by divers approaching it from a downstream direction. Meter marks on transect lines identify the upstream corners of meter-squared quadrants visualized on the stream bottom within which species counts and size estimates are made by divers along the stream cross section. Transect lines are encountered consecutively by divers while conducting continuous linear searches (referred to as Linear Counts in Kido 2008) from 0 %—downstream to 100 %—upstream points in the grid framework. This standard UVC methodology was found to be effective for estimating densities, composition, and size class structure of benthic dwelling native fish and macroinvertebrates in Hawaiian streams with the grid sampling an estimated 10 % of available stream habitat within sites (Kido 2008). Linear count data are used to calculate HS-IBI metrics related to species diversity, relative abundance, and size class characteristics, while transect data provide the species density estimates (individuals per meter squared) needed to score related metrics.

To evaluate the cost effectiveness of this streamlined procedure and its effect on metric performance, survey data collected in Limahuli Stream sites from Jan 1998 to Jan 1999 where extracted from the dataset for additional analyses. A Monte Carlo simulation (SAS Institute, Inc. 2000) was used to randomly remove transect lines from the UVC surveys to the required eight lines, and data calculations were adjusted accordingly. Time recorded by divers for each transect were used to adjust total UVC survey time in a simulated rapid assessment procedure.

Results

Rapid assessment protocol

Comparison of stream assessment procedures developed in Limahuli Stream (Kido 2008) with an abbreviated RAP designed for the HS-IBI showed an estimated 21.7 % reduction in the dive time required by biologists to conduct UVC surveys. This did not include additional time savings realized during site setup; therefore, clearly, the rapid procedures would enable more sites to be sampled per unit effort. Linear Count data were not affected by transect line removal, and no effect on HS-IBI metrics utilizing these data were found. Mean species density estimates, however, were discovered to be somewhat lower as compared to the long-term monitoring dataset in Limahuli Stream

(Kido 2008). Over the dataset analyzed, total fish densities were found to be on average 1.7±0.005 % lower in the RAP (therefore more conservative) as compared to long-term monitoring results among all study sites in Limahuli Stream (Kido 2008). However, calculation of the HS-IBI from either dataset did not yield noticeably different results; therefore, the cost effectiveness provided by use of the RAP outweighed any minor variability determined in HS-IBI performance.

HS-IBI ecological categories and metrics

Eleven metrics incorporating relevant ecological guild/assemblage features of native Hawaiian stream animals were sorted into five ecological categories (Table 2) and validated for use in the HS-IBI to establish a benchmark of expected biological integrity characterized by reference Hawaiian stream environments. Each metric represents a key guild/assemblage feature that changes reliably as human influence increases.

Taxonomic richness Taxa richness is one of the most reliable indicators of degradation for aquatic groups particularly in assemblages that contain native species which tend to disappear as human impacts increase (e.g., Karr and Chu 1999). Three metrics, therefore, were designed in the HS-IBI to determine in study sites the: (1) total number of native species present, (2) percent of native taxa in the sampled population, and (3) number of alien taxa in estuarine vs. non-estuarine stream reaches (Table 3). Specific native species are expected in mountain stream vs. estuarine habitat (Kido 2008); thus, scoring is scaled so as to partition variation in species composition expected in ecological zones from mountain-to-sea (Kido 2008). As human impact increases, native species are removed from the assemblage (sensitive species first) and are gradually replaced by alien aquatic species; therefore, richness metrics track both the number of alien species present and their increasing proportionate abundance in the sampled population as stream condition degrades.

Sensitive (sentinel) species In the context of Hawaiian stream environments, sensitive or sentinel fish species include two endemic, herbivorous gobiid fish species *Sicyopterus stimpsoni* (Gill) and *Lentipes concolor* (Gill) which are used in the HS-IBI as "type-specific sensitive species" as they are highly sensitive to habitat and trophic disturbance (Kido 1996a, b). The two fish species are morphologically similar, reliant on benthic algae, and typically partition habitat so that

Table 2 Metrics and scoring used in the HS-IBI

		Scoring criteria		
Category	Metric	5 (best)	3	1 (worst)
Taxonomic richness	1a. Number native species (non-estuary)	4–3	2–1	0
	1b. Number native species (estuary reach)	6–5	4–2	1–0
	2. % native taxa	100–75 %	74–50 %	≥49 %
	3. Number alien taxa	0–1	2–3	<3
Sensitive "sentinel"	4. % sensitive native fish[a]	≤50 %	49–20 %	≥19 %
Species	5. Sensitive native fish density (fish m^{-2})[b]	≤0.46	0.45–0.20	≥0.19
Reproductive capacity	6. Sensitive native fish size (%≥6.0 cm TL)[c]	≤50 %	49–25 %	≥24 %
	7. *Awaous guamensis* size (%≥8.0 cm TL)[c]	≤50 %	49–25 %	≥24 %
Trophic/habitat	8. Total native fish density (fish m^{-2})	≤0.75	0.74–0.36	≥0.35
Capacity	9. Community weighted average (CWA)	1.0–4.0	4.1–9.0	9.1–10
Tolerance capacity	10. % Tolerant alien species	0 %	1–4 %	≤5 %
	11. % Diseased or parasitized fish	≥1 %	2–10 %	≤11 %

[a] Sensitive species are *L. concolor* and *S. stimpsoni*

[b] Either *L. concolor* or *S. stimpsoni* (whichever is in highest density)

[c] Excluding post-larval size classes (≤3.0 cm TL)

Table 3 Weighting values scoring relative species sensitivities to habitat–trophic disturbance in streams for calculation of the CWA

Weighting values for Hawaiian stream macrofauna	
Species	Weighting value
Lentipes concolor	1
Sicyopterus stimpsoni	1
Neritina granosa	2
Atyoida bisulcata	3
Macrobrachium grandimanus	3
Stenogobius hawaiiensis	3
Awaous guamensis	4
Eleotris sandwicensis	4
Alien species—group I[a]	10
Alien species—group II[b]	9

[a] Alien predators/competitors or disease vectors (e.g., *Tilapia* spp., Poeciliidae, etc.)

[b] *Macrobrachium lar*

they tend to exhibit "mirror image" distributions along the stream continuum achieving high population densities in near-pristine Hawaiian streams (Kido 2008). In these environments, at least 50 % of the sampled population of fish is expected to include *S. stimpsoni* and/or *L. concolor* (depending upon elevation) always achieving the minimal density thresholds established in Kido (2008) (Table 3).

Reproductive capacity The total length (TL) of three indicator species (*Awaous guamensis and L. concolor/ S. stimpsoni*) in the sampled population is used to evaluate the reproductive capacity of Hawaiian stream environments with a minimum of 50 % of the sampled population expected to be comprised of reproductively mature adults (i.e., greater than the conservative values of 8.0 cm TL [Kido et al. 1993; Ha and Kinzie 1996] and 6.0 cm TL [Way et al. 1998], respectively). These metrics were validated in reference quality streams where native fish populations always met or exceeded these criteria (Kido 2008), indicating robust ecological integrity with a sufficient proportion of reproductively viable adults in the resident population to sustain indicator species assemblage and abundance characteristics. In order to eliminate the confounding effects of periodically high numbers of larval recruits in the population, counts of individual fish ≤3 cm are excluded from the calculation. The percentage of reproductively viable individuals in the population is expected to decline with increasing environmental degradation.

Trophic/habitat capacity The size, vitality, and spatial distribution of stream species rely upon the spatiotemporal quality/quantity of their habitat and related trophic environment (e.g., Karr 1999); therefore, an estimate of total native fish density (conservative 0.75 fish$\,$m^{-2} value or greater expected—Kido 2008) is used as a metric to evaluate habitat and hydrological functioning of the stream environment. Habitat changes which affect the structure and availability of food resources within this environment alter the ecological guild structure of species in the assemblage and their proportionate abundances. To further characterize this change, a "Community Weighted Average (CWA)" metric (Table 3) was developed as a numerical expression to reflect the relative sensitivities of freshwater taxa to habitat and related trophic disturbance by their relative abundances determined in a particular sample population (Hilsenhoff 1987) (Table 3). Relative rankings (weighting values) for species groups were derived through professional judgment and available ecological information (e.g., Kido et al. 1993; Kido 1996a, b, 2008) (Table 3). The CWA is calculated as the sum of the proportionate numerical abundances of individual taxa in the sampled population multiplied by their respective weighting values (Table 3). The metric is sensitive to increases in the proportion of generalist species in the assemblage that are able to subsist off a broader range of food resources (e.g., alien insects–fish–algae) present as stream habitat becomes increasingly disturbed by human influence.

Tolerance capacity Assessment of the tolerance of species to human disturbance is commonly used in ecological assessment (e.g., Noble et al. 2007) and is based upon the premise that intolerant species (e.g., natives) will thrive and be less susceptible to disease in high-quality habitat to which they are adapted but be absent from the assemblage under disturbed conditions where tolerant species will dominate (e.g., Karr 1981; Karr and Chu 1999). Two metrics are used in the HS-IBI to test tolerance capacity: (1) at the level of the individual by determining the proportion of fish sampled in the population with external evidence of disease (e.g., body lesions, external parasites, etc. [Font and Tate 1994]) and (2) at the population level through an assessment of the presence (i.e., percent abundance in the sampled population) of any of 29 alien fish species thus far introduced into Hawaiian streams statewide (Timbol et al. 1978; Devick 1991). Disease incidence and the percent abundance in the sampled population of tolerant alien fish species will increase as human-induced habitat disturbance increases.

Spatial–temporal performance of the HS-IBI

Calculated for monthly then bi-monthly UVC surveys of Limahuli Stream from Jan 1998 to Dec 2003, HS-IBI metrics were able to distinguish relatively subtle differences occurring in the human-impacted lower site from more pristine conditions present in the middle/upper locations higher up in the watershed. The overall HS-IBI mean rating for Limahuli Stream (i.e., all sites combined) was 92.1±0.004 % (Fig. 2). HS-IBI means for individual sites were 87.3±0.007, 95.6±0.006, and 93.3±0.005 % for lower, middle, and upper sites, respectively (Fig. 2). Over the 6-year dataset used to calculate its metrics, the HS-IBI varied most in the lower site (CV=6.25 %) but was more stable in higher-quality middle and upper sites (CV=4.81 % and CV=3.87 %, respectively) (Fig. 3). These results are compatible with the analysis of Kido (2008) which used the Berger–Parker Index (Ludwig and Reynolds 1988) as a dominance measure to show a distinct and persistent species diversity pattern in Limahuli Stream which was found to be limited spatiotemporally to a 22 % variation overall. The HS-IBI, therefore, tracked closely variation occurring in the native species assemblage; however, it was highly sensitive to fluctuations occurring in the abundances of the one alien species in the assemblage (i.e., the amphidromous Tahitian prawn (*Macrobrachium lar*)) in the lower site which inversely influenced the HS-IBI through its effect on metrics targeting the impact of alien species (Fig. 2). Over the 6-year period, the HS-IBI as an ecological health indicator for Limahuli Stream remained within the 80 to 100 % bracket overall (Fig. 3), indicative of a high-quality Hawaiian stream environment whose ecological functioning is naturally self-sustaining and resilient to normal environmental variation (Karr 1999).

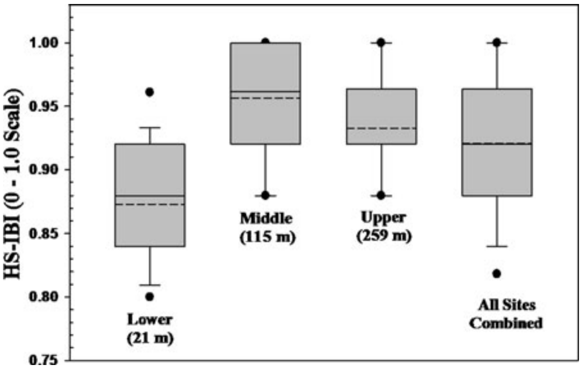

Fig. 2 Boxplots of HS-IBI application in Limahuli Stream (lower–middle–upper–combined sites) (Jan 1998 to Dec 2003) (*upper/lower box boundaries* indicate 75th/25th percentiles, respectively; *upper/lower error bars (whiskers)* indicate 90th/10th percentiles, respectively; all outliers are shown; *solid line in box* is the median, *dashed line* is the mean)

For the 18 streams (39 sites) on the five major Hawaiian islands in which the HS-IBI was tested, linear regression analyses indicated that stream integrity ratings were significantly related (R^2=0.752, P<0.001) overall to surrounding landscape condition as estimated by the Watershed Health Index (WHI) (Table 4). Hanakapiai Stream, paired with adjacent Limahuli Stream in HS-IBI development/testing, always achieved a perfect rating (i.e., 100 %) with Hanakapiai Valley (as expected) showing better overall watershed condition (WHI=92.33 and 85.82 %, respectively) (Table 4). The relationship of stream to surrounding watershed catchment condition was similarly strong for all streams sampled except for a small subset with substantial water diversions visibly reducing natural flow regimes (i.e., Huleia, Helemano, Opaeula, Kawailoa) (Table 4). This hydrological condition apparently was not detected in these watersheds by WHI metrics analyzing agricultural ditch/diversion extent and arrangement. However, the overall results validate the HS-IBI's ability to robustly evaluate the diverse responses from biological systems in Hawaiian streams to human actions and categorize sites over a practical range from near-pristine to impaired. Conversely, the Watershed Health Index also proved to be a relatively good presumptive predictor of the overall biological integrity of a Hawaiian watershed's perennial stream environment.

Over all stream sites sampled, the 11 HS-IBI metrics performed as expected with seven metrics determined to be positively correlated and four metrics inversely correlated to index outcome (Table 5). Therefore, metrics responded predictably to gradients of human influence. Correlations were all significant

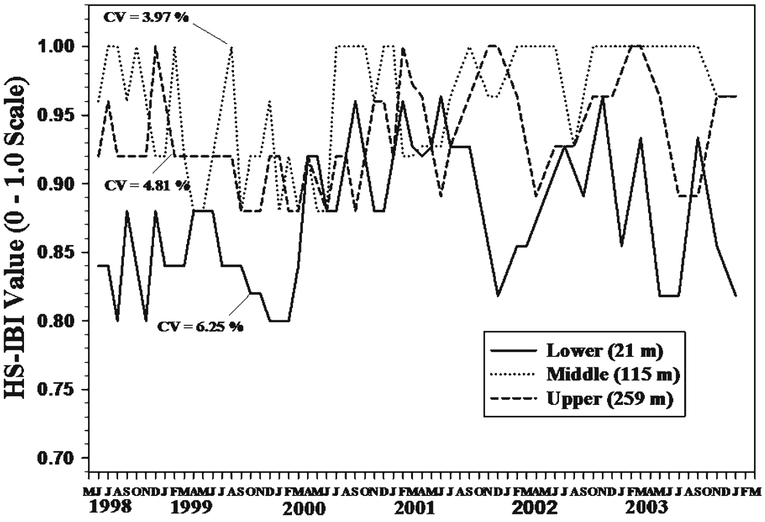

Fig. 3 Spatiotemporal performance of the HS-IBI in lower–middle–upper sites in Limahuli Stream, Kauai (1998 to 2003) (CV indicated by site)

($P<0.0001$) except for the metric assessing individual condition (percent diseased and parasitized fish) which is likely due to the smaller relative number of disturbed sites sampled in the dataset. As greater numbers of such sites are sampled, particularly in urbanized landscapes, visible signs of stress on individuals (skeletal deformities, parasites, tumors, fin erosions, etc.) will become more common and provide a useful biological indicator for detecting high levels of environmental degradation.

Table 4 Summary of mean (±SE) HS-IBI ratings for the 18 streams sampled on five islands with corresponding WHI ratings (0 to 100 % scales)

Island	Stream	HS-IBI (mean %+SE)	Sites or times sampled	WHI (percent)
Kauai	Limahuli[a]	92.1+0.004	6	85.82
	Puali	37.0	2	30.27
	Huleia	32.00+0.041	3	56.84
	Hanakapiai[a]	100.00+0.000	9	92.33
Molokai	Wailau[a]	99.00+0.008	6	93.15
Maui	Hanawi[a]	100.00+0.000	3	93.73
	Alelele	92.00	2	87.03
	Makamakaole	59.00	2	58.45
	Palauhulu	76.00	1	80.94 (Piinao)
Hawaii	Nanue	84.00	1	93.92
	Hakalau	88.00	1	70.93
	Wailoa	81.00+0.021	3	78.18
	Hiilawe	77.00+0.024	3	78.18 (Wailoa)
Oahu	Poamoho	22.00	1	38.75
	Helemano	20.00	1	61.12
	Opaeula	28.00	1	65.52
	Kawailoa	28.00	1	58.32
	Kalihi	21.00	1	36.13

Watershed name in parenthesis if different from stream name

[a] Reference streams

Table 5 Results of Pearson's correlation coefficient statistic applied to evaluate metrics vs. HS-IBI relationship (N=58)

Metric	Correlation coefficient	Probability (P)
1. Number native species	0.876	P<0.0001
2. % native taxa	0.932	P<0.0001
3. Number alien taxa	−0.792	P<0.0001
4. % sensitive native fish	0.831	P<0.0001
5. Sensitive native fish density	0.692	P<0.0001
6. Sensitive native fish size	0.747	P<0.0001
7. *Awaous guamensis* size	0.804	P<0.0001
8. Total native fish density	0.763	P<0.0001
9. Community weighted average	−0.919	P<0.0001
10. % tolerant alien species	−0.913	P<0.0001
11. % diseased or parasitized fish	−0.0652	P=0.6270

Discussion

A novel approach is described in this study for adaptation of Karr's (1981) standard IBI framework to incorporate expected functional ecological guild/assemblage features of native fish and macroinvertebrates to evaluate levels of human disturbance to streams on tropical Pacific islands. The Hawaii Stream Index of Biological Integrity (HS-IBI) was shown to effectively differentiate relative environmental quality in streams on all Hawaiian islands across gradients of human use from near-pristine to severely impaired.

Applicable for ecological assessment of entire stream systems or single/multiple sites established within and among streams regardless of elevation, the HS-IBI "… translates into a verbal and visual portrait of biological condition" (Karr and Chu 1999) in Hawaiian stream environments through use of five "integrity classes" (excellent–good–fair–poor–impaired) (Table 6). Metric ratings provide information about the sources of human disturbance that are known to erode expected ecological guild/assemblage features. HS-IBI/integrity class ratings provide operational guides for management applications focused on understanding/mitigating the full extent of human impact on the "health" (Haskell et al. 1992) of Hawaiian stream environments.

The overall health of streams is reflective of the condition of whole watersheds (e.g., Westra 1995), and regional land use has been found to be a prime determinant of local stream condition (e.g., Allan and Johnson 1997). A key challenge is to relate human-induced impacts occurring in the landscape to dynamic ecological processes occurring in aquatic systems which can be accomplish through the integrated use of biotic vs. landscape indicators (Gergel et al. 2002). Human disturbances in watersheds can be quantified geospatially by landscape indicators that measure the amount and arrangement of natural vs. human-influenced land cover, vegetation structure, etc. (Meyer and Turner 1994). Suitable indicators must target biotic and landscape features that are relevant (Maddock 1999) as well as be ecologically interpretable and able to synthesize complex relationships (Feld et al. 2010). This was effectively accomplished in this study through the coupling of the HS-IBI with the HI-WHI which found positive correlation between the health of stream environments with the extent/spatial arrangement of landscape disturbance in their surrounding watersheds. Moreover, in a recent study, Rodgers et al. (2012) compared HI-WHI vs. Reef Health Index ratings for 170 coral reef stations at 52 reef sites adjacent to 42 watersheds throughout the Hawaiian islands and found a significant positive correlation between the health of watersheds and that of adjacent reef environments. Therefore, healthy Hawaiian watersheds support robust biological integrity in their streams and connected coral reef ecosystems.

As demonstrated in this study, species native to a particular locale are ideal indicators of regional biological condition as they are representative of compositional, structural, and functional attributes of biodiversity and presumably persist at that locale because of a relatively natural, intact, supportive landscape. The biotic and landscape indicators developed in this study are effective tools for assessment and monitoring of these landscapes, meeting Feld et al.'s

Table 6 HS-IBI ratings, integrity classes, and class attributes

HS-IBI score as % of reference	Integrity class	Attributes
90–100 %	Excellent	Comparable to reference (near-pristine) conditions with minimal human disturbance exemplified by having the full complement of native macrofauna grouped into functional ecological guilds that maintain specific structure, diversity, and abundance characteristics at expected locations along the stream continuum from mountain-to-sea; meets native species density/size-class expectations including those for sensitive fish species (*S. stimpsoni*/*L. concolor*) at all elevations; no disease, deformities, or parasites observed on individuals; no alien species (except *M. lar*) present in any location along the stream continuum.
79–89 %	Good	Lowered biotic integrity as evidenced by reduced densities of expected native macrofauna; however, native species generally present in the assemblage at expected locations along the stream continuum; sensitive fish species (*S. stimpsoni*/*L. concolor*) densities/size classes below expectations; minimal evidence of disease, deformities, or parasites observed on individuals (>1 % numerically); no alien aquatic species present in middle-to-upper elevation reaches (except *M. lar* in low densities); however, small populations may be present at lower elevations often associated with ditches and other water diversion infrastructure.
69–78 %	Fair	Some native macrofauna absent depending upon elevation with expected species assemblage pattern disrupted; total native gobiid and sensitive fish species (*S. stimpsoni/L. concolor*) densities/size classes well below expectations at all elevations; alien aquatic species common compared to natives, but generally confined to lower elevations; individuals with external symptoms of disease, deformities, or parasites present, but not very common (2 to 10 % numerically).
40–68 %	Poor	Few (if any) native macrofauna present with sensitive native species absent and species densities/size classes never meeting expectations; tolerant native species (*A. guamensis*/*E. sandwicensis*) generally only found in lower elevation/estuarine stream reaches; aliens dominant particularly high tolerance species (e.g., Poeciliidae); individuals with external symptoms of disease, deformities, or parasites common (<10 % numerically).
<39 %	Impaired	Stream apparently devoid of life; native macrofauna absent regardless of elevation; if tolerant alien species present, only in very low abundances; nearly all individuals with external symptoms of disease, deformities, and/or parasites.

(2010) criteria for suitable indicators of biodiversity and ecosystem services which are: "(1) reliable and capable of simplifying complex relationships, (2) quantifiable and transparent… to enable easy communication, and (3) fit for the purpose of indication." As shown, these tools can be applied to assess and monitor the impact of environmental change on ecosystem health and integrity in "whole systems" (Westra 1995). This can improve our ability to better understand the patterns, linkages, pathways, and mechanisms causing ecological degradation (hydrological, chemical, geophysical, and biological) in regional watershed environments. The core challenge is to protect biodiversity and ecosystem services (e.g., native biodiversity, water resources, etc.) and affect a transition into sustainability that will meet human development needs yet protect earth's life support systems by maintaining their inherent health and integrity (e.g., Cash 2000). To achieve these goals will require an understanding of the boundaries, dynamics, and interactions of human–environment systems (e.g., Walker et al. 2002) as well as the technical ability to identify/track long-term trends in environment and development (e.g., Kates and Parris 2003). For this, the approach and methodologies described in the development of the Hawaii Stream Index of Biological Integrity are applicable within the framework of "coupled human and natural systems" (Liu et al. 2007) which is integrative and focuses on the links and interactions of humans with their environment. The ultimate goal is to determine realistic thresholds for the type and spatial extent to which watersheds can be modified for human use yet sustain acceptable levels of ecological integrity in the landscape.

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References

Allan, J. D., & Johnson, L. B. (1997). Catchment-scale analysis of aquatic ecosystems. *Freshwater Biology, 37*, 107–111.

Austen, D. J., Bayley, P. B., & Menzel, B. W. (1994). Importance of the guild concept to fisheries research and management. *Fisheries, 19*, 12–20.

Barbour, M., & Karr J.R. (1996). Biological criteria: technical guidance for streams and small rivers. *Technical Report* to U.S. EPA 822-B-96-001, May 1996.

Cash, D. W. (2000). Distributed assessment systems: an emerging paradigm of research assessment and decision-making for environmental change. *Global Environmental Change, 10*, 241–244.

Devick, W.S. (1991). Patterns of introductions of aquatic organisms to Hawaiian freshwater habitats. In: W. S. Devick (Ed.), *New directions in research, management and conservation of Hawaiian freshwater stream ecosystems*. Conference Proceedings, December 1991, pp. 189–213.

Feld, C. K., Sousa, J. P., Martins da Silva, P., & Dawson, T. P. (2010). Indicators for biodiversity and ecosystem services: towards an improved framework for ecosystem assessment. *Biodiversity and Conservation, 19*, 2895–2919.

Fitzsimons, J. M., Parnham, J. E., & Nishimoto, R. T. (2002). Similarities in behavioral ecology among amphidromous and catadromous fishes on the oceanic island of Hawaii and Guam. *Environmental Biology of Fishes, 65*, 123–129.

Font, W. F., & Tate, D. C. (1994). Helminth parasites of native Hawaiian freshwater fishes: an example of extreme ecological isolation. *Journal of Parasitology, 80*, 682–688.

Gergel, S. E., Turner, M. G., Miller, J. R., Melack, J. M., & Stanley, E. H. (2002). Landscpae indicators of human impacts to riverine systems. *Aquatic Science, 64*, 118–128.

Gon, S.M., Allison, A., Cannarella, R.J., Jacobi, J.D., Kaneshiro, K.Y., Kido, M.H., Lane-Kamahele, M., Miller, S.E. (2006). The Hawaii gap analysis project. *Technical Report* to the U.S. Geological Survey Biological Resources Division, Gap Analysis Program, Cooperative Agreement 01HQAG0195, February 2006.

Ha, P. Y., & Kinzie, R. A., III. (1996). Reproductive biology of, *Awaous guamensis*, an amphidromous Hawaiian goby. *Environmental Biology of Fishes, 45*, 383–396.

Haskell, B. D., Norton, B. G., & Constanza, R. (1992). What is ecosystem health and why should we worry about it? In R. Constanza, B. G. Norton, & B. D. Haskell (Eds.), *Ecosystem health: New goals for environmental management* (pp. 3–20). Washington: Island Press.

Hilsenhoff, W. F. (1987). An improved biotic index of organic stream pollution. *Great Lakes Entomology, 20*, 31–39.

Hughes, R. M., Kaufman, P. R., Herlihy, A. T., Kincaid, T. M., Reynolds, L., & Larsen, D. P. (1998). A process for developing and evaluating indices of fish assemblage integrity. *Canadian Journal of Fisheries and Aquatic Science, 55*, 1618–1631.

Karr, J. R. (1981). Assessment of biotic integrity using fish communities. *Fisheries, 6*, 21–27.

Karr, J. R. (1999). Defining and measuring river health. *Freshwater Biology, 41*, 221–234.

Karr, J. R., & Chu, E. W. (1999). *Restoring life in running waters: Better biological monitoring*. Washington: Island Press.

Kates, R. W., & Parris, T. M. (2003). Long-term trends and a sustainability transition. *Proceedings of the National Academy of Science, 100*, 8062–8067.

Kido, M. H. (1996a). Diet and food selection in the endemic Hawaiian amphidromous goby, *Sicyopterus stimpsoni* (Pisces: Gobiidae). *Environmental Biology of Fishes, 45*, 199–209.

Kido, M. H. (1996b). Morphological variation in feeding traits of native Hawaiian stream fishes. *Pacific Science, 50*, 184–193.

Kido, M.H. (2006) A GIS-based Watershed Health Index for the State of Hawaii. *Technical Report* to the Hawaii Department of Health, Environmental Health Administration—Environmental Planning Office, July 2006.

Kido, M. H. (2008). A persistent species assemblage structure along a Hawaiian stream from catchment-to-sea. *Environmental Biology of Fishes, 82*, 223–235.

Kido, M. H., Tamaru, P., & Kinzie, R. A., III. (1993). Insect introductions and diet changes in the endemic Hawaiian amphidromous goby, *Awaous stamineus* (Edouyx and Souleyet) (Pisces:Gobiidae). *Pacific Science, 47*, 43–50.

Kinzie, R.A. III (1990). Amphidromous macrofauna of Hawaiian island streams. Species profiles: life histories and environmental requirements of coastal vertebrates and invertebrates, Pacific Ocean Region, Report 3. *Technical Report* EL-89-10. U.S. Army Corp of Engineers, August 1990.

Leopold, L. B., Wolman, M. G., & Miller, J. P. (1964). *Fluvial processes in geomorphology*. San Francisco: WH Freeman.

Liu, J., Dietz, T., Carpenter, S. R., Folke, C., Alberti, M., Redman, C. L., Schneider, S. H., Ostrom, E., Pell, A. N., Lubchenco, J., Taylor, W. W., Ouyang, Z., Kratz, T., & Provencher, W. (2007). Coupled human and natural systems. *Ambio, 36*, 639–649.

Ludwig, J. A., & Reynolds, J. F. (1988). *Statistical ecology*. New York: John Wiley & Sons.

Lyons, J. (2006). A fish-based index of biotic integrity to assess intermittent headwater streams in Wisconsin, USA. *Environmental Monitoring and Assessment, 122*, 239–258.

Maddock, I. (1999). The importance of physical habitat assessment for evaluating river health. *Freshwater Biology, 41*, 373–391.

McDowall, R. M. (1992). Is there such a thing as amphidromy? *Micronesica, 30*, 3–14.

Meyer, W.B., & Turner, B.L.(eds) (1994). *Changes in land use and land cover: A global perspective*. Cambridge: Cambridge University Press, 537 pp.

Miller, P., & Rees, W.E. (2000). Introduction. In:, D. Pimental, L. Westra, R.F. Noss (Eds.) *Ecological integrity: Integrating environment, conservation, and health*. Island Press, pp. 3–18.

Noble, R. A. A., Cowx, I. G., Goffaux, D., & Kestemont, P. (2007). Assessing the health of European rivers using functional ecological guilds of fish communities: standardizing species classifications and approaches to metric selection. *Fisheries Management and Ecology, 14*, 381–392.

Resh, V. H., & Jackson, J. K. (1993). Rapid assessment approaches to biomonitoring using benthic macroinvertebrates. In D. M. Rosenberg & V. H. Resh (Eds.), *Freshwater biomonitoring and benthic macroinvertebrates* (pp. 195–233). New York: Chapman and Hall.

Rodgers, K. S., Kido, M. H., Jokiel, P. L., Edmonds, T., & Brown, E. K. (2012). Use of integrated landscape indicators to evaluate the health of linked watersheds and coral reef environments in the Hawaiian Islands. *Environmental Management, 50*, 21–30.

SAS Institute, Inc. (2000). *SAS/STAT user's guide, version 8, volumes 1, 2, and 3*. Cary: SAS, Inc.

Sherwood, A. R., & Kido, M. H. (2002). Watershed-scale comparisons of algal biodiversity in high-quality proximate Hawaiian stream ecosystems. *Pacific Science, 56*, 431–440.

Stearns, H. T. (1985). *Geology of the State of Hawaii*. Palo Alto: Pacific Books.

Timbol, A.S., & Maciolek, J.A.(1978) Stream channel modification in Hawaii. Part A: Statewide inventory of streams, habitat factors and associated biota. *Technical Report*, Fish and Wildlife Service, U.S. Department of the Interior, FWS/OBS-78/16, April 1978.

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G. D., & Pritchard, R. (2002). Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conservation Ecology, 6*, 14–16.

Way, C. M., Burky, A. J., Harding, J. M., Hau, S., & Puleloa, W. K. C. (1998). Reproductive biology of the endemic goby, *Lentipes concolor*, from the Makamaka'ole Stream, Maui and Waikolu Stream, Molokai. *Environmental Biology of Fishes, 51*, 53–65.

Westra, L. (1995). Ecosystem integrity and sustainability: the foundation value of the wild. In L. Westra & J. Lemons (Eds.), *Perspectives on Ecological Integrity* (pp. 12–33). Dordrecht: Kluwer Academic Publishers.