Use of Forest Inventory and Analysis Grid-Based Animal Population Data To Develop an Index of Ecological Diversity

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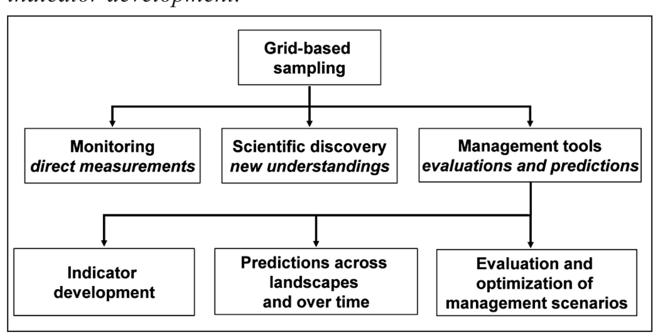
Abstract.—Data collected in association with the forest inventory and analysis (FIA) systematic grid has the potential to make multiple contributions to meeting land management information needs, including the development of indicators for application in management and monitoring programs. We derived bird, small mammal, and mammalian carnivore indexes of ecological diversity for the Lake Tahoe Basin using population data collected near FIA grid points, along with two additional data sets. The resulting index provided a robust measure of ecological diversity relative to existing landscape patterns of human development. We used the index to compare reference and existing conditions, and demonstrate its potential to meet National Forest System needs to evaluate progress toward desired ecological diversity conditions across landscapes and over time.

Introduction

Emphasis on large-scale environmental monitoring on public lands has increased dramatically over the past 10 years. Within the Forest Service, U.S. Department of Agriculture, the development of national protocols has been promoted and supported in an attempt to foster monitoring efforts that are implemented consistently and are compatible with national databases, both intended to improve the utility of environmental data (e.g., Holthausen *et al.* 2006; Manley, Van Horne, Roth *et al.* 2006, Woodbridge and Hargis 2006). The Forest Inventory and Analysis (FIA) program is designed to gather critical information on the status of forests in the United States (Roesch and Reams 1999). The systematic grid upon which FIA program data collection is based has the potential to serve as a valuable foundation for other complementary data collection efforts with grid-based data collection making multiple contributions to meeting public land management agency information needs, including the development of indicators, predictive models, and evaluation and assessment tools (fig. 1).

The National Forest Management Act (1976) and its implementation target the maintenance of species and ecological diversity in pursuit of sustainability. Indicators of species and ecological diversity are needed as measures of success in sustaining ecosystems on National Forest System (NFS) lands. To that end, ecological indicators are commonly employed in monitoring and assessing trends in environmental conditions, signaling rapid environmental changes, and diagnosing ecosystem health (Cairns *et al.* 1993). The national forests face many potential challenges, with loss of open space from urbanization being one

Figure 1.—*Potential information yields from grid-based population and habitat inventory and monitoring, including indicator development.*



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of the four primary threats, as recently identified by the Chief of the Forest Service (www.fs.fed.us/projects/four-threats). To meet management challenges on the nation's forest lands, measures that indicate the status of this threat are needed.

One tool for representing ecosystem diversity or integrity is to use indices that reflect multiple aspects of the biological community. A multimetric index of biotic integrity (IBI) was first developed by Karr (1981), using responses of fishes to indicate the biological condition or health of streams. Since its inception, the concept of the IBI has evolved and undergone modifications using various taxonomic indicators to assess diverse environments, from streams and wetlands, to terrestrial environments (e.g., Angermeier and Karr 1986, Bradford *et al.* 1998, Bryce *et al.* 2002, Karr and Kimberling 2003, Moyle and Marchetti 1999). The premise of indicators is based on the assumption that characteristics of the indicator (e.g., presence/absence, changes in the abundances, occurrences, survival) reflect changes or perturbations in the environment and associated species, processes, or functions (Noon *et al.* 1999). Many authors warn against the selection of only one or a few species as surrogate indicators of ecological condition (Feinsinger 2001, Landres *et al.* 1988, Morrison 1986, Noss 1990). IBI-type indices avoid this potential pitfall because they are typically based on a diversity of multispecies metrics, such as a diversity of trophic levels, species-group nesting guilds or foraging strategies, species richness and diversity measures, and tolerances of human disturbance.

Our objective was to demonstrate how indicators can be derived using basic field survey data collected, in part, in association with the FIA systematic grid, and then use those indicators to develop an index of ecological diversity that reflects changes in vertebrate biota in response to land development. Here we develop an index of terrestrial ecological diversity for the Lake Tahoe Basin patterned after the IBI approach. We then demonstrate how such an index of ecological diversity (IED) can be used to evaluate the status of terrestrial ecological diversity on a landscape subject to development and a diversity of other land uses.

Methods

Study Area

The Lake Tahoe Basin is a distinctive montane ecosystem located in the central Sierra Nevada Mountains. Lake Tahoe occupies nearly 10 percent of the 88,000-ha basin, with more than 80 percent of the remaining area consisting of national forest lands. The basin spans elevations from approximately 1900 m at Lake Tahoe to 3300 m at the surrounding peaks and encompasses four life zones (Holdridge 1967, Lugo *et al.* 1999): lower montane, upper montane, subalpine, and alpine (Manley *et al.* 2000). The basin's diversity has been altered over the past 150 years through a variety of human activities, most recently in the form of land development, including urban centers and more dispersed land conversion activities (Lindstrom *et al.* 2000). Currently human development and associated recreation impacts are greatest in the lower elevation zones (Manley *et al.* [2009]).

Sample Sites and Biotic Sampling

The Lake Tahoe Basin implemented a monitoring program based on the FIA grid (Roesch and Reams 1999) in 2002. The program entailed establishing monitoring points as per the national Multiple Species Inventory and Monitoring (MSM) protocol (Manley, Van Horne, Roth *et al.* 2006), with the addition of three more sample points randomly located within each FIA hexagon for a density of four points per 2400 ha. An increased density of points was needed to reach a sufficient sample size for monitoring in the relatively small Lake Tahoe Basin. In 2002–2004, 80 monitoring points distributed across all the hexagons were sampled for birds and small mammals (Roth *et al.* 2004), and in 2002–2005, a total of 61 monitoring points distributed across all the hexagons were sampled for mammalian carnivores. We combined these FIA-based MSM data with additional data sets for birds, small mammals, and mammalian carnivores from studies conducted in the Tahoe Basin. One data set (URB) included a survey conducted in 2003–2004 across land ownerships at lower elevations (less than 2200 m) in the basin (Manley, Murphy, Campbell *et al.* 2006), where 71 to 77 sites were sampled for birds, small mammals, and mammalian carnivores. Sites were randomly selected, stratified by degree of surrounding land development (in an area of 300 m radius), which ranged from 0 to 80 percent. The final data set (RIP) was from a survey of streamside riparian ecosystems that was conducted in 1995–1996 across multiple land ownerships (Manley 2000). The data set consisted of 80 sites that were sampled for birds and small mammals, which included four stream reaches randomly selected from the headwaters to the mouth of 20 randomly selected watersheds. The three data sets were combined for a total of 305 sites. The three data sets overlapped spatially, and together they provided a broad representation of the diversity of ecological conditions in the basin.

We used point counts to characterize the bird community at 235 sites, and we detected 94 terrestrial bird species. Field methods were consistent among surveys as per standardized methods (Blondel *et al.* 1981, Ralph *et al.* 1993): distance between stations (200 m), timing (from mid-May to mid-August between 0530 and 1000 hours), duration (10 min), and number of visits ($n = 2$). The number and spatial arrangement of count stations varied minimally among data sets: MSM used seven count stations in a hexagonal configuration; URB used five stations in a cross-like configuration; and RIP used eight stations in a crosshatch configuration. We used frequency of detection among count stations (i.e., proportion of count stations per site with detections) as a representative measure of abundance to avoid any potential bias associated with the year of sampling or number of count stations.

We used live trapping to characterize the small mammal community at 231 sites, and we detected 22 small mammal species. Field methods were consistent among surveys: timing (June to September), duration of sampling (3 days and nights), bait (oats and seeds), trap check frequency (twice per day), distance between adjacent traps (15 m), primary trap type (extra-long Sherman traps; 7.5 x 9 x 22.5 cm), and marking (all captured individuals were marked). The number, configuration, and size of traps did vary: MSM used 104 extra-long traps in an open hexagonal configuration occupying approximately 10 ha; URB used 50 to 64 traps arrayed in a square grid, with every third trap being an extra large Sherman trap (10 x 11 x 37.5 cm); and RIP used 108 extra-long traps arrayed in a rectangular grid of 6 x 18 traps centered on the stream reach. We used the number of first captures per trap opportunity as a measure of relative abundance to avoid potential biases associated with recapture rates based on grid configuration. Trap opportunity was corrected (TO_c) for traps that were stolen, sprung, or otherwise rendered unable to capture animals,

$$TOc = (trapsset*trapchecks*trapdays) - (unavailabletraps / 2)$$

Mammalian carnivores were sampled at a total of 128 sites, and we detected 10 carnivore species. Sampling consisted of four or five enclosed sooted aluminum track plates (Barrett 1983, Fowler 1994, Zielinski and Kucera 1995) and two remote cameras (Zielinski and Kucera 1995). One track plate was positioned at the center of each sample unit and one camera was positioned 100 m from the center track plate at a random azimuth. For MSM, four track-plate stations were located 500 m from the center, one in each cardinal direction. The URB study had a similar configuration, with the exception of having only three track-plate stations placed 250 m from the center at 0, 120, and 240 degrees. In both efforts, one additional camera was paired and placed in the same fashion with one of the surrounding track plates. Track plates and cameras were baited with chicken and baby carrots, and a commercial scent was used as a lure. Track plates and cameras were checked every 2 days for a total of five visits. A species was determined to be present in a sample unit if any device recorded a detection event during the survey period. The response variable derived from these methods was species presence.

We grouped bird and small mammal species detected during sampling into species assemblages—21 and 8 groups, respectively—based on their ecological characteristics, in an effort to provide insights into the sensitivity of species that are known to be associated with specific forest resources (e.g., nesting and foraging substrates, primary diet during the breeding season). Assemblage or group membership was determined based on a variety of published sources and databases (as per Manley *et al.* 2004), and is documented (along with scientific names) in Manley and McIntyre (2006). Species detected incidentally or not directly associated with terrestrial ecosystems were not included in species groups. Species frequently belonged to more than one assemblage. For each group, we calculated richness and abundance. Abundance of species groups per site was calculated as the sum of detection frequencies across all species in the group.

Vegetation Community Classification

We first classified all 305 sites into vegetation community types using cluster analysis (CA). The CA was based on the proportion of the 50-ha (400-m radius) area occupied by each of five forest types (Jeffrey pine, mixed conifer, lodgepole pine, subalpine conifer, and aspen), shrubs, and meadow. The proportion of the area occupied by nonvegetative cover types (e.g., barren, water, development) and riparian vegetation was not included in the CA to ensure that the clusters reflected emergent properties of the primary environmental gradients in the Tahoe Basin. We chose a 50-ha area because it was the minimum area that encompassed most survey locations. The EVEG vegetation layer (USDA Forest Service 1991, 2001) derived from satellite imagery was the source for vegetation data. The California Wildlife Habitat Relationships vegetation classification scheme was used to represent vegetation types (CDFG 2002, Mayer and Laudenslayer 1988). We used ArcView Geographic Information System (GIS) (ESRI, Inc. 1995) to perform calculations. The CA was performed with flexible beta linkage (*beta* = -0.25) and Sørensen's (Bray-Curtis) distance in PC-ORD (Windows Version 4.17; McCune and Mefford 1999).

Once clusters were derived, we used principal components analysis (PCA) to examine the relationships of vegetation community types relative to principal environmental axes. For the PCA, we entered the original seven vegetation variables, plus four additional environmental variables: mean elevation, mean percent slope, mean precipitation, and percent riparian. Mean elevation and slope were derived from digital elevation models, while mean precipitation was derived from PRISM data (Daly 1995). The amount of riparian vegetation was represented by a map derived from infrared aerial photo interpretation of the entire Lake Tahoe Basin in the early 1990s. The cross-products matrix was created using Pearson correlation coefficients among all column variables to produce a "standardized" PCA, and a varimax rotation was used. Use of correlation coefficients serves to standardize column variables (McCune and Mefford 1999). Only factors with eigenvalues of more than 1.0 were retained and reported.

Land Development

We generated a spatially explicit GIS model of human development derived from land-use designations on county parcel maps, combined with roads and trails from Forest Service transportation maps (see Manley *et al.* [2009]). Development was defined as the removal of native vegetation. Average percent of parcels occupied by development was estimated based on land use designation (as identified on county parcel maps), roads, and trails. An average percent developed value was calculated for each of 90 land uses based on a sample of parcels in each land use. For each land use type, we estimated the amount of development within a 300 m radius using digital orthophoto quadrangles. The average percent developed was assigned to all parcels of each land use type. Roads and trails were assigned widths based on their respective average widths (Caltrans 2001), and added to the parcel development map to create the final development map. Sites were placed into one of three development classes: No/Low (less than or equal to 01.0 percent), Moderate (more than 1.0 to 10 percent), or High (more than 10 percent) development. For comparisons where the sample of sites was low at the upper end of the development gradient, only two classes were used: No/Low (less than or equal to 1.0 percent) or Mod/High (more than 1.0 percent) development.

Indicator Analysis

We used a combination of indicator species analysis (ISA) (PC-ORD for Windows Version 4.17; McCune and Mefford 1999), a technique originally developed by Dufrêne and Legendre (1997), and simple linear correlations to identify species and species groups that showed strong responses to development across all vegetation community types.

Indicator values (IV) produced from the ISA were based on a combination of species frequency of occurrence and abundance, and those values determine how strongly each species is associated with a particular group (vegetation or development). IV range from 0 (never present) to 100 (always present and exclusive to that group) (McCune and Mefford 1999). We tested the significance of each maximum IV using a Monte Carlo permutation procedure, and then compared the observed IV to randomly generated values (per Dufrêne and Legendre 1997). We used an alpha-level of $\alpha = 0.10$ to determine significance. Species and species groups that differed significantly between development classes were considered candidate indicators. We did not perform ISA for large mammals, because only presence/absence data were available for these species.

In addition to ISA, linear relationships between species and development were examined. We identified all species and species groups that were significantly correlated ($P < 0.10$ based on Pearson's correlation coefficient) with development across all sites from all vegetation communities. We chose a minimum P value of < 0.10 for significance so that patterns of association would be more apparent. We then evaluated correlations of those species and species groups with development by vegetation community type. Despite apparent trends based on scatterplots, the limited occurrence of many species and the limited development in some vegetation communities (e.g., higher elevations) rendered most correlations insignificant; therefore, bivariate scatter plots also were consulted to evaluate relationships between species and development in each vegetation community.

Index Derivation and Ecological Diversity Assessment

Species and species groups were first evaluated for their potential as metrics in the IED. Species or species groups with strong and/or consistent relationships with human development among vegetation communities and analyses (i.e., ISA and correlations) were considered primary candidates. If their relationships were less consistent or weaker, then they were identified as secondary candidates. IED metrics selected were combinations of ecological groups and composites of individual species that exhibited strong shared relationships with development within and among vegetation communities. Individual species identified as having a strong positive or negative relationship with development were combined creating development-tolerant and development-intolerant species groups, respectively.

We wanted to have the same metrics for each vegetation community to enhance comparisons of conditions among them and reduce any potential for bias associated with sample size inequities among development classes. Based on the strength of the relationship with development, no more than 10 metrics were selected to represent each taxonomic group, consistent with the IBI approach (Karr and Chu 1995); however, the actual number was usually less than 10, as a function of the strength and number of candidate indicators.

Once metrics were selected, the values of each metric were rescaled to vary from 0 to 1. Generally, metric rescaling is done by dividing each metric value by the maximum value; however, in some cases, high values were considered outliers, effectively depressing the remaining range of values. The range and distribution of values for selected metrics were examined to select maximums to represent the primary range of values for each metric and to be used as the denominator in the rescaling procedure. For intolerant metrics, 1 indicates high diversity and 0 indicates low diversity. The values for tolerant metrics were subtracted from 1.0 to invert the values (1 indicates low diversity, 0 indicates high diversity). All rescaled metric values were then summed for each site, and the result was divided by the number of metrics used, and multiplied by 100 to obtain the final index with a potential maximum value of 100.

For birds and small mammals, we evaluated differences in richness and abundance relative to land development within and among the vegetation communities to identify potential metrics. Only species that were present at more than or equal to 10 percent of sites within two or more vegetation communities were evaluated for inclusion in tolerant or intolerant species groups. Species present at less than 10 percent of all sites were considered rare, and were included in the rare species group.

Only 10 mammalian carnivore species were detected across the three studies in the Lake Tahoe Basin. Large mammal data consisted of detection or nondetection events for each of those 10 species at each of the 128 sites, and ($n = 10$). As a result of the small species pool, the IED calculation was simplified relative to birds and small mammals. Species were classified as being either tolerant of land development or intolerant based on bivariate scatterplots. Given the small range of values associated with each metric, we assigned set values (0, 0.5, or 1) to each increment of increase in species richness. As for the birds and small mammals, the assigned values for the three metrics were added together and divided by 3, the theoretical maximum, to obtain a commensurate index value per site, which can range from 0 to 1.

It is likely that strong signals will be provided by the more abundant, lower trophic-level species (e.g., herbivorous small mammals, insectivorous birds), because of the greater range of values they may portray, but higher trophic-level species can be very sensitive to human disturbance because of their large area requirements. A diversity of trophic levels in the IED thus is likely to provide a stronger indication of ecological conditions than one alone. We used the subset of sites from which birds, small mammals, and large mammals all were sampled (n = 98 of the 305 sites) to generate a multi-taxonomic IED. We averaged the bird, small mammal, and large mammal IED values for each site to create the composite IED.

Finally, we used the composite IED to compare existing conditions in the basin to those of undeveloped (i.e., reference) conditions to provide a context for evaluating current terrestrial ecological diversity based on vertebrate biota. Reference sites were those with less than 5 percent development (*n* = 60 basinwide). Existing conditions were represented by a randomly selected subset of sites stratified in a basinwide grid to ensure equivalent representation. We then summarized the statistical distribution of IED values for existing conditions and compared them to reference conditions by vegetation community. We used t-tests to compare existing and reference conditions.

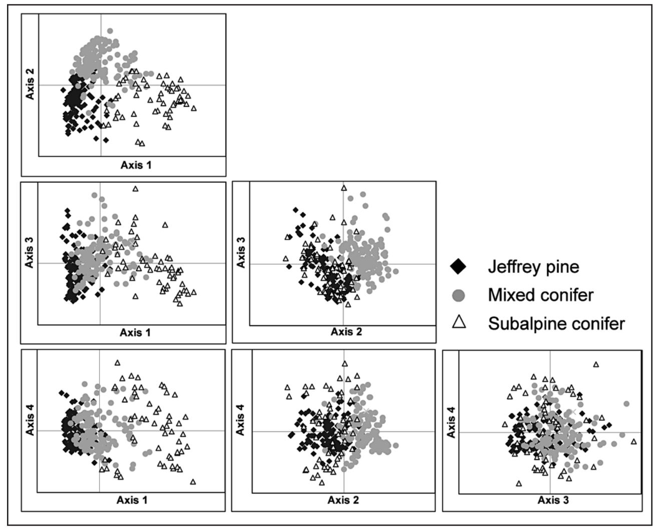
Results

Vegetation Community Types and Associated Land Development

The cluster analysis revealed three primary vegetation community types: Jeffrey pine dominated (*n* = 123 sites), mixed conifer (*n* = 127 sites), and subalpine conifer (*n* = 55 sites; fig. 2) communities. Four principal components had eigenvalues of more than 1.0 that together explained 70.0 percent of the variation in vegetation and environmental variables among sites. Factor 1 separated the Jeffrey pine community type (lowest elevation) from the subalpine conifer community type (highest elevation), and factor 2 separated the mixed conifer community type (midelevation) from the Jeffrey pine type.

The number of sites in each development class differed among the vegetation communities and among taxonomic groups. Based on the entire sample of 305 sites, the Jeffrey pine type had the most equitable distribution of sites along the development gradient, but only had eight sites with low development. Conversely, mixed conifer and subalpine conifer types had many sites with low development (42 and 44 sites, respectively), but only 11 sites in the mixed conifer type had high development, and only 11 sites in the subalpine conifer type had more than 1 percent development.

Figure 2.—*Factor score plots for axes 1–4 from principal components analysis of vegetation and environmental features of 305 sites illustrating the features separating the three primary vegetation community types, Lake Tahoe Basin, CA and NV.*



Individual and Cross-Taxonomic IEDs

Birds. Although 40 bird species were identified as significant indicators of a particular development level in one or more vegetation communities based on ISA results, only 22 bird species were consistently associated with low or high development conditions across vegetation communities and/or consistent with correlation results (appendix A). Similarly, 16 bird species groups, including total bird abundance, were significant indicators of development level based on ISA; but only five were consistently associated with low or high development conditions across vegetation communities. With the addition of species and species groups significantly correlated with development, 28 bird species and 16 species groups were identified as negatively associated with developed conditions, and 11 species and 8 species groups as positively associated with developed conditions (appendix A).

A final set of metrics was determined by evaluating the consistency and strength of the relationships between a species or species group and land development among the three vegetation communities. Eight metrics were selected: seven negatively associated and one positively associated with development (table 1). Richness value responses of foliage foragers, invertivores, shrub nesters, ground nesters, habitat specialists, and rare species either exceeded or paralleled corresponding abundance values; therefore, we chose to include those richness-based metrics. Consistently, granivore richness and ground forager richness were positively associated with development, but it is likely that those species groups would not increase in abundance at the highest land development levels, and their relationships with development were not steeply sloped, so these two groups were not included as metrics. The development-intolerant species group included all 28 species classified as either primary or secondary candidates. Intolerant species richness and abundance were highly correlated ($r = 0.804$); therefore, only richness was retained as a metric.

The resulting bird IED for each vegetation community, and the three types combined, displayed consistent declines in IED values with development. The strongest patterns were apparent in the Jeffrey pine and mixed conifer types, where the development gradient was strongest (fig. 3a).

Small Mammals. A total of 12 small mammal species, 8 species groups, and total small mammal abundance were significant indicators of a land development level in one or more vegetation communities, based on ISA results; however, only six species and eight species groups were consistently associated with low or high development conditions across vegetation communities and/or were consistent with correlation results (appendix A). With the addition of species significantly correlated with development, five small mammal species and nine species groups were identified as negatively associated with developed conditions and 5 species and 10 species groups were positively associated with developed conditions (appendix A).

Strong correlations between species and species groups eliminated many candidate groups from inclusion in the final set of metrics. Deer mouse abundance was a primary contributor to the abundance of three species groups, resulting in high correlations between deer mouse abundance and the abundance of associated groups: *Peromyscus* ($r = 0.99$), nocturnal species abundance ($r = 0.92$), and omnivore abundance ($r = 0.94$). Similarly, Douglas squirrel abundance was a primary contributor to canopy associate abundance ($r = 0.99$). Therefore, none of these groups was considered for inclusion as metrics in the final index.

A final set of five species metrics was selected, including one tolerant and four intolerant (table 1). Metrics of species intolerant of land development included the richness of intolerant species, rare species, ground associates, and herbivorous species. Six species comprised the intolerant species group, including the infrequently detected long-tailed weasel and ermine. These two mustelid species were included in the group of intolerant species, as opposed to being a separate metric (*Mustela* abundance), because they were infrequently occurring species and alone did not constitute a strong metric. Only the relative abundance of development-tolerant species (comprised of four species) was included as a tolerant metric. The small mammal IED for each vegetation community displayed consistent declines in the IED values with development (fig. 3b).

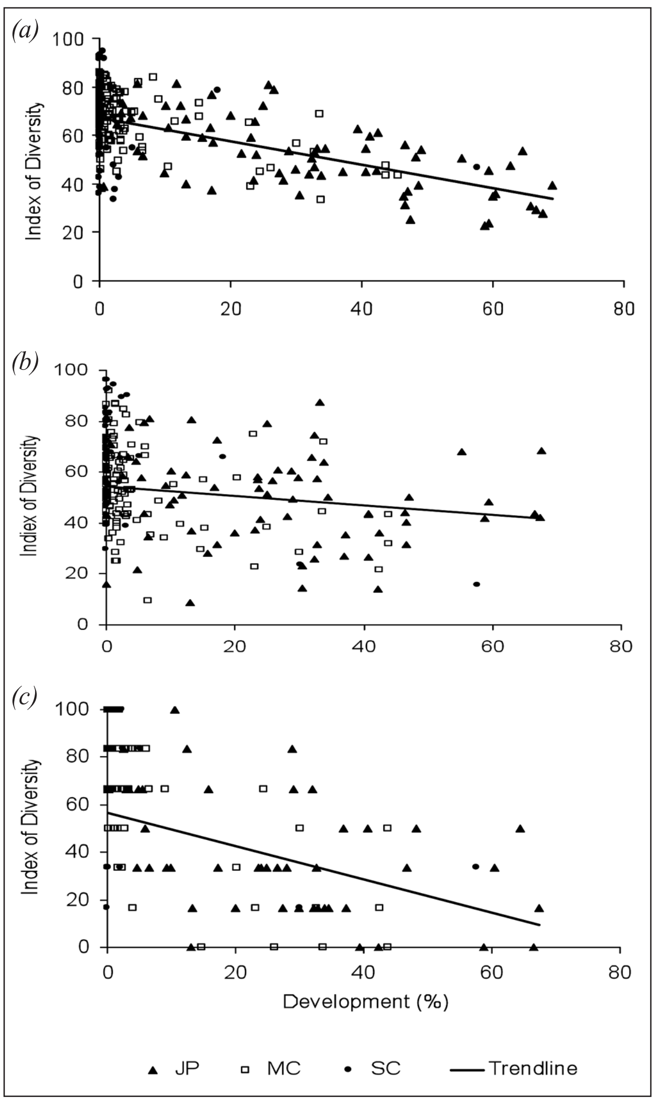
Mammalian Carnivores. Three metrics were used in the large mammal carnivore IED: richness of species intolerant of or impacted by land development (marten, bobcat, weasels, spotted skunk, bear); richness of species tolerant of development and able to exploit and benefit from it (coyote, ringtail, striped

Table 1.—*Descriptive statistics for composite multitaxonomic Index of Ecological Diversity values for reference and existing conditions in each of the three primary vegetation community types the Lake Tahoe basin based on conditions in 2006.*

Vegetation community type	Reference condition			Existing condition			t-test	
	n	Mean	s.d.	n	Mean	s.d.	T	P
Jeffrey pine	5	64.5	7.93	11	40.6	17.57	– 3.74	0.002
Mixed conifer	33	67.0	10.43	15	63.2	15.96	– 0.85	0.408
Subalpine conifer	22	67.93	13.27	14	68.0	13.65	0.01	0.992

skunk, gray fox, raccoon); and richness of domestic animals known to harass and negatively impact wildlife (domestic dogs and cats). The large mammal IED was significantly correlated with development at the basinwide scale, and within each of the three vegetation communities (fig. 3c). Although the variance in large mammal index values was high relative to development, an evident decline in maximum values was observed as development increased particularly within the Jeffrey pine and mixed conifer types. Maximum large mammal index values of 1.0 were observed for sites with 10.6 percent or less development, and index values greater than 0.5 were not observed at sites exceeding 32 percent development.

Figure 3.—*Index of Ecological Diversity values for birds (a), small mammals (b), and mammalian carnivores (c) in the Lake Tahoe Basin. Sites associated with each of the three primary vegetation community types are indicated (JP = Jeffrey pine; MC = mixed conifer; SC = subalpine conifer).*



Cross-Taxonomic Relationships. The composite IED showed significant negative associations with land development for each vegetation community (fig. 4). Correlations of the composite index and development were strongest in the mixed conifer type (r = -0.688, P < 0.001), followed by the Jeffrey pine type (r = -0.629, P < 0.001), and the subalpine conifer type (r = -0.539, P = 0.007). The basinwide composite index was also highly significant (r = -0.722, P < 0.001).

Ecological Diversity Assessment

The existing conditions of Jeffrey pine, mixed conifer, and subalpine conifer types were represented by 11, 15, and 14 sites, respectively. Reference sites in the Jeffrey pine type were limited (n = 5); however, comparisons between reference and existing conditions across vegetation communities showed clear patterns (fig. 5). Existing conditions in Jeffrey pine were significantly degraded compared to reference conditions based on IED values, and showed greater deviation from reference compared to mixed conifer and subalpine conifer. The majority of existing Jeffrey pine sites (more than 80 percent) had IED values less than 50, while reference sites had values more than 50 (fig. 5). Existing conditions in mixed conifer had a wider range of IED values, including sites with IED values less than 40, which were absent from reference sites, but as a group, IED values for existing conditions were not significantly

Figure 4.—*Index of Ecological Diversity values for the composite-taxonomic index in the Lake Tahoe Basin. Sites associated with each of the three primary vegetation community types are indicated (JP = Jeffrey pine; MC = mixed conifer; SC = subalpine conifer).*

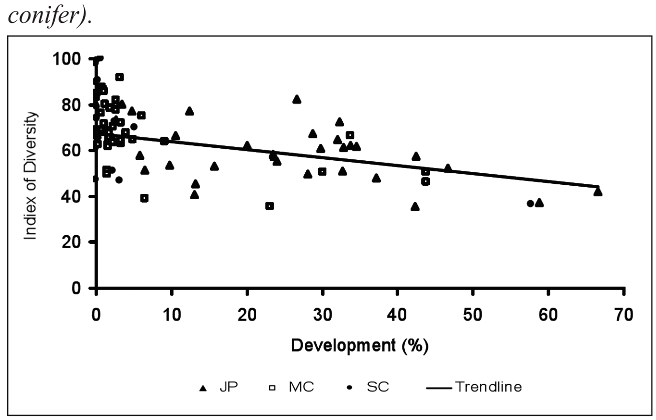
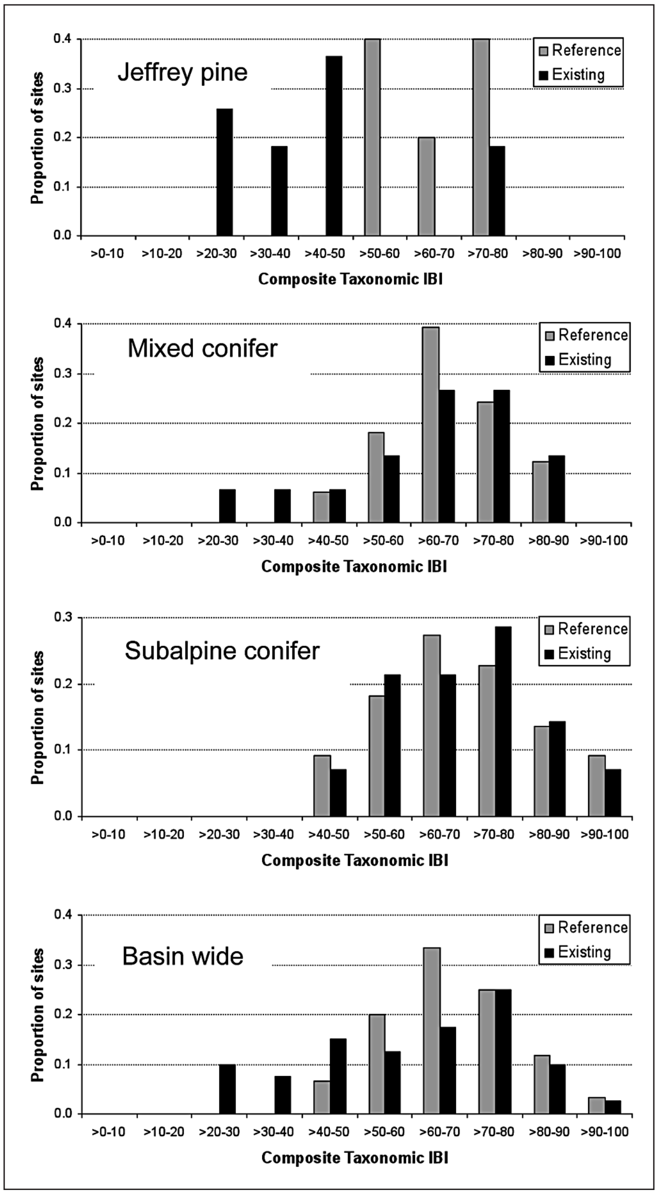


Figure 5.—*A comparison of the distribution of composite taxonomic Index of Ecological Diversity values for reference (less than 5 percent development) and existing sites in each of the three primary vegetation community types (Jeffrey pine, mixed conifer, and subalpine conifer) and basinwide in the Lake Tahoe Basin.*



different from those of reference sites. Existing conditions in the subalpine type did not deviate significantly from reference conditions. Basinwide roughly 20 percent of the sites fell outside the range of reference conditions, with most of those sites in the Jeffrey pine type.

Discussion

Efficiency of Multispecies Indicators

The search for indicators of ecological diversity is a challenging endeavor. The label indicator in the context of individual species has been used in multiple references, including individual species whose presence or abundance indicates a set of resource conditions associated with a number of other species (i.e., umbrella species), species dependent upon a particular resource for some aspect of their life history (e.g., secondary cavity nesters), and species that are particularly sensitive to environmental change (Caro and O'Doherty 1999). The alternative to individual species indicators is to use composite species metrics that represent a significant proportion of the ecosystem being monitored. In general, species assemblages have a greater probability of representing the condition of the resources upon which they are dependent, since individual species respond idiosyncratically to changing environmental conditions.

Monitoring species occurrences based on a systematic sampling design, specifically the FIA grid, provides a wealth of information that can serve to address agency information needs, including the development of indicators of ecological diversity. Despite the typical need to minimize the cost of environmental monitoring and assessment, it is unlikely that one or a few species, vertebrate or otherwise, will be able to provide a sensitive and informative representation of the condition of entire communities or ecosystems. Although only three survey methods were employed in this example, a large number (n = 126) and proportion (more than 90 percent of species expected to be detected with these methods and 84 percent of all terrestrial vertebrate species in the study area) were actually detected (Manley *et al.* 2005). This indicates that multiple-species and multi-taxonomic surveys in association with a systematic grid are likely to detect a portion of resident of species sufficient to derive species assemblage indicators.

ISA succeeded in allowing identification of species uniquely associated with one end of the land development gradient; however, it was important to consider multiple sources of information on patterned associations between species and species groups, and land development. ISA is a valuable tool for identifying species that are highly sensitive to development, but it is insensitive to more subtle impacts on species (e.g., gradual declines in species abundance or frequency of occurrence). Furthermore, ISA cannot be used to evaluate species richness measures for potential indicator metric purposes. Conversely, correlations are sensitive to consistent declines in abundance or richness, but are insensitive to declines in maximum abundance and richness (i.e., depression of highest values as development increases or decreases). Notably both methods fail to identify impacts to species with low frequency of occurrence, a condition exhibited by a large proportion of species in most ecosystems (Gaston 1994), particularly upper trophic-level species.

The bird IED showed the most consistent and precise indication of biotic changes associated with land development. The strength of the bird IED is probably a function of both the sensitivity of songbirds to local conditions and the large number of species in the bird community conferring a greater range of richness and abundance values. The small mammal IED was intermediate in its precision relative to birds and mammalian carnivores. Although mammalian carnivores were the least precise, they did not decrease the precision of the composite IED, and they added a valuable ecological component to the index.

The systematic grid design made it possible to stratify the sample of sites into two different subpopulations of sites—reference and existing conditions—such that we could evaluate the current condition of ecological diversity for each vegetation community and throughout the study area. The use of reference conditions as a baseline against which existing conditions are evaluated has proved to be a valuable and reliable environmental assessment method (e.g., Wright *et al.* 2000). Although the sample size was limited, we were able to identify a significant deviation of existing conditions in the lowest elevation Jeffrey pine type, and thus identify an increase in the integrity of native vertebrate diversity in vegetation communities that were successively distant from the primary concentration of land development in the Lake Tahoe Basin.

The success of this approach in assessing ecological diversity suggests promise for applications of grid-based population monitoring using basic survey methods in meeting agency requirements to evaluate and monitor progress toward meeting desired ecological conditions. The approach provided sufficient information to derive reliable indicator metrics and apply them in developing a baseline of condition descriptors associated with reference conditions, and in evaluating existing conditions relative to reference or desired conditions. In this research effort, land development was used as the measure of human-generated land disturbance, but IEDs and deviations between existing and desired conditions could be developed for any number of anthropogenic stressors, such as pollution, human activity, and forest management activities. In the case of National Forest System lands management, it would be both prudent and feasible to develop IEDs that are informed by multiple stressors, using them individually and together to inform management on the status of ecological diversity and the environmental factors that put that diversity at risk.

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Appendix A (1 of 3)

Bird and small mammal species and species groups identified as candidate metrics in Indexes of Biological Diversity (scientific names available in Manley and McIntyr 2006). Selected metrics indicated in bold. Species relationships with development were evaluated based on indicator species analysis (ISA), Pearson's correlation coefficients across all three vegetation community types (= $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$) and per type (significant correlations per type represented by X), and bivariate scatterplots (not shown). Dashes indicate not applicable*

Potential metrics	Basinwide	Vegetation community type					
		Jeffrey pine		Mixed conifer		Subalpine conifer	
	Correlation	ISA	Correlation	ISA	Correlation	ISA	Correlation
Birds—intolerant metrics							
Primary species:							
Black-backed woodpecker	**– 0.149***	**X**	**X**				
Chipping sparrow	**– 0.163***		**X**	**X**			
Dark-eyed junco	**– 0.493****	**X**	**X**	**X**	**X**		**X**
Dusky flycatcher	**– 0.430****	**X**	**X**	**X**	**X**		
Green-tailed towhee	**– 0.183****	**X**	**X**	**X**			
Hairy woodpecker	**– 0.143****	**X**	**X**			**X**	
Hermit thrush	**– 0.384*****	**X**	**X**	**X**	**X**	**X**	
MacGillivray's warbler	**– 0.220*****		**X**	**X**	**X**		
Mountain quail	**– 0.245*****	**X**	**X**		**X**		
Nashville warbler	**– 0.286*****	**X**	**X**				
Olive-sided flycatcher	**– 0.292*****	**X**	**X**	**X**	**X**		
Townsend's solitaire	**– 0.375*****	**X**	**X**		**X**		
Warbling vireo	**– 0.256*****	**X**	**X**	**X**	**X**		
Western tanager	**– 0.163****	**X**	**X**	**X**			
Secondary species:							
Brown creeper	**– 0.206****				**X**		
Cassin's vireo	**– 0.204****		**X**				
Golden-crowned kinglet	**– 0.304*****		**X**		**X**		
Hermit warbler	**– 0.193****				**X**		
Lincoln sparrow	**– 0.178****		**X**				
Pine grosbeak	**– 0.237*****					**X**	
Pine siskin	**– 0.154****		**X**				
White-breasted nuthatch	**– 0.159****		**X**				
Wilson's warbler	**– 0.267*****				**X**		
Yellow-rumped warbler	**– 0.334*****		**X**		**X**		
Blue grouse	**– 0.179****						
Calliope hummingbird	**– 0.169****						
Cassin's finch	**– 0.200****						
Pileated woodpecker	**– 0.140***						
Primary groups:							
Foliage forager richness	**– 0.427*****	**—**	**X**	**—**	**X**	**—**	
Invertivore richness	**– 0.417*****	**—**	**X**	**—**	**X**	**—**	
Foliage forager abundance	– 0.434***		X	X	X		
Invertivore abundance	– 0.266***	X	X	X	X		
Secondary groups:							
Air forager richness	– 0.114*	—	X	—	X	—	
Ground nester richness	**– 0.493*****	**—**	**X**	**—**	**X**	**—**	
Habitat specialist richness	**– 0.335*****	**—**	**X**	**—**		**—**	
Rare species richness	**– 0.225*****	**—**		**—**	**X**	**—**	
Moderate specialist richness	– 0.136*	—	X	—		—	
Shrub nester richness	**– 0.321*****	**—**	**X**	**—**	**X**	**—**	
Air forager abundance	– 0.315***		X				
Ground forager abundance	– 0.334***		X				

ISA = indicator species analysis.

Appendix A (2 of 3)

Bird and small mammal species and species groups identified as candidate metrics in Indexes of Biological Diversity (scientific names available in Manley and McIntyr 2006). Selected metrics indicated in bold. Species relationships with development were evaluated based on indicator species analysis (ISA), Pearson's correlation coefficients across all three vegetation community types (= P < 0.05, ** P < 0.01, *** P < 0.001) and per type (significant correlations per type represented by X), and bivariate scatterplots (not shown). Dashes indicate not applicable*

Potential metrics	Basinwide	Vegetation community type					
		Jeffrey pine		Mixed conifer		Subalpine conifer	
	Correlation	ISA	Correlation	ISA	Correlation	ISA	Correlation
Ground nester abundance	– 0.535***	X	X	X	X		
Habitat specialist abundance	– 0.247***	X	X		X		
Habitat generalist abundance	– 0.258***		X				
Shrub nester abundance	– 0.345***		X	X	X		
Birds—tolerant metrics							
Primary species:							
Band-tailed pigeon	**0.421*** **			**X**	**X**		
Brewer's blackbird	**0.671*** **	**X**		**X**	**X**		**X**
Brown-headed cowbird	**0.635*** **	**X**		**X**	**X**	**X**	**X**
Mountain chickadee	**0.236*** **	**X**		**X**			
Mourning dove	**0.468*** **		**X**	**X**	**X**	**X**	**X**
Pygmy nuthatch	**0.643*** **	**X**	**X**	**X**	**X**	**X**	**X**
Steller's jay	**0.485*** **	**X**	**X**	**X**	**X**		
Secondary species:							
Common raven	**0.304*** **		**X**		**X**		**X**
Downy woodpecker	0.128*				X		
Northern flicker	**0.342*** **				**X**		
White-headed woodpecker	**0.317*** **				**X**		
Primary groups:							
Corvid abundance	0.292***	X		X	X		X
Omnivore abundance	0.303***	X			X		X
Malentity abundance	0.605***	X	X	X	X	X	X
Malentity richness	0.338***				X		X
Moderate specialist abundance	0.122*	X					
Tolerant species—relative abundance	0.859***	X	X	X	X	X	X
Secondary groups:							
Granivore richness	0.168*	—		—		—	X
Ground forager abundance	0.333***		n				X
Small Mammals—Intolerant Metrics							
Primary species:							
Lodgepole pine chipmunk	**– 0.253*** **			**X**	**X**		**X**
Secondary species:							
Deer mouse	**– 0.332*** **				**X**		**X**
Golden-mantled ground squirrel	– 0.122						X
Shadow chipmunk	**– 0.133***					**X**	
Western jumping mouse	**– 0.117**						

ISA = indicator species analysis.

Appendix A (3 of 3)

Bird and small mammal species and species groups identified as candidate metrics in Indexes of Biological Diversity (scientific names available in Manley and McIntyr 2006). Selected metrics indicated in bold. Species relationships with development were evaluated based on indicator species analysis (ISA), Pearson's correlation coefficients across all three vegetation community types (= P < 0.05, ** P < 0.01, *** P < 0.001) and per type (significant correlations per type represented by X), and bivariate scatterplots (not shown). Dashes indicate not applicable*

Potential metrics	Basinwide	Vegetation community type					
		Jeffrey pine		Mixed conifer		Subalpine conifer	
	Correlation	ISA	Correlation	ISA	Correlation	ISA	Correlation
Primary groups:							
Ground associate richness	**– 0.240*** **	**—**		**—**		**—**	
Herbivore richness	**– 0.329*** **	**—**	**X**	**—**	**X**	**—**	
Peromyscus species abundance	– 0.332***			X			
Nocturnal species abundance	– 0.281***			X			
Omnivore species abundance	– 0.130*			X			
Secondary groups:							
Habitat generalist richness	– 0.127	—		—		—	
Rare species richness	**– 0.149***	**—**		**—**		**—**	
Intolerant species richness	**– 0.139***						
***Mustela* species abundance**	**– 0.126***				**X**		**X**
Small mammals—tolerant metrics							
Primary species:							
Douglas squirrel	**0.496*** **	**X**	**X**	**X**	**X**		**X**
California ground squirrel	**0.487*** **	**X**	**X**	**X**	**X**	**X**	
Long-eared chipmunk	**0.325*** **			**X**	**X**		
Secondary species:							
Long-tailed vole	0.193**		X				
Yellow-pine chipmunk	**0.197** **					**X**	**X**
Primary groups:							
Nocturnal species richness	0.066**	—		—		—	
Omnivore richness	0.340***	—		—		—	
Canopy species richness	0.480***	—		—		—	
Microtus species abundance	0.121*	X					
Diurnal species abundance	0.205**	X			X	X	X
Habitat specialist abundance	0.133*	X		X			
Spermophilus species abundance	0.189**			X			
Canopy species abundance	0.323***						
Tamias species abundance	0.121*					X	
Tolerant species relative abundance	**0.559*** **			**X**	**X**	**X**	**X**

ISA = indicator species analysis.