

What do site condition multi-metrics tell us about species biodiversity?☆



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ABSTRACT

Site-based habitat condition multi-metrics offer a simple surrogate for biodiversity assessment, but their merit has seldom been tested. Three such multi-metrics – *Habitat Hectares*, *BioCondition*, and *BioMetric* – are prominent in Australia. They all measure similar attributes, convert primary data into attribute condition scores (metrics), then weight and aggregate attribute condition scores into a single site condition score (multi-metric). We compared these multi-metrics and tested whether site condition scores were correlated with the species richness of a range of plant, vertebrate and invertebrate taxa recorded from Poplar Box (*Eucalyptus populnea*) woodland remnants in eastern Australia in a range of condition states. Site condition scores ($n=43$) ranged from 17 to 88/100, and the summed richness of all taxa recorded from sites ranged from 93 to 192 species. The multi-metrics ranked sites similarly ($r_s \geq 0.79$), but *BioMetric* scored sites significantly lower. Site condition scores were significantly correlated with the total species richness at sites (*Habitat Hectares* $r = 0.51$, *BioCondition* $r = 0.49$, *BioMetric* $r = 0.43$), however, 75% or more of the variation was left unexplained. Linear modelling of attribute condition scores (metrics) showed that nearly 50% of the variation in total richness could be explained by a parsimonious model containing only nine condition attributes drawn from the three multi-metrics. This finding revealed that the independent explanatory power available within attribute condition scores (metrics) was not fully utilised by the site condition scores (multi-metrics). To refocus attention on the importance of careful selection, weighting and aggregation of condition attribute scores, and to improve communication and interpretation of the derived site condition multi-metrics, we introduce the *weighted wedge diagram*, a schematic that conveys visually and quantitatively: (i) the condition status of all attributes; (ii) the relative weightings applied to all attributes; and (iii) whether sites are degraded in terms of composition, structure and/or functional components.

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1. Introduction

Site condition multi-metrics are used in natural resource management as surrogates for more expensive and time-consuming surveys of species presence and abundance (Andreasen et al., 2001; Niemi and McDonald, 2004). Well known approaches are the Habitat Suitability Indices (HSI) and the Habitat Evaluation

Procedures (HEP), which have been in use in the U.S. for over 30 years (Brooks, 1997; Hirzel and Le Lay, 2008; U.S. Fish and Wildlife Service, 1980). HEP scores the condition of a range of habitat variables with known or predicted importance to a species, combines scores into a composite HSI, and multiplies the HSI by the area of habitat under consideration to generate habitat units (HUs) for individual species. Individual HUs may be summed across multiple species to represent the amount of habitat lost, impacted, or created, depending on the natural resource management application (Brooks, 1997). “HEP is a method which can be used to document the quality and quantity of available habitat for selected wildlife species” (U.S. Fish and Wildlife Service, 1980). In Australia, the HEP-HSI approach finds analogues in *Habitat Hectares* in Victoria (DSE, 2004; Parkes et al., 2003), *BioCondition* in Queensland (Eyre et al., 2011), and *BioMetric* in New South Wales (DECCW, 2011a,b; Gibbons et al., 2009a,b). However, whereas HEP and HSI

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have mostly been used for well known vertebrate species, the Australian multi-metrics aim to deliver an “integrated view of the habitat for all the indigenous species that may reasonably be expected to use a site” (Parkes et al., 2003). Australian site condition multi-metrics therefore operate within a much broader context of terrestrial biodiversity assessment and conservation (see Gibbons and Freudenberger, 2006; Keith and Gorrod, 2006; Oliver et al., 2002).

The Australian multi-metrics are used for: assessing the loss of biodiversity from clearing native vegetation; determining offsets for these losses; and to prioritise funding for improved management, conservation, and restoration of terrestrial native vegetation (Gibbons et al., 2009a,b; Parkes and Lyon, 2006). They all: measure a similar set of site and landscape-scale attributes (see Appendix S1); convert site data into attribute condition scores (metrics) using benchmark data or expert rules (see Appendix S2); weight attribute condition scores, based largely on the difficulty of attribute replacement (see Appendix S1); and combine weighted attribute condition scores into the site condition multi-metric score, by simple summation (*Habitat Hectares* and *BioCondition*), or summation and multiplication (*BioMetric*). Assessment of the site condition components represents 75% and 80% of the *Habitat Hectares* and *BioCondition* multi-metrics respectively, with the remainder based on landscape-scale attributes (*BioMetric* assesses landscape-scale, and regional-scale attributes separately, see Appendix S1). The multi-metrics are designed to be a transparent, repeatable and defensible assessment of terrestrial habitat condition for biodiversity. They remove the subjectivity associated with previous habitat condition assessment approaches, but continue to strive for an optimal balance between; operational need (rapid, cost-effective, and practical field based approaches suitable for implementation by non-specialists (see Gorrod and Keith, 2009; Gorrod et al., 2013; Kelly et al., 2011)), and rigorous biodiversity science (the on-going search for defensible biodiversity surrogates (see Mandelik et al., 2010; Sakar and Margules, 2002)).

Literature associated with each of the Australian multi-metrics suggests a positive relationship between site condition scores and the status of species-level biodiversity, assessed via species inventory (see Appendix S2), however, few authors have tested the predictive power of this relationship (see Giblett, 2011; Gorrod, 2012; Peacock, 2008; Weinberg et al., 2008), and none has done so using plant, vertebrate and invertebrate data combined. Even accepting that Connell's (1978) intermediate disturbance hypothesis (which predicts that sites with moderate disturbance will have more species than undisturbed sites) may sometimes be true (but see Fox, 2013), we would expect low species richness at low scoring sites, and moderate to high species richness at high scoring sites (when sites sample the same vegetation community).

Our aim was to evaluate the above hypothesis for the three multi-metrics, *Habitat Hectares*, *BioCondition* and *BioMetric*, by testing how well the site condition scores (excluding landscape attributes, see Appendix S1) explained the species richness of terrestrial plants, vertebrates and invertebrates collected from eucalypt woodland remnants in eastern Australia. We also tested the same hypothesis using linear modelling of the unweighted attribute condition scores (metrics). Our interest in these relationships was restricted to a “within-vegetation-community” comparison of sites, and we do not suggest that species richness per se (e.g. between vegetation communities) is a valid measure of biodiversity status or value (see Humphries et al., 1995; Oliver and Beattie, 1997; Sakar and Margules, 2002). We also acknowledge that even within the same vegetation community, sites in different condition states, may provide habitats and resources for different suites of indigenous species, and assessments of species richness take no account of this complementarity of sites (see Faith et al., 2003; Sakar and Margules, 2002). The inability of

contemporary site condition multi-metrics to account for within-vegetation-community complementarity has already been noted (McCarthy et al., 2004; Parkes et al., 2004).

2. Methods

Our study was located on the northern floodplains of New South Wales Australia, within an area of 50 km × 50 km described by the 1:50,000 Burren Junction (8637-N) and Pilliga (8637-S) topographic maps (148°30'–149°00'E and 30°00'–30°30'S). Existing vegetation mapping (Peasley, 1999) was used to select candidate study sites within mapped Poplar Box (*Eucalyptus populnea* subsp. *bimbil*, L.A.S. Johnson and K.D. Hill) woodland remnants (mapped woody vegetation crown cover ≥5%). The Poplar Box woodland community was selected for study because it once had a broad distribution in eastern Australia, but has been extensively cleared and continues to be vulnerable to further clearing and over-grazing (Benson, 2006). Candidate sites were assessed by field inspection and 43 were selected to provide a range of condition states resulting from a range of past land use and land management intensities (that is, a range among sites in; woody and non-woody native vegetation cover, overstorey age structure, amount of fallen timber, woody recruitment, weed cover, cover of litter, and stock disturbance of bare ground). Sites were located on both private properties ($n=34$) and travelling stock routes ($n=9$). Poplar Box woodland was not present in the nearby State Forests, and there were no conservation reserves in the study area.

Sites were located centrally within small remnants (<10 ha) or at least 100 m from the remnant edge. At each site, a 50 m fixed transect was located in an area representative of the remnant. Transects were orientated along the length of maximum slope (generally <1%) and were the fixed location about which habitat assessments were undertaken (see Appendix S2) and species biodiversity data were collected for: ants, beetles, spiders, wasps, flies, butterflies, frogs (as an unintended by-catch), reptiles, birds, vascular and non-vascular plants (bryophytes and lichens) (see Appendix S2). Habitat assessment data, or data derived from the vascular plant surveys, were used to calculate attribute condition scores for each of the three multi-metrics (see Appendix S2).

Before exploring the predictive power of the relationships between multi-metrics and species richness, we tested whether the three multi-metrics scored sites similarly. We used one-way ANOVA on homoscedastic data (Levene's test, Statsoft, 2010) to test the significance of differences between site condition score means. Spearman rank order correlation was then used to test whether the three multi-metrics' site condition scores ranked sites similarly. Finally, Pearson's correlation was used to detect significant negative correlations between the species richness of different taxonomic groups prior to summing the richness of all taxa to derive measures of (sampled) total site richness.

To explore the predictive power of the relationships between multi-metrics and species richness, Pearson's correlations were calculated between site condition scores (multi-metric), and the richness of all taxa combined (“total richness” hereafter), and the richness of different taxonomic groups (“taxon richness” hereafter). To further elucidate any relationships with species richness, Pearson's correlations were also calculated between attribute condition scores (metric) and total richness, and taxon richness. Where Pearson's correlations were calculated, scatter-plots were checked for evidence of non-linear relationships.

Distance-based linear modelling (DISTLM) was used to find the most parsimonious set of condition attributes for explaining total richness (PERMANOVA statistical package, Anderson et al., 2008). DISTLM is robust to non-normal data, and errors do not need to be normally distributed as p -values are obtained through permutation

Table 1

Total numbers of species (species richness) and number of specimens recorded (abundance) from the 43 *Eucalyptus populnea* woodland sites.

Taxon	Species richness	Abundance
Ants	119	57,880
Beetles	173	1180
Spiders	165	3716 ^a
Wasps	195	2496
Flies	39	253
Butterflies	26	290
Frogs	12	550
Reptiles	16	299
Birds	102	7404
Vascular plants ^b	174	na
Non-vascular plants ^c	47	na
Total	1068	74,068

^a Included 2011 juvenile specimens that could not be identified to species.

^b Does not include 32 introduced species also recorded from plots.

^c Bryophytes and lichens.

na not applicable.

(Legendre and Anderson, 1999; McArdle and Anderson, 2001). We used a Euclidean distance matrix and based our model building on the BEST procedure, and the *adjusted R*² selection criterion, with 9999 permutations. The BEST procedure examines the value of the selection criterion for all possible combinations of predictor variables, and the *adjusted R*² takes into account the number of predictor variables within the model. DISTLM determined the most parsimonious suite of condition attributes drawn from: (1) a single multi-metric, (2) from among the three multi-metrics, and (3) from among the three multi-metrics, but without the BioMetric attribute *vascular plant richness*. This last analysis recognised the non-independence between predictor and response variables. To avoid collinearity between predictors, variables with $r > 0.76$ ($n = 10$; see Appendix S3) were omitted prior to the latter analyses (2 and 3).

3. Results

Our species biodiversity data represented 1068 (morpho)species, comprised of 221 native vascular and non-vascular (bryophytes and lichens) plant species, 717 invertebrate morphospecies (Oliver and Beattie, 1997), and 130 native vertebrate species (Table 1). Richness varied widely among taxa, with ants, birds, and vascular plants recording the highest average site richness, and flies, butterflies, frogs, and reptiles the lowest (Fig. 1). Total site richness ranged from 93 to 192 species, with a median of 153 species. A number of significant positive correlations, but only one weak negative correlation, were recorded among taxa (Table 2), supporting the use of summed total richness in subsequent analyses.

3.1. Do site condition scores from different multi-metrics rank and score sites similarly?

The three multi-metrics ranked sites similarly, with all spearman rank order correlation coefficients significant with $r_s \geq 0.79$ (Fig. 2a–c). There were, however, significant differences among the three multi-metrics in the scores that sites received, with BioMetric scores significantly lower than the other two multi-metrics ($F_{2,126} = 45.7$, $p < 0.001$; Fig. 1d). Scores ranged from 17/100 (BioMetric) to 88/100 (Habitat Hectares; Fig. 1d).

3.2. Are site condition scores positively correlated with total richness and/or taxon richness?

Site condition scores were significantly, but weakly, positively correlated with total richness, with Habitat Hectares explaining

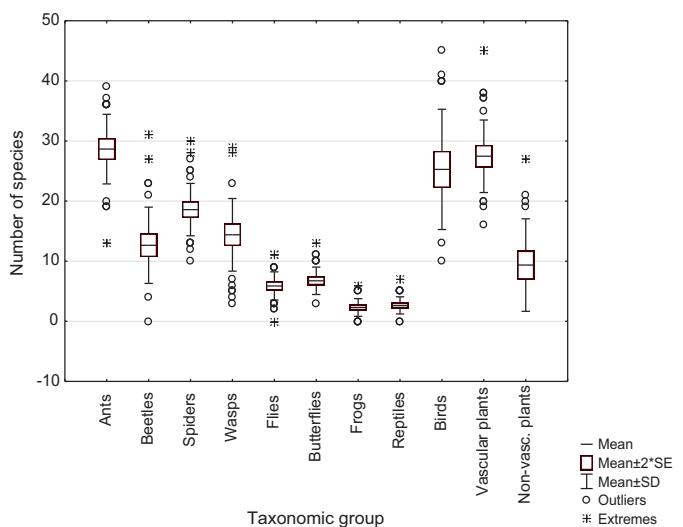


Fig. 1. Box-plots showing the distributions of species richness data for the 11 major taxonomic groups sampled from the 43 *Eucalyptus populnea* woodland sites.

26%, BioCondition 24%, and BioMetric 18% of the variation (Fig. 3). However, much of the explanatory power resulted from significant positive correlations between site scores and vascular plant species richness (Table 3), which was itself a condition attribute in all multi-metrics, in one form or another (see Appendix S1). Other significant positive correlations between site scores and taxon richness were limited to: birds and all three multi-metrics; wasps and *Habitat Hectares* and *BioCondition*; and non-vascular plants (bryophytes and lichens) and *Habitat Hectares* (Table 3).

3.3. Are attribute condition scores positively correlated with total richness and/or taxon richness?

Recruitment was the only attribute with condition scores significantly positively correlated with the total richness for all multi-metrics (Table 4). Of the remaining attributes assessed by all multi-metrics: *number/length of logs* was significantly correlated with total richness, but only for *Habitat Hectares* and *BioCondition*; and *cover – native canopy* was significant, but only for *BioMetric*. *Organic litter* returned relatively strong positive correlations where it was assessed, as did the similar attributes *cover – native mid-storey* (*BioMetric*) and *cover – native shrubs* (*BioCondition*). Importantly, some of these attribute condition scores (metrics) yielded similar values of r to the more complex site condition scores (multi-metrics), that were constructed by weighting and summing (and for *BioMetric* multiplying) many attribute condition scores. *Weed cover* and the *number of trees with hollows* were not significantly correlated with total richness for any multi-metric. Numerous significant positive correlations were revealed between attribute condition scores and the richness of taxa (Table 5; Appendix S4).

3.4. Can total richness be better explained by modelling attribute condition scores?

Our distance-based modelling used fewer attributes than the multi-metrics, and explained more variation in total richness. Using *Habitat Hectares* attributes, the most parsimonious model (highest *adjusted R*²) included *understorey life-form richness* and *cover*, *cover – canopy*, *recruitment*, *litter cover*, and *length of logs* and explained 38% of the variance in total richness (R^2). Using *BioCondition* attributes, the most parsimonious model included *cover – shrubs*, *exotic cover*, *recruitment*, and *litter cover* and explained 32%

Table 2

Significant Pearson's correlations between the richness of each taxon^a recorded from the 43 *Eucalyptus populnea* woodland sites.

Taxon	Significantly correlated with		
Ants	Wasps (0.46**)	Flies (0.55***)	Butterflies (0.42**)
Spiders	Flies (0.38*)	Birds (-0.32*)	
Wasps	Ants (0.46**)	Flies (0.41**)	
Flies	Ants (0.55***)	Spiders (0.38*)	
Butterflies	Ants (0.42**)		Wasps (0.41**)
Frogs	Non-vascular plants (0.32*)		
Reptiles	Flies (0.42**)		
Birds	Spiders (-0.32*)		
Vascular plants	Birds (0.50***)	Non-vascular plants (0.45**)	
Non-vascular plants	Frogs (0.32*)	Birds (0.38**)	Vascular plants (0.45**)

^a All taxa recorded at least one significant correlation with the exception of beetles.
 $r_{0.05(2) \times 41} = 0.30$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

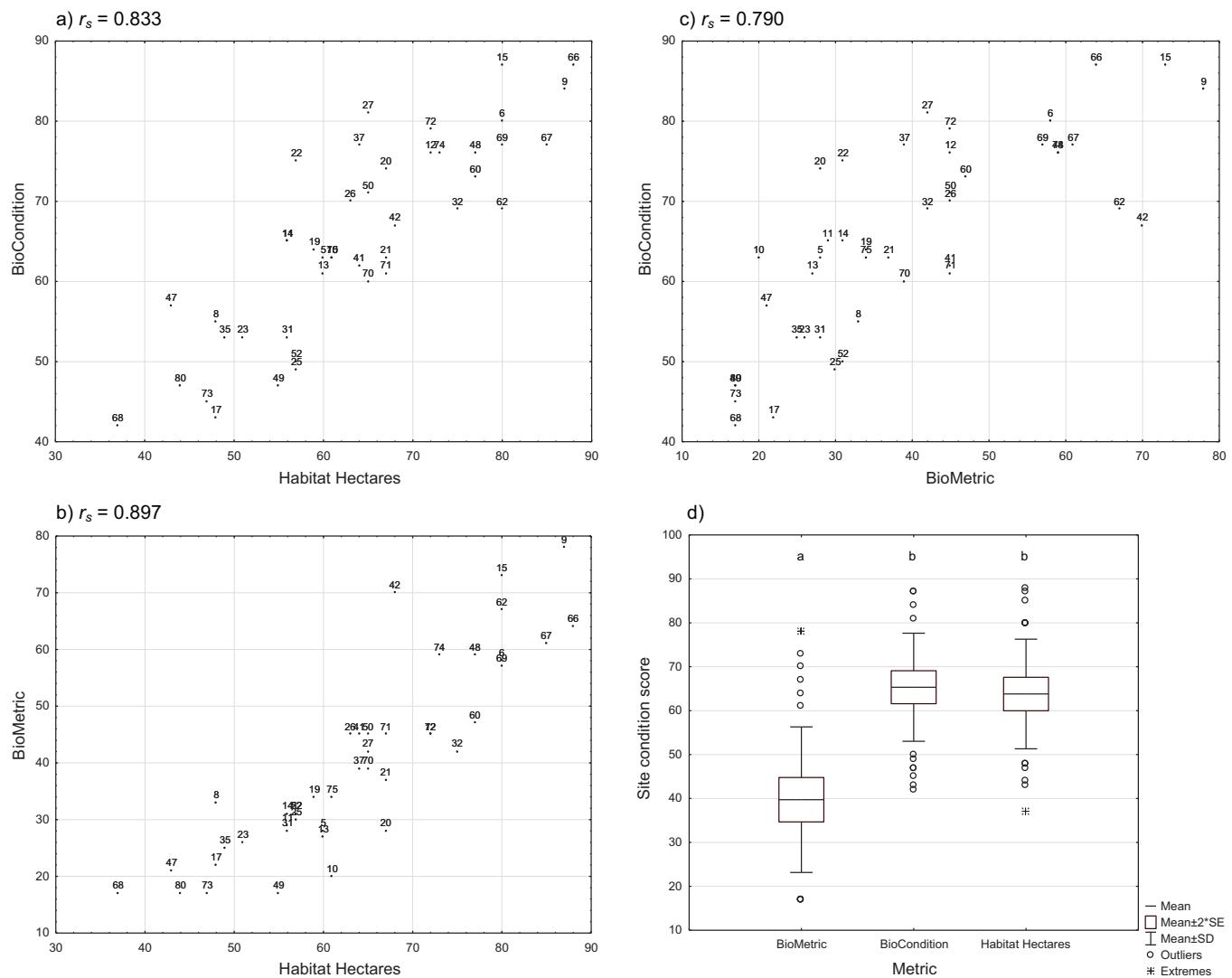


Fig. 2. Scatter-plots and Spearman rank correlation coefficients (a–c) and box-plots (d) showing the relationships between site condition scores generated by the three multi-metrics (site numbers label the points (a–c)), and letters indicate significantly different means (d)).

of the variance (R^2). Using *BioMetric* attributes, *vascular plant richness*, *cover – overstorey*, *exotic cover* and *recruitment*, were included and explained 40% of the variance in total richness (R^2).

When all attributes from the three multi-metrics were simultaneously submitted to distance based modelling, the most parsimonious model included eight attributes drawn from two different multi-metrics (*recruitment*, *vascular plant richness*, *understorey*

life-form richness and cover, *canopy cover*, *cover – groundcover grass*, *litter cover*, and the *exotic cover* attributes from both *Habitat Hectares* and *BioMetric*) and explained more than 50% of the variance in total richness (R^2 Appendix S5). Importantly, there was little loss in explanatory power when the non-independent *BioMetric* attribute *vascular plant richness* was excluded from the model ($R^2 = 48\%$ Appendix S6). In this case, the most parsimonious

model included the attributes shown above, but added the *BioMetric* attribute *cover – groundcover other*, and the *BioCondition* attribute *richness – trees*.

4. Discussion

4.1. The value of multi-metrics as surrogates for species biodiversity survey

The aim of our study was to explore the relationships between site condition multi-metrics and species richness, and thereby test their efficacy as surrogates for more expensive and time-consuming surveys of species presence (Mandelik et al., 2010). We compared the site condition scores of three contemporary terrestrial biodiversity multi-metrics and tested whether they were correlated with the total number of plant, vertebrate and invertebrate species recorded from woodland remnants in a range of condition states. Although scores varied significantly among the multi-metrics, they ranked the sites similarly, and were significantly, though weakly, positively correlated with total species richness. However among the 11 major taxa studied, only vascular plant and bird species richness were significantly positively correlated with site condition scores generated by all multi-metrics. Results for vascular plant richness were of limited value because it was itself a component of all multi-metrics. It is therefore questionable whether this attribute should be included in site condition assessments that are used as surrogates for species biodiversity surveys (but see Mandelik et al., 2010; Oliver et al., 2007), especially when substantial expertise and time is required to assess the attribute (Cook et al., 2010; Gorrod, 2012). Our linear modelling also revealed that when this attribute was excluded, two other more tractable attributes took its place, and similar variation in total species richness was explained.

In agreement with similar studies by Weinberg et al. (2008) and Peacock (2008), we found significant, though weak, positive relationships between the total number of vertebrate species recorded at sites, and the site condition scores. However in all studies, bird species dominated the vertebrate biodiversity data (Table 1 and Fig. 1), and our study revealed that significant relationships for vertebrates were limited to bird richness and condition scores. Giblett (2011) also reported a significant relationship between bird richness and *BioMetric* condition scores. Biodiversity multi-metrics may therefore provide some value over more expensive and time consuming surveys of woodland birds (Mandelik

Table 3

Pearson's correlations between site condition scores and the richness of all taxa combined, the richness of invertebrates, vertebrates and plants, and the richness of individual taxa.

	Habitat Hectares	BioCondition	BioMetric
All taxa	0.507***	0.491***	0.426**
All invertebrates	0.123	0.181	0.059
Ants	0.244	0.220	0.222
Beetles	-0.227	-0.128	-0.222
Spiders	-0.057	-0.024	-0.136
Wasps	0.300*	0.300*	0.235
Flies	0.105	0.138	0.023
Butterflies	0.092	0.189	0.081
All vertebrates	0.327*	0.289*	0.379**
Frogs	0.023	-0.023	0.050
Reptiles	0.084	0.030	0.068
Birds	0.319*	0.295*	0.370**
All plants	0.506***	0.430**	0.398**
Vascular plants	0.595***	0.553***	0.457**
Non-vascular plants	0.295*	0.191	0.221

$r_{0.05(1):41} = 0.254$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

et al., 2010). However, we also showed that some individual condition attribute scores (metrics) explained similar amounts of variation in bird richness, to the site condition scores (multi-metric) (Table 5 and Appendix S4). The value of multi-metrics derived through weighting and adding (and for *BioMetric* multiplying) many condition attribute scores, over targeted selection of the most informative attributes, is therefore worthy of further investigation.

Few studies have explored the efficacy of site condition multi-metrics as surrogates for terrestrial invertebrate species survey, and to our knowledge, no other study has explored multiple invertebrate groups combined. We found no significant correlations between total invertebrate richness and site scores for any multi-metric (Table 3). With the exception of wasp richness, we found no significant relationships between site condition scores and the richness any other invertebrate group (also see Giblett, 2011; Gorrod, 2012), but as for the vertebrates, we found numerous significant correlations between taxon richness and individual attribute condition scores (Table 5 and Appendix S4). Overall, our results provide evidence that biodiversity multi-metrics have value as surrogates for few components of species biodiversity. However, we have also shown that the richness of individual taxa, and all taxa combined,

Table 4

Pearson's correlations between attribute condition scores and total taxon richness.

Condition Attribute	Habitat Hectares	BioCondition	BioMetric
Recruitment of woody, or canopy species	0.279*	0.279 *	0.282 *
Number of trees with hollows	0.157	0.076	0.076
Length/number of logs	0.334*	0.295*	0.183
Weed cover	0.005	0.102	-0.037
Organic litter cover	0.375**	0.375**	na
Cover – native canopy	0.217	0.238	0.355**
Cover – native mid-storey	na	na	0.400**
Cover – native shrubs	na	0.429**	na
Cover – native perennial grass	na	0.054	na
Cover – native groundcover grasses	na	na	0.057
Cover – native groundcover other	na	na	-0.311
Richness – trees	na	0.366**	na
Richness – shrubs	na	0.046	na
Richness – forbs	na	0.325*	na
Richness and cover of understorey life-forms	0.467***	na	na
Richness – all vascular plants	na	na	0.485***

$r_{0.05(1):41} = 0.254$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

na attribute not assessed by the particular multi-metric. Several multi-metric attributes are missing from the table: *canopy height (BioCondition)* which was not assessed in our study; *richness of grass (BioCondition)* which showed no variation in attribute condition scores; *cover-groundcover shrubs (BioMetric)* which was not scored in the multi-metric for the benchmark vegetation type used (see Appendix S2).

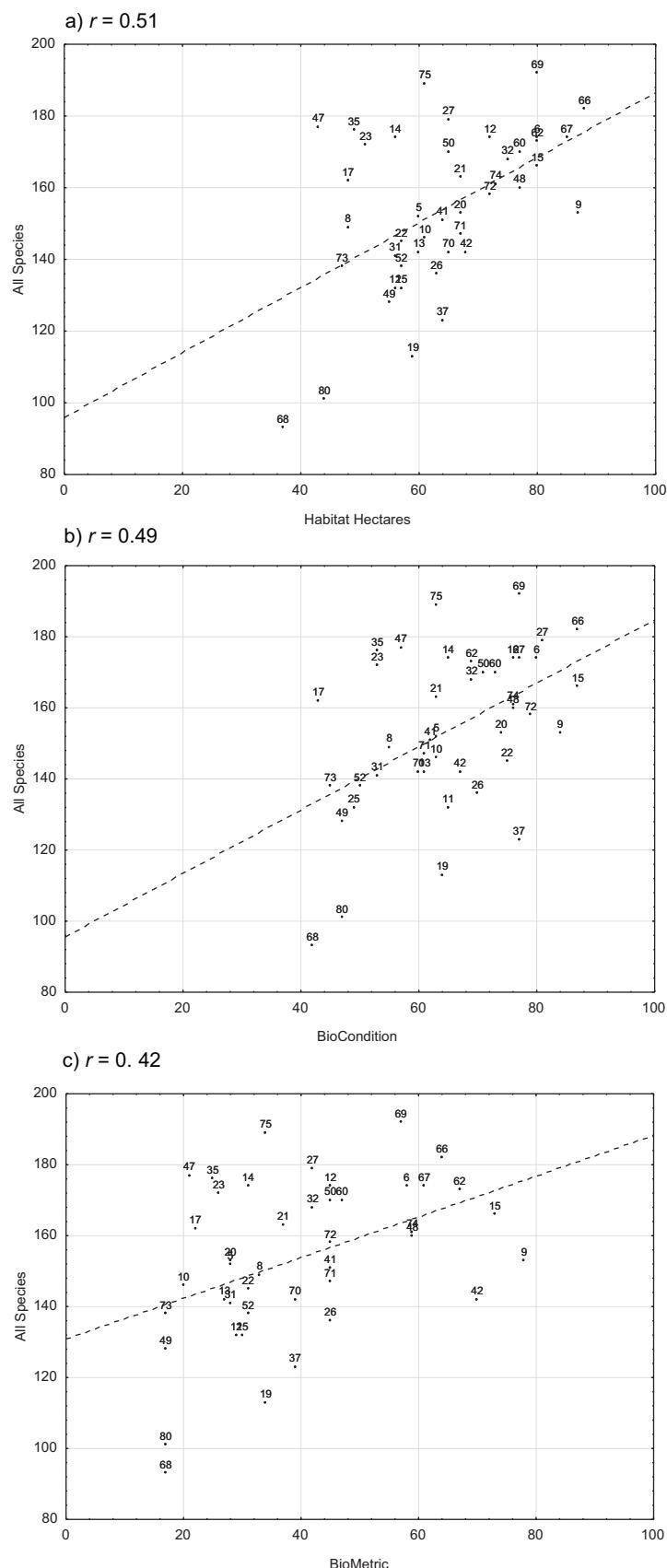


Fig. 3. Relationship between the species richness of all taxa combined and; (a) Habitat Hectares ($R^2 = 0.26$), (b) BioCondition ($R^2 = 0.24$), and (c) BioMetric ($R^2 = 0.18$) site condition scores (site numbers label the points).

Table 5 Summary of significant positive Pearson's correlations between attribute condition scores and taxon richness (cells contain the number of multi-metrics that reported a significant relationship; see Appendix S4 for full details).

	Length/number of logs	Organic litter cover	Canopy cover	Shrub cover	Grass cover	Recruitment	Vascular plant richness	Exotic cover	Understorey life-form richness and cover	Number hollow bearing trees	Tree richness	Shrub richness	Forb richness
Ants	2	1			1	3				1	1	1	
Beetles										2			
Spiders		2	1	1					1	3			
Wasps	2	2								3			
Flies													
Butterflies	2			2					1				
Frogs													
Reptiles	1	2											
Birds	2		1		2	2							
Vascular plants	2												
Non-vasc. plants	1												

could in some cases be equally well explained by individual condition attributes.

4.2. The basis of biodiversity multi-metrics: attribute replaceability or habitat condition?

Different multi-metrics reflect different goals of biodiversity assessment, and these are realised by the choice of attributes and the weightings applied to those attributes (Andreasen et al., 2001; McCarthy et al., 2004; McElhinny et al., 2005, 2006a; Oliver et al., 2007; Weinberg et al., 2008). The multi-metrics explored here used similar attributes, but applied different weightings (Appendix S1). *BioMetric* weighted attributes according to the “relative ease with which the variable can be restored or regenerated with management” (Gibbons et al., 2009a). Therefore ‘slow’ attributes, such as the *number of trees with hollows*, were rated highly because once lost they are replaced relatively slowly (Gibbons et al., 2000). *BioCondition* and *Habitat Hectares* used the same criterion, but also considered “the potential of each attribute to affect long-term condition, and each attribute’s habitat value based on empirical research” (Eyre et al., 2011). It is therefore not surprising that the multi-metrics varied in their attribute weightings, and consequently, in how well they predicted taxon richness. For example, while *BioMetric* was a better predictor of bird richness, it was less able to explain the richness of wasps, vascular and non-vascular plants (bryophytes and lichens), and all species combined, than the other two multi-metrics.

By using different weightings, the multi-metrics have variously attempted to strike a balance between delivering: (1) site condition scores that take account of attribute replaceability; and (2) site condition scores that take an “integrated view of the habitat for all the indigenous species that may reasonably be expected to use a site” (Parkes et al., 2003). We suggest however, that by attempting to balance weightings to achieve both goals, neither is best served. This was supported by our linear modelling of unweighted attribute scores which explained twice as much variation in the number of species compared with each multi-metric’s site condition score. Recognition of these potentially competing goals supports the need for careful consideration of how attributes are weighted and aggregated to best deliver to a clearly specified goal (see Failing and Gregory, 2003; Gorrod, 2012; Kurtz et al., 2001; McElhinny et al., 2005, 2006a). This is especially important when site condition scores are used as surrogates for species survey, and for guiding biodiversity management and conservation decision making, applications for which we suggest that attributes should be weighted to deliver to the goal expressed above by Parkes et al. (2003).

4.3. Multi-metrics or individual condition attributes?

The development of multi-metrics as a means of providing integrative measures of terrestrial habitat condition is becoming more widespread (Andreasen et al., 2001; Schoolmaster et al., 2013), although they have a long, albeit somewhat controversial, history in aquatic environments (see Karr and Chu, 1999). Consequently, decisions about whether to use multi-metrics, or individual attribute metrics, or primary habitat data, as surrogates for comprehensive biodiversity survey, have challenged ecologists (Andreasen et al., 2001; Karr and Chu, 1997, 1999; Schoolmaster et al., 2013). Numerous studies have demonstrated significant correlations between primary habitat data, and the number of species of birds (Bennett and Ford, 1997; Kavanagh et al., 2007; Kinross, 2004; MacNally et al., 2001; McElhinny et al., 2006b; Watson et al., 2001), reptiles (James, 2003; McElhinny et al., 2006b; Woinarski and Ash, 2002), and other taxa (McElhinny et al., 2006b). However these data do not account for differences in physiognomy, prohibiting the evaluation of habitat condition among different ecosystems

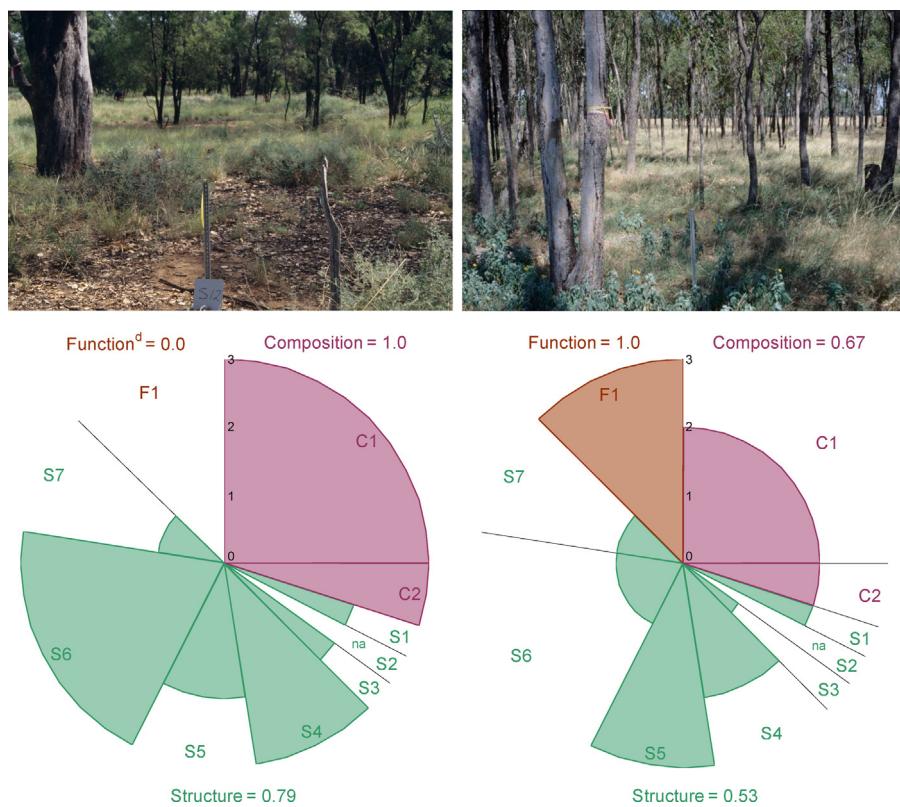


Fig. 4. Two sites (Site 12 left panel, Site 71 right panel) that received identical site condition scores, and their weighted wedge diagrams. Attributes were grouped according to Noss' three attributes of biodiversity, and wedges plotted according to BioMetric attribute condition scores. C1, vascular plant richness; C2, weed cover; S1, groundcover-grass; S2, groundcover-shrubs (na = not assessed by the vegetation condition benchmark (see Appendix S2)); S3, groundcover-other; S4, cover-midstorey; S5, cover-canopy; S6, number of tree with hollows; S7, length of logs; F1, recruitment. Alternative attributes may apply. Attributes grouped as compositional (C1–2), structural (S1–7), or functional (F1) according to Oliver et al. (2007). Alternative groupings may apply. BioMetric attribute condition scores are 0, 1, 2, and 3. Alternative axes may apply (see text). Composition, structure and function sub-index scores were calculated as weighted averages within categories (C, S, and F).

or different vegetation communities. Natural resource managers require metrics and multi-metrics that take account of physiognomy (using benchmark or reference data, see Appendix S2) in order to make decisions concerning the relative costs and benefits to habitat condition of management actions across a wide range of vegetation communities. However despite this need, single site condition scores generated by multi-metrics have two distinct shortcomings: (i) dimensional reduction results in the loss of useful information at the attribute level, and (ii) multi-metrics can result in similar scores for very different sites through attribute eclipsing (i.e. the absence of one attribute being compensated for by the presence of another; see Andreason et al., 2001; Game et al., 2013; Gibbons et al., 2009a; McCarthy et al., 2004; Appendix S2). All multi-metrics would therefore benefit from an uncomplicated integrative approach to conveying the status of each habitat attribute compared with the expected state of that attribute in long-undisturbed benchmark or reference sites.

4.4. Conveying a practical message about site condition for biodiversity

We draw on Andreason et al. (2001) and present a new site condition schema – the *weighted wedge diagram* – to overcome the short-comings associated with multi-metric scores, and to enhance the understanding and communication of site condition (Fig. 4). The *weighted wedge diagram* presents the attribute condition status for all attributes, so for natural resource managers, clearly shows attributes that are degraded and in need of management attention. For example, in Fig. 4, Site 12 scores well for the *number of trees with hollows* (Fig. 4 attribute S6), but poorly for *recruitment*

(Fig. 4 attribute F1), whereas the converse is true for Site 71. Axes can be classified (e.g. the BioMetric condition scores 0–3 used in Fig. 4), or they can be continuous. For example, axes could represent the observed attribute state (from the field site) divided by the expected attribute state (from benchmark or reference data, see Gibbons et al., 2009b) which would overcome the “mistake” of arbitrariness of classified attributes discussed by Game et al. (2013). Wedge angles are varied according to the weightings applied to each attribute, so convey additional information to land managers about the perceived relative importance of attributes. For BioMetric, the perceived importance of the attributes *vascular plant richness* (Fig. 4 attribute C1) and *number of trees with hollows* (Fig. 4 attribute S6) is visually conveyed, as is the low importance given to groundcover attributes (Fig. 4 attributes S1–3).

The *weighted wedge diagram* also groups attributes according to composition, structure, and function (*sensu* Noss, 1990) to: (i) focus attention on the often under-represented functional attributes category (see Oliver et al., 2007); (ii) convey visually the nature of site degradation i.e. structural, compositional, and/or functional; and (iii) allow for the calculation of structural, compositional, and functional sub-indices. Attribute grouping according to Noss' attributes of biodiversity also helps to reduce problems of eclipsing. This is illustrated in Fig. 4 where the site condition sub-indices differed markedly between the two sites, yet both received the same site condition score. The *weighted wedge diagram* clearly communicates: (i) the status of all condition attributes; (ii) the relative weightings applied to all attributes; and (iii) whether the site is degraded in terms of composition, structure and/or functional components. The *weighted wedge diagram* holds much promise for enhancing existing site condition assessment methods, by

providing an uncomplicated, integrative, and informative approach, that will aid communication and interpretation of the site condition scores derived from multi-metrics. It also provides multi-metric developers and researchers a simple unified approach to further explore the efficacy of individual attributes (metrics), groups of attributes (sub-indices), or complete multi-metrics, for use as surrogates for more expensive and time-consuming surveys of species presence and abundance (Mandelik et al., 2010).

Supplementary material

The following are available online: Site and landscape-scale condition attributes and attribute weights, used by *Habitat Hectares*, *BioCondition* and *BioMetric* (Appendix S1); detailed methods describing biodiversity surveys, vegetation condition benchmark selection, site condition score construction and habitat assessment (Appendix S2); attributes not submitted to distance based linear modelling due to collinearity (Appendix S3); Pearson's correlations between the richness of individual taxa, and the attribute condition scores generated by *BioMetric* (Appendix S4a), *BioCondition* (Appendix S4b), and *Habitat Hectares* (Appendix S4c); variance in the richness of all taxa combined explained by distance-based linear modelling of attribute score data for 17 site condition attributes (Appendix 5), and after excluding the *BioMetric* attribute *vascular plant richness* (Appendix 6). The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecolind.2013.11.018>.

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