

Assessing biodiversity intactness at multiple scales

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Abstract

The Southern Africa Millennium Ecosystem Assessment developed an index for quantifying the state of biodiversity. The Biodiversity Intactness Index (BII) operates at the species level, and is based on changes in species abundance, rather than changes in richness brought about by extinction. The BII uses spatial data on species richness and land use activities per ecosystem type to weight estimates, provided by taxon experts, of the reduction in abundance of all well-known species under a range of land uses. The result is a single score for a particular spatial area, with a confidence range. The index can be disaggregated in various ways, including spatially and by taxonomic group. This paper tests and confirms the ability to calculate and interpret the index at a variety of policy-relevant scales. It furthermore tests the sensitivity of the BII to normal variations in data quality and resolution of species richness and land use data, and confirms the robustness of the index in these respects.

Introduction

The loss of biodiversity in the modern era, at rates that appear unequalled since the major extinction events in the distant geological past (WCMC 2000; Anderson 2001), is a matter of considerable policy concern. The World Summit on Sustainable Development in its Johannesburg Plan of Implementation, aims to reduce the rate of biodiversity loss by 2010 (UN 2002). For this and other policy targets to be met, a method of measuring biodiversity status must be agreed on. At present no such consensus measure exists (Royal Society 2003), although several candidates have been proposed (Reid *et al.* 1993; CBD 2003b). Difficulties in establishing operational indicators stem largely from the complex, multi-dimensional nature of biodiversity, which is defined in terms of composition, structure and function at multiple scales (Noss 1990). While there is no shortage of ways to express biodiversity (CBD 2003a; Magurran 2004), most methods impose unattainable data needs, focus on a single scale and aspect of the biodiversity hierarchy, or are scale-dependent and thus hard to interpret in a comparative context. For instance, the most widely used biodiversity metric, species richness, is more sensitive to new discoveries resulting from increased inventory effort than it is to species loss resulting from extinction. Secondly, the relationship between species richness and area is non-linear and ecosystem-type dependent: what is a high species richness number for a small area is a low species richness in a large area.

The Biodiversity Intactness Index (BII) developed for use in the Southern African Millennium Ecosystem Assessment addresses both the problems of excessive data requirements and scale dependence. The BII is an indicator of the state of biological

diversity within a given geographical area, which may coincide with a political or ecological boundary, or any other defined region. BII is formally defined as the average, across all species chosen for consideration (typically, the well-known taxonomic groups: plants, mammals, birds, reptiles and amphibians), of the change in population size relative to a reference population. The reference population is conceived as that occurring in the landscape before it was altered by modern industrial society during the colonial period (i.e. pre-1700). In the southern African context, the current populations in large protected areas in each ecosystem type serve as a proxy for the reference populations.

The BII is an aggregate index, intended to provide an intuitive, high-level synthetic overview for the public and policy makers. At the same time, it can be disaggregated spatially, or by taxonomic group, to meet the information needs of various users, providing transparency and credibility. Mathematically and conceptually the BII has the same meaning at all spatial scales, and can thus be compared within and across scales, as well as between geographically separated areas of the same or different sizes. It is possible to estimate the value of BII for the past, and project it into the future under various scenarios of land use change.

The data available for computing BII and other indices vary in quality and resolution, and this variability is itself scale dependent. At small scales (for instance, a single well-studied protected area) very complete and high-resolution data may be available, whereas at the scales relevant to national or international policy, data is typically patchy and of coarse resolution. The BII is able to use data of differing quality and levels of detail as input, making it applicable immediately, but amenable to incremental improvement in the future. An error bar can be associated with the BII, and the long-term research and observation goal can then be defined in terms of shrinking this uncertainty range.

The objectives of this paper are two-fold. Firstly, to illustrate that the index can be meaningfully scaled up and down, and therefore usefully and consistently applied at the typical levels of environmental decision-making. In the case of South Africa, these are the constitutionally-defined three tiers of government: national (1.2 million km²), provincial (9 units, average area 135461 km²) and local (262 units, average area 4647 km²). The second objective is to test the sensitivity of the index to the resolution and quality of the input data used. In particular, we aim to explore the sensitivity of the BII to improved spatial estimates of species richness and to a higher-resolution land use map.

The Biodiversity Intactness Index algorithm

The derivation and logic of the BII are given in Scholes and Biggs (*in prep*). In essence, BII is a richness-and-area weighted average of the population impact of a set of land use activities, on a given groups of organisms, in a given area. If the population impact (I_{ijk}) is defined as the relative population of taxon i (as compared to the reference state) under land use activity k in ecosystem j , then BII gives the average remaining fraction of the populations of all species considered:

$$BII = \frac{\sum_i \sum_j \sum_k R_{ij} A_{jk} I_{ijk}}{\sum_i \sum_j \sum_k R_{ij} A_{jk}}$$

where

R_{ij} = Richness (number of species) of taxon i in ecosystem j

A_{jk} = Area of land use k in ecosystem j

BII can be disaggregated to successive levels of detail along different axes. For instance, the intactness of a particular taxonomic group i , and for a particular taxon i in a given ecosystem j are respectively given by:

$$BII_i = \frac{\sum_j \sum_k R_{ij} A_{jk} I_{ijk}}{\sum_j \sum_k R_{ij} A_{jk}} \qquad BII_{ij} = \frac{\sum_k A_{jk} I_{ijk}}{\sum_k A_{jk}}$$

Note that I_{ijk} typically lies between 0 and 1, but can take on values greater than one in some circumstances. For example, cultivation greatly increases the populations of certain categories of bird species, such as granivores, relative to ‘natural’ areas. Similarly, frugivores are enhanced in urban areas.

Data sources

I_{ijk} is a matrix of estimates of the fraction of the original populations of specific taxa that persist under a given land use activity in a particular ecosystem. While I_{ijk} can in principle be exactly measured, the species-by-species population data needed to do so are currently available only for a few species in a few locations. In the study that developed the BII (Scholes and Biggs *in prep.*), expert judgement was used to generate the matrix of values of I_{ijk} . Three or more highly-experienced specialists for each selected taxonomic group (plants, mammals, birds, reptiles and amphibians) independently estimated the degree of reduction of populations, relative to populations in a large protected area in the same ecosystem type, caused by a pre-defined set of land use activities (Table 1). This was achieved by dividing each taxonomic group into 5-10 functional types that responded in similar ways to human activities. Aggregation up to the broad taxonomic level (birds, mammals etc.) was done by weighting the I_{ijk} estimates for each functional type by the number of species in that functional type in the particular ecosystem. It is also possible to calculate a ‘functional biodiversity intactness index’ (FII), in which weighting is done by functional group rather than by species richness. I_{ijk} estimates are conceivably sensitive to the resolution of the land use classification used in the calculation of BII. In this study, a 1 x 1 km resolution was used so that, for example, the ‘cultivated’ category would generally include a fraction of uncultivated land. Experts were asked to account for this in making their population impact estimates.

R_{ij} is the species richness per broad taxon (plants, mammals etc), per ecosystem type. Species richness data is typically available as total species counts per ecosystem and the assumption is made that every species occurs throughout the extent of the

particular ecosystem type. Le Roux (2002) recently compiled such data for South Africa, for eight taxonomic groups in seven biomes; these data were used in this study. Individual species distribution grids are available digitally for certain taxonomic groups in South Africa. The BII is based on potential distribution ranges, and in this paper, the potential mammal distribution data of Friedman *et al.* (*in prep.*) was used to explore the sensitivity of BII to the input of more highly resolved spatial species richness data. The potential distribution maps of 272 mammal species were rasterized, and the total number of mammal species per 1 x 1 km grid cell calculated as an alternative R_{ij} input for BII.

A_{jk} is the area of a particular land use within a specific ecosystem, derived by overlaying a land use map on an ecosystem-type map. Ecosystem types were defined as the biomes of South Africa, the boundaries of which were obtained from the National Botanical Institute (Rutherford and Westfall 1994; Low & Rebelo 1996). In this study, the assumption was made that broad classes of land use can be inferred from land-cover and land tenure boundaries. We defined six levels of land use intensity and mapped these by combining data from several global to continental scale data sources (Table 1). In order to test the sensitivity of BII to the land use classification employed, a second land use map for South Africa was derived from the South African national land-cover map (CSIR 1996; Fairbanks *et al.* 2000), combined with a national protected areas map (CSIR 2003). The South African national land cover map was derived from high-resolution satellite imagery (fundamental resolution ~20 m, but effectively aggregated to about 500 m), whereas the main source for the southern African regional scale land use map was low to medium resolution imagery with a fundamental resolution of about 1 km.

Scalability of the index

A central feature of the BII is that conceptually it can be applied at different levels of decision-making, and results can be compared directly within and across scales. This was tested in practice by applying the BII to the three levels of environmental decision-making in South Africa: national, regional and local government (Figure 1). The results show that BII delivers intuitively meaningful results down to at least the scale of local government (municipal level). The ability to apply the index at multiple levels of decision-making is very useful: aggregation allows the information to be collapsed to an appropriate level of detail, while disaggregation ensures transparency and allows for the definition of finer-level policy goals. BII can similarly be disaggregated by taxa or biome (Table 2); mathematically it is possible to disaggregate BII down to any defined spatial area and any group of species.

Functional diversity intactness

The possible use of BII as an indicator of functional biodiversity intactness (as opposed to compositional biodiversity intactness, see Noss (1990)) was explored by weighting the taxon-level I_{ijk} estimates by functional group, as defined by the experts, instead of by species richness. In principle this is another form of scaling: it coarsens the resolution along the taxon axis rather than along a geographical scale axis. Conceptually, it would assign greater weight to heavily impacted, but relatively species-poor groups, such as megaherbivores.

The functional intactness (FII) of South Africa, calculated across all taxa, is 0.81, and therefore slightly *higher* than the species-weighted BII (Table 3). The FII was lower than the BII in savannas, by 0.038; shrubland and *fynbos* both increased by 0.065. Mammals showed by far the largest decline, 0.097, in comparison to the species-based estimate. Reptiles also showed a slight decline; all other taxa showed marginal increases in the value of FII as compared to BII.

While the functional groups used in this calculation were not specifically defined for the purpose of calculating FII, the results suggest that other than in the case of mammals, there do not appear to be specific functional groups that are currently suffering excessively greater impact than other functional groups. The results indicate that under such circumstances, FII serves as a good proxy to BII. This suggests that in regions lacking species-level data, FII could serve as a first approximation for BII: I_{ijk} would be estimated based on a sample of species per functional group, and R_{ij} would be a count of the number of functional groups present in a particular biome.

Sensitivity of the index

Ideally, any biodiversity index should be sufficiently sensitive to reflect the impacts of changing land use over time, but should not be overly sensitive to differences in the interpretation of land use classes or estimates of species richness that are within the normal uncertainty in those parameters.

Sensitivity to R_{ij} (species richness)

Sensitivity to the spatial resolution of species richness data was explored by comparing the values of BII obtained using the richness surface derived by summation of individual mammal distribution grids, as opposed to using biome-level mammal species richness data (i.e. the same richness value is assigned to every grid cell in a particular biome).

For South Africa overall (area 1.2 million km²), BII for mammals declined from 0.675 using the biome-level data to 0.661 using the individual species distribution data (Table 3). At the level of individual biomes, the largest difference between the two methods was 0.006, and at both the provincial and municipal levels the largest difference was 0.03. No correlation was found between the calculated difference and the size of the units of aggregation.

At the scales at which we envisage BII being applied (areas of 500 km² upward), it appears robust to the use of coarse-level species richness data, at least in the case of mammals. This may be due to the fact that the distribution ranges of a large fraction of mammal species coincide with biome boundaries (Erasmus *et al.* 2002). In the case of amphibians and reptiles, which are less mobile and more habitat-dependent than mammals, resulting in a larger fraction of the species having very restricted ranges, the robustness of BII to the use of coarse-resolution species richness data must still be verified. Where individual species distribution data are available, the estimation of BII can be further improved by using the disaggregated functional group level estimates

of I_{ijk} , rather than the weighted average taxon level estimates of I_{ijk} in the calculation of BII.

Sensitivity to A_{jk} (land use classification)

The results presented thus far are based on the global to continental scale data sources used in Scholes and Biggs (*in prep.*) to map land uses for the southern African application of BII (Table 1, Data source (1)). In this section, a national scale land use classification (Table 1, Data source (2)) was used to explore the sensitivity of BII to the input A_{jk} , the area in each ecosystem type under a given land use category. Table 4 summarizes the relative proportions of South Africa apportioned to the different classes using the two data sources.

The land use classification derived from the South African national-level data gives a BII value of 0.812, compared to the value of 0.796 (Table 3) determined using the southern African regional-scale data. The BII values for all taxa and all biomes were marginally higher (less than 0.03) in the national than regional products, except for the forest biome, which increased by 0.07. While there are large differences in the total area assigned to certain classes (for example the urban and degraded categories), these are generally classes that, while having a high impact, constitute a relatively small fraction of the total land surface. Consequently, differences in their classification have a limited impact on the value of BII. In addition, classes where there are large differences in the areas assigned are often classes that are partially overlapping, as evidenced by the fact that the sum of their areas is very similar using the different data sources (e.g. the sum of urban and degraded is 5.8% using national-level data, and 7.5% using regional-level data).

These results suggest that, at the coarse level of land use classification used in this study (six broad classes of impact), there is sufficient agreement between the main land cover and land tenure data sources that the choice of a particular data source will not significantly change the value of BII.

Conclusions

1. The Biodiversity Intactness Index (BII) can be applied at scales at least down to 500 km² (i.e. to the level of local government) while retaining its intuitive meaning.
2. The values given by the BII at the national scale (~ 1 million km²) are robust to variations within the normal range in data quality and resolution, specifically to:
 - a. Biome-level species richness data versus species-by-species distribution data;
 - b. Missing information on species richness, which can to a degree be substituted by functional type richness;
 - c. Reasonable differences in the interpretation of land use classes.

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Table 1. Classes used to derive a land use map from land cover, land tenure boundaries and other available information. Two classifications were used: (1) a classification used by Scholes & Biggs (*in prep*) for the southern African analysis, and (2) a classification largely based on the South African national land-cover map. Classification was carried out at a 1 x 1 km resolution and based on the dominant category within a particular unit. A ‘cultivated’ unit would therefore consist predominantly of cultivated fields, but usually also contain a fraction of uncultivated land. Where classes overlapped, land use was assigned in the following order of priority: urban, plantation, cultivated, degraded, protected, light use.

<i>Land use class</i>	<i>Description</i>	<i>Data source</i>
Protected	Minimal recent human impact on structure, composition or function of the ecosystem. Biotic populations inferred to be near their potential. <i>Examples: Large protected areas, ‘wilderness’ areas.</i>	(1) World Database on Protected Areas (IUCN & UNEP 2003). All designated protected areas of IUCN categories I-V. (2) South African national protected areas (CSIR 2003)
Lightly used	Some extractive use of populations and associated disturbance, but not enough to cause continuing or irreversible declines in populations. Processes, communities and populations largely intact. <i>Examples: Forest areas used by indigenous peoples or under sustainable, low impact forestry; grasslands grazed within their sustainable carrying capacity.</i>	All remaining areas not classified into one of the other five categories.
Degraded	High extractive use and widespread disturbance, typically associated with large human populations in rural areas. Productive capacity reduced to approximately 60% of ‘natural’ state. <i>Examples: Clear-cut logging, areas subject to intense harvesting, hunting or fishing, areas invaded by alien vegetation.</i>	(1) All areas falling below 75% (forest, grassland and savanna) or 50% (shrublands) of expected production as estimated by non-linear regression (Michaelis-Menten function) of maximum annual NDVI on growth days. Degraded areas not estimated for desert, wetland and <i>fynbos</i> . (2) South African national land-cover map (CSIR 1996)
Cultivated	Land cover permanently replaced by planted crops. Most processes persist, but are significantly disrupted by ploughing and harvesting activities. Residual biodiversity persists in the landscape, mainly in set-asides and in strips between fields (matrix), assumed to constitute approximately 20% of class. <i>Examples: Commercial and subsistence crop agriculture.</i>	(1) SADC Landcover Dataset (CSIR 2002), filled with GLC2000 (EC 2003) for Namibia and Botswana. (2) South African national land-cover map (CSIR 1996)
Plantation	Land cover permanently replaced by timber plantations. Matrix areas assumed to constitute approximately 25% of class. <i>Examples: Plantation forestry, typically <i>pinus</i> and <i>eucalyptus</i> species.</i>	(1) SADC Landcover Dataset (CSIR 2002) (2) South African national land-cover map (CSIR 1996)
Urban	Land cover replaced by hard surfaces such as roads and buildings. Dense populations of people. Most processes are highly modified. Matrix assumed to constitute 10% of class. <i>Examples: Dense urban and industrial areas, mines and quarries.</i>	1) CIESIN urban areas mask (2) South African national land-cover map (CSIR 1996)

Table 2. A cross-tabulation of BII per major ecosystem type and broad taxonomic group for South Africa, showing how the overall score (0.80 ± 0.06 at the 95% level) can be disaggregated into column or row scores for ecosystems or taxa, or down to taxa within ecosystems. Note that the aggregations are not simple averages, but are weighted by biome-level species richness (Le Roux 2002) and area (southern African regional scale land use classification given in Table 1).

	<i>Area (km²)</i>	Plants	Mammals	Birds	Reptiles	Amphibia	ALL TAXA
<i>Richness</i>		<i>23420</i>	<i>258</i>	<i>694</i>	<i>363</i>	<i>111</i>	<i>24846</i>
Forest	<i>7 148</i>	0.68	0.71	0.84	0.77	0.75	0.69
Savanna	<i>416 484</i>	0.82	0.71	0.93	0.86	0.93	0.83
Thicket	<i>41 349</i>	0.78	0.66	0.89	0.82	0.90	0.78
Grassland	<i>294 815</i>	0.69	0.54	0.90	0.73	0.78	0.71
Nama Karoo	<i>297 810</i>	0.86	0.70	1.06	0.93	1.29	0.88
Succulent Karoo	<i>82 490</i>	0.83	0.69	1.03	0.90	1.25	0.84
Fynbos	<i>77 111</i>	0.70	0.78	0.91	0.77	0.79	0.71
ALL BIOMES	<i>1 217 207</i>	0.78	0.68	0.95	0.84	0.92	0.80

Table 3. Results of a sensitivity analysis of BII to inputs of species richness and land use. *Column 2:* Comparison of BII values to those of FII (Functional Intactness Index), where FII is derived by weighting I_{ijk} by functional group instead of by species richness; *Column 3:* Comparative values of species-weighted BII as derived from the regional-scale land use classification (1) and the national-level classification (2) (see Table 1); and *Columns 4 and 5:* Comparison of the values of BII obtained for mammals using aggregated biome-level richness data as opposed to individual species distribution grids. Note that the results presented here are for the biomes as defined in the expert interviews: the thicket biome is therefore included with savanna, and the Succulent and Nama Karoo are lumped together as shrubland.

Index	BII	FII	BII	Mammals	
	(1)	(1)	(2)	BII	BII
Land use	(1)	(1)	(2)	(1)	(1)
Species richness	Biome	Biome	Biome	Biome	Grid
Biomes					
Forest	0.690	0.734	0.761	0.706	0.712
Savanna	0.826	0.788	0.831	0.708	0.700
Grassland	0.708	0.713	0.731	0.537	0.538
Shrubland	0.866	0.931	0.892	0.699	0.696
Fynbos	0.706	0.770	0.737	0.778	0.772
Taxa					
Plants	0.784	0.832	0.802		
Mammals	0.676	0.579	0.686	0.675	0.661
Birds	0.949	0.960	0.949		
Reptiles	0.840	0.798	0.857		
Amphibia	0.923	0.924	0.936		
SOUTH AFRICA	0.796	0.810	0.812		

Table 4. Comparison of the percentage of South Africa classified into the classes described in Table 1. Area (1) refers to the land use classification derived from the regional-scale data sources, while Area (2) refers to the classification derived from national-scale data (see Table 1). There is a good correspondence between the two classifications for all classes except “degraded” and “urban”.

<i>Land use</i>	<i>% Area (1)</i>	<i>% Area (2)</i>	<i>Area (1)/ Area (2)</i>
Protected	5.00	6.96	0.72
Light Use	75.59	74.22	1.02
Degraded	2.34	4.68	0.50
Cultivated	10.68	11.73	0.91
Plantation	1.22	1.26	0.97
Urban	5.17	1.14	4.52

Figure 1. The Biodiversity Intactness Index applied at the three levels of environmental decision-making in South Africa: national, provincial and local government. The results are richness and area weighted averages of BII as estimated at a base resolution of 1 km. Values of BII obtained at different scales are directly comparable: they refer to the average abundance of all species in the particular area, expressed as a fraction of pre-industrial era abundance.

