ECOLOGICAL INDICATORS 8 (2008) 530–549

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ecolind

Rehabilitation index for evaluating restoration of terrestrial ecosystems using the reptile assemblage as the bio-indicator

Scott A. Thompson [a], *Graham G. Thompson* [b,*], *Philip C. Withers* [c]

[a] *Coffey Environments, Dilhorn House, 2 Bulwer Street, Perth, Western Australia 6000, Australia*
[b] *Centre for Ecosystem Management, Edith Cowan University, Joondalup Drive, Joondalup, Western Australia 6027, Australia*
[c] *Zoology, School of Animal Biology, M092, University of Western Australia, Crawley, Western Australia 6009, Australia*

ARTICLE INFO

Article history:
Received 4 September 2006
Received in revised form
23 June 2007
Accepted 1 July 2007

Keywords:
Reptiles
Restoration
Rehabilitation
Disturbance
Mining
Biotic integrity
Indices

ABSTRACT

We developed an index to quantify rehabilitation success for terrestrial environments using data on reptile assemblages from five rehabilitated mine site waste dumps and adjacent undisturbed areas. It is based on the multi-metric principles of the index of biotic integrity (IBI). This rehabilitation and degradation index (RDI) is a quantitative measure of the extent to which the reptile assemblage in a rehabilitated site resembles that in an analogue site. It utilises a combination of diversity, assemblage composition and ecological parameters. Each of these parameters is further sub-divided and an overall weighted score out of 100 can be calculated for a disturbed area. This index can also be used to quantify the impact of grazing, feral predators or noise and dust on functional terrestrial ecosystems. Data from the Western Australian goldfields are used to explain the calculations necessary to achieve an RDI score.

1. Introduction

The rehabilitation objective for most mine sites and other large-scale landscape disturbance projects is to restore biotic integrity to a disturbed area. Biotic integrity is defined here as the ability of an ecosystem to support and maintain "a balanced, integrated, adaptive community of organisms having a species composition, diversity and functional organization comparable to that of the natural habitat of the region" (Karr, 1981).

1.1. *Bio-indicators*

To fully understand an ecosystem it is necessary to understand the community and how all of its organisms interact among themselves and the abiotic parameters of the habitat. In most circumstances this information is not available and prohibitively expensive to collect. Bio-indicators are used as a proxy for measuring every aspect of the ecosystem. Intuitively it seems obvious that within a developing ecosystem, some species are sufficiently similar, that the inclusion of both adds redundancy to the bio-indicator. However, in the absence of this information it is not possible to distinguish which species are redundant. So what then are some of the useful indicators?

Within a developing ecosystem there are a number of functional levels. These may include the physical and chemical properties of the environment. The next are trophic levels, with the first being the producers (e.g. vegetation), then the consumers of the producers or their products (e.g. primary

* *Corresponding author*. Tel.: +61 8 9385 2398.
E-mail addresses: scott_thompson@coffey.com.au (S.A. Thompson), g.thompson@ecu.edu.au (G.G. Thompson), pwithers@cyllene.uwa.edu.au (P.C. Withers).
1470-160X/$ – see front matter
doi:10.1016/j.ecolind.2007.07.001

consumers). Then there are those that consume consumers, and this group includes secondary and tertiary consumers. In addition there are the detritivores and the decomposers which function to break down the remains of various organisms and recycle the nutrients. Although this structuring of the ecosystem is overly simplified and to some extent arbitrary, it makes the point that to have the full suite of secondary and tertiary consumers in a developing ecosystem, then the appropriate prey must be present, which in turn requires the appropriate vegetation be in place, which requires the appropriate physical and chemical properties be in place. To have the full suite of secondary and tertiary consumers therefore requires most, if not all of the elements of the lower trophic levels to be functional. If the full suite of secondary and tertiary consumers are present, it is probably reasonable to assume there is a functional ecosystem present.

We have presumed that the primary objective of the rehabilitation program is to create a self-sustaining, functional ecosystem, similar to that which would have existed prior to a disturbance such as mining. In this circumstance it is often appropriate to use an undisturbed habitat either adjacent to the rehabilitated area or nearby as the analogue site for comparison purposes.

Karr (1987) in discussing the conceptual framework for biological monitoring indicated two of the most common errors were the use of single species and species diversity indices by themselves. He went on to suggest that 'ecological guilds' were better bio-indicators but this approach also had weaknesses. He concluded that the best long-term approach was to develop a suite of metrics that reflect individual, population, community and ecosystem attributes in an integrative framework. Karr and his colleagues (Angermeier and Karr, 1986; Fausch et al., 1984; Karr, 1977, 1981, 1987; Karr et al., 1987) developed the index of biotic integrity (IBI) to measure the extent of freshwater stream degradation. The IBI uses 12 metrics of the fish community to assess biotic integrity of an ecosystem; six are attributes linked with species richness, three are based on trophic composition and three are based on attributes of abundance and individual condition (Karr et al., 1986).

Since changes in habitat (e.g. degradation or rehabilitation) are likely to impact on species, taxonomic groups and guilds differently then a diverse range of species that occupy various niches makes for a better bio-indicator of habitat change (Hilty and Merenlender, 2000). It is for this reason that single or keystone species are seldom an adequate indicator.

Karr et al.'s IBI and variations on the theme have subsequently been used in a variety of aquatic habitats (Breine et al., 2004; Butcher et al., 2003; Simon et al., 2000) and in a modified form in terrestrial environments where taxa other than fish have been used, including invertebrates (Bisevac and Majer, 1999; Nakamura et al., 2003) and birds (Bradford et al., 1998; O'Connell et al., 1998, 2000; Glennon and Porter, 2005). Karr et al. (1986) explains that the 'strength of the IBI is its ability to integrate information from individual, population, community, zoogeographic and ecosystem levels into a single ecologically based index'.

We selected reptiles as the bio-indicator taxon because they:

- have high species richness across Australia;
- are easily sampled and identified;
- are readily identified by field ecologists compared with mammals or invertebrates;
- generally have defined activity areas;
- generally have relatively long life spans enabling recolonisation in disturbed areas;
- have a complex and diverse community structure based on dietary requirements, activity period, habitat requirements and predatory strategies and;
- have a range of body sizes (Thompson and Thompson, 2005).

We also have a good knowledge of reptile assemblage structure in semi-arid and arid Australia (Thompson et al., 2003). We considered adding small mammals and amphibians to the index. However, for arid and semi-arid Australian habitats, small mammals are mostly nocturnal, have low species richness, can be difficult to identify in the field, are mostly widely foraging and their numbers fluctuate based on environmental factors such as rainfall. Although plentiful in arid and semi-arid environments, amphibians are difficult to sample as they only become surface-active after heavy rain. Birds could have been used but rehabilitation sites are generally small (<50 ha) and birds being very mobile could visit rehabilitated areas during their foraging but not be dependent on these sites. Many are also migratory or shift around arid and semi-arid areas based on local conditions which are often driven by rainfall. These attributes detracted from using mammals, amphibians and birds as a robust bio-indicator, so we developed the index using reptiles.

1.2. *Rehabilitation and degradation index*

The rehabilitation and degradation index (RDI) that we have developed assesses the extent to which a rehabilitated or disturbed area has progressed toward the creation of a functional ecosystem similar to that in an undisturbed area. The approach adopted here was based on the assumption that the full suite of terrestrial fauna in the adjacent undisturbed area will recolonise the rehabilitated or disturbed site if the chemical and physical parameters and the vegetation in that site are suitable, presuming there are suitable interfaces (corridors) between the undisturbed and the rehabilitated site through which the fauna can move. Below we describe the components and calculations necessary to obtain a RDI score for a particular site. We use a rehabilitated mine site waste dump in the Ora Banda region of Western Australia (WA) as an example to illustrate how to calculate a RDI for a particular site (see Appendix A).

Three broad parameters are used in the RDI; diversity, species composition and ecological groups. Each of these parameters is divided into sub-parameters. The parameters chosen are measurable attributes of the reptile assemblage. The sub-parameter scores are summed to provide a single score between zero (a totally degraded ecosystem) and the highest possible score of 100, which represents a natural, self-sustaining, functional ecosystem equivalent to that in the undisturbed area.

2. Methods

2.1. Study sites

We sampled communities of reptiles at five rehabilitated mine site waste dumps (Gimlet, Golden Arrow, Palace, Rose and Wendy Gully) and the adjacent 'undisturbed' areas, plus another five 'undisturbed' areas (Salmon Gums, Spinifex, Davyhurst, Security and Crossroads) in the gold mining region of Ora Banda (30° 27′ S, 121° 4′ E; approximately 50 km north of Kalgoorlie, WA). Undisturbed areas were relatively intact with no obvious changes to the soils or vegetation and it was presumed that the reptile assemblages in these areas had been largely unaffected by any minor anthropogenic disturbance impacts to the area. Rehabilitation had been in place at the commencement of this project (June 2000) at Wendy Gully for 3 years, Palace for 4 years, Rose for 7 years, and Gimlet for 8 years. At Golden Arrow there was a two-stage rehabilitation; rehabilitation on the top of the waste dump was there for 5 years and on the sides for 9 years. Natural sites that were only separated from the waste dump by a vehicle track were surveyed as undisturbed sites. Five undisturbed areas not adjacent to a waste dump were also included in our analysis of; (a) the maximum practical index score; and (b) a target score (see Section 2).

Ora Banda lies on Archaen granites that underlie lateritic gravel soils. The vegetation in the region was heterogenous, ranging from Eucalypt-Casuarina-Mulga woodlands interspersed with *Acacia*, to sparsely distributed spinifex (*Triodia* spp.) and shrubs (*Acacia* spp.) to dense shrubs (*Acacia* spp., *Atriplex* spp., *Allocasuarina* spp.). The 10 undisturbed areas were located in different habitats based on major vegetation types identified for the area by Mattiske Consulting (1995). Each site was a homogenous habitat type (i.e., it did not incorporate multiple habitat types).

2.2. Data collection

Field survey data were collected over a period of 2 years to develop the RDI and for another three additional January surveys to monitor rehabilitation progress. All sites other than Golden Arrow were pit-trapped on 13 occasions between September 2000 and January 2006 (September and December in 2000; January, April, June, September and December in 2001; January, April and June in 2002 to develop the RDI and then again in January 2003, 2004 and 2006 to monitor rehabilitation progress) using alternating 20 L PVC buckets and 150 mm PVC pipes (600 mm deep) joined by 250 mm high × 30 m long fly-wire drift fences. Golden Arrow was added to the survey program in September 2001 and was included in all subsequent surveys. Each undisturbed site had eight rows of six pit-traps that were joined by a drift fence (a line). On waste dumps there were six lines on the side of the waste dump and six lines on the top of the waste dump. All pit-traps were dug in during June–July 2000 (except Golden Arrow, which was dug in, during June 2001) to minimise potential digging-in effects on reptile capture rates. For the surveys from September 2000 until January 2003, each pit-trap was opened for 7 days and pit-traps were cleared daily. For the January 2004 and 2006 surveys, six funnel traps (800 mm × 200 mm × 200 mm, with a funnel at each end) were placed along each drift fence and all traps were left open for 14 days to increase the survey effort as it became evident that a high trapping effort was important to obtain robust RDI scores (see Section 3). The difference in trapping effort on waste dumps compared with the adjacent undisturbed areas can be adjusted for in the calculations.

2.3. RDI analysis

Fox (1982) and Fox and Fox (1984) reported that densities for early colonisers were generally higher in the early stages of succession than when the ecosystem had matured. Therefore, our RDI is structured to measure deviation for each parameter or sub-parameter from the undisturbed value, be it lower or higher. If the waste dump had the same reptile assemblage as the adjacent undisturbed area, then each site would contribute 50% of the total captures for the combined area, both sites would have the same diversity and evenness scores for the same trapping effort, and they would have a similarity score of 1. The greater the deviation between the rehabilitated and adjacent undisturbed area, the less the rehabilitated area resembled the adjacent undisturbed area. In our RDI this deviation is converted to a percentage. The relative difference between the rehabilitated site and the adjacent undisturbed area for each sub-parameter shows the extent to which this rehabilitated site is similar to (or deviated from) the adjacent undisturbed area. The formula used to calculate the difference between a rehabilitated site and adjacent undisturbed area for each sub-parameter as a percentage is:

$$\text{Relative score} = 100 - \left(2 \times \left(\text{ABS}\left(50 - \left(\frac{\text{rehab}}{\text{undist} + \text{rehab}}\right) \times 100\right)\right)\right) \quad (1)$$

where rehab = sub-parameter score for the rehabilitation site (i.e., evenness, Log series diversity or S_R score), undist = score for the undisturbed area (i.e., evenness, Log series diversity or species richness score), and ABS = absolute values (all values are converted to a positive).

2.4. Diversity parameter

The diversity parameter consists of four sub-parameters: species richness, Log series diversity, similarity and evenness. It is appreciated that there is some interdependence among these measures, however, they are sufficiently different for each to make a significant contribution to the RDI score. The method for calculating each of these scores is described below.

2.5. Species richness

Absolute species richness is rarely if ever known for a faunal community (Gotelli and Graves, 1996; Rodda et al., 2001), so we need an acceptable proxy for species richness in the RDI. Species richness (S) calculated from rarefaction curves (S_R) was used to compare S between the disturbed (with a smaller sample size) and undisturbed (with a larger sample size) areas. Rarefaction calculates the expected number of species in each sample, if samples were of a standard size

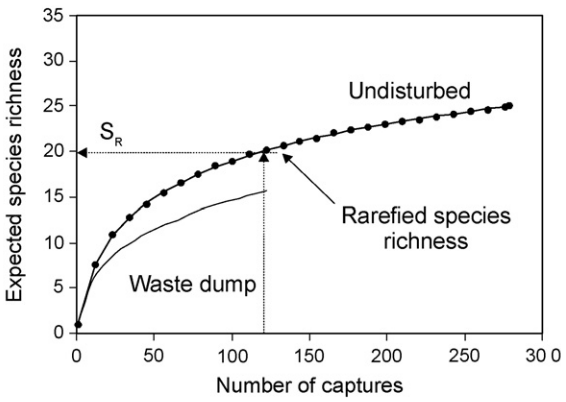

Fig. 1 – Species richness calculated from the relationship between the abundance at the example waste dump and the expected species richness for the adjacent undisturbed area.

(Gotelli and Graves, 1996). Rarefaction is based on the shape of the species abundance curve rather than the absolute number of individuals per sample. A line of best fit was plotted through the rarefied data for the undisturbed area using the Beta-P non-linear regression model (Thompson et al., 2003). The S_R for the undisturbed area was calculated using the total number of individuals caught for the rehabilitated area (see Fig. 1) as the measure of effort. In our examples, species richness for a given trapping effort was always higher in the undisturbed area than the rehabilitated area. However, should the number of individuals caught in the rehabilitated area exceed that in the adjacent undisturbed area, the lower value for the undisturbed area is used when assessing relative species richness in the two sites.

The reptile assemblage in the undisturbed area was ranked from those species with the highest abundance to those with the lowest abundance, and rarefied using EcoSim Software (http://www.worldagroforestrycentre.org/sites/RSU/resources/biodiversity/software/EcoSim.asp). The default randomisation algorithm with independent sampling was set at 100 iterations (Gotelli and Entsminger, 2001). The formula for the Beta-P non-linear regression model to calculate a curved line of best fit through the data is:

$$\text{Beta-P non-linear model} = a \times \left(1 - \left(1 + \left(\frac{\#}{c}\right)^{d}\right)^{-b}\right) \qquad (2)$$

where a = asymptote or total number of species (S), b = rate of accumulation, c = scaling factor for the x-intercept, d = index for shape of the function; and # = number of individuals captured (Thompson et al., 2003).

Using the maximum number of individuals caught on the waste dump and reading off the number of species for this number of individuals on the rarefied curve for the undisturbed area enables a direct comparison to be made between the number of species likely to be caught in the undisturbed and waste dump areas for the same number of individuals caught. This relative species richness score for the undisturbed area and the actual species richness score for the waste dump are then inserted into Eq. (1) to calculate a relative species richness index score.

2.6. Log series diversity

Log series diversity was used to compare the diversity in rehabilitated sites with the adjacent undisturbed areas because it has good discriminating ability, low sensitivity to sample size and is simple to calculate (Kempton and Taylor, 1974; Magurran, 1988). Its low sensitivity to sample size is a result of its greater dependence on the number of species of intermediate abundance and is therefore relatively unaffected by rare or very common species (Magurran, 1988).

The Log series diversity scores for the waste dump and adjacent undisturbed area were calculated using the procedure described in Magurran (1988; p. 132–135). The relative score for the waste dump compared with the adjacent undisturbed area for Log series diversity was calculated using Eq. (1).

2.7. Similarity

Morisita–Horn similarity scores were used to compare the similarity of reptile assemblages between waste dumps and adjacent undisturbed areas. The Morisita–Horn similarity index (C_{mH}) is a quantitative similarity index (Magurran, 1988) and was selected because it is not strongly influenced by species richness or sample size (Wolda, 1981), and was recommended by Magurran (1988). The Morisita–Horn similarity index was calculated using EstimateS software (Colwell, R.; http://viceroy.eeb.uconn.edu/EstimateS).

2.8. Evenness

Evenness (E) of a population was used as another measure of diversity since it describes the extent to which individuals are equally partitioned among all species. If the evenness score for a site is 1, then each species makes up an equal proportion of the assemblage (i.e., equal abundance of each species; Magurran, 1988).

The score for the waste dump compared with the adjacent undisturbed area for evenness is then calculated using Eq. (1). Equal weightings (25%) were applied to each of the four sub-parameters then added to calculate a score out of 100 for the diversity parameter.

2.9. Assemblage composition

The 'assemblage composition' compares the number of individuals in each taxa (e.g. for our example the number of agamids, geckos, pygopods, skinks, varanids, scolecophidians and elapids found on the waste dump with the adjacent undisturbed area). We refer to these as 'taxonomic groups'. Each of these taxonomic groups was considered a sub-parameter of the assemblage composition parameter. If the relative abundance for each taxonomic group was similar for the waste dump and the adjacent undisturbed area, then the waste dump could be considered approaching an advanced stage in the development of an ecosystem similar to the adjacent undisturbed area.

If the trapping effort on the rehabilitated area and the undisturbed area differ, then the number of individuals used in the calculation of the assemblage composition and ecological parameters needs to be adjusted to reflect this difference. This is done using the proportion of trap effort on the waste dump and the undisturbed area (i.e., adjusted abundance on the waste dump = actual abundance on the waste dump × trapping effort on undisturbed area/trapping effort on waste dump).

The relative score for the waste dump compared with the adjacent undisturbed area for each taxonomic group was then calculated using Eq. (1).

Different weightings are applied to each of these sub-parameters because each taxonomic group is not equally represented in the reptile assemblage in each undisturbed area. The weightings were calculated based on the relative proportion that each taxonomic group represents in the undisturbed area. For example, if 5% of all reptiles captured on the undisturbed area were agamids, then agamids would be weighted as 5% of the total.

2.10. *Ecological parameter*

The niche structure for an assemblage of reptiles can be partitioned in at least three basic ways; temporally, spatially and trophically (Pianka, 1973). A difference among species in activity period, use of space and dietary preference reduces competition and presumably allows the coexistence of a variety of species (MacArthur, 1972; Pianka, 1973, 2000). If the ecological groups were similarly proportioned for the waste dump and the adjacent undisturbed area, then the waste dump could be considered adequately rehabilitated in terms of reptile ecological assemblage structure.

The ecological parameter compares how reptile assemblages in rehabilitated areas and the adjacent undisturbed areas are segregated into these niches. The ecological sub-parameters are dietary preference, dietary specialists, habitat preference, predatory strategy and activity period. Each sub-parameter is further divided into categories [dietary preference—O, predominantly omnivore; C, predominantly vertebrate carnivore; and I, predominantly invertivore (a species that predominantly eats invertebrates); habitat preference—predominantly terrestrial, T; predominantly arboreal, A; and predominantly fossorial, F; predatory strategy—predominantly sit-and-wait predator, S; predominantly active forager, A; and predominantly widely foraging reptile, W; activity period—predominantly nocturnal, N; and predominantly diurnal, D]. The categories selected for each species are based on a search of the literature, our on-site observations, and personal communication with an expert panel. Occasionally multiple preferences are presented in the literature, some of which may reflect geographic variation. In these circumstances we chose the most common or took advice from an expert panel. We defined an active-foraging species as a species that forages over a large search area looking for dispersed food sources (e.g. *Varanus gouldii*). A widely-foraging reptile was defined as a species that forages for a concentrated food source and then stays at the site of this food source for a period of time (e.g. *Moloch horridus* eating ants). A sit-and-wait predator does not move around searching for prey but waits in ambush for its prey to come past.

Species are assigned to a category in each sub-parameter based on adult species behaviour. It is acknowledged that some of these categories are somewhat artificial as there is likely to be an overlap as some species will fit into more than one category; for example, see Perry (1999) for discussion on predatory strategies.

After adjusting for the different trapping effort on the rehabilitated waste dump and the adjacent undisturbed area the relative score for the waste dump compared with the adjacent undisturbed area for each category was calculated using Eq. (1). Each sub-parameter was given an equal weighting, as was each category score within each sub-parameter. These weighted scores were summed to provide the ecological parameter score for the waste dump.

2.11. *Parameter weightings and RDI calculations*

The diversity, assemblage composition and ecological parameters were weighted differently to calculate the final RDI score. The weights were determined so that the RDI score had minimum variance for 'identical' undisturbed sites. The parameter weightings for diversity, taxonomic and ecological groups in our example were calculated by comparing two hypothetical 'near identical' sites. Data sets for the 'near identical' sites were obtained by sub-sampling each of the 10 undisturbed areas surveyed at Ora Banda between 2000 and 2002. Captures from each undisturbed area were divided into two sub-areas (lines 1, 3, 5, 7; and lines 2, 4, 6, 8) for the 2 year survey period. Sub-sampling from the same pit-trapping grid was considered the most similar that any two data sets could be in the Ora Banda area.

A minimum variance model between the overall scores for the 20 sub-sampled undisturbed areas was used to calculate the most appropriate weightings for each parameter. An RDI score was calculated for each sub-sampled undisturbed area (i.e., odds *versus* evens, and evens *versus* odds; $n = 20$) for all possible combinations (i.e., 4851) of different weightings for each of the three parameters (i.e., weightings of 1,1,98; 1,2,97; 1,3,96, etc.) for the 20 sub-sampled undisturbed areas. These were ranked and the mean weightings for the 50 combinations with lowest variance calculated. Fifty combinations were chosen, as there were only minimal differences in variance for many different combinations. The mean weightings that resulted in the minimum variance for the sub-sampled undisturbed areas were 32 for the diversity parameter, 43 for the assemblage composition parameter, and 25 for the ecological parameter. These weightings when multiplied by the parameter score optimised the RDI score for the rehabilitated site. These weightings have been used in all further calculations of RDI scores.

2.12. *Target RDI score*

A score of 100 for a rehabilitated waste dump, although ideal, is unlikely. Even if the reptile assemblage on the waste dump was a perfect replica of the adjacent undisturbed area, pit-trapping data for the two sites are unlikely to be identical due to sampling error, and a range of other variables. As a consequence a target score of 100 for a waste dump is an unreasonable expectation but what is a reasonable target score?

Complete rehabilitation of a waste dump is likely to take many years, possibly decades or even longer. The ultimate goal is to identify when land managers can be relieved of their environmental obligations to the site, knowing that with time and natural processes, the rehabilitated area will eventually become a near-natural, self-sustaining, functional ecosystem similar to that in the adjacent undisturbed area. This is a judgement decision, and science can only provide the information to be used as a basis for making this judgement. What follows is a rationale for a practical target RDI score for a rehabilitated area. This is a level that when achieved requires no further intervention by land managers and the rehabilitated areas will continue to progress towards a functional ecosystem similar to that in the adjacent undisturbed area.

To develop a target score, each of the 10 homogenous undisturbed biotopes was sub-divided into two sampling areas (as used when calculating a weighting for each parameter). One was called the 'undisturbed area' and the other the 'rehabilitation area', and RDI scores were calculated for each. The designation of each of the two sampling areas was then reversed and RDI scores calculated for the other 10 sites, providing RDI scores for 20 sites compared with their 'identical' neighbour. These are the maximum scores likely to be achieved with the sampling effort we employed.

The mean RDI score for the 20 'rehabilitation sites' was 86.5 ± S.E. 0.91. This suggests that when an undisturbed area was sub-sampled the highest rehabilitation score that could be achieved was approximately 86.5, reflecting sampling variability and minor variations in the homogeneity of sites. So an appropriate target rehabilitation score for practical purposes is about 86. The decision as to how far below this score is 'reasonable', is an arbitrary judgement. However, government regulators will require such a score if they are to use the RDI. Based on an assessment of the Ecosystem Function Analysis (Tongway, 2001) scores for four waste dumps and a detailed knowledge of their reptile assemblages, it is suggested that the target score might be 10 standard errors below a mean of 86.5 (i.e., 77.5). A similar target score could be calculated as two standard deviations below the mean score (i.e., 78.5) or a distance below the mean score equivalent to the distance above to reach 100 (i.e., 100–86.5 = 13.5; 86.5–13.5 = 73). These are likely to be 'high' target scores and continued refinement of the RDI will assist in assessing whether the target score needs to be adjusted.

3. Discussion

3.1. *What does the RDI score mean?*

A waste dump is devoid of vegetation and fauna when it is created. An appropriately constructed and vegetated waste dump should then move through various succession stages as the rehabilitation matures, to eventually achieve the final objective of a self-sustaining, functional ecosystem. As the rehabilitated site develops its biotic integrity, the RDI score will increase. A completely disturbed area (e.g. newly constructed waste dump) that is devoid of reptiles will have a score of zero. The score will increase towards 100 as the reptile assemblage on the waste dump converges with that in the adjacent undisturbed area. The attributes for each of the stages in this progression are described in Table 1. These are not discrete stages, but are a continuum of rehabilitation progress.

Our advice to practitioners using the RDI is that the scores should generally progressively increase with time in a well planned rehabilitation program, however, small reductions in the score can occur over a period of a couple of years that are the result of local environmental variables such as an extended dry period or a period of unusually high rainfall that impacts on the composition of the local reptile assemblage. Increases in the RDI score will be faster in the initial stages of the rehabilitation program when the earlier colonisers move into the area. For example, Thompson and Thompson (in press) reported in excess of 50% of the species in the adjacent undisturbed areas were present on rehabilitated waste dumps within 10 years of commencing the rehabilitation program. However, species with a specialist diet or micro-habitat requirements are generally much slower to colonise rehabilitated waste dumps. These specialised diets (e.g. termites) and microhabitats (e.g. loose surface soil, hollows in mature trees) often take many years to develop in rehabilitated areas. Our monitoring of five sites at Ora Banda (2001–2006) indicates that RDI scores of 50–75 were achievable within 10 years of the rehabilitation program commencing, for high, steep-sided waste dumps that were often badly eroded and where the surface soil and vegetation community on the waste dump differed appreciably from that in the adjacent undisturbed areas. Higher scores should be anticipated on flat areas, with similar soils and a vegetation community that matches that in the adjacent undisturbed areas.

Table 1 – Suggested reptile assemblage attributes associated with each class of RDI score

Attributes	RDI score
Comparable to the best situation without human impact; regionally expected species for habitat type; species present with a full array of age (size) classes; balanced ecological structure; self-sustaining functional ecosystem	86–100
Species richness approaching expected levels; not all late succession species present, some species present with less optimal abundances or size distribution; ecological structure incomplete	61–85
Species richness below that in the undisturbed area, some groups not well represented, some specialists not present	41–60
Lack of specialists, fewer species than in the undisturbed area, skewed ecological structure and relative abundances	21–40
Few vertebrates present; only early colonisers present, lack of community structure.	11–20
Only opportunistic early colonisers are present. No community structure	0–10
No reptiles present	0

Our advice to environmental regulators is that a RDI score that is 10 standard errors below the target score, when calculated as shown above, would indicate that without further intervention and management the rehabilitated area is likely to continue to develop into a functional ecosystem and environmental bonds could be returned. However, as a note of caution, waste dumps in the goldfields of Western Australia are often high and unstable structures that are prone to severe erosion during periods of unusually high rainfall. Significant failure of all or part of a waste dump due to an episodic high rainfall event may destroy a large section of rehabilitated fauna habitat resulting in an immediate drop in the RDI score for that area. RDI scores for rehabilitated areas below 50 would be viewed as unacceptable for the release of environmental bonds.

3.2. *Robustness of the RDI*

If a measure of biotic integrity or a bio-indicator is to become widely accepted, then it must be robust. The RDI could be considered robust if:

- the calculated results were intuitively correct,
- the index score was not overly influenced by sample-to-sample fluctuations in reptile assemblages that were not related to rehabilitation progress (e.g. year-to-year variation or hatching of reptiles),
- the index score was not overly influenced by rare species (e.g. singletons and doubletons),
- the index score was not overly influenced by small sample sizes and;
- it could be successfully applied in a range of habitats.

We can address three of these criteria empirically; sample size, temporal variations (e.g. year-to-year, temporary presence of hatchlings), and number of rare species in the reptile assemblage.

3.3. *Influence of sample size*

The number of reptiles captured on waste dumps and adjacent undisturbed areas can greatly affect the RDI score if surveying effort is inadequate. When sample sizes were small the change in the RDI was pronounced. When the sample size was larger, small variations in captures were less influential on the overall RDI score. During January 2004 and 2006 we quadrupled the trapping effort to provide a much more robust RDI score for each of the waste dumps (Table 2). We believe the January 2004 and 2006 RDI scores provide the most robust assessment of rehabilitation success for the five waste dumps we examined.

3.4. *Temporal variation*

Thompson and Thompson (2005b) demonstrated significant temporal variations in the reptile assemblages in undisturbed sites. Re-surveying all sites in January 2003, 2004 and again in 2006 provided an opportunity to assess changes over five January periods. There were noticeable differences in the RDI scores across the five January survey periods (Table 2). It had been unusually dry for the 2 years leading up to the January 2003 survey and we believe the reptile assemblage had changed as a result of this, thus the reason for the very different results in January 2003 compared with other years for Wendy Gully, Rose and Palace. Sampling error that is associated with small samples and natural variations in assemblage structure influence RDI scores particularly for the first three January surveys. However, we believe that RDI scores are robust enough to reflect changes in ecosystems, as long as there is an appreciation that there are variations in vertebrate assemblages due to temporal variations in environmental variables.

3.5. *Effect of rarity*

A singleton is defined as a species of reptile that was sampled once (i.e., a single individual), and a doubleton is a species caught twice (i.e., two individuals). A singleton may be a rare species or a common species that is not easily trapped. Removing singletons or both singletons and doubletons, reduced the index score for each site (Table 3). When catch rates were low (e.g. single survey periods) the effect of removing singletons or both singletons and doubletons was greater than when catch rates were high. In some cases the removal of singletons/doubletons resulted in the removal of entire families of reptiles from data sets (e.g. pygopods, varanids or elapids). There was an increased propensity for the common reptiles in the assemblage to appear ‘rare’ (i.e., represented by singletons and doubletons) when only a small number of reptiles had been captured, simply because insufficient individuals had been caught (Thompson and Withers, 2003). With adequate surveying effort the relative impact of ‘rare’ species on the RDI was diminished. It is therefore recommended that singletons and doubletons are left in the data set, but the data sets need to be sufficiently large so that common species do not appear ‘rare’.

3.6. *Effect of hatchlings*

For some species, hatchlings are highly seasonal, and seem more easily pit-trapped than adults. It is probable that many of these hatchlings will not survive to join the adult population

Table 2 – RDI scores for five waste dumps calculated from data collected during January survey periods

	Wendy Gully	Rose	Palace	Gimlet South	Golden Arrow
January 2001	31.7	51.2	38.5	39.5	
January 2002	54.3	59.8	36.1	38.2	51.1
January 2003	71.0	36.0	25.0	51.8	49.7
January 2004	44.2	68.6	52.6	49.7	51.3
January 2006	57.9	61.2	76.8	49.3	58.3

(Tinkle and Dunham, 1986) due to predation and will therefore not form part of the reproductive population for that species in the area. Catching large numbers of hatchlings alters the interpretation of the reptile assemblage for an area and can therefore affect the RDI score (see Table 3). The influence of hatchlings on the RDI score was therefore potentially significant in survey periods when young are frequently caught. Most hatchlings were captured in January and April survey periods, as they generally hatched from December to March. It is therefore recommended that hatchlings be excluded from the analysis.

3.7. *Other variables affecting the robustness of the Index*

Other issues such as the homogeneity or heterogeneity of the sampled undisturbed area, the spatial placement of the traps, the trapping effort, the size of rehabilitated areas, the size of the areas sampled, and the impact of unknown anthropogenic

Table 3 – Summary of RDI scores for pooled data for the two years of survey effort with and without singletons and doubletons, and with and without hatchlings for Wendy Gully, Rose, Palace and Gimlet South waste dumps

		All data							
		Undisturbed captures				Waste dump captures			
	weighted score	Wendy Gully	Rose	Palace	Gimlet South	Wendy Gully	Rose	Palace	Gimlet South
Abundance		314	278	240	241	68	129	75	161
Number of species		25	24	23	30	9	16	11	14
Diversity parameter									
Log series diversity	25					20.5	23.3	24.7	14.7
Evenness	25					15.2	24.3	18.1	14.5
Similarity	25					14.3	9.1	7.3	3.0
S_R	25					17.7	21.7	18.8	17.1
Diversity parameter	100					67.6	77.3	68.8	49.3
Assemblage composition parameter	100					23.7	45.2	29.2	51.8
Ecological parameter	100					20.4	45.9	34.6	39.4
Weighted scores									
Diversity parameter						21.6	24.8	22.0	15.8
Assemblage composition parameter						10.2	19.4	12.6	22.3
Ecological parameter						5.1	11.5	8.6	9.8
Overall score for each site	**100**					**37.0**	**55.7**	**43.2**	**47.9**
		No singletons or doubletons							
Abundance		304	269	234	227	62	120	68	151
Number of species		17	17	19	19	5	9	6	6
Diversity parameter									

Table 3 (*Continued*)

Log series diversity					12.40	17.94	12.26	10.66
Evenness					19.91	24.49	22.22	17.90
Similarity					14.03	8.90	6.43	2.68
S_R					13.23	17.89	13.41	12.07
Diversity parameter					59.6	69.2	54.3	43.3
Assemblage composition parameter					22.5	43.4	26.9	50.5
Ecological parameter					17.4	37.2	32.4	37.7
Weighted scores								
Diversity parameter					19.1	22.2	17.4	13.9
Assemblage composition parameter					9.7	18.7	11.6	21.7
Ecological parameter					4.4	9.3	8.1	9.4
Overall score for each site					**33.1**	**50.1**	**37.0**	**45.0**
No hatchlings								
Abundance	296	266	231	222	68	119	65	157
Number of species	24	23	22	27	9	15	9	14
Diversity parameter								
Log series diversity					15.5	22.2	16.1	15.8
Evenness					20.1	23.9	24.0	14.7
Similarity					14.3	8.5	6.4	2.6
S_R					18.2	22.0	17.4	18.0
Diversity parameter					68.1	76.6	63.9	51.2
Assemblage composition parameter					24.8	43.8	25.6	54.7
Ecological parameter					22.5	44.3	32.2	41.1
Weighted scores								
Diversity parameter					21.8	24.5	20.4	16.4
Assemblage composition parameter					10.7	18.8	11.0	23.5
Ecological parameter					5.6	11.1	8.0	10.3
Overall score for each site					**38.1**	**54.4**	**39.5**	**50.2**

influences (e.g. vehicle movements, dust, noise) on both the rehabilitated and the 'undisturbed' analogue sites are unknown. But they are largely unknown for most bio-indicators reported in the literature and therefore warrant further investigation. Rehabilitated areas such as waste dumps are often small in size increasing the edge effects, which are known to alter fauna assemblages (Anderson and Burgin, 2002; Bragg et al., 2005; and references therein). The extent to which edge effects will impact on the robustness of the Index is not known, but they will probably vary from site-to-site and with the relative size of the rehabilitated areas. Suffice to say, the larger the rehabilitated area, the smaller the edge effects.

In some situations rehabilitated areas are 'islands' where the developing habitat is different to those in adjacent areas. Different species in the reptile assemblage have different space and habitat requirements. As a consequence, small 'islands' will place constraints on the use of that space for some species. For example, large, widely-foraging carnivorous reptiles (e.g. *Varanus gouldii*) require larger home ranges than

Table 4 – Summary of RDI scores for Mount Whaleback, WA (Walker et al., 1986), for Cobar, NSW (Halliger, 1993) and the Misima mine site

	Maximum weighted score	Mount Whaleback	Cobar		Misima		
			last mined 1919	last mined 1952	20 months rehab.	5 years rehab.	9-10 years rehab.
Abundance of reptiles (und / wd)		289/154	44/33	44/22	130/88	42/88	97/88
Species richness (und / wd)		21/10	14/13	14/10	3/15	5/15	9/15
Diversity parameter							
Log series diversity	25	19.2	23.1	24.6	4.8	11.0	15.9
Evenness	25	15.7	23.6	25.0	24.2	18.9	23.0
Similarity	25	9.6	11.3	4.3	0.1	0.0	2.3
S_R	25	17.5	24.1	24.8	25.0	15.3	24.8
Diversity parameter	100	62.1	82.1	78.7	54.1	45.3	65.9
Assemblage composition parameter	100	32.9	81.4	54.1	45.5	60.4	73.6
Ecological parameter	100	43.4	37.6	12.6	5.7	10.5	6.4
Weighted scores							
Diversity parameter	32	19.9	26.3	25.2	17.3	14.5	21.1
Assemblage composition parameter	43	14.2	35.0	23.2	19.6	26.0	31.7
Ecological parameter	25	10.8	9.4	3.1	1.4	2.6	1.6
Overall score for each site	**100**	**44.9**	**70.7**	**51.6**	**38.3**	**43.1**	**54.4**

und – undisturbed area, wd – waste dump or rehabilitated site.

und, undisturbed area; wd, waste dump or rehabilitated site.

the smaller sit-and-wait agamids or widely-foraging skinks. It would therefore be unrealistic to expect these large, widely-foraging species to occupy and remain in small rehabilitated sites, but they will include these areas within their activity areas when conditions are appropriate, as frequently happens around Ora Banda in the more mature rehabilitated sites. This is more of a constraint on establishing a functional ecosystem in a rehabilitated area than it is on the RDI, but it is a factor that must be considered when interpreting the RDI score for a particular site.

3.8. *Applicability of RDI scores for other habitats*

One of the criteria for assessing the robustness of the RDI is its applicability over a range of habitats. There is a paucity of data in the literature on reptile assemblages that have been systematically surveyed in rehabilitated areas and adjacent undisturbed areas over a period of years or even 1 year. We calculated RDI scores for data from two other Australian sites and a wet-dry tropical site on Misima Island east of Papua New Guinea.

3.8.1. *Mount Whaleback, WA*

Walker et al. (1986) reported a survey of the Mount Whaleback waste dump at Mount Newman between March 1984 and January 1986. The recaptures and unidentified reptiles are excluded from the calculation of the RDI score. Mount Whaleback had a RDI score of 45 (parameter scores are shown in Table 4). These data show that 9 years after rehabilitating the area, the reptile assemblage was still appreciably different to the adjacent undisturbed site. The RDI score was similar to the waste dumps around Ora Banda where scores ranged from 37 to 55. Walker et al. (1986) made no overall comment about the success of the rehabilitation on the Mount Whaleback waste dump, but did say that almost half of the regionally present vertebrate ground fauna species were caught, despite having only minor remnants of vegetation and a steep unvegetated slope.

3.8.2. *Cobar, NSW*

Halliger (1993) investigated the development of two rehabilitated mine site areas near Cobar, New South Wales and compared them to an adjacent unmined site. One area was mined until 1919, and the other until around 1952. Although not explicitly stated, it is implied that no planned rehabilitation was undertaken at either of these mine sites and the vegetation and fauna present were due to natural processes. Recaptures are excluded from these analyses. The area that had not been mined since 1919 had an RDI score of 70.7 and the area not mined since 1952 had a score of 51.6. Although the species richness was lower than at Ora Banda and fewer reptiles were captured, the RDI score showed that the older rehabilitated site more closely resembled the nearby analogue undisturbed area (Table 4).

3.8.3. *Misima, PNG*

The RDI was applied to three rehabilitated areas associated with the Misima mine site and an adjacent rainforest site. These areas had been rehabilitated for 20 months, 5 years and 9–10 years at the time of the assessment. Reptiles and frogs were incorporated into the calculations of RDI scores. The comparison between these three sites and the rainforest indicates that there was a clear progression in the development of the rehabilitated sites from the site rehabilitated 20 months ago (RDI = 38.3), to the site rehabilitated 5 years ago (RDI = 43.1) to the site rehabilitated 9–10 years ago (RDI = 54.4; Table 4). These three waste dumps all had low scores for the ecological parameter. This is often the case for emerging ecosystems, as a range of niches for particular species are not available during the early stages of the rehabilitation process. It might also be expected that the relatively rare species, with particular niche requirements, would be slow to colonise the rehabilitated sites and this will significantly reduce the ecological parameter score. Most of the herpetofauna caught were invertivores, which was what would generally be expected for an assemblage of small tropical lizards and frogs (Vitt and Zani, 1998; Vitt et al., 1999). Differences between natural and rehabilitated sites were most noticeable in the number of individuals that were arboreal and fossorial. In the rainforest analogue sites, 20 of the 88 individuals caught were arboreal, and 31 of the 88 individuals caught were fossorial. However, the number of individuals in each of these categories in the sites rehabilitated 20 months, 5 years and 9–10 years ago were 1 of 130, 10 of 42 and 0 of 97 being arboreal, and 0 of 130, 3 of 42 and 0 of 97 being fossorial. This is not surprising and is typical of developing rehabilitated areas in the early stages of succession. Few mature trees and a different substrate in rehabilitated areas means that it takes much longer for ecological niches suitable to sustain arboreal and fossorial species to become available compared with the terrestrial niches.

3.9. *Trapping effort*

Our data (Thompson et al., 2003, 2007) suggest that about 180 individuals are necessary to catch 80–90% of the species present in most habitats as long as the trapped animals are not dominated by one or two species. This represents the number of individuals that should be caught in the undisturbed area. The comparable number of individuals caught in the rehabilitated area will vary in accordance with the development of the ecosystem in the rehabilitated site. We are confident this number of individuals caught will provide a reasonably robust RDI score.

3.10. *Correlations and redundancy among diversity and ecological sub-parameters*

It is acknowledged that in most habitats sampled there will be a correlation among measures of species richness, Log series diversity, similarity and evenness (e.g. see discussion in Hayek and Buzas, 1997; Magurran, 2004 about links between measures of species richness, evenness and diversity). We relied on the advice of earlier researchers that developed various indices of biotic integrity that each of these sub-parameters make a useful contribution to the overall index score and no one sub-parameter makes any of the others redundant. However, this issue needs to be examined when data are available for numerous sites. This should be a relatively simple task. Systematically deleting each of the sub-parameters from the calculation of the RDI score and then correlating the new score with some independent measure of rehabilitation success should provide an indication of any redundancy of sub-parameters. It is also possible that there will a significant correlation between some of the ecological sub-parameters, but it is our view that this is less likely than a correlation among the diversity sub-parameters, as differences among species in activity period, use of space and dietary preference reduces competition and presumably allows the coexistence of a variety of species (MacArthur, 1972; Pianka, 1973, 2000). Again this issue should be tested when data are available for numerous sites.

3.11. *Weightings*

To some extent the method of weighting parameter and sub-parameter scores is arbitrary. Overall, the diversity, assemblage composition and ecological parameters could have been weighted equally, but this would provide slightly lower overall index scores for each rehabilitated site, and we saw merit in providing a weighting system that maximised the index score. However, this is offset by the need to calculate the weightings for each parameter for each rehabilitated area assessed. This is an additional calculation that some users of the RDI may wish to ignore. Whether the weighting system for parameter scores is or is not used, is much less important than consistency in what is done, particularly if scores for successive years are to be compared and used to monitor rehabilitation progress.

We could see no good reason why the sub-parameters that make up the diversity and ecological parameters should be weighted differently so they are weighted equally. The weighting for each of the taxonomic groups reflects the proportion of individuals represented by each taxonomic group in the assemblage. Intuitively this seemed a better approach than weighting each taxonomic group equally when the number of individuals in each group varied appreciably within and among sites.

3.12. *RDI as a degradation index*

The RDI is calculated by comparing the reptile assemblage on one site with another. For rehabilitated degraded areas, the ecosystem is progressing through numerous succession stages and RDI scores should progressively increase as the reptile assemblage in the rehabilitated area moves closer to mimicking that in the adjacent undisturbed area. The reverse is the situation for an area where the ecosystem is being impacted on by a disturbance variable such as pollution, feral animals or weed invasion. The RDI can be used to compare a 'control' site with one that is progressively being degraded. It is therefore a useful tool in quantifying rehabilitation success and degradation of habitats if appropriate analogue sites are available.

4. Conclusion

The RDI provides an indication of the relative success or degradation of a site compared to the functional ecosystem present in the nearby or adjacent comparison area, measured in terms of the reptile assemblage. The RDI score is a multi-metric measure of the extent to which the reptile assemblage in a disturbed or rehabilitated area resembles the reptile assemblage in the adjacent undisturbed area. The principles underlying the RDI are the same as for the IBI. If the reptile assemblage is a useful proxy of the development of the functional ecosystem for a rehabilitated site when compared with the adjacent undisturbed area (see Thompson and Thompson, 2005a), this score can be used by land managers as a measure of rehabilitation success. As the RDI only monitors the assemblage structure of small reptiles, it needs to be considered in conjunction with other measures or indices of soil stability (e.g. Landscape Function Analysis; Tongway, 2001) and vegetation structure to provide an overall assessment of ecosystem function.

Karr et al. used the IBI to measure the degradation in freshwater streams and rivers using fish assemblages. The RDI can also be used in a similar fashion to measure the impact of a disturbance factor on a functional terrestrial ecosystem. Disturbance factors such as grazing, introduction of feral pests (e.g. cane toads), mine site impact on adjacent undisturbed areas, noise and dust pollution are all likely to impact on ecosystems.

Our RDI provides an objective and relatively easy to interpret tool that can be used to measure both the success of a rehabilitation program in creating a functional ecosystem in a degraded area or the impact of a disturbance on a functioning ecosystem. The results are influenced by seasonal and year-to-year fluctuations and changes in the reptile assemblage but are not overly influenced by rare species and can be applied in a variety of habitats. Small field sample sizes reduce the robustness of the RDI scores.

Acknowledgements

This research was undertaken with ethics approval granted by Edith Cowan University and licences issued by the Department of Environment and Conservation. This research was financially supported by Norilsk Nickel Pty Ltd. and Barrick Kanowna Pty Ltd. for which we are very appreciative.

Appendix A. Calculations for a rehabilitated waste dump at Ora Banda

Below we have used data from a single rehabilitated waste dump and adjacent undisturbed area to illustrate how a RDI score is calculated.

Twenty-eight species of reptile were caught on the example waste dump and adjacent undisturbed area (Table A1). The classification for each of these 28 species into their primary trophic level, habitat preference, predatory strategy and activity period is shown in Table A1.

A.1. *Calculation of species richness*

The reptile assemblage in the undisturbed area was ranked from those species with the highest abundance to those

Table A1 – Abundance, trophic level, habitat preference, predatory strategy and activity period of reptile species captured at an example waste dump and adjacent undisturbed area

Species	Abundance in undisturbed area	Abundance in rehabilitation area	Trophic level	Habitat preference	Predatory strategy	Activity period	Source for categorical data
Geckos							
Diplodactylus granariensis	31	26	I	T	S	N	Chapman and Dell (1985); Roberts (1998)
Diplodactylus maini	34		I	T	A	N	Chapman and Dell (1985); How, R. unpublished data; EX
Diplodactylus pulcher	50		I	T	W	N	Pianka (1969a,1986); Pianka and Pianka (1976); Roberts (1998)
Gehyra purpurascens	3		I	A	S	N	How, R. unpublished data; EX
Gehyra variegata	20	7	O	A	S	N	Henle (1990a,b); Kitchener et al. (1988); Pianka (1969a), Pianka and Pianka (1976)
Heteronotia binoei	5	4	I	T	W	N	Bustard (1968); Henle (1990b); Pianka (1969c); Pianka and Pianka (1976)
Nephrurus laevissimus		1	I	T	S	N	Delean and Harvey (1981); How et al. (1990); Pianka (1969a, 1986); Pianka and Pianka (1976); EX
Oedura reticulata	4		I	A	A	N	How, R. unpublished data; How and Kitchener (1983); Kitchener et al. (1988); Pianka and Pianka (1976); EX
Rhynchoedura ornate	40		I	T	W	N	Pianka (1969a, 1986): Pianka and Pianka (1976); Roberts (1998)
Underwoodisaurus milii	5	36	I	T	S	N	Chapman and Dell (1985); How et al. (1990); Read (1999); EX
Skinks							
Cryptoblepharus plagiocephalus	6		I	A	A	D	James et al. (1984); Pianka (1986); EX
Egernia formosa	1		I	A	S	D	Cogger, 1992; EX
Egernia inornata	17		I	T	S	N	Greer (1989); Henle (1989); Pianka (1969a, 1986); Pianka and Giles (1982)
Lerista muelleri	4	2	I	F	A	N	Pianka (1986); EX
Lerista picturata	3		I	F	A	N	EX
Menetia greyii	18	23	I	T	A	D	Henle (1989); Pianka (1986); Smyth and Smith (1974)
Morethia butleri	14	3	I	T	A	D	Pianka (1986); EX
Agamids							
Ctenophorus cristatus	1	1	I	T	S	D	Pianka (1971); EX
Ctenophorus reticulatus	12	9	O	T	S	D	Pianka (1986); EX
Pogona minor	2	9	O	T	A	D	Chapman and Dell (1985); Pianka (1986); Thompson and Thompson (2003)
Tympanocryptis cephala		1	I	T	S	D	EX
Varanids							
Varanus caudolineatus		1	I	A	A	D	Pianka (1969a,b, 1986); Thompson (1993, 1995)
Varanus gouldii	2		I	T	A	D	Pianka (1970, 1986, 1994): Shine (1986); Thompson (1996); EX
Pygopods							
Lialis burtonis		2	C	T	S	D	Bustard (1970); Chapman and Dell (1985); Martin (1972); Patchell and Shine (1986a, b); Pianka (1986)
Elapids							
Parasuta monachus	1	3	C	T	A	N	Greer (1997); Shine (1988); EX
Simoselaps bertholdi	1		C	F	A	N	How and Shine (1999); Strahan et al. (1998); Swan (1983)

Table A1 (Continued)

Species	Abundance in undisturbed area	Abundance in rehabilitation area	Trophic level	Habitat preference	Predatory strategy	Activity period	Source for categorical data
Scolecophidians							
Ramphotyphlops bituberculatus	1		I	F	W	N	Storr et al. (2002); Webb and Shine (1993); EX
Ramphotyphlops hamatus	3	1	I	F	W	N	Storr et al. (2002); Webb and Shine (1993); EX
Total	278	129					

Trophic level: O, predominately omnivore; C, predominately vertebrate carnivore; I, predominately invertivore. Habitat preference: T, terrestrial; A, arboreal, F, fossorial. Predatory strategy: S, sit-and-wait; A, active forager; W, wide forager. Activity period: N, nocturnal; D, diurnal. EX, personal communication with expert panel (R. How, B. Maryan, E. Pianka, G. Harold, G. Shea). Where multiple preferences are presented in the literature, the most common was chosen or advice from the expert panel was used.

species with the lowest abundance (Table A2) and rarefied using EcoSim Software (http://www.worldagroforestrycentre.org/sites/RSU/resources/biodiversity/software/EcoSim.asp). The default randomisation algorithm with independent sampling was set at 100 iterations. The output diversity data for the undisturbed area from EcoSim Software (Table A2) were used in a Beta-P non-linear regression equation (NLREG software with 1000 iterations; http://www.nlreg.com) to calculate a curved line of best fit though the data. Parameter scores calculated from the Beta-P non-linear regression for the undisturbed area were: *a*—298.89, *b*—0.0178, *c*—4.0944, and *d*—1.1156, for 278 reptile captures.

When 278 individuals were caught in the undisturbed area a total of 24 species (we caught four species on the waste dump that were not caught in the adjacent undisturbed area) had been captured (Fig. 1). The expected species richness for the undisturbed area is calculated when 129 individuals were caught (i.e., equivalent to the total number of individuals caught on the waste dump). The expected species richness value for the undisturbed site is 19.85 (Fig. 1). A total of 16 species were captured at the waste dump. The relative species richness score for the waste dump was calculated using Eq. (1), and is as follows:

$$\text{Relative score} = 100 - \left(2 \times \left(\text{ABS}\left(50 - \left(\frac{16}{19.85 + 16}\right) \times 100\right)\right)\right)$$
$$= 89.25$$

A score of 89.25 represents the relative species richness score for the waste dump compared with the adjacent undisturbed area, out of a possible score of 100.

A.2. Calculation of Log series diversity

The Log series diversity scores for the waste dump and adjacent undisturbed area were calculated using the procedure described in Magurran (1988, p. 132–135). The input data are in Table A3. The Log series diversity scores were 6.30 and 4.81 for the undisturbed area and waste dump, respectively. The relative score for the waste dump compared with the adjacent undisturbed area for Log series diversity is calculated using Eq. (1), and is as follows:

$$\text{Relative score} = 100 - \left(2 \times \left(\text{ABS}\left(50 - \left(\frac{4.81}{6.30 + 4.81}\right) \times 100\right)\right)\right)$$
$$= 86.6$$

The score of 86.6 represents the relative Log series diversity score for the waste dump compared to the adjacent undisturbed area, out of a possible score of 100.

A.3. Calculation of similarity

The Morisita–Horn similarity index was calculated using EstimateS software (Colwell, R.; http://viceroy.eeb.ucon.edu/EstimateS) and input data are shown in Table A3. The calculated similarity score between the waste dump and the adjacent undisturbed area was 0.365, which was then multiplied by 100. The relative similarity between the waste dump and adjacent undisturbed area was 36.5, out of a possible 100.

Table A2 – Input and output data from EcoSim Software to calculate species richness from rarefaction

Input		Output					
Species category	Example undisturbed area data	Abund.	Ave. diversity	Median diversity	Variance diversity	95% Conf. low	95% Conf. high
1	1	1	1.00	1	0.00	1.00	1.00
2	1	12	7.65	8	1.38	5.35	9.95
3	1	24	10.98	11	2.36	7.97	13.99
4	1	35	12.89	13	2.97	9.51	16.27
5	1	47	14.48	15	3.30	10.92	18.04
6	2	58	15.60	15	3.03	12.19	19.01
7	2	70	16.51	17	2.78	13.24	19.78
8	3	81	17.25	17	2.43	14.19	20.31
9	3	93	18.03	18	2.62	14.86	21.20
10	3	104	18.68	19	2.28	15.72	21.64
11	4	116	19.23	20	1.96	16.49	21.97
12	4	127	19.68	20	1.88	17.00	22.36
13	5	139	20.24	20	1.64	17.73	22.75
14	5	150	20.78	21	1.75	18.19	23.37
15	6	162	21.24	21	1.92	18.52	23.96
16	12	173	21.50	22	1.93	18.78	24.22
17	14	185	21.91	22	1.78	19.30	24.52
18	17	196	22.14	22	1.60	19.66	24.62
19	18	208	22.38	23	1.31	20.14	24.62
20	20	219	22.65	23	0.96	20.73	24.57
21	31	231	22.99	23	0.70	21.35	24.63
22	34	242	23.25	23	0.55	21.79	24.71
23	40	254	23.52	24	0.39	22.29	24.75
24	50	265	23.73	24	0.30	22.66	24.80
		277	23.98	24	0.02	23.70	24.26
		278	24.00	24	0.00	24.00	24.00

Ave., mean; Abund., cumulative abundance.

Table A3 – Input data for Log series diversity and Morisita Horn similarity

Species	Undisturbed species abundance	Waste dump species abundance
Diplodactylus granariensis	31	26
Diplodactylus maini	34	0
Diplodactylus pulcher	50	0
Gehyra purpurascens	3	0
Gehyra variegata	20	7
Heteronotia binoei	5	4
Nephrurus laevissimus	0	1
Oedura reticulata	4	0
Rhynchoedura ornata	40	0
Underwoodisaurus milii	5	36
Cryptoblepharus plagiocephalus	6	0
Egernia formosa	1	0
Egernia inornata	17	0
Lerista muelleri	4	2
Lerista picturata	3	0
Menetia greyii	18	23
Morethia butleri	14	3
Ctenophorus cristatus	1	1
Ctenophorus reticulatus	12	9
Pogona minor	2	9
Tympanocryptis cephala	0	1
Varanus caudolineatus	0	1
Varanus gouldii	2	0
Lialis burtonis	0	2
Parasuta monachus	1	3
Simoselaps bertholdi	1	0
Ramphotyphlops bituberculatus	1	0
Ramphotyphlops hamatus	3	1

A.4. *Calculation of evenness*

The calculated evenness for the waste dump was 0.52 and the adjacent undisturbed area was 0.55 using data in Table A3. These values are then inserted in Eq. (1).

$$\text{Relative score} = 100 - \left(2 \times \left(\text{ABS}\left(50 - \left(\frac{0.52}{0.55 + 0.52}\right) \times 100\right)\right)\right) = 97.04$$

A score of 97.04 represents the relative evenness score for the waste dump compared with the adjacent undisturbed area, out of a possible score of 100.

A.5. *Diversity parameter weights*

Equal weightings (25%) were applied to each of the four sub-parameters then added to calculate a score out of 100 for the diversity parameter (i.e., Log series diversity = 86.6/4, S_R = 89.25/4, evenness = 97.04/4, and site similarity = 36.5/4 and summed together). In this example the waste dump scored 77.35 for the diversity parameter.

A.6. *Differential trapping effort on rehabilitated site and undisturbed site*

The trapping-effort (pit-trap nights) was greater for each waste dump than the adjacent undisturbed area. There were

Table A4 – Data for taxonomic groups

	Undisturbed reptile abundance	Waste dump reptile abundance	Adjusted waste dump reptile abundance
Agamids	15	20	13.33
Geckos	192	74	49.33
Pygopods	0	2	1.33
Skinks	63	28	18.67
Varanids	2	1	0.67
Scolecophidians	4	1	0.67
Elapids	2	3	2.00

Table A5 – Results for taxonomic groups

	Output score	Weighting (%)	Adjusted score
Agamids	94.1	5.40	5.08
Geckos	40.9	69.06	28.24
Pygopods	0.0	0.00	0.00
Skinks	45.7	22.66	10.36
Varanids	50.0	0.72	0.36
Scolecophidians	28.6	1.44	0.41
Elapids	100.0	0.72	0.72
Total			45.16

Table A6 – Data for ecological parameter sub-categories

Species	Abundance in undisturbed area	Abundance in rehabilitation area	Adjusted abundance in rehabilitation area
Trophic			
Carnivores	2	5	3.33
Omnivores	34	25	16.67
Invertivores	242	99	66.00
Dietary strategy			
Dietary Sp	95	3	2.00
Non dietary specialist	183	126	84.00
Habitat preference			
Arboreal	34	8	5.33
Fossorial	12	3	2.00
Terrestrial	232	118	78.67
Predatory strategy			
Active forager	89	41	27.33
Sit and Wait forager	90	83	55.33
Widely foraging	99	5	3.33
Activity period			
Diurnal	56	49	32.67
Nocturnal	222	80	53.33

Sp, specialist.

5040 pit-trap nights on the waste dump and 3360 pit-trap nights for the adjacent undisturbed area. The abundance of reptiles captured could not be scaled to equal trapping effort, as diversity indices, species richness, similarity and evenness must be calculated on actual data (i.e., not scaled data). Our higher trapping effort on each waste dump would most probably result in slightly inflated index scores (more similar to undisturbed area) for the diversity parameter, but this is not of concern here as we are describing the concept and methods only. Adjusted abundance on the waste dump = actual abundance × 3360/5040. The input and adjusted data are shown in Table A4.

The relative score for the waste dump compared with the adjacent undisturbed area for the agamid taxonomic group was calculated first by obtaining the relative score using Eq. (1), and is as follows:

Relative score for agamids

$$= 100 - \left(2 \times \left(\text{ABS}\left(50 - \left(\frac{13.33}{15 + 13.33}\right) \times 100\right)\right)\right)$$
$$= 94.10$$

The same calculations were done for each taxonomic group. The results are in Table A5.

Table A7 – Results for trophic groups

	Calculated score	Weighting	Adjusted score
Trophic			
Carnivores	75.00	1/15	5.00
Omnivores	65.79	1/15	4.39
Invertivores	42.72	1/15	2.86
Dietary strategy			
Dietary Sp	4.12	1/10	0.41
Not dietary specialist	62.92	1/10	6.29
Habitat preference			
Arboreal	27.12	1/15	1.81
Fossorial	28.57	1/15	1.90
Terrestrial	50.64	1/15	3.38
Predatory strategy			
Active forager	46.99	1/15	3.13
Sit and Wait forager	76.15	1/15	5.08
Widely foraging	6.51	1/15	0.43
Activity period			
Diurnal	73.68	1/10	7.37
Nocturnal	38.74	1/10	3.87
Total			45.92

Sp, specialist.

Table A8 – Results for trophic parameters

	Calculated score	Weighting (%)	Overall adjusted score
Diversity parameter	77.35	32	24.75
Assemblage composition parameter	45.16	43	19.42
Ecological parameter	45.92	25	11.48
Total			55.65

Table A9 – A summary of all scores used in the calculation of the RDI for the example rehabilitated waste dump

	Maximum weighted score	Example waste dump
Abundance		129
Number of species		16
Diversity parameter		
Log series diversity	25	22.31
Evenness	25	24.26
Similarity	25	9.13
S_R	25	21.65
Diversity parameter	100	77.35
Assemblage composition parameter	100	45.16
Ecological parameter	100	45.92
Weighted scores		
Diversity parameter		24.75
Taxonomic parameter		19.42
Ecological parameter		11.48
Overall score for each site	**100**	**55.65**

A.7. *Weights for taxonomic groups*

The weightings for each taxonomic group were calculated based on the relative proportion that each taxonomic group represents in the undisturbed area. For example, 5.40% of all reptiles captured on the undisturbed area were agamids. Therefore, if the waste dump was a perfect replica of the undisturbed area, 5.40% of captures on the waste dump should be agamids. The adjusted taxonomic group scores are calculated by multiplying the relative score for each family by the weighting; scores are shown in Table A5. Weighted scores were summed and the taxonomic parameter score for the waste dump was 45.16. This score represents the relative similarity between the waste dump and the adjacent undisturbed area for the taxonomic parameter, out of a possible score of 100.

A.8. *Ecological parameter calculation*

The number of individuals caught on the rehabilitated waste dump was adjusted to equate the trapping effort (based on pit-trap nights) with that in the adjacent undisturbed area. There were 5040 pit-trap nights on the waste dump and 3360 pit-trap nights in the adjacent undisturbed area; thus adjusted abundance on the waste dump = actual abundance × 3360/5040. The input and adjusted data are in Table A6. The relative score for the waste dump compared with the adjacent undisturbed area for each category of the ecological parameter was calculated using Eq. (1), as follows:

Relative score for carnivores

$$= 100 - \left(2 \times \left(\mathrm{ABS}\left(50 - \left(\frac{3.33}{2 + 3.33}\right) \times 100\right)\right)\right) = 75.0$$

The same calculations were performed for each ecological category; results are in Table A7.

Each ecological sub-parameter was given an equal weighting (i.e., 0.2). Categories within each ecological sub-parameter are also equally weighted (i.e., nocturnal and diurnal activity periods each have a 0.1 weighting; and carnivore, omnivore and invertivore dietary preferences each have a 0.067 weighting; Table A7). The adjusted ecological category scores are in Table A7. These weighted scores are summed to provide the ecological parameter score for the waste dump (i.e., 45.92).

A.9. *Parameter weightings and RDI calculations*

The mean weightings that resulted in the minimum variance for the 20 sub-sampled undisturbed areas were 32 for the diversity parameter, 43 for the assemblage composition parameter, and 25 for the ecological parameter. These weightings when multiplied by the parameter score optimise the RDI score for the rehabilitated site (Table A8). These adjusted scores are summed to give the RDI score for the waste dump (55.4). Table A9 provides a summary of all the parameter and sub-parameter scores that added together made up the total score for the example waste dump.

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