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Measuring uncertainty in estimates of biodiversity loss: The example of biodiversity intactness variance

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ABSTRACT

Developing adequate indicators of biodiversity change is an urgent task for biodiversity studies and policy. An important component of any indicator is a measure of the uncertainty in the estimates it produces. In this paper, we derive the biodiversity intactness variance (BIV) as a formal measure of uncertainty to accompany the recently developed biodiversity intactness index (BII) (Scholes and Biggs [Scholes, R.J., Biggs, R., 2005. A biodiversity intactness index. Nature 434, 45–49]). The BII is based on estimates of baseline species richness, the area of different land-uses, and the abundance of different species under different land uses. The BIV quantifies uncertainty in the abundance estimates, which are the main source of uncertainty in BII. The BII for southern Africa in the year 2000 has been estimated at 84.4%. We calculate the accompanying BIV at 50.4, providing a 95% confidence interval of 76.6–92.2% for BII. By applying the BIV, we can quantify the major sources of uncertainty in the BII for southern Africa: they stem from the abundance estimates for mammals and birds, and for savanna regions and degraded areas. The BIV therefore provides a means for better assessing the state of biodiversity loss and for highlighting research priorities.

1. Introduction

Biodiversity losses have accelerated worldwide due to the over-exploitation of natural resources, habitat destruction, and climate change (Pimm et al., 1995; Sala et al., 2000; Thuiller et al., 2005; Millennium Ecosystem Assessment, 2005). In an effort to address this concern, the Convention on Biological Diversity (CBD) set a goal to achieve a significant reduction in the current rate of biodiversity loss at global, regional and national levels by 2010 (Mace, 2005; Fontaine et al., 2007). A major factor hampering progress towards this goal is the lack of practical indices to monitor rates of biodiversity change in terrestrial, aquatic, and marine ecosystems (Purvis and Hector, 2000; Sala et al., 2000; Saterson et al., 2004; Balmford et al., 2005; Pereira and Cooper, 2006).

To help meet this need, Scholes and Biggs (2005) developed the biodiversity intactness index (BII), a simple, robust indicator of biodiversity loss that satisfies the criteria set by the CBD (Scholes and Biggs, 2005; Mace, 2005). The BII estimates the mean change in the abundance of terrestrial plants and vertebrates (birds, mammals, reptiles and amphibians), relative to their reference populations in a particular ecosystem. Changes in population abundances are assumed to be a function of various land use practices, and are estimated from a combination of sources including expert surveys, observational and experimental studies. Although Scholes and Biggs

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(2005) estimated the error range of BII, they did not define a formal measure of uncertainty to accompany the BII. Such measures are missing from most proposed indicators of biodiversity loss, but are critical to assessing the significance of changes in an indicator over time.

The aim of this paper is to provide a formal measure of uncertainty, the biodiversity intactness variance (BIV), that can be applied in conjunction with the BII. The BIV does not aim to capture all sources of uncertainty in the BII, but instead to account for the most important sources. In order to illustrate the application of the BIV, we apply it to the same southern African dataset used by Scholes and Biggs (2005).

2. Defining the biodiversity intactness variance (BIV)

The biodiversity intactness index (BII) (Scholes and Biggs, 2005) is defined as:

$$\mathrm{BII} = \sum_i \sum_j \sum_k R_{ij} A_{jk} I_{ijk} \Big/ \sum_i \sum_j \sum_k R_{ij} A_{jk}$$

where I_{ijk} is the mean population impact estimate for a particular species group i under land use k in ecosystem j, based on several sources. The population impact is defined as the present-day abundance of a particular species or group of species relative to the reference abundance in the same ecosystem type. R_{ij} represents the species richness of taxon i in ecosystem j, while A_{jk} is the area of land use k in ecosystem j. R_{ij} and A_{jk} function as weighting factors for the I_{ijk} estimates.

Using similar notation, we define the biodiversity intactness variance (BIV) as:

$$\mathrm{BIV} = \sum_i \sum_j \sum_k \sum_{l=1}^{m_{ijk}} R_{ij} A_{jk} \frac{(I_{ijkl} - I_{ijk})^2}{m_{ijk} - 1} \Big/ \sum_i \sum_j \sum_k R_{ij} A_{jk} \qquad (1)$$

where I_{ijkl} is the population impact estimated from source (l). The sources (l) may include results from published studies, estimates obtained from experts as in Scholes and Biggs (2005), or any other data that are deemed appropriate. m_{ijk} is the number of sources (l) from which each I_{ijk} is derived. If the number of sources is substantially similar for each I_{ijk}, the formula may be simplified by substituting an average value, m, for m_{ijk}.

The BIV is therefore defined as a measure of the uncertainty associated with the population impact estimates I_{ijk}. We chose to define the BIV in this way for three reasons. First, our desired measure is one that reflects the uncertainty in BII, rather than describing the variation between taxa, ecosystems or land uses (as would be the case if the term $(I_{ijkl} - I_{ijk})$ was replaced by $(I_{ijk} - I)$). Second, multiple independent estimates for R_{ij} and A_{jk} are seldom available in practice, and incorporating the uncertainty associated with these factors would therefore be impossible in many situations. Third, Scholes and Biggs (2005) found I_{ijk} to be the primary source of uncertainty in BII. There is also uncertainty associated with R_{ij} and A_{jk}, but it was found to be approximately five times smaller than that associated with I_{ijk} (Scholes and Biggs, 2005).

Our definition of the BIV provides a formalization of the error approximation approach applied by Scholes and Biggs (2005). Scholes and Biggs (2005) estimated the error range in BII by applying the BII formula using 95% high and low confidence estimates for I_{ijk}. The BIV formula provides a means to assess uncertainty directly from the underlying I_{ijkl} data, and therefore obviates the need to make assumptions about the distribution of the I_{ijk} data, which may be problematic when sample sizes are small.

As in the case of the BII, the BIV can be calculated for its partial components. For example, the variance in the BII estimate of a particular taxonomic group i ($\mathrm{BIV_i}$) is given by:

$$\mathrm{BIV_i} = \sum_j \sum_k \sum_l R_{ij} A_{jk} (I_{ijkl} - I_{ijk})^2 \Big/ \left[(m-1) \sum_j \sum_k R_{ij} A_{jk} \right] \qquad (2)$$

Further estimates of variation, such as the standard error (SE), coefficient of variation (CV) and 95% confidence intervals (95% CI), can be derived from the BII and BIV as $\mathrm{SE} = \sqrt{\mathrm{BIV}}/\sqrt{m}$, $\mathrm{CV} = \sqrt{\mathrm{BIV}}/\mathrm{BII} \times 100$, $95\%\ \mathrm{CI} = \mathrm{BII} \pm t_\alpha \mathrm{SE}$ (Hui and Jiang, 1996).

3. An example: calculating the BIV for southern Africa

We apply the BIV to southern Africa using the original dataset of Scholes and Biggs (2005) to demonstrate its application. In brief, the population impact data I_{ijkl} for this dataset were generated using expert judgment. At least three experts judged the impact of six different land use classes, in each of six broad ecosystem types (biomes), on the populations of 5–10 functional groups within each of five broad taxonomic groups. The mean number of sources (m) used to estimate I_{ijk} is 3.2 (three expert estimates for each cell of the I_{ijk} matrix for plants, mammals, birds and amphibians, and four expert estimates for reptiles). Species richness (R_{ij}) was defined as the total species count per ecosystem sub-type (WWF ecoregions) (Burgess et al., 2004). The area of a particular land use within a specific ecosystem type, A_{jk}, was determined by overlaying land use and ecoregion maps as described by Scholes and Biggs (2005).

Based on this dataset, the BII for southern Africa in the year 2000 was estimated at 84.4% (Scholes and Biggs, 2005). This is interpreted as an estimated decline of 15.6% in the abundance of wild organisms in southern Africa, averaged across all plant, mammal, bird, reptile and amphibian species, relative to their reference pre-colonial (pre-1700) populations. Applying the BIV, we estimate the variance associated with this BII estimate at 50.4 (Table 1). The 95% confidence interval for the estimate therefore ranges from 76.6% to 92.2%, indicating an estimated decline in southern Africa's biodiversity of between 7.8% and 23.4% since pre-colonial times.

The BIV may be particularly useful in highlighting the main sources of uncertainty in an analysis (Table 1). Our analyses show that among different taxa, the uncertainty associated with the impacts on mammals was the largest. The BII for mammals was estimated at 71.3%, and we estimate the associated BIV at 77.9%^{2}, yielding a 95% confidence interval ranging from 61.3% to 81.3%. BII estimates for birds and amphibians were relatively high (96% and 92.9%, respectively) and application of the BIV resulted in 95% confidence intervals that included 100%. Among different ecosystems (bio-

Table 1 – Biodiversity intactness index (BII), biodiversity intactness variance (BIV), coefficient of variation (CV), and 95% confidence intervals (95% CI) calculated per taxonomic group, biome and for southern Africa as a whole

	BII (%)[a]	BIV ($\%^2$)	CV	n[b]	95% CI (%)[c]
Southern Africa					
Region	84.4	50.4	8.5	496	76.6–92.2
Per taxon					
Plants	82.4	49.2	8.5	93	74.4–90.3
Mammals	71.3	77.9	12.4	93	61.3–81.3
Birds	96.0	76.9	9.1	93	86.1–105.9
Reptiles	88.1	35.8	6.8	124	82.2–93.9
Amphibians	92.9	68.3	8.7	93	85.8–104.5
Per biome					
Forest	78.0	47.5	8.9	80	70.6–85.6
Savanna	87.0	60.0	9.0	80	78.5–95.4
Grassland	74.1	36.3	8.2	96	67.5–80.7
Shrubland	88.4	36.8	6.9	80	81.9–95.2
Fynbos	76.4	32.4	7.5	96	70.2–82.7
Wetland	91.3	17.9	4.7	64	86.7–96.0

a BII was estimated in Scholes and Biggs (2005).
b n gives the number of independent estimates (I_{ijkl}) on which the BIV calculation was based.
c $t_\alpha = 1.96$ is used for calculating the 95% CI.

mes), the largest uncertainty was associated with the BII estimate for savanna, with a 95% confidence interval ranging from 78.5% to 95.4%.

The BIV can be applied at finer scales of analysis to inform research priorities (Table 2). For instance, the large uncertainty in the BII estimates for mammals are due to high uncertainties about population impacts in the *fynbos* and grassland. Overall, the greatest uncertainties are associated with the BII estimates for amphibians in the *fynbos* (15.5%), while the smallest uncertainties are associated with the BII estimates for birds in wetlands (1.4%). Amphibian estimates showed large variation in uncertainty across different ecosystems. Within *fynbos*, shrublands, and grasslands, standard errors for different taxa varied substantially. For example, in *fynbos*, the standard error of BII for plants was 2.9%, while that for amphibians was 15.5%.

An analysis of the uncertainties associated with different land use types can be similarly insightful (Table 3). Variation in the uncertainties associated with the BII among different land use classes was substantial. The smallest uncertainties occurred in protected areas (0.3%). Large uncertainty was found in degraded area (6.1%), especially for amphibians (17.2%) and birds (12.5%). Such analyses can clearly help direct research activities toward areas where knowledge of biodiversity impacts is most uncertain.

4. Discussion

In order to monitor and assess changes in biodiversity, indicators of biodiversity loss need to be accompanied by measures of uncertainty. In this paper, we define a formal measure, the biodiversity intactness variance (BIV), to assess uncertainty in estimates of biodiversity loss derived from the biodiversity intactness index (BII). Our definition of the BIV provides a formalization of the error approximation approach applied by Scholes and Biggs (2005). Importantly, it obviates the need to make assumptions about the distribution of the I_{ijk} data by allowing us calculate the uncertainty in BII directly from the underlying data sources I_{ijkl}.

Estimates of the uncertainty in BII provide at least two useful forms of information. First, they provide policy makers and the scientific community with better scientific assessments of the status and rate of biodiversity loss. Second, they can highlight the areas of greatest uncertainty and help focus research effort. Uncertainty in the estimates of BII can be reduced by increasing sample sizes (number of sources l), thus

Table 2 – Standard error (SE, %) of biodiversity intactness index (BII) for southern Africa, per biome and taxonomic group

	Plants	Mammals	Birds	Reptiles	Amphibian	All taxa
Forest	4.3	2.4	3.9	2.2	4.6	3.8
Savanna	4.7	4.1	4.9	3.0	1.8	4.3
Grassland	3.1	7.8	4.3	3.7	6.7	3.4
Shrubland	2.3	6.4	6.9	2.7	10.2	3.4
Fynbos	2.9	8.1	5.2	2.9	15.5	3.2
Wetland	2.0	6.6	1.4	1.8	4.1	2.4
All biomes	4.0	5.1	5.1	3.0	4.8	4.0

Table 3 – Standard error (SE, %) of biodiversity intactness index (BII) for southern Africa, per land use class and taxonomic group

	Plants	Mammals	Birds	Reptiles	Amphibian	All taxa
Protected	0.0	0.2	0.5	0.7	0.0	0.3
Moderate use	4.5	5.3	3.7	2.8	3.1	4.0
Degraded	4.4	6.4	12.5	6.0	17.2	6.1
Cultivated	2.4	4.6	9.9	4.5	8.2	4.4
Plantation	1.2	10.4	9.7	3.0	3.1	3.8
Urban	1.4	6.8	9.8	2.7	12.6	4.0
All land use	4.0	5.1	5.1	3.0	4.8	4.0

increasing the precision of the population impact estimates. This can be accomplished by including more I_{ijkl} estimates from published studies, or by increasing the number of experts that were interviewed. Lowering the variation in the population impact estimates (I_{ijk}), especially in ecosystems with large changes in land use, would decrease uncertainty in biodiversity loss estimation.

Given the multi-faceted nature of biodiversity, it is clear that a single indicator cannot address all the important dimensions. More indicators of biodiversity loss are therefore needed (Dudley et al., 2005; Scholes and Biggs, 2005; van Jaarsveld et al., 2005; Balmford et al., 2005; Hess et al., 2006; Nielsen et al., 2007). One objective of this paper was to raise awareness of the need for measures of uncertainty when biodiversity indicators are developed. Regardless of which indicator is used, quantifying its uncertainty will improve our ability to assess biodiversity loss. If indicators of biodiversity status, such as the BII, are to be widely adopted, we believe that they must be accompanied by robust estimates of their uncertainty, such as the BIV.

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REFERENCES

Balmford, A., Bennun, L., ten Brink, B., Cooper, D., C ôté, I.M., Crane, P., Dobson, A., Dudley, N., et al, 2005. The convention on biological diversity's 2010 target. Science 307, 212–213.

Burgess, N., D'Amico Hales, J., Underwood, E., Dinerstein, E., Olson, D., Itoua, I., Schipper, J., Ricketts, T., Newman, K., 2004. Terrestrial Ecoregions of Africa and Madagascar: A Continental Assessment. Island Press, Washington DC, USA.

Dudley, N., Baldock, D., Nasi, R., Stolton, S., 2005. Measuring biodiversity and sustainable management in forests and agricultural landscapes. Philosophical Transactions of the Royal Society B 360, 457–470.

Fontaine, B., Bouchet, P., Achterberg, K.V., Alonso-Zarazaga, M.A., Araujo, R., Asche, M., Aspock, U., Audisio, P., et al, 2007. The European union's 2010 target: putting rare species in focus. Biological Conservation 139, 167–185.

Hess, G.R., Bartel, R.A., Leidner, A.K., Rosenfeld, K.M., Rubino, M.J., Snider, S.B., Ricketts, T.H., 2006. Effectiveness of biodiversity indicators varies with extent, grain, and region. Biological Conservation 132, 448–457.

Hui, D., Jiang, C., 1996. Practical Statistical Analysis System (SAS) Usage. Beijing University of Aeronautics and Astronautics Press, Beijing, China.

Mace, G.M., 2005. An index of intactness. Nature 434, 32–33.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Biodiversity Synthesis. World Resources Institute, Washington, DC, USA.

Nielsen, S.E., Bayne, E.M., Schieck, J., Herbers, J., Boutin, S., 2007. A new method to estimate species and biodiversity intactness using empirically derived reference conditions. Biological Conservation 137, 403–414.

Pereira, H.M., Cooper, H.D., 2006. Towards the global monitoring of biodiversity change. Trends in Ecology and Evolution 21, 123–129.

Pimm, S.L., Russell, G.J., Gittleman, J.L., Brooks, T.M., 1995. The future of biodiversity. Science 269, 347–350.

Purvis, A., Hector, A., 2000. Getting the measure of biodiversity. Nature 405, 212–219.

Sala, O.E., Chapin III, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., et al, 2000. Global biodiversity scenarios for the year 2100. Science 287, 1770–1774.

Saterson, K.A., Christensen, N.L., Jackson, R.B., Kramer, R.A., Pimm, S.L., Smith, M.D., Wiener, J.B., 2004. Disconnects in evaluating the relative effectiveness of conservation strategies. Conservation Biology 18, 597–599.

Scholes, R.J., Biggs, R., 2005. A biodiversity intactness index. Nature 434, 45–49.

Thuiller, W., Lavorel, S., Arau'jo, M.B., Sykes, M.T., Prentice, I.C., 2005. Climate change threats to plant diversity in Europe. Proceedings of the National Academy of Sciences USA 102, 8245–8250.

van Jaarsveld, A.S., Biggs, R., Scholes, R.J., Bohensky, E., Reyers, B., Lynam, T., Musvoto, C., Fabricius, C., 2005. Measuring conditions and trends in ecosystem services at multiple scales: the southern African millennium ecosystem assessment (SAfMA) experience. Philosophical Transactions of the Royal Society B 360, 425–441.