‘BIOHYETS’: A HOLISTIC METHOD FOR DEMONSTRATING THE EXTENT AND SEVERITY OF ENVIRONMENTAL IMPACTS.

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Abstract

Bioindicators are often more sensitive indicators of both ecosystem health and environmental change than measurement of abiotic pollution parameters. The responses of selected plants and animals to particular anthropogenic impacts can be used to assess environmental responses at a variety of spatial and temporal scales. This study maps the response of key plant, reptile, mammal and bird species to airborne contaminants around a large mine and mineral processing operation at Olympic Dam in arid Australia.

The responses of different bioindicators should ideally be integrated in order to comprehend overall changes in the severity and extent of changes to biological integrity adjacent to pollution sources. Assimilation of different bioindicator responses allows greater precision and geographic coverage of the monitored region and reduces potential distortion from unrelated biological or monitoring responses of individual indicator groups. A single, integrated measure of ecosystem health is also of more value to industrial operators and environmental regulators than several disparate responses. Biohyets, which are the contours of multimetric bioindicator index plots, are used to map variability in ecosystem health.

Key-words: bioindicators, biological integrity index, monitoring, mining.

INTRODUCTION

Contemporary industries are typically required to measure and monitor ecosystem health, which is often simplified as a measure of biodiversity, in the regions that they operate. Industrial environmental monitoring programs should describe the extent and severity of environmental impacts that are attributable to industrial perturbations. Although various forms of disturbance and pollution can be measured directly, monitoring the response of biological parameters is a more valid and often more sensitive method of assessing impacts (Hopkin 1993; Fore et al. 1996). Since comprehensive biological monitoring is rarely
feasible, selected bioindicators, with quantifiable responses to known perturbations, should be selected. Measurable environmental responses may range in severity from a change in fitness or reproductive success of individuals, to a shift in relative abundance of different species, or even the extirpation of vulnerable species.

A range of bioindicators, sensitive to different anthropogenic impacts at a variety of spatial and temporal scales, should be used for comprehensive impact assessment (Landres et al. 1988; Noss 1990). The response of these bioindicators should ideally be assimilated into a holistic and quantifiable measure of environmental health, or index of biological integrity (IBI, Karr 1981). Multivariate statistical correlation of IBI scores with disturbance variables are not necessarily the most valid approach of analysing bioindicator data and are difficult for industry managers, regulators and the public to interpret (Yoccoz 1991; Stewart-Oaten 1996). Rather, graphical techniques for displaying the response of multimetric bioindicator indexes, such as IBI, to human perturbations are more valuable because they incorporate ecological information and are simple to interpret (Fore et al. 1996).

A system for quantifying and displaying the IBI signature, or ‘biohyets’, to map the extent and severity of environmental perturbations from an Australian arid zone mine and mineral processing plant is described.

**Case study: Olympic Dam Mine**

The Olympic Dam mine in arid South Australia, located approximately 520 km north of Adelaide, mills 9 million tonnes of ore per annum to produce copper, uranium, gold and silver per annum at an onsite metallurgical plant, smelter and refinery. Physical disturbance from the underground mine, acid spray and elevated radiation levels are spatially restricted and thus have a limited impact on the regional environment (Read 1997; Read & Pickering 1998). In contrast, the most pervasive and significant environmental impacts of the mining and processing operations are noise and dust, oxides of sulphur and nitrogen from the
smelter and refinery, acid mists from sulphuric acid production and salt spray and particulates entrained from saline aquifers by exhaust air from the underground mine. Research at Olympic Dam has identified reptile, bird, and plant species that are sensitive to these perturbations. No locally-recorded vertebrates or plants are of sufficient conservation significance in the region to warrant specific monitoring.

The optimum habitats, sampling methodology and timing vary for different response variables. Small magnitude anthropogenic impacts are difficult to detect with confidence when natural variability is high (Osenberg et al. 1994). Therefore, the response variables need to be either related to concurrent responses at control localities, or demonstrable by patterning, in order to assess their significance. Where possible, these responses should also be measured against pre-impact levels at the same sites and compared with contemporaneous changes at control sites (Underwood 1995).

**Vertebrate monitoring**

Bioindicator responses were selected that were largely independent of the influence of dramatic climatic variability on the recording rates of many local vertebrates. Therefore, instead of using raw data such as capture rates, ratios of those species that are considered to be indicative of a healthy environment were compared with those species that increase in disturbed environments.

Birds are readily monitored and certain species have responded to local mining impacts at Olympic Dam. Crested Bellbirds (*Oreoica gutturalis*) and mixed-species flocks of insectivorous birds, namely thornbills (*Acanthiza* spp.), southern whiteface (*Aphelocephala leucopsis*) and red-capped robins (*Petroica goodenovii*) are detrimentally affected by the mining and processing operation (Read et al. 2000a). In contrast, a suite of species including magpie-lark (*Grallina cyanoleuca*), zebra finch (*Taeniopygia guttata*), white-plumed honeyeater (*Lichenostomus penicillatus*), red-backed kingfisher (*Todiramphus pyrrhopygia*), white-breasted woodswallow (*Artamus leucorhynchus*), whistling kite (*Haliastur sphenurus*), black kite (*Milvus migrans*), nankeen kestrel (*Falco cenchroides*), introduced species and some waterbirds have benefited from provision of
water, artificial nest sites, additional food supplies or amenity plantings associated with mining (Read et al. 2000a; 2000b). When these birds that benefit from disturbance are excluded, avifauna richness is reduced in disturbed areas (Read et al. 2000a).

The most appropriate habitats and most efficient sampling methods were selected to maximise efficiency and minimise extraneous variability in the data collection. Mulga (Acacia aneura) groves were selected for avifauna monitoring because they are widespread and support a high diversity of potential indicator species (Read et al. 2000a). An inventory of birds seen or heard was compiled during ten-minute visits to 49 groves of mulga trees on still mornings (Fig. 1). Due to the likelihood of overlooking mobile indicator species during these short surveys, the avifauna response score used in this study was the average of the highest 4 scores from 6 sampling periods between November 1998 and October 2000.

Chenopod shrublands support the highest diversity and abundance of small vertebrates at Olympic Dam (Read 1992) and hence were optimal habitats for monitoring. Small terrestrial vertebrates were sampled annually at 12 pitfall sites in zones both near the smelter and ventilation bores and at remote localities (Fig. 1). Each site comprised 13 pits, 150mm in diameter, spaced at 6 metre intervals in a cross. All pits were open concurrently for ten consecutive days, which has been shown to be a sufficient period for representatively sampling the terrestrial fauna (Moseby & Read 2001). The termite-specialist geckos, Rhynchoedura ornata and Diplodactylus conspicillatus are both locally abundant and apparently sensitive to air pollution (Read 1996). Fecundity in geckos, which is easily assessed by checking for visible eggs in adult females, is also reduced in polluted areas (Read 1996). Capture of more than four termite specialist geckos or at least half of the adult females gravid suggest that the monitoring site has not been severely affected by air pollution. The ratio of open-habitat favouring agamids to skinks is typically higher in disturbed local environments than in low impact areas (Read 1999). Disturbed areas also typically support higher numbers of the introduced house mouse (Mus domesticus), compared with unaffected regions where native rodents, with the exception of desert mouse (Pseudomys desertor), are typically more abundant (Read et al. 1999).
Figure 1 Location of the Olympic Dam Mine and Processing Plant and the monitoring sites for plant bioassays (triangles), terrestrial vertebrates (circles) and avifauna (squares).
The biological integrity index for each sampling site was compiled by summing arbitrary scores of 1 for each bioindicator group that indicated a healthy, rather than disturbed environment (Table 1). The total site scores used for this study was the average of the scores from the sampling sessions in December 1998 and 1999.

**Table 1** Vertebrate responses indicative of undisturbed environments

<table>
<thead>
<tr>
<th>Monitoring type</th>
<th>Score of 1 assigned for each of these responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial vertebrates</td>
<td>Skink (<em>Ctenotus</em>) captures exceed dragons (<em>Ctenophorus</em>)</td>
</tr>
<tr>
<td></td>
<td>Native rodent (excluding desert mouse) captures exceed house mouse captures</td>
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<tr>
<td></td>
<td>&gt;4 termite specialist gecko captures or &gt;=50% of female geckos gravid</td>
</tr>
<tr>
<td>Bird transects</td>
<td>crested bellbirds present</td>
</tr>
<tr>
<td></td>
<td>Either chestnut-rumped or inland thornbill, southern whiteface or red-capped robin recorded</td>
</tr>
<tr>
<td></td>
<td>Bird richness (excluding disturbance birds) &gt;5</td>
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**Vegetation bioassay**

Two widespread perennial plant species, sandhill wattle (*Acacia ligulata*) and narrow-leafed hopbush (*Dodonaea viscosa*), have been used as the basis for emissions bioassay at Olympic Dam since 1989, when the basic symptomology and sampling was established (Fatchen & Associates 1989). Foliar damage is easily seen on both species, and individuals are widespread throughout the study area. The species together provide responses of phyllodes (*Acacia ligulata*) and true leaves (*Dodonaea viscosa*).

The most reliable foliar damage symptoms have been necrotic stippling, whether from direct acid aerosol effects or from jammed stomata, and tip necrosis or “leaf-burn”. The first occurs almost entirely under acid aerosol release or gaseous fumigation, whilst the second is
almost entirely due to salt deposition from saline aerosols. Other symptoms (eg from Boubel et al. 1994) are present but are confounded. Chlorotic responses, in particular, may be wholly satisfactory as a damage symptom in a moist growth period, and wholly misleading in extended drought when most individuals may become chlorotic.

Sampling was on a radial grid, at each of 32 sites centred on the main smelter stack, to a maximum distance of 6.2 km (Fig.1). Simple presence/absence scoring was applied. Five bushes of each species were sampled at a given sample point, and the number displaying a given symptom noted. The simple additive nature of the scoring allows for both individual sensitivity and varying atmospheric dilution to be reflected in scores. In severely-impacted areas, all individuals show symptoms regardless of individual resistance. In lightly-impacted areas, only one or two individuals may show symptoms.

**Environmental response**

The score at each site for each bioindicator type was plotted using Golden Software Ltd Surfer v.7 surface modelling software and applying maximum kriging for interpolation. Mapping of the extent and severity of environmental impacts attributable to the operations was then achieved by integrating the responses of all of the bioindicators. In each case a low rescaled standardised score indicates low environmental health. For example, sites with few disturbance-sensitive vertebrates receive a low score and plant bioassay sites with an abundance of pathological symptoms also receives a low score.

For both birds and terrestrial vertebrates, the maximum score achievable for each site was three. For the two plant bioassay symptoms, the maximum score over ten bushes at the most heavily-impacted sites is 20, and the minimum score 0. To facilitate incorporation with the other bioindicators, the plant bioassay spectrum was also divided into three classes. Up to six cases of symptoms was classed as ‘undetectable’ and received a score of 3, to allow for a modicum of field scoring error such as mistaking insect attack for stippling. 7-13 symptoms were classed as ‘detectable’ and given a score of 2, and 14 or more cases classed as ‘pronounced’ with a score of 1.
It was likely that maximum potential bioindicators for birds and terrestrial vertebrates would not be recorded from remote control sites, particularly when the scores were the averages of several sampling sessions. Equally, it was unlikely that all sites in the heavily-affected zone would return minimum scores for all of the bioindicators. Therefore, we considered sites within the lowest third of the range of scaled scores recorded for each of bioindicators to represent heavily-impacted sites, whereas biological integrity scores in the highest third of the range represented sites of negligible disturbance. For both terrestrial vertebrates and plant bioassays, biological integrity scores of less than 1.2 were considered to be heavily-impacted sites, scores of 1.2 to 2.2 were considered to represent affected sites and scores in excess of 2.2 represented sites of negligible disturbance. The range of biological integrity site scores for avifauna differed, hence the respective cutoff for high and detectable disturbance were 1.13 and 2.06 respectively.

Evenly weighted scaled scores of each of the bioindicator groups were used to model the integrated biological integrity index. Again, the zone incorporating sites within the lowest third of modelled site score range (IBI <1.27) was considered to represent heavily-disturbed region and sites within the highest third of the range (IBI >2.14) were considered to represent unaffected the back-ground region.

RESULTS

Each of the IBI plots for different bioindicator groups reveals a near concentric reduction in measurable impact, centred upon the processing plant. Impacts for the plant bioassay and terrestrial vertebrate groups were negligible at the margins of the Olympic Dam mine lease (Figs 2 & 4). The avifauna response also included several apparent impact anomalies to the north and west of the mine (Fig. 3).
Figure 2 Pronounced and detectable impact zones, around the Olympic Dam processing plant, as modelled from plant bioassay indices.

Figure 3 Pronounced and detectable impact zones, around the Olympic Dam processing plant, as modelled from avifauna indicator indices.
Figure 4 Pronounced and detectable impact zones, around the Olympic Dam processing plant, as modelled from terrestrial vertebrate indicator indices.

For each of the bird, terrestrial vertebrates and plant bioassay plots, the biohyets joining sites with IBI scores within the minimum one third of the score range represented the most disturbed zones. In all cases this zone was confined to within were confined to within three kilometres of the smelter and ventilation bores (Figs 2-4). When these responses were combined to a single environmental response (Fig. 5), the zone within the 1.27 biohyet measured 600 ha (Fig. 6). In keeping with this classification, IBI scores greater than the combined indicator biohyet of 2.14 was used to indicate the zone where environmental responses were negligible. The intermediate zone of detectable impact identified by the amalgamation of all bioindicators was 3400 ha at the time of this study.
Figure 5 Biohyets representing the amalgamated averaged scaled biological integrity scores of the three bioindicators groups.
**DISCUSSION**

The IBI response plot using biohyets compiled from a range of different bioindicators provides an objective indication of the degree and extent of environmental impacts. The extent and severity of environmental impacts displayed in this study will serve as a benchmark for monitoring future trends in environmental health. This output is superior to conventional site-based analytical and statistical reporting of environmental impacts at the Olympic Dam minesite for the following reasons:

1) The responses of a range of bioindicators are integrated to a single IBI signature. The extent and severity of environmental impact are clearly visible from a simple plot. Temporal changes in environmental health can be quantified and displayed visually. The validity of pollution modelling as a predictive tool can be readily assessed. Biohyet plots can be compared to plots of the monitored exogenous variables to facilitate understanding of causal relationships between environmental responses and particular anthropogenic insults.
Key regions are identified to establish additional monitoring sites for existing bioindicators and for assessment of other bioindicators, such as frogs, that are opportunistically collected in broad regions.

The greatest potential risk of displaying biological integrity with a combined biohyet plot is its simplicity. The permutations of potential biotic responses to industrial activities prohibit the measurement of changes to the ‘health’ of all ecosystem components. Modelled interpolation of the scaled responses of selected bioindicators only provides an overview of the degree and extent of environmental change. Therefore, the interpretation of biohyet plots must be made on the understanding that responses at finer symptomatic, taxonomic, spatial and temporal scales are masked by this process. Furthermore, the objective scaling of bioindicator responses and interpretation of the biological significance of different biohyet scores can potentially be manipulated depending upon the agenda of the monitoring and reporting agency. Therefore, use of integrated biological integrity monitoring must be accompanied by absolute transparency in scaling and modelling procedures as well as biologically supported pragmaticism in the designation of impact zones.

The development of the IBI for monitoring ecosystem response to perturbations at Olympic Dam is clearly an iterative process. Research and additional data collection should facilitate refinements to the scaling of responses from the chosen bioindicators. For example, the outliers caused by several avifauna monitoring sites may be able to be eliminated by rescaling the effect of not recording particular species from these sites. Our analysis considers the absence of Crested Bellbirds from a remote site to indicate a disturbance response, whereas it may simply reflect patchy distribution of this species, or a reduction in their calling frequency outside the breeding season. Further research may allow this anomaly to be overcome through changing either the monitoring technique or through scaling of the Crested Bellbird response.
Another method of reducing the influence of stochastic outliers is through incorporating a larger range of bioindicators throughout a broader range of sites. Ants are an additional bioindicator group that could be integrated in the future. Although use of ant functional groups to indicate environmental health have proven to be valuable elsewhere (Andersen 1990), modifications to these groups are necessary before they may be useful locally (Read 1996; Read & Andersen 2000). The ecology and disturbance response of other biotic groups, including lichens (Erhardt et al. 1992), could also be researched and possibly incorporated into a more holistic biological integrity monitoring system for Olympic Dam. The distribution of weeds and feral animals affect ecosystem health and are also potentially influenced by the mining operation. Therefore exotic species, along with indigenous bioindicators could also be incorporated into an expanded monitoring program.

The validity of accurately defining the extent of impact zones would be enhanced by sampling all bioindicator groups on a radial or geometric grid that extends beyond the limits of disturbance. Whilst this is readily achieved with bioassays of widespread plants and possibly insect populations, spatial habitat heterogeneity may preclude the sampling of other organisms in such a regulated manner. Distribution patterns are therefore important considerations in determining the types or ranges of bioindicators selected.

Although the types of bioindicators and the nature of sampling are in some cases site-specific, the approach of integrating biological integrity indices has widespread potential for a range of biological monitoring tasks. Biohyets will be most effective for monitoring point-based perturbations, particularly when regulations require, or resources permit, intensive research and sampling. Biohyets may also prove a useful technique for integrating ground-based monitoring of biodiversity components, such as the cover and diversity of vegetation, or the abundance of threatened species, weeds and feral animals, with broadscale indices such as aerial surveys, remote sensing and rainfall. Monitoring precision and applicability in these broadscale applications will be heavily dependant upon the distribution and timing of ground-based surveys. Other potential applications of integrating biological integrity indices include monitoring biodiversity or ecosystem response to habitat restoration, in both terrestrial and aquatic ecosystems.
ACKNOWLEDGEMENTS

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