‘Sum of inverse range-sizes’ (SIR), a biodiversity metric with many names and interpretations

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Abstract Range restriction is an important measure of species rarity that is also interpreted as endemism. A simple biodiversity metric, the sum of inverse range-sizes (‘SIR’) for species within a sampling unit is useful for conservation planning but has multiple names and applications: for example, to highlight areas of high biodiversity and biological uniqueness (the *hotspots* problem, e.g. ‘*weighted endemism*’/WE) and as a range proportion-explicit metric for calculating complementarity in reserve selection (the *representation* problem, e.g. ‘*rarity-weighted richness’*/RWR). This paper outlines the development, implementation and duplication of SIR. We propose that terminology for equivalent metrics can be unified if:- ‘SIR’ refers to them generally; those based on site or grid cell occupancy, or area of occupancy, are referred to specifically as *‘range-rarity richness*’ (RRR); while those aimed at measuring endemism based on extent of occurrence are referred to specifically as ‘*georeferenced weighted endemism*’ (GWE). The phylogenetic equivalents would then be ‘*phylogenetic range-rarity*’ (PRR) and ‘*georeferenced phylogenetic endemism*’ (GPE), respectively.

Keywords

area of occupancy; extent of occurrence; range rarity; rarity-weighted richness; species richness; weighted endemism

Introduction

Range rarity is a major consideration for conservation planning because it informs spatial management priorities and can be estimated from readily available incidence data (Crisp et al. 2001; Peters et al. 2015). Restriction in area of occupancy (AOO), extent of occurrence (EOO) or landscape-scale frequency is a basic species conservation metric because species with more restricted ranges are considered at greater risk of extinction and contribute to biological uniqueness (Csuti et al. 1997; Crisp et al. 2001; Peters et al. 2015). Meanwhile, species richness is established as a general metric for biogeography and conservation planning (Steck et al. 2006).

The desire to conserve species diversity leads to two important problems: 1) how to score diversity weighted by relative species range restriction as a measure of spatial importance to conservation (the *hotspots* problem); 2) how to select reserves containing the maximum number of species across a landscape from metrics that account for range restriction (the *representation* problem). The problems of identifying rarity hotspots and representing species diversity are only occasionally dealt with together (Steck et al. 2006). Despite related aims and methods, relatively separate literature streams have developed around these two approaches, leading to a soup of metrics that essentially boil down to 'the sum of inverse range-sizes' or 'SIR' (Table 1).

Below, we review the development of SIR metrics and propose a more coherent terminology.

Development of SIR

Dony and Denholm (1985) set out to use "the number of [plant] species and their local rarity" as a quantitative measure of the conservation importance of forest patches. Among the metrics applied was the *'plant rarity factor'*, calculated by assigning categorical scores, ranging from 1 to 7, to species based on their recorded frequency in 4 km^2 sampling units. For example, species recorded in one unit were assigned the maximum score, and species recorded in 64-127 units the minimum. Species recorded in an (arbitrary) 128 or more units were excluded. Species scores were summed for each site, so that sites with more rare species present, or with more restricted species had higher scores.

SIR metrics evolved to a more numerically continuous form with Kershaw et al. (1994), who sought the best method for choosing reserves to represent species of Afrotropical antelopes. They defined '*restricted-range diversity'* for sites, using "species rarity measures … calculated as the inverse of the number of sites in which a species is recorded." The scores for each species were summed for a site and given as a percent of the total score for all species in the dataset:

$$Restricted - range\ diversity\ = \sum_1^n \frac{100}{X} \Big/ \sum_1^{n_1} \frac{1}{X} \qquad (1)$$

where X is the number of sites occupied by individual species, *n* is the number of species at a site and n_1 the total number of species in the dataset.

Following '*restricted-range diversity*', Williams et al. (1996) introduced a simpler metric for the representation problem that used range size as a continuous rarity measure. They defined what has become known (in the representation stream of literature) as '*rarity-weighted richness'* (RWR; originally referred to as '*rarity score*'):

$$RWR = \sum_1^n \frac{1}{c_i} \qquad (2)$$

where *c* is typically the number of map grid cells occupied by species *i* and *n* is the number of species. Similarly, Csuti et al. (1997) also weighted species richness by inverse range-size rarity ('*inverse rarity weight'* and '*square inverse rarity weight*') to find minimum areas needed to conserve species diversity, referring to Kershaw et al. (1994).

As part of a continental assessment of endemism in the Australia flora, Crisp et al. (2001) built on earlier SIR metrics such as Dony and Denholm (1985) to define '*weighted endemism'* (WE), which is identical to equation (2) but interpreted as revealing centres of endemism. Seeing the mathematical relationship with species richness (Kier and Barthlott 2001) as a confounding factor, Crisp et al. (2001) also proposed dividing WE by species richness to give the per-species average '*corrected weighted endemism'* (CWE). Kier and Barthlott (2001) introduced the term '*endemism richness'* to describe the same SIR calculation but interpreted the inverse range weights for species as quantifying the proportion of their total habitat that was included in the sampling unit.

Areas of endemism, also defined via occurrences of categorically defined endemics or optimization methods including branch-and-bound and parsimony (Linder 2001; Szumik et al. 2002), are expected to contain multiple species within a confined region. Clearly, equation (2) implemented via grid cell occupancy measures frequency and/or AOO (Peters et al. 2015), and does not account for the geographical relationship of the cells, or EOO. Guerin et al. (2015) reworked '*weighted endemism'* (i.e. equation (2)) using georeferenced measures of range restriction as species weights. That is, the span across a species range (i.e. in distance units) or the area of a convex polygon surrounding the range (in distance squared units) was calculated to give a metric more explicitly related to restriction in EOO rather than AOO.

SIR metrics have also been extended beyond weighting species richness. Rosauer et al. (2009) proposed a related extension to phylogenetic diversity (PD; the sum of branch lengths of a phylogenetic tree containing species in a community sample; Faith 1992). In Rosauer et al.'s (2009) '*phylogenetic endemism'* (PE), summed branch lengths are weighted by the inverse of their spatial range (via occurrences of terminal taxa). PE has since been implemented using the georeferenced range extents of branch lengths, rather than grid cell occupancy (Guerin 2015).

The interpretation of SIR metrics and their resulting heat maps is also an area of development, for example as to their scale dependency, relationship to beta diversity and nonparametric methods for disentangling them from species richness (Laffan and Crisp 2003; Mishler et al. 2014; Guerin et al. 2015).

Proposed terminology

Terminology for SIR metrics needs unification. The most frequent implementations use grid cell occupancy to measure range restriction, or occasionally AOO (in non-cell units) or number of habitat sites, which are conceptually equivalent, differing only in units or sampling scale. The existing term '*rarity-weighted richness*' (RWR) could be confused with richness of rare species defined by criteria such as endangered status, while the term '*weighted endemism'* (WE) is a younger synonym and something of a misnomer as it does not account for the spatial relationship of occupied sites. We propose this metric be referred to as *'range-rarity richness*' (RRR) and the PD equivalent '*phylogenetic range-rarity'* (PRR).

The equivalent SIR calculation based on EOO, on the other hand, has been shown to correlate poorly with RRR (Guerin et al. 2015) and could be referred to as '*georeferenced weighted endemism*' (GWE), and the phylogenetic equivalent as '*georeferenced phylogenetic endemism*' (GPE), to distinguish them from implementations identical to RRR (Fig. 1).

While there is a risk that new unifying terms will also be redundant, it provides a much-needed unification and more precisely defines terms for metrics that better describe their intention.

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Table 1 Example implementations of 'sum of inverse range-size' metrics

Author	Metric name	Acronym	Metric type	Application	Proposed equivalent term	Proposed acronym
Dony and Denholm (1985)	Plant rarity factor	PRF	Categorical, habitat occupancy	Relative conservation importance	-	-
Kershaw et al. (1994)	Restricted-range diversity	-	Continuous (proportion), site occupancy	Reserve selection	-	-
Williams et al. (1996)	Rarity-weighted richness (or rarity score)	RWR	Continuous, grid cell occupancy	Species representation	*Range-rarity richness*	RRR
Csuti et al. (1997)	Inverse rarity weight	-	Continuous, grid cell occupancy	Species representation	*Range-rarity richness*	RRR
Csuti et al. (1997)	Square inverse rarity weight	-	Continuous, grid cell occupancy	Species representation	-	-
Kier and Barthlott (2001)	Endemism richness	-	Continuous, grid cell occupancy	Contribution to 'global' biodiversity	*Range-rarity richness*	RRR
Crisp et al. (2001)	Weighted endemism	WE	Continuous, grid cell occupancy	Centres of endemism	*Range-rarity richness*	RRR
Crisp et al. (2001)	Corrected weighted endemism	CWE	Continuous, grid cell occupancy, species average	Centres of endemism	*Corrected range-rarity richness*	CRRR
Rosauer et al. (2009)	Phylogenetic endemism	PE	Continuous, grid cell occupancy	Spatial biodiversity patterns	*Phylogenetic range-rarity*	PRR
Guerin et al. (2015)	Weighted endemism, georeferenced implementation	-	Continuous, extent of occurrence (EOO)	Spatial biodiversity patterns	*Georeferenced weighted endemism*	GWE
Peters et al. (2015)	Summed range rarity scores	-	Continuous, area of occupancy (AOO), identify top 10%	Identify threatened areas supporting range-rare species	*Rang-rarity richness*	RRR
Guerin (2015)	Phylogenetic endemism, georeferenced implementation	-	Continuous, EOO	Spatial biodiversity patterns	*Georeferenced phylogenetic endemism*	GPE

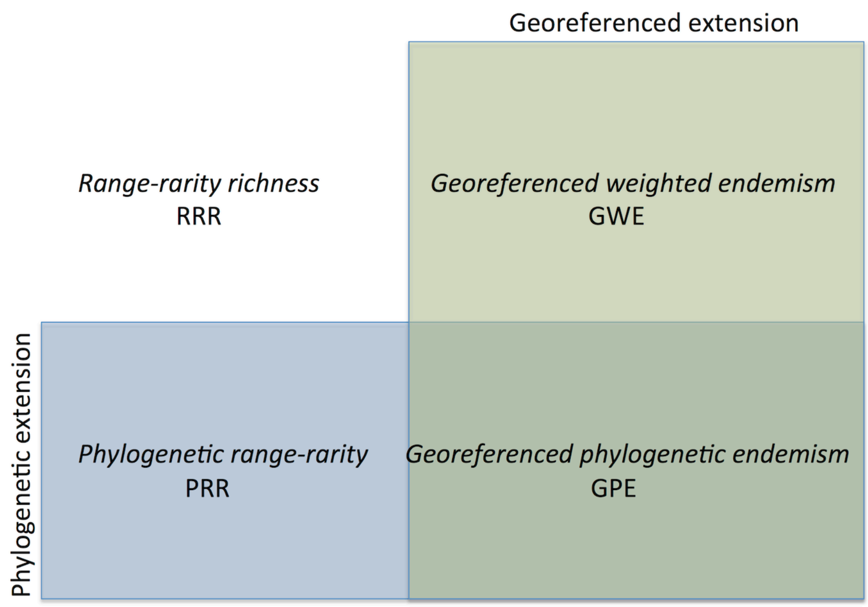

Fig. 1 Categorisation and extensions of sum of inverse range-sizes (SIR) metrics