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Methods for identifying, selecting and interpreting indicators for assessing biodiversity condition in desert Australia, using the Stony Plains bioregion as a case study

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Department for Environment and Heritage

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The Desert Knowledge Cooperative Research Centre is an unincorporated joint venture with 28 partners whose mission is to develop and disseminate an understanding of sustainable living in remote desert environments, deliver enduring regional economies and livelihoods based on Desert Knowledge, and create the networks to market this knowledge in other desert lands.

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Shortened forms

AGO	Australian Greenhouse Office
ACRIS	Australian Collaborative Rangelands Information System
CSIRO WPAC	CSIRO Wet Period Average Cover
DEH	Department for Environment and Heritage, South Australia
DEM	Digital elevation model
DWLBC	Department of Water, Land and Biodiversity Conservation, South Australia
GAB	Great Artesian Basin
GABSI	Great Artesian Basin Sustainability Initiative
GDM	General dissimilarity modeling
IBRA	Interim Biogeographic Regionalisation of Australia
Landsat TM	Landsat is a satellite that uses the Thematic Mapper sensor
NLWRA	National Land and Water Resources Audit
NRM	Natural Resource Management
PIRSA	Primary Industries and Resources, South Australia
PMIS	Pastoral Monitoring Information System
SRTM	Shuttle Radar Topography Mission
TGP	Total Grazing Pressure

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Glossary

Alpha diversity	A component of biodiversity described by species richness (i.e. the number of species)
Beta diversity	Beta diversity describes the difference in composition of species between different habitats or environments located close together in the same landscape. It is synonymous with compositional dissimilarity, the term used throughout this report.
Biodiversity condition	See ecological integrity
Biodiversity values	Society's perceptions of plants, animals and their habitats based on its experiences, principles, ethics and ideals of nature. For the Stony Plains bioregion, we interpreted these values as the significant biodiversity assets of the region and the value placed on those assets by people of the region and society as a whole.
Compositional dissimilarity	Compositional dissimilarity is synonymous with beta diversity, and it quantifies the difference in composition of species between different habitats or environments located close together in the same landscape. It is quantified in General dissimilarity modeling (GDM) with a dissimilarity measure (Ferrier 2002 and references therein). GDM predicts biological dissimilarity between sites across landscapes as a function of gamma diversity and beta diversity (see this Glossary).
Ecological integrity	A multi-concept describing the health of ecological phenomena, including biodiversity, based on its sustainability, naturalness and resilience (Andreasen et al. 2001).
Gamma diversity	A component of biological diversity that describes the differences in the composition of species between geographically isolated occurrences of the same habitat or environment (Ferrier 2000 and references therein).
Indicator	Product of environmental measurement that is intended to signal something in the environment that is not measured but is of interest (Suter 2001).
Outcome-based indicator	An indicator that measures surrogates of biodiversity or environmental phenomena that relate to the desired outcomes of monitoring programs for sustaining or improving biodiversity condition. They link monitoring data for biodiversity to the assessment of its risk and management.
PD54	Index of vegetation cover
Surrogate	An attribute that represents biodiversity either as a true or estimator surrogate (Sakar & Margules 2002). Estimator surrogates estimate true biodiversity by using environmental or disturbance attributes (e.g. climate variables, total grazing pressure). True surrogates represent actual biodiversity (e.g. vegetation cover).

Summary

The assessment of biodiversity condition is becoming increasingly important in natural resource management (NRM), especially within the context of climate change. The challenge facing land and biodiversity conservation managers is knowledge about what biodiversity to assess, how to measure it and how to interpret complex ecological information to inform policy and management decisions. There are few operational frameworks to solve these challenges. This technical report examines the feasibility of identifying appropriate indicators to monitor and assess biodiversity, focusing on an arid rangeland landscape.

Using an ecological risk assessment philosophy, we developed a method to identify and select outcome-based indicators to audit biodiversity and assess its condition. We interpreted this challenge as an exercise in designing a biodiversity monitoring program at the regional scale where the purpose of monitoring was to detect change, interpret monitoring data to assess condition and make management decisions. We focused on the regional scale because most planning, management decisions and reporting for biodiversity occurs at this level. Lessons learned in other studies indicated that we needed to take a strategic approach to identifying indicators, as not all indicators will be suitable to measure information pertaining to the desired management outcomes. We were also aware of the importance of acceptance of indicators; therefore, it was important to identify a set of field-based and remotely derived indicators that were scientifically credible and practical to measure. We also propose a new method to interpret biodiversity condition, and we illustrate it using a hypothetical example.

Using the Stony Plains bioregion in northern South Australia as a case study region, we identified four desired outcomes for managing the region's biodiversity. These desired outcomes were devised in targeted workshops following an assessment of biodiversity at risk in the region. They are:

1. maintaining and restoring native vegetation typical of the study region's communities

2. reducing the loss of the existing complement of rare and regionally significant native flora and fauna species, populations and ecological communities

3. maintaining and restoring natural surface water flows and natural drainage lines

4. creating a mosaic of water remote areas.

For each outcome, we identified relevant biodiversity surrogates and assessed the ecological function of those surrogates. This meant the indicators were not only outcome-based – being related to the management outcomes – but also had a degree of ecological meaning depending on the depth of our knowledge of the relationship of ecosystem processes (including disturbances) in the region. We initially selected a number of potential indicators and then refined it to a workable set, using 33 selection criteria that covered such indicator properties as conceptual relevance, historical information, measurement qualities, feasibility of implementation and policy and management utility. Only those indicators that met a 'rule-of-thumb' of around two-thirds of the criteria were included in the final set. Each of the four desired outcomes had the following number of indicators selected:

1. 10 (48%)   2. 14 (77%)   3. 5 (63%)   4. 2 (100%)

Not all indicators met the same criteria. The following list shows the range in the number of criteria out of a total of 33 met by the different indicators of the final set for each of the four desired outcomes:

1. between 22 and 29 across 10 indicators
2. between 16 and 29 across 14 indicators
3. between 21 and 29 across 5 indicators
4. between 28 and 30 across 2 indicators

The number of criteria met by those indicators excluded from the final set for each of the four outcomes were:

1. between 10 and 21 across 11 indicators
2. between 10 and 17 across 14 indicators
3. between 13 and 15 across 5 indicators
4. none excluded.

We attempted to use spatial modelling techniques to identify valid biodiversity surrogates to add to our toolbox of indicators. Using general dissimilarity modelling, we modelled persistent native plants species against a number of biophysical variables (climate, topography, soil attributes, broad habitat features and surrogates of total grazing pressure). This approach was not useful because we had insufficient knowledge about the relationship between biodiversity patterns and these environmental variables.

Biodiversity condition is difficult to assess with current data sets; therefore, two additional indicators will need to be monitored over time at ‘condition state sites’ and monitoring sites within each land type. Condition state sites are localised control sites that represent biodiversity responses under extreme conditions ranging from severely to hardly degraded sites. Monitoring data for these sites provide baseline information for interpreting results from the monitoring program. Both types of these data were depicted in radar plots in different ways to illustrate how practitioners may need to interpret the data. Radar plots are XY line graphs with Cartesian coordinates and can be produced from any good statistical or graphical software. We rejected the notion of a biodiversity condition metric because a single number can mask the ecological complexity of stressed environments and lead to perverse policy and management decisions. For example, measuring the percent cover of native vegetation without considering the diversity of that vegetation could lead to interpretations of ‘good condition’, especially when cover values are high. In reality, the vegetation may be depauperate with low species richness, or it may be a monoculture of a species favoured by disturbance. The benefits of graphically depicting the values of the indicators are that they show the complexity of information in a way that is easy for most people to interpret, aiding recognition of changes in biodiversity degradation over time. However, we do propose metrics be used for gilgai degradation and excessive grazing pressure.

We conclude that it is fundamental to undertake a strategic biodiversity risk assessment to identify and select a potential set of indicators for auditing biodiversity and assessing its condition. The final set of indicators is outcome based (i.e. relating to the desired outcomes for managing biodiversity), theoretically credible and practical. These indicators are complete in that they collectively cover the complexity of biodiversity as well as the causal relationship between driving forces, stressors, condition, impact and response. It is not feasible to use regional spatial modelling techniques at this stage to identify regional surrogates of biodiversity. We recommend more research to comprehensively test the merit of the indicators to identify changes in biodiversity condition. This will help us to understand the relationship of remotely derived indicators to biological patterns.

1. Introduction

Assessing the condition of biodiversity is a fundamental requirement of natural resource management (NRM) regulations in Australia and worldwide. NRM managers are increasingly being challenged to answer questions about what biodiversity to assess and how to measure its condition in ecological systems that are inherently complex and which can be perceived as having disparate *biodiversity values* (see Glossary for definition) by different natural resource managers. In early 2004 the Pastoral Land Management program of the South Australian Department of Water, Land and Biodiversity Conservation (DWLBC) was confronted with this challenge. They planned to audit biodiversity and assess its condition in the arid rangelands with the intent of rewarding landholders for ecologically sustainable outcomes. A partnership was formed between CSIRO; South Australian Department for Environment and Heritage and the Department for Water, Land and Biodiversity Conservation; and BHP Billiton to identify methods to undertake this work.

1.1 Background

Maintaining biodiversity by auditing and assessing its condition is problematic. Monitoring has been simply defined as an 'on-going assessment of the abundance of biodiversity to ensure both its protection and the effectiveness (and refinement) of its management' (Hunt et al. 2006). Ideally, we seek a simple, systematic and repeated measurement of biodiversity values to detect changes specifically for the purposes of indicating which elements of biodiversity are at risk and to guide management decisions to ensure its integrity. As part of the process, biodiversity is audited and its condition assessed. Much research has been devoted to the monitoring of Australia's rangeland biodiversity (Smyth et al. 2003, James 2004, Smyth & James 2004, see papers in the thematic issue on this topic in *Austral Ecology* Volume 29 (1), Hunt et al. 2006), but it is not straightforward. Considerable strategic planning is required before any work can start on the ground. Hunt et al. (2006) describe some of the complexity involved in developing biodiversity monitoring programs at the regional scale, using guiding principles for a worked example for the Burdekin Dry Tropics (see Appendices 1 and 2 for a detailed description of each respectively).

The monitoring of biodiversity is an outcome-based activity that is meant to positively improve the condition of biodiversity at risk. Often it is a necessary activity to achieve the desired outcomes of NRM plans (e.g. the Burdekin Dry Tropics example in Hunt et al. 2006). One of the challenges with monitoring is that it is not possible to detect changes and know everything about biodiversity in all places, and not all biodiversity will need to have its condition assessed (Sakar & Margules 2002). The auditing of biodiversity will involve using scientifically credible indicators as measurements of biodiversity surrogates (see the Glossary for a definition of a *surrogate* and an *indicator*). Most studies on biodiversity monitoring have devoted attention to producing sets of indicators (e.g. Smyth et al. 2003, James 2004, Hunt et al. 2006), but little work has been done on developing a methodology for the selection of indicators.

A significant gap in the biodiversity monitoring research is a conceptual statement about 'improved condition of biodiversity', which we refer to as biodiversity condition. It has been conceptualised using the notion of ecological integrity. Considerable research has been undertaken in this area (e.g. Karr & Dudley 1981, Majer & Beeston 1996, Cornforth 1999, Dale & Beyeler 2001, Suter 2001, Carignan & Villard 2002, Read et al. 2005) as a means of assessing condition for making management decisions. Integrating the concepts of sustainability, naturalness and resilience, which are recommended qualities of indicators for measuring biodiversity, is a multi-concept (Andreasen et al. 2001). Studies on its measurement have generated useful selection criteria for identifying scientifically meaningful indicators for assessing condition. However, the challenge of choosing a realistic and credible set of indicators for monitoring biodiversity remains.

Another hurdle with monitoring biodiversity is that the biodiversity at risk will differ regionally (see the bioregional summaries reported by Whitehead et al. 2001 and a summary of ‘at risk’ vertebrate species in the rangelands by Smyth & James 2004). Although disturbances affecting biodiversity may overlap for some regions, the intensity and extent of disturbances will vary substantially depending on ecosystem resilience. Its condition will be regionally specific and its assessment, as measured by the biodiversity at risk, will involve predicting the nature and likely effects of environmental stressors on biodiversity (Suter 2001). However, predicting the behaviour of dynamic ecosystems is an impossible task; therefore, it is easy for scientists to delve into the detail of complex biophysical dynamics that hamper rather than inform decision making. Nevertheless, NRM decisions are being made on the overall integrity of ecological systems rather than on detailed knowledge that cannot be understood nor predicted under present ecological theory (see the thematic issue on new perspectives in ecology in *Conservation Biology*, Volume 14). In this context, the indicators with known and predictable responses to environmental stressors with known levels of confidence in a general sense are recommended for measuring biodiversity condition (Suter 2001). Most indicators recommended for rangelands biodiversity monitoring have not been evaluated for predictive qualities.

Indicators for monitoring Australia’s rangelands have been grouped into two types, namely pressure and response indicators (Smyth et al. 2003, Hunt et al. 2006). Niemeijer and de Groot (2007) described five different types that represent different links of the causality chain for disturbed ecosystems: driving force, pressure, state, impact and response indicators. In modified ecosystems, societal driving forces (e.g. land uses) mediate pressures (e.g. mineral extraction). These pressures then influence the state of biodiversity (e.g. habitat structure of animals), which may or may not impact on it (e.g. richness of small ground mammals) and, as a consequence, society responds (e.g. people act to prevent the extinction of an iconic species). Niemeijer and de Groot (2007) recommend that condition should be measured and assessed using each of the five indicator types.

The monitoring and management of biodiversity are recognised as important activities in regional NRM plans where there is a need to monitor biodiversity against resource condition targets (Hunt et al. 2006). Because the biodiversity values and their stressors will be regionally specific, bioregions will have different biodiversity conservation issues, management objectives and outcomes to achieve. Often resources will be limited to priority conservation issues and there may be a subset of desired outcomes pertaining to each priority. Each outcome has its own specific set of biodiversity values and indicators for measurement. Therefore, the selection of indicators is related to the biodiversity values summarised by the desired outcomes of management. Very little research has been devoted to developing methodological frameworks for how to relate indicator selection to management outcomes.

An area of research that has received attention is that of interpreting biodiversity condition. Awareness of the complexity of ecosystems and their functioning means that any attempt to distil such complexity into a single number will be viewed as mostly foolhardy. The result is arbitrary at best and seriously deceptive at worst (Andreasen et al. 2001, Suter 2001). The customers of a ‘condition measure’ in our study are mostly land managers and possibly producers, and they have already expressed concerns about simplifying information. There are many approaches that could be adopted for measuring biodiversity condition, ranging from simple aggregates (e.g. Ant Index of Biological Integrity: Majer & Beeston 1996; Biohyets: Read et al. 2005; the biodiversity significance score of biodiversity incentive metrics: Oliver & Parkes 2003) and graphical representations (e.g. radar diagrams: Suter 2001) to more sophisticated multivariate mathematical treatments (Andreasen et al. 2001). We draw on graphical presentations in this study.

This report describes new methods for identifying and interpreting a realistic set of outcome-based indicators for assessing the condition of biodiversity in Australia’s arid rangelands, using the Stony Plains bioregion in northern South Australia as a case study. We identified a set of field- and remotely-detected indicators that were related to a set of desired outcomes for managing biodiversity in the case study region. These were evaluated for scientific credibility against a set of selection criteria, and a method was developed for interpreting condition based on a hypothetical set of results for the chosen indicators.

1.2 Aims

This project had the following five aims relevant to the South Australian arid rangelands:

1. to review the content, structure and design issues of biodiversity incentive metrics presently in use in Australia
2. to develop methods for selecting and interpreting biodiversity condition from outcome-based indicators
3. to document a set of realistic field- and remotely-based indicators relating to the outcomes for biodiversity condition in the Stony Plains bioregion
4. to appraise the feasibility of these tools to help allocate rewards for high biodiversity condition
5. to appraise the potential of incentives for achieving biodiversity outcomes.

The review (Aim 1) is to be presented elsewhere (Davies & Smyth, submitted). Aim 5 has been reported in a linked project (Smyth et al. 2007a). Aims 2, 3 and 4 are reported here.

1.3 Report structure

Section 2 describes the methodology for identifying appropriate indicators that can be measured in the field or remotely to assess biodiversity condition.

Section 3 describes the results of expert and analytical approaches to identify indicators and an approach to assess biodiversity condition.

Section 4 discusses our findings, the feasibility of the indicators and a condition assessment approach, whether our aims were met and the next challenges ahead in this area of research.

2. Methodology

In this chapter, we describe new methods for selecting and interpreting a realistic set of *outcome-based indicators* (see Glossary for definition) for assessing biodiversity condition. We chose the Stony Plains bioregion as a case study to explore the feasibility of this approach because other linked research projects were already underway in the region and a number of scientific and regional planning resources were available.

A new method for selecting indicators is used to identify field-based and remotely-derived indicators that are presently recognised as potential surrogates for biodiversity (Bastin & Ludwig 2006, Jafari et al. 2007). We refer to these indicators as *field* and *remote* indicators respectively. We have chosen to include both types of indicators because feedback from selected landholder workshops in a related project indicated a strong acceptance for the use of both types together to represent biodiversity patterns rather than either type by itself (Gorddard et al. 2007). Remote indicators also enable condition to be assessed at regional scales and therefore link into regional planning processes more directly than field indicators that represent patterns at local scales. Once the potential set of indicators was identified, we then applied a rule-of-thumb based on the number of criteria met by each indicator to select the final set of indicators. The criteria were an integrated and evolving set based on a synthesis of the most recent information published in the ecological indicators literature on metric credibility and indicator selection for ecological integrity. The criteria balanced a set of desirable characteristics against the practicalities of choosing a realistic number of indicators that can be measured on the ground or derived remotely.

We also explored the feasibility of predicting a set of biophysical attributes as estimator surrogates for true biodiversity as measured by persistent, native plant species. These were added to the list of potential remote indicators. Estimator surrogates can be easier and less costly to monitor than true surrogates of biodiversity. This work extended our case study region just beyond the Stony Plains bioregion and will be discussed later in this chapter.

The second method – interpreting the values of indicators for assessing biodiversity condition – is based on a graphical representation. It builds on the value of radar plots or XY plots with Cartesian coordinates found in most statistical and graphical software. In this report, we used hypothetical data for a subset of final indicators relevant to the Stony Plains bioregion to illustrate the method.

2.1 Stony Plains bioregion

The case study region covered an area of 129 240 km^2 (13.2%) of South Australia (see Figure 1). Of this, most is under pastoral lease and therefore potentially subject to grazing by cattle. Its key features are the vast undulating gibber and gypsum plains that can be separated into the following five major landforms, each supporting broadly different ecological communities:

- drainage lines and flood plains
- stony plains and tablelands
- Great Artesian Basin (GAB) springs
- dunefields and sand plains
- breakaways and stony hills.

The bioregion supports 17 major vegetation types, 784 plant species, approximately 230 bird species, 100 reptile species, five frog species, and 41 native and 11 feral mammal species (Brandle 1998). Seventy-seven land types representing broad ecoregions have been mapped for the case study region by DWLBC (Fleming & Brook 2007).

Figure 1: Map of the Stony Plains case study bioregion (dark grey) in the rangelands of Australia (light grey)

The Stony Plains bioregion is situated in the most arid region of Australia with a median annual rainfall of 150 mm. Summers are hot to extremely hot and dry, while winters are short, dry and cool to cold (Brandle 1998). Rainfall is highly variable and unpredictable in locality, timing and quantity (Figure 2). Although heavier showers are more likely in summer than winter months, they are patchy and highly variable in timing. In these environments, the norm is 'dry' drought-like conditions interspersed with occasional unpredictable showers and even rarer periods of heavy rain.

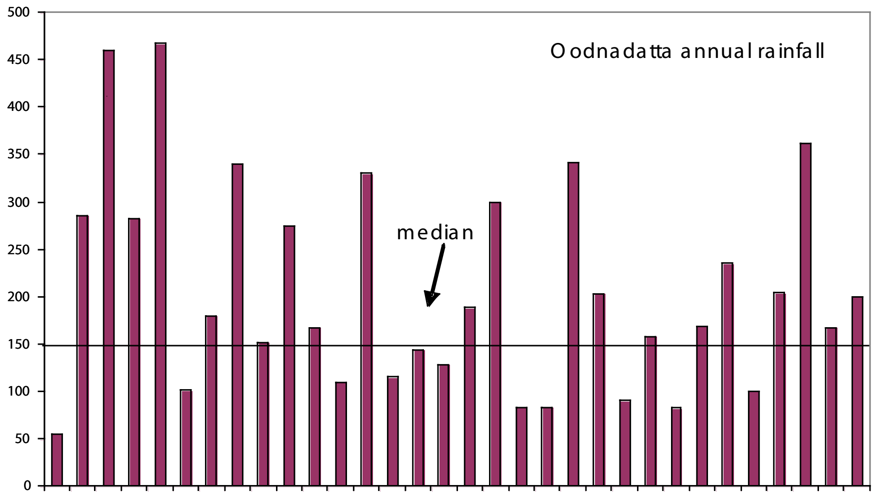


Figure 2: Rainfall at Oodnadatta Station, 1972–2003

Land uses are cattle grazing, mining, ecotourism, protected areas and regional towns, with cattle grazing being the most widespread, especially in the pastorally productive Stony Plains vegetation communities. Cattle producers, through leasehold and existing or pending Indigenous land use arrangements, are the major landholders in the bioregion. Biodiversity is important for the region's production and for its natural and cultural heritage values. The key threats and pressures to biodiversity specific to the Stony Plain bioregion, as identified in a series of workshops for related research (Smyth et al. 2000), are:

- loss, fragmentation and degradation of functioning ecological communities through excessive grazing pressure exerted by domestic stock, feral herbivores (camels, donkeys, horses and rabbits) and kangaroos north of the dog fence
- loss of species through increased predation by introduced predators (e.g. foxes and cats) and excessive grazing pressure
- changes in natural surface water flows caused by mechanical disturbances of natural water flows and/or flooding regimes of watercourses associated with grazing (e.g. building of artificial flow barriers, storage areas and dams).

2.2 Selecting indicators

We cannot select indicators for the monitoring and management of biodiversity without understanding the biodiversity management priorities at the regional scale. We also need to know how assessing condition relates to those priorities, the management objectives and the desired outcomes. We need to focus at the regional level to gain this understanding because biodiversity conservation planning, management and reporting happen mostly at this level. More importantly, biodiversity and its stressors tend to be regionally specific, which means that mitigation will be mostly unique to regions although overlap may occur among nearby regions depending on the scales of ecological dynamics and disturbances.

The methods used to select field and remote indicators for auditing biodiversity and assessing its condition involved undertaking three broad tasks (Figure 3):

- prioritising significant biodiversity at risk at the regional scale
- identifying a potential set of outcome-based indicators for monitoring
- selecting, based on criteria, a credible and realistic set of outcome-based indicators.

Information for Tasks 1 and 2 was obtained during three workshops involving stakeholders, technical experts and landholders, held during 2005 and 2006 (see Appendix 3 for a list of participants).

This overall approach to Task 1 followed conceptual frameworks used by the US Environmental Protection Agency for their environmental monitoring programs. The monitoring identifies the attributes that are 'important, susceptible and valued; stressors that are of regional concerns; and environmental properties that are relevant to the relationship between stressors and the receptors [the impact attributes]' (Suter 2001). The method of Hunt et al. (2006) also reflects this logic. Potential indicators therefore reflect information about significant biodiversity, stressors and priority biodiversity at risk.

Task 2 identified indicators that relate to the desired outcomes of management arising from the assessment of at-risk biodiversity. In this context, the indicators signal information about biodiversity at risk and improvements in its condition as summarised by the management outcomes. Another benefit of this task is that it identifies those biodiversity values that specifically relate to management outcomes. Once we understand the ecological function of the biodiversity surrogates (a subset of biodiversity values identified in the assessment of biodiversity at risk), we are then able to identify a set of potential indicators that are not only outcome based but are more ecologically meaningful, to the best of our knowledge, than a long 'wish list' would be (Gibbons & Freudenberger 2006). At this point, the potential indicators should be scientifically credible tools for auditing biodiversity, assessing its condition and managing decision-making. However, are they a practical set that can be applied on the ground?

Not all potential indicators can be applied on the ground because of limits in their qualities. In Task 3, each potential indicator was evaluated against a set of criteria compiled from the scientific literature on ecological indicators and metrics (Table 1). As a rule-of-thumb only those indicators that meet at least two-thirds of the criteria were selected. This rule is based on expert judgement, which is necessary, as different indicators relate to different outcomes, and true surrogates tend to meet fewer criteria because our scientific knowledge is incomplete. For this reason, we did not develop a cut-off rule for the number of criteria to be met. After completing this step, we propose that the final set of indicators will be useful tools for monitoring biodiversity, assessing its condition and making management decisions.

2.3 Predicting estimator surrogates of regional biodiversity

The first step involved using predictive general dissimilarity modelling (GDM) to identify indicators of biodiversity where floristic diversity was used as a surrogate for the compositional aspects of floristic biodiversity at broad landscape scales. This is a valid surrogate because vegetation across arid rangeland environments can be observed, provides food and habitat resources for animals, is vulnerable to excessive grazing pressures (Havstaad et al. 2007) and provides an essential ecosystem service for pastoralism. Spatial modelling of environmental attributes (e.g. climate, terrain, soil attributes and habitat or vegetation), as surrogates of biodiversity, is used in biodiversity conservation planning because it provides better geographical coverage than biological survey data. The value of remotely derived environmental data is enhanced when it is linked with biological data through statistical analysis and modelling (Ferrier et al. 2007).

Where valid surrogates were found, we then evaluated them against the selection criteria and included them in the final set of indicators – if they met at least two-thirds of the criteria.

2.3.1 GDM and community-level modelling

There are many methods for modelling the distribution of species at a community level (Elith et al. 2006), but for the purpose of this study we chose GDM (Ferrier 2002; Ferrier et al. 2002, 2007). GDM is a non-linear matrix regression technique used to analyse the species turnover in community composition (beta diversity or compositional dissimilarity) between pairs of survey sites or a collection of localities in relation to environmental differences between, and geographical separation, of these localities (e.g. Ferrier & Guisan 2006) (see Glossary for a definition of *beta diversity* and *compositional dissimilarity*). To avoid confusion, we have used the term compositional dissimilarity for the remainder of this report.

Compositional dissimilarity has high surrogacy value for true biodiversity as shown by many independent applications and validations of GDM (Elith et al. 2006). The technique superimposes a spatial grid over the study area, which can consist of many thousands or millions of cells, depending on the spatial extent and resolution of the study area.

The GDM technique can be applied in a number of ways (see Ferrier et al. 2007 for examples) but, in this context, it has been used to identify explanatory variables that explain the regional patterns in floristic diversity and biophysical attributes. GDM is similar to general linear or general additive modelling approaches used for single-species-habitat modelling, but it differs by modelling the occurrence (presence and absence) of all species recorded during systematic biological surveys. We used this method because we hoped to identify statistically and ecologically valid surrogates of true biodiversity at the regional scale for monitoring.

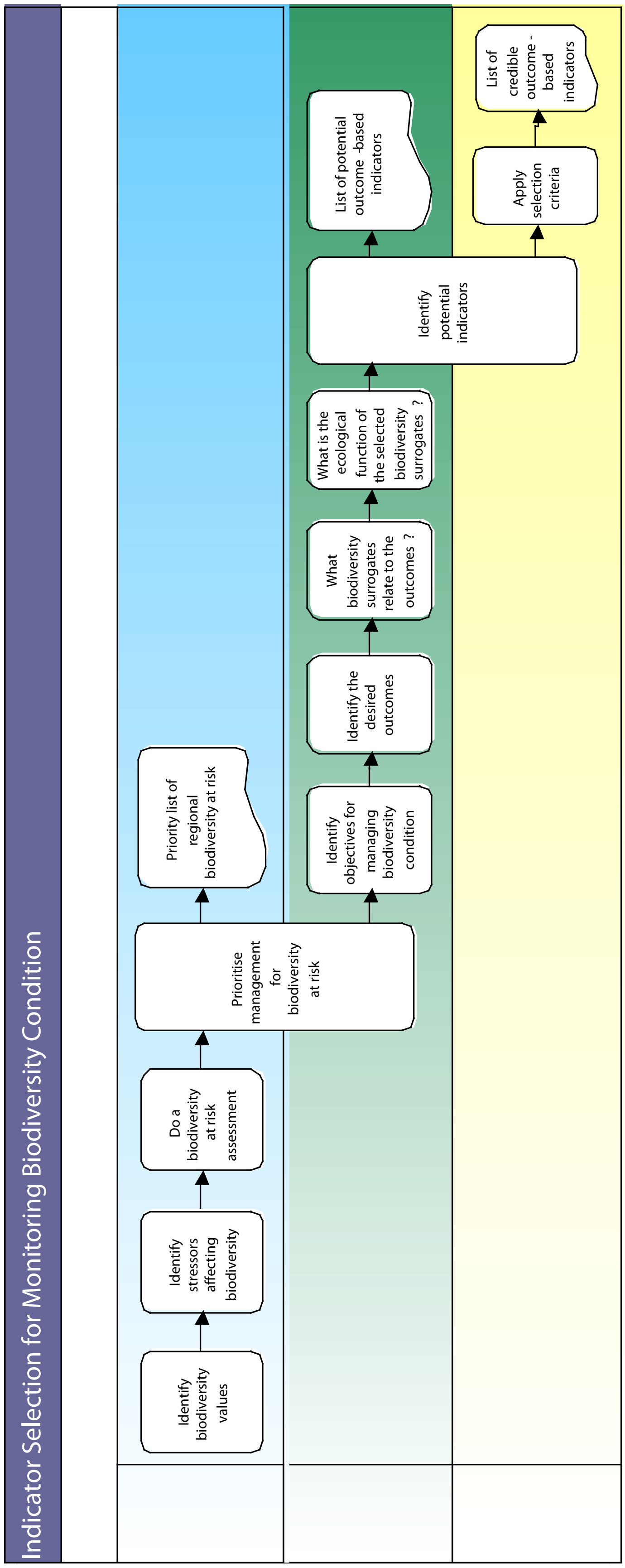


Figure 3: Method for identifying scientifically credible outcome-based indicators for auditing biodiversity and assessing its condition

Table 1: Criteria for selecting appropriate indicators for assessing biodiversity condition

Category: Criteria		Information required
1.	**Conceptual relevance**	
1.1	Abiotic or biotic	Does the indicator relate to abiotic or biotic components? Biotic indicators more directly measure biodiversity condition.
1.2	Grounded in natural history	Selecting appropriate indicators often relies on expert judgement. This judgement must be based on knowledge of the natural history of organisms, their habitat affiliations and interactions with other organisms, and their function in ecosystems.
1.3	Biodiversity complexity	Does the indicator relate to composition (C), structure (S) or function (F) and the different biological hierarchy within (i.e. species (Sp), ecological community (EC), land type (LT)?
1.4	Multi-scaled	What temporal/spatial scale(s) of biodiversity condition is being measured?
1.5	Terrestrial–aquatic link	Does the indicator provide information on the linkage between terrestrial and aquatic environments?
1.6	Ecosystem function	Is the indicator measuring driving force (D), pressure (P), state (S), impact (I), response (R) or combinations of these indicators?
2.	**Historical dimension**	
2.1	Historical record	Are historical data available?
2.2	Reliability	Is there a proven track record?
3.	**Measurement qualities**	
3.1	Anticipatory	Signifies an impending change in key characteristics
3.2	Predictable	Has low variability
3.3	Robustness	Relatively insensitive to expected sources of interference
3.4	Sensitive to pressures	Sensitive to land use pressures
3.5	Space-bound	Sensitive to changes in space
3.6	Time-bound	Sensitive to changes in time
3.7	Measurability	Measurable in qualitative or quantitative terms
3.8	Portability	Repeatable and reproducible in different contexts
3.9	Specificity	Clearly and unambiguously defined
3.10	Statistical properties	Allows unambiguous interpretations
3.11	Universality	Applicable to many areas, situations and scales
4.	**Feasibility of implementation**	
4.1	Costs, benefits and cost-effectiveness	Costs are appropriate to the benefits (including non-economic costs and benefits)
4.2	Data	Manageable data collection or good availability of existing data
4.3	Necessary skills	Highly developed data collection skills not required
4.4	Operational simplicity	Simple to measure, manage and analyse
4.5	Resource demands	Achievable in terms of available resources
4.6	Time demands	Achievable in the available time
5.	**Policy and management utility**	
5.1	Comprehensible	Easily understood by target audience
5.2	Compatibility	Be compatible with indicators of other regions
5.3	Links with societal measures	Linkable to socio-economic indicators
5.4	Links to management	Well-established links with specific management practices or interventions
5.5	Progress towards NRM targets	Links to NRM targets
5.6	Recognisable significance	Information should be easily quantifiable in a way that its significance is apparent
5.7	Acceptance	Readily accepted by the target audience
5.8	Facilitative	Encourages community involvement and new learnings

Source: Niemeijer & de Groot 2007, Smyth & James 2004, Failing & Gregory 2003, Carignan & Villard 2002, Andreasen et al. 2001, Kurtz et al. 2001, Landsberg et al. 1999.

Two types of data inputs were used: (1) biological data based on well-designed, systematic field surveys, and (2) remotely-derived environmental predictors, which cover the entire grid. The outputs of the modelling are mostly used to produce spatial output for modelling turnover in community composition or macroecological properties (Ferrier & Guisan 2006). Other outputs of the technique that were of more interest in our work were the identification of a list of significant predictors (see Table 5) and plots of fitted functions. The latter directly relates remotely derived environmental surrogates to biological data.

Details of the methods used can be found in Ferrier et al. (2007). After data preparation, the first few steps involved in fitting a GDM model included calculating compositional dissimilarity between all pairs of survey sites, deriving I-spline functions for each environmental layer and applying these functions to the survey sites. The modelling process identified a subset of the predictors (see Table 5) available that contribute to the model. Plots of these fitted functions were used to identify the relationship between the selected predictors and the compositional dissimilarities in GDM space. This information was useful for identifying the appropriateness of these indicators.

The software used to run GDM includes a suite of scripts written by Glen Manion, one of Ferrier's colleagues, which uses ArcView 3.2 (ESRI 2002) software and S-Plus software.

Gaps in the spatial extent of many of the predictors meant that coverage was less than the whole bioregion, with 56 predictors covering a subregion called the GDM area (Figure 4). The grazing pressure predictor (p21 – see Table 5) covered a much smaller area called GP masked area, which was 22% smaller than the GDM area.

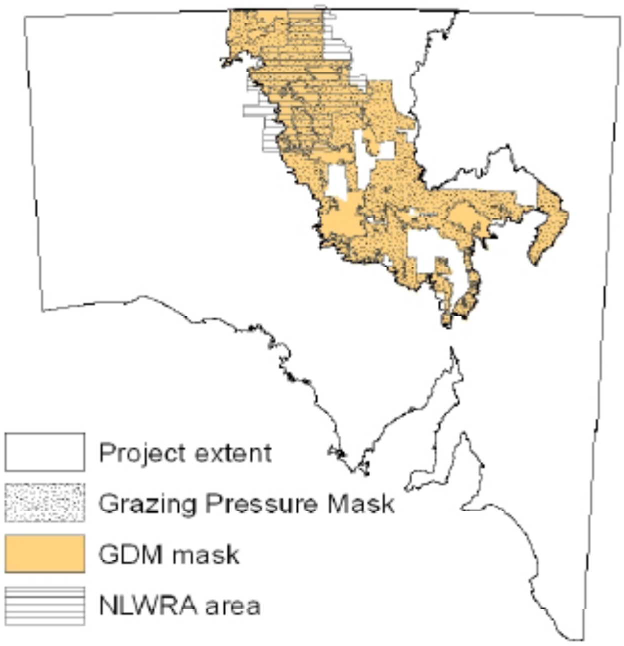


Figure 4: Location of study area and mask for predictive modelling of estimator surrogates, referred to as GDM mask

2.3.2 Biological and environmental datasets

All IBRA subregions in the Stony Plains bioregion plus Finke bioregions three and four (FIN3, FIN4), Simpson Strzelecki Dunefields two and four (SSD2, SSD4) and Gawler bioregions four, six and seven (GAW4, GAW6 and GAW7) were used. Only those polygons that are spatially continuous were included.

All datasets were processed to the same spatial extent and then prepared for spatial modelling. Justification for developing datasets is given in Table 2. Sources and processing for each type of dataset are listed in Appendix 4. Grid datasets were produced at a cell resolution of 100 metres.

Table 2: List of datasets and justification for development

Datasets	Justification
Biological survey data	
Flora records	Best widespread dataset available (temporal and spatial).
Environmental data	
Land types	Stratification important across region as region is highly variable.
Digital elevation model (DEM) derived from Shuttle RADAR Topography Mission	In arid environments, slight changes in topography can influence the availability of surface and ground water. Changes in run-on patterns are influential in driving the patterns of vegetation cover and the ecological dynamics in arid environments (Stafford Smith & Morton 1990, Ludwig et al. 2007).
DEM derived layers	Slope, aspect, catchment size, wetness, position in landscape, elevation diversity and log catchment size are topographical features that have the potential to influence variability in microhabitats and the compositional dissimilarity of plant composition.
Climate layers of temperature, radiation and moisture	Climate is increasingly becoming a driver in the continental and regional distribution of biodiversity (Ferrier & Guisan 2006; Lethbridge 2007, pers. comm. 17 May, about climate change predictive vegetation modelling for the Mt. Lofty Ranges, South Australia). Temperature and radiation could be removed before modelling but GDM removes poorly performing variables early in the process (Manion 2006, pers. comm. 26 March). Rainfall patterns are the key drivers of vegetation patterns in the rangelands (Friedel 1990).
Satellite data Landsat TM mosaics bands 2,3,4 for 1988, 1989, 1997, 2000, 2002	These data were used in an exploratory sense. Similar work around Alice Springs indicated that some of these bands detect vegetation patterns but the underlying reasons for this remain unknown (Smyth, unpublished data). Ratios of TM bands 3/2 or 3/1 signal ferric material of red sand dunes and the strong desert varnish of silcrete gibber plains (Waclawik 2006). TM bands 4/3 is a reasonable indicator of vegetation cover where high values indicate vegetation greenness and low values may indicate little greenness or low cover (McCloy 1995). It is possible that these data could be possible surrogates of different soils or bare ground.
PD54 (index of vegetation cover) for 2000 and 2002	An index of vegetation cover derived from Landsat TM. Use of this variable as a surrogate of biodiversity was exploratory. Alone, it does not represent significant aspects of biodiversity, but in combination with other variables may be important.
Variance and contrast (derived using PD54 for 2000 & 2002 data)	We used the texture coverage as a surrogate for vegetation structure in the same way as Catling & Coops (1999) in an exploratory sense. They used texture measures with high resolution aerial videography to describe and quantify habitat structure. These variables would have been removed early in the run if they did not contribute much to the variation in plant composition.
Radiometrics – potassium, thorium, uranium	These data were used as surrogates for the differences in soil types of the region in an exploratory sense. In an Alice Springs study, these variables were highly significant predictors of compositional dissimilarity (Smyth, unpublished data).
Land use pressure data	
Distance to water	Indicative of the spatial extent and patchiness of total grazing pressure in the region.
Grazing gradients	Indicative of the ability of a land type to respond to rainfall.
Grazing pressure	A pressure surrogate of the intensity of total grazing pressure.

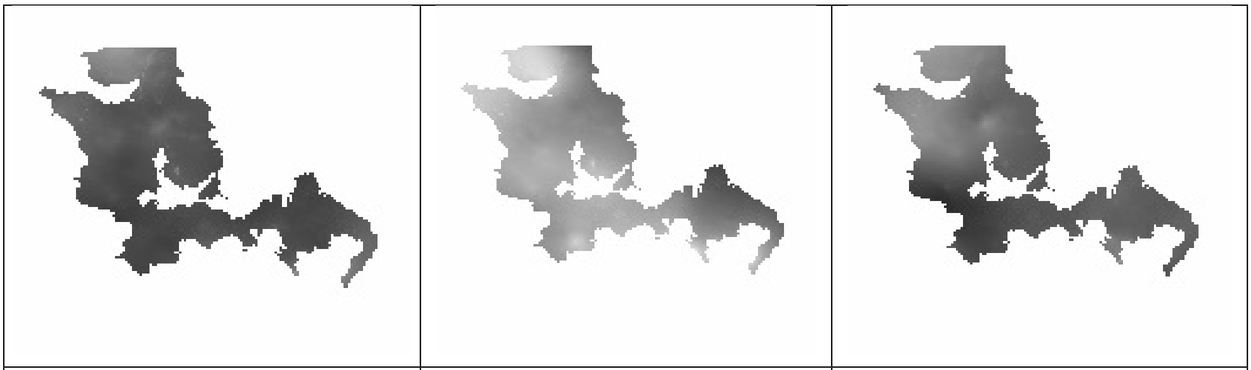
2.3.2.1 Biological survey data

Persistent, native plant species (i.e. those species that can be observed during long dry periods) were used as a surrogate for biodiversity in the case study region. The combined flora dataset within the GDM area used for the predictive modelling represents presence of species for 1128 sites as shown in Figure 6. A total of 255 species were used to predict compositional dissimilarity for the study area. These data were the response variables for the statistical modelling and were not aggregated into assemblages or taxonomic groups.

2.3.2.2 Environmental predictors

Slope, aspect and position in the landscape had widespread null values so could not be used as predictors for the GDM modelling.

As can be seen in Figures 2 and 5, rainfall has been highly variable for the last 30 years, with major dry/wet periods in 1988–1989 and 2000–2002. Rainfall in 2001 was spatially variable across the Stony Plains bioregion, ranging from 98–366 mm, with a mean of 254 mm. As shown in Figure 5, there was more rainfall in the north than in the southern areas, especially in 2000. Figure 6 shows the areas where a good vegetation response could be expected, and areas with a poorer response. These pulses were used to choose suitable satellite imagery from existing archives.



SILO image for 1999 (a)	SILO image for 2000 (b)	SILO image for 2001 (c)

Figure 5: Spatial distribution of annual rainfall for Stony Plains bioregion for 1999, 2000 and 2001

Note: Light values indicate higher rainfall.

Source: SADEH n.d.

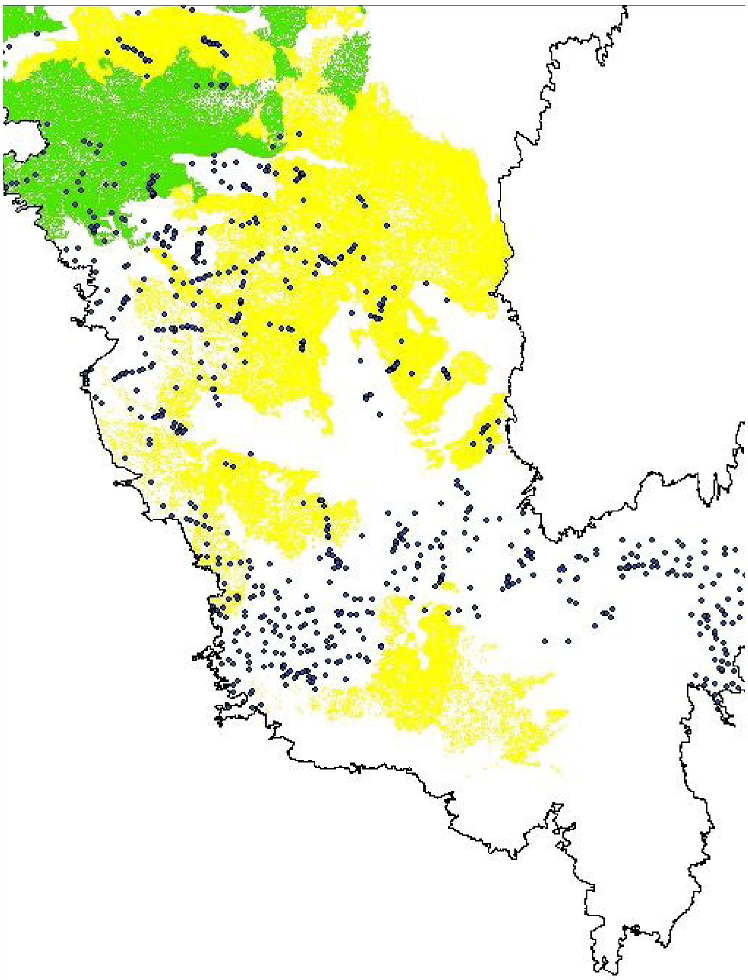


Figure 6: Map of good and poor vegetation responses to rainfall

Note: The green areas represent land types with sufficient rainfall for a good vegetation response in 2002. The yellow areas are likely to have had a poorer response. The dots indicate flora sites within the stony plains IBRA.

Note: The AGO 2000 mosaic consists of images acquired between September 1999 and January 2000. The 2002 mosaic consists of images acquired during between January and March 2002.

Radiometrics data were used in an exploratory sense in the absence of high-resolution soils coverage. The diversity of soils was used as a surrogate for predicting the turnover in plant composition at a regional scale. Previous work on the Peake Station found that thorium is strongly associated with sandy streams while potassium and uranium are associated with the interfluves, that is, the surrounding rises or hills of a catchment (Waclawik 2006). A mixture of uranium and thorium tends to dominate stream content whereas the highly ferruginised and silicified sediments are evident as areas high in potassium and uranium. It is likely that the uranium gamma count on the hills, rises and plateaux is derived from heavy minerals and silica related to the gibber and the sand dunes. Potassium and thorium are more associated with clays and stream sands.

2.3.2.3 Land use pressure datasets

Distance from water was calculated in relation to the distribution of stock watering points in the region (Figure 7).

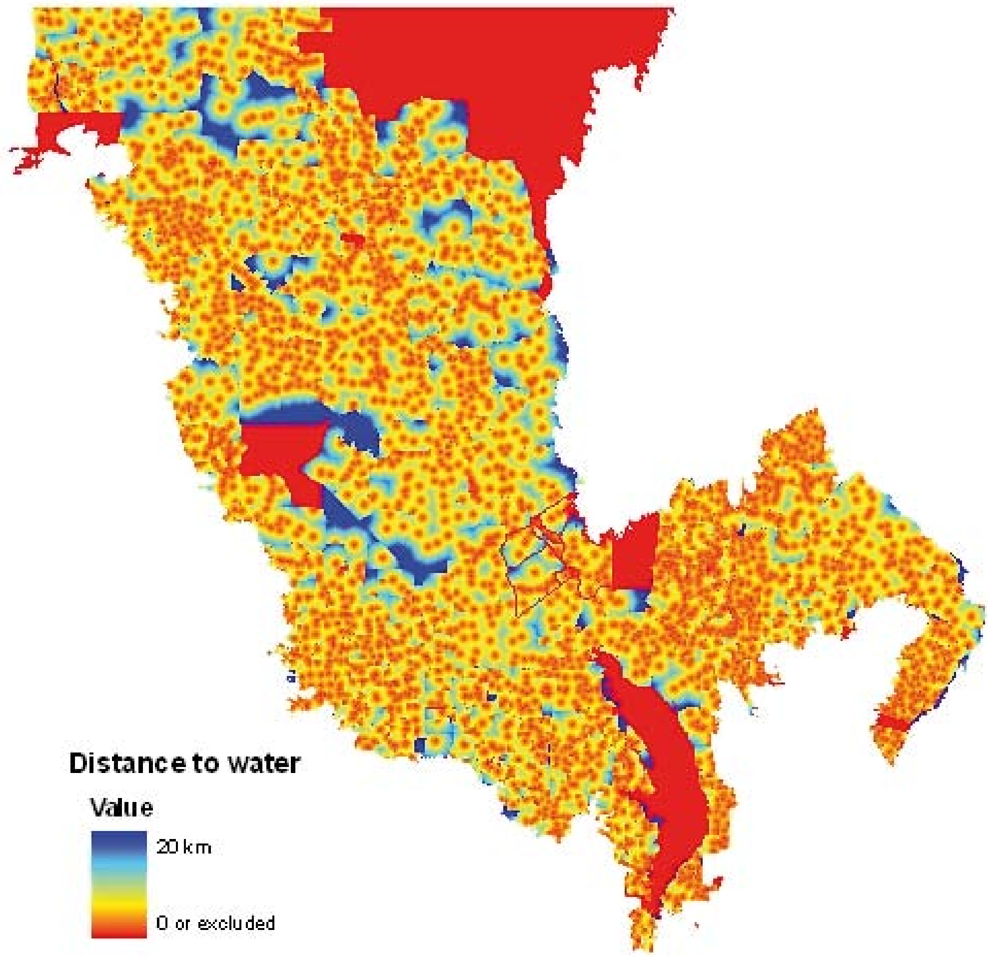


Figure 7: Distribution of stock watering points in the study area to 20 km

Grazing gradients (Bastin et al. 1993) have been used in pastoral areas to indicate both utilisation (as shown by vegetation cover) and the degree of disturbance or alteration of habitat value. Figure 8 shows a stylised version of this methodology.

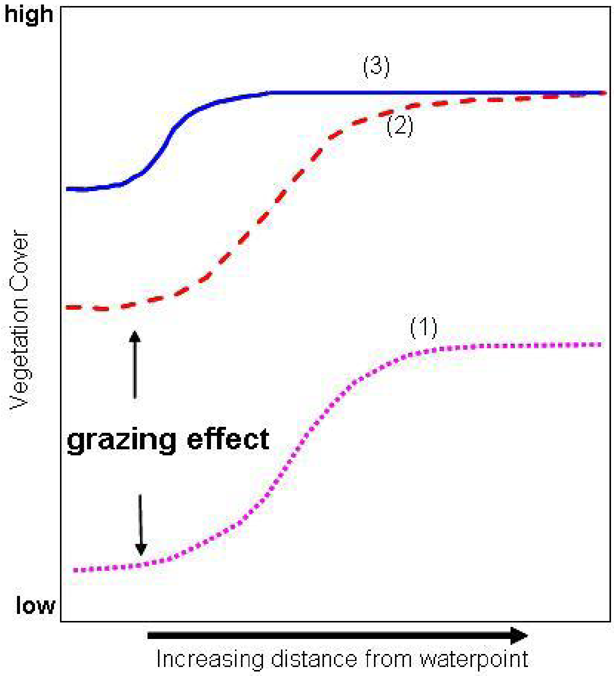


Figure 8: Stylised grazing gradient

Note: Line (1) shows average cover increasing with distance from water before a large rainfall event. Line (2) shows a landscape where the cover gradient persists following a large rainfall event. Line (3) shows a landscape that recovers well from grazing.

Grazing gradient data and graphs were calculated for selected individual land types, combinations of land types and subregions for five mosaic dates (1988, 1989, 1997, 2000 and 2002) for an area of 210 000 km^2. The pattern of rainfall distribution through the reporting period saw considerably more rain in the northern portion than in the south. Input layers were the PD54 mosaics, distance to water and gridded land types. Note that 1988, 1989 and 1997 grazing gradient results are for the National Land and Water Resources Audit (NLWRA) area only (30 000 km^2). These results are reported in Fleming & Brook (2007) and the information was used to derive the grazing pressure data. Average cover at incremental distance to water categories also reported in Fleming & Brook (2007) was used to derive the grazing pressure data.

Productivity ratings, approximate stocking rates and distances that cattle walk from water were provided for the grouped land types and used to derive a grazing pressure layer. The grazing pressure grid (Figure 9) was derived from regression functions of decreasing grazing pressure with increasing distance from water. Fleming and Brook (2007) show that the more productive land systems have more persistent grazing gradients extending further from water, inferring greater land degradation.

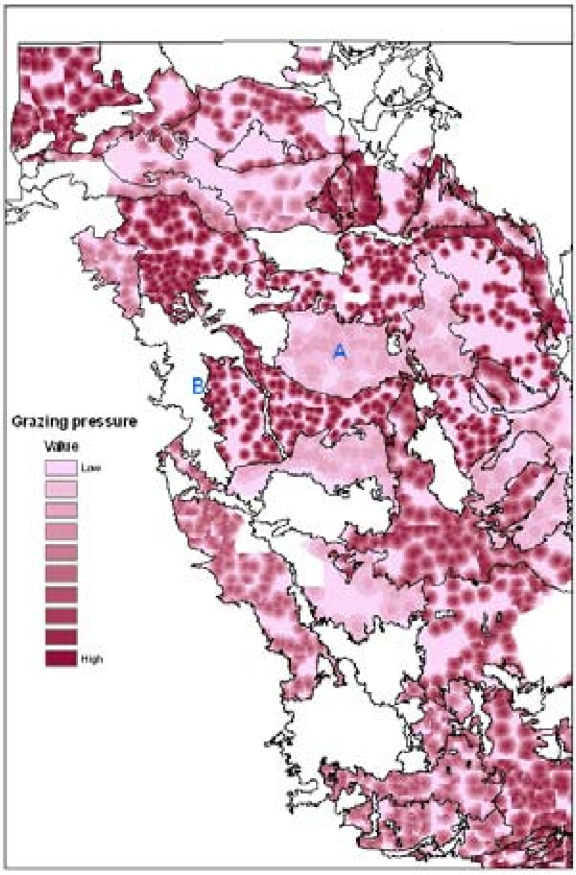


Figure 9: Grazing pressure for part of the study region

Two contrasting land types are indicated by A and B in Figure 9. The area indicated by A is STP7-Baltana land type (plains), where there is a low number of cattle per km^2 (0.3) and cattle walk up to 12 km from water. Consequently, the grazing pressure is diffused over the area. In contrast, the area indicated by B is STP2-Oodnadatta land type (gibber plains, tableland and plateaux), which has a relatively high carrying capacity (around 2 cattle per km^2) and cattle walk a relatively short distance from water, about 5 km.

2.4 Interpreting biodiversity condition

We have chosen to depict a hypothetical set of indicator data using radar plots, which are XY graphs with a Cartesian coordinate system. We used Statsoft Statistica V7 to draw the plots. We chose this approach for the following reasons: a picture communicates information easily; the problem of eclipsing is avoided (i.e. the positive value of one indicator offsetting the negative value of another in a single, aggregate metric); there is the potential to add stochastic qualities in the reference condition; and adjustments can be made when new scientific information becomes available.

3. Results

3.1 Field and remote indicators

A set of potential field indicators for assessing biodiversity condition in the Stony Plains bioregion was identified after we undertook a systematic assessment of biodiversity at risk and identified priorities for its management in the region. (See Appendices 5–7 for a full list of the significant biodiversity values, and the threats and pressures putting them at risk). The Stony Plains bioregion is rich in assets and has many significant biodiversity values, which are:

- connectedness and extensiveness of natural mosaics supporting nine different types of ecological communities and habitats across a diversity of land types (e.g. over 50 have been mapped)
- connectedness of minor and island communities and habitats to neighbouring ecological communities
- relatively uninterrupted surface water flows across the region into source and sink patches
- richness of natural ecological communities (e.g. mound springs, stony plains)
- richness of native plant and animals assemblages
- endemic species and those species for which the Stony Plains represent the largest area of remaining habitat
- threatened species.

The biodiversity values are stressed by:

- loss, degradation and fragmentation of ecological communities through high total grazing pressure
- loss of species through increased predation by feral predators and reduced recruitment of native plants due to total grazing pressure
- change in natural surface water flows.

The priorities for managing biodiversity of the region were:

- to manage total grazing pressure (TGP) across the watered areas to avoid further degradation of biodiversity and production values
- to manage threats and pressures on species vulnerable to extinction in areas where they are known to occur
- to plan infrastructure development to avoid affecting natural surface water flow.

The management objective, the desired outcomes and the biodiversity surrogates associated with those outcomes were identified based on the management priorities. Next, we identified a set of potential indicators that related to the desired outcomes for the region. The results of these activities are presented in Table 3.

3.1.1 Biodiversity management objective

The recognisable ecological communities of significance in the Stony Plains are numerous and include:

- mound springs – internationally recognised heritage sites, geology and endemic species
- gypsum clay plains – endemic and threatened plant species and important areas for small native mammal species including the nationally vulnerable plains rat *Pseudomys australis*
- breakaway hills – endemic and threatened plant species, distinctive flora and fauna assemblages, endemic reptile species including nationally vulnerable bronze-backed legless lizard *Ophidiocephalus taeniatus*
- drainage lines and floodplains – rich in plant and bird species, critical for most frog and fish species in the region
- swamps – high periodic productivity provides important breeding habitat for aquatic fauna and waterbirds
- waterholes – enable the survival of aquatic vertebrates (particularly fish) and sustain many bird species through dry periods
- arid ranges – provide habitat for plant and animal species that have specialised for rocky range habitats and contribute to an archipelago of ranges that spans from the MacDonnell to the Flinders Ranges
- areas of stony plains with gilgais – provide productive areas for native and non-native species following relatively minor rainfall events. This occurs through the concentration of water and nutrients within the gilgais and is important for the continuous existence of most small mammals and low shrub-dependent birds in the region (e.g. thick-billed grasswren *Amytornis textilis*)
- areas of stony tableland with sand mounds – important habitat for small mammals adapted to hopping (e.g. kultarr *Antechinomys laniger*, kowari *Dasyuroides bynie)* ground-roosting birds (e.g. gibber bird *Ashbyia lovensis*) that are susceptible to nocturnal predation in better vegetated areas.

For the Stony Plains bioregion, the key management objective (Table 3) was to:

> *Retain or restore (if possible) the resilience and connectedness of terrestrial ecological communities/habitats across land types of the Stony Plains.*

In our study, *resilience* was a measure of the ability of ecological communities to 'bounce back' from disturbances, especially after long dry periods of little or no rain.

Issues of *connectivity* or landscape linkages are also important for the bioregion. In the grazed lands of the Stony Plains, ecological communities/habitats mostly form a continuous natural mosaic that is broken up by disturbance associated with natural and artificial water sources (e.g. natural waterholes in drainage lines, troughs, dams). At a landscape level, this gives a 'Swiss cheese' effect where the total grazing pressure by herbivores creates gradients of grazing pressure that taper off irregularly at increasing distances from water depending on the local topography. For biota sensitive to frequent high grazing pressure, this can lead to isolation of biota and habitat loss and/or decline, all of which over time have the potential to reduce biodiversity, production and aesthetic values.

3.1.2 Desired outcomes for biodiversity

Of all the plants and animals of the Stony Plains, medium-sized mammals have been the most threatened. However, in the grazed lands, native vegetation is widely threatened by disturbance (e.g. trampling, browsing) caused by the total grazing pressure of native and non-native herbivores (SADEH 2005, Neagle 2003). The changes to native vegetation cover in some productive land types will not only affect biodiversity values through habitat loss and modification, the productivity of grazing lands will also be affected by the composition and recruitment of palatable, perennial native plants. Feral herbivores (donkeys, camels, horses and rabbits in some land types), weed invasions and the densities of kangaroo north of the dog fence are added pressures for some already stressed ecological communities. The loss of habitat and its modification will most likely result in increased predation of native animals by introduced predators at some times in some places.

Natural surface water flows and floodplains are critical to maintaining the ecological and genetic integrity of native aquatic plants and animals. Erratic rainfall, limited capacity of natural sources and the cost of artificial water infrastructure have led to perverse management: landholders redirect natural water surface flows to capitalise on water collection when it rains. This leads to disruption of natural waters flows and can cause a dramatic change in flooding dynamics and a loss of habitat for aquatic biodiversity.

In the arid rangelands, water availability is a driver of stocking rates and spelling cycles. With new artificial waterpoints being installed across the region, total grazing pressure is increasing throughout landscapes to the extent where previously undisturbed, ecological communities in water-remote areas are diminishing (Figure 7).

Great Artesian Basin (GAB) mound springs are present in a variety of geological forms and have high conservation value as they support a high proportion of endemic species (SADEH 2005). Major issues for biodiversity management of mound springs are:

- keeping the natural balance of habitat variation and composition within mound springs
- retaining surrounding GAB water pressure
- decreasing the impact of tourism at springs
- controlling both weeds infestations and potential invasions and the disturbance caused by total grazing pressure.

Therefore, the desired biodiversity outcomes for the region agreed to in the workshops (Table 3) were for:

- maintain and restore native vegetation typical of the study region's communities
- reduce the loss of the existing complement of rare and regionally significant native flora and fauna
- maintain or restore natural surface water flows and natural drainage lines
- create a mosaic of water remote areas.

3.1.3 Key biodiversity surrogates

Key biodiversity surrogates were a subset of the biodiversity values identified in the biodiversity 'at risk' assessment (Section 3.1) but pertaining to each of the desired outcomes (see Appendix 8). We prioritised these (as shown in Table 3) based on their close alignment with the bioregion's conservation priorities in Section 3.1. There are some interdependencies between the first two outcomes but the surrogates for the other two outcomes are unique.

3.1.4 Ecological functions of the biodiversity values

The ecological function of the biodiversity surrogates (Table 3) was determined in the technical workshops. For most surrogates, ecological function was poorly known and largely unstudied. Using our collective wisdom, we identified a coarse but incomplete list of key functions for each value (see Appendix 9 for a detailed list of ecological functions of each biodiversity surrogate listed in Table 3). Most ecological functions of biodiversity surrogates can be broadly summarised as relating to maintaining soil structure, providing various types of habitat (e.g. breeding places, shelter and food), and domestic stock forage. It is an evolving list that will change as new knowledge becomes available.

Table 3: Desired outcomes, key biodiversity values and appropriate indicators for assessing biodiversity condition to meet the desired outcomes for the Stony Plains bioregion

Goal	**Retain or restore (if possible) the resilience and connectedness of terrestrial ecological communities/habitats across land types of the Stony Plains**			
Desired outcomes	Maintain and restore native vegetation typical of the study region's communities	Reduce the loss of the existing complement of rare and regionally significant native flora and fauna	Maintain or restore natural surface water flows and natural drainage lines	Create a mosaic of water remote areas
Key biodiversity surrogates	Vegetation cover Plant diversity Structural complexity Natural integrity (i.e. negligible rabbits, donkeys, camels, feral horses, and kangaroo densities at pre-settlement numbers.)	Endemic and threatened species and communities Species that decline when grazed Significant ecological communities (gypsum clay plains, stony plains with gilgais, breakaway hills, drainage lines and flood plains, arid ranges, stony tableland with sand mounds) Pre-settlement densities of dingos Negligible densities of foxes and cats Negligible densities of introduced weeds	Landscape function defines "the capacity of landscapes to regulate (i.e. capture, retain, not leak) rainwater and nutrients" (Bastin & ACRIS Management Committee 2008).	Interconnected tracts of functioning water-remote areas that support grazing-sensitive species and ecological communities
Final indicator set	Within land types: Average % dry-period vegetation cover[1] Frequency and cover of *Abutilon halophilum* at 1.5 km from water sources Cracking Index of gilgais Presence of non-native (terrestrial/ aquatic) invasive weeds Total grazing pressure as measured by presence of feral herbivores, kangaroo abundance, preferred grazing area of all stock most of the time, productive value of grazed areas, number of domestic stock per water point and historical numbers of all stock and kangaroos per water point	Within land types: Preferred grazing area of all stock most of the time Number of domestic stock per water point Presence of feral herbivores Presence of dingos or foxes Presence of non-native (terrestrial/ aquatic) invasive weeds Presence of terrestrial endemic and threatened species Change in composition and abundance of mound spring threatened and endemic fauna Change in composition and distribution of mound spring threatened and endemic plants Presence of aquatic endemic and threatened fauna Status of regionally significant aquatic communities of drainage lines an floodplains Water quality Cumulative sum of the standard deviations for rainfall Seasonality of temperature and rainfall	Within catchments: Change in extent and distribution of floodwaters Presence of non-native (terrestrial/ aquatic) invasive weeds Presence of native saplings below 2 m in height No artificial earthworks in drainage lines Reduced estimated no. of erosion gullies and central windrows on tracks per km	Within land types: % area remote from water by length of time Density of artificial waterpoints by age
% of total indicators (n out of N). See Appendix 10 for full list of indicators.	50% (10/21)	67% (14/18)	63% (5/8)	100% (2/2)
Number of criteria met (n = 33). See Table 1 for a full list of criteria.	22–29	16–29	21–29	28–30

1 Dry period vegetation cover is the vegetation cover that is typical after long periods of little or no rain.

3.1.5 Potential outcome-based indicators

Using information gained on the function of biodiversity values for each desired outcome described in Section 3.1.4, we produced a list of potential indicators that relate to each of the desired outcomes (see Table 3). Descriptions of the indicators, their relevance and potential acceptance for achieving each of the desired outcomes are provided in Appendix 10.

3.1.6 Final set of outcome-based indicators

The monitoring data for indicators are used to assess biodiversity condition. More importantly, they also inform end users about the information used to assess biodiversity condition. Therefore, it is important that they are scientifically credible and acceptable measures for assessing the desired management outcomes for biodiversity. After applying the selection criteria, the final set of outcome-based indicators was chosen (Table 3). (For details on the evaluation of each indicator against the selection criteria, see Appendices 11–19). For diversity outcomes 1–4 we selected 10, 14, 5 and 2 indicators respectively for auditing biodiversity and assessing its condition. The following list shows the range in the number of criteria out of a total of 33 met by the different indicators of the final set for each of the four desired outcomes:

1. between 22 and 29 across 10 indicators
2. between 16 and 29 across 14 indicators
3. between 21 and 29 across 5 indicators
4. between 28 and 30 across 2 indicators

The number of criteria met by those indicators excluded from the final set for each of the four desired outcomes were:

1. between 10 and 21 across 11 indicators
2. between 10 and 17 across 14 indicators
3. between 13 and 15 across 5 indicators
4. none excluded.

The 'measurement quality' criterion was the least met by indicators for the 'native vegetation' and 'biologically significant species and ecological communities' outcomes. This was not the case for the outcomes of the drainage systems and water remoteness (Appendices 17–19). In these cases, fewer criteria could be applied.

For each desired outcome, the biodiversity complexity and the ecosystem function are well represented with indicators spanning all three (composition, structure and function) and five (driving force, pressure, state, impact, response) properties of each feature respectively (see Appendices 11–19). Three of the indicators for the first two outcomes were the same for total grazing pressure.

3.2 Predicting estimator surrogates

3.2.1 Grazing pressure

A persistent grazing gradient is an indicator of the degree of disturbance in a landscape. The results of the grazing gradient calculations undertaken for this project have also been used for ACRIS reporting. The project area is 30 000 km^2 for the 1998 Landsat images and 210 000 km^2 for the 2000 and 2002 imagery, and the results shown here are from Fleming and Brook (2007). The status of the landscape was reported for most of the study area; however, only the green areas in Figure 6 had sufficient rainfall for change to be reported.

Two examples for STP1-Coongra (Figures 10 and 11) show that there was relatively low cover and a strong gradient in 1988 following a dry period. After a wet period in 1989 there was a good cover response and a smaller persistent gradient.

For the more recent time periods, the graph indicates that there was higher cover in 2000 (dry) than in 1988. The 2000 (dry) cover matches the higher cover in 1997 (wet). There was highest cover response in 2002 with the gradient disappearing approximately 2 km from water. This land type is preferred for grazing and there is recovery (as determined by the cover index) in both 1989 and 2002.

The graphs for STP6-Coongra tell a different story. There are very strong cover gradients in both dry periods in 1988 and 2000. The 2000 image shows a higher cover than the 1988 image. There was an increase in cover in 1989 (wet) compared with 1988 (dry); however, a strong gradient persisted suggesting a fairly profound grazing effect in this land type.

As for STP6-Coongra, there is highest cover response in 2002 with a composite gradient extending to approximately 3.4 km from water. This indicates that this landscape can recover substantially after very big rains, but recovery following less effective rainfall is reduced (1989 rain was substantial here but of reduced duration compared with the 2000 and 2001 extended event).

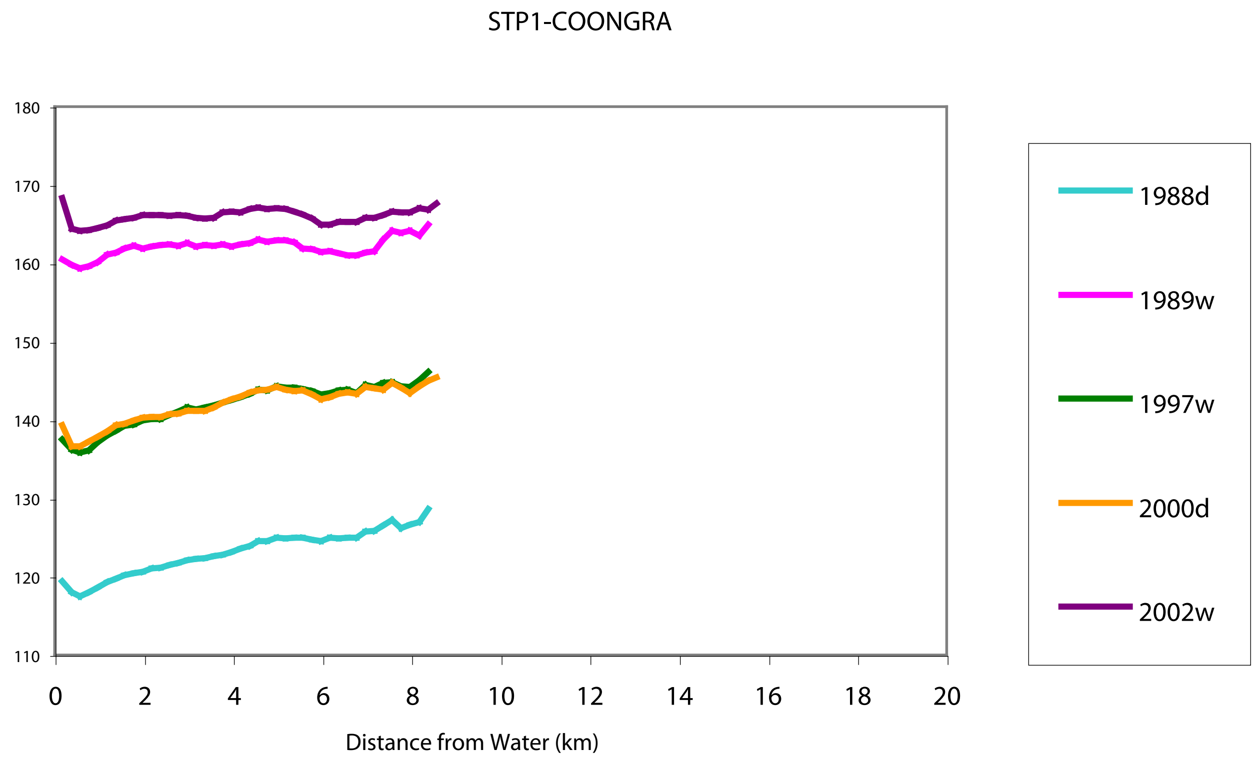
The area with good summer rains was insufficient for us to include the results from the grazing gradient calculations in the GDM modelling. This highlights the difficulties of using this approach in arid environments. It may not be possible to calculate grazing gradients over large areas using short timeframes when relying on remotely sensed datasets and ground sampling. Consequently, we were not able to derive a good measure of the actual resource condition.

(a) (b)

Figure 10: Location of land types within the Stony Plains bioregion (a) STP1 Coongra (b) STP6 Coongra land type

3.2.2 GDM modelling

We used 57 predictors to model the relationship between compositional dissimilarity of persistent, native plant species for a subset of the Stony Plains bioregion. The spatial extent of all predictors was less than the whole bioregion, with 56 covering a subregion called the GDM area (Figure 4). The grazing pressure predictor (p21) covered a GP masked area, which was 22% smaller than the GDM area (see Figure 4 and Table 4). The number of biological survey sites used in the GDM and GP modelling was 1128 and 691 respectively. For a detailed explanation of the output parameters listed in Table 4 and Figures 12–14, see Ferrier et al. (2007) and Ferrier & Manion (2007).



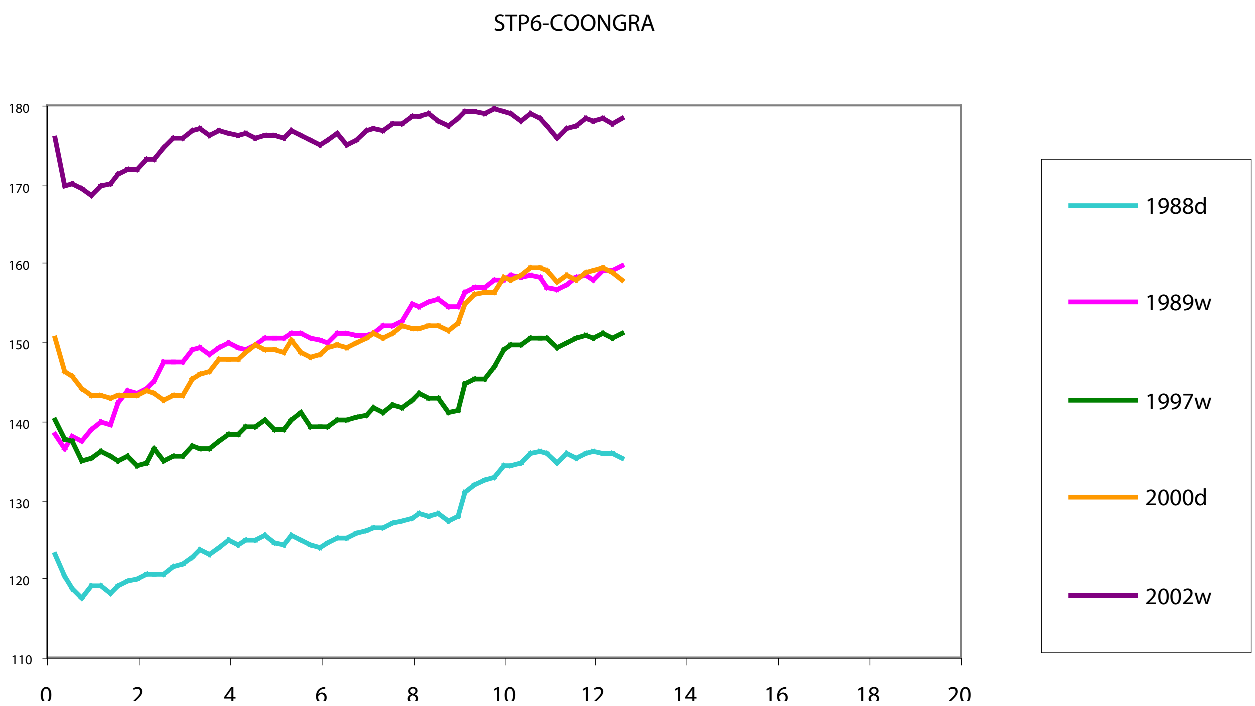


Figure 11: Grazing gradients for the STP1 Coongra and STP6 Coongra land types

Table 4: Summary of the results of GDM modelling of flora compositional dissimilarity

Parameter	GDM area 1	GP masked area 2	GP masked area3 (with p21)
Area	140 999 km^2	108 712 km^2	108 712 km^2
No. of sites	1128	691	691
Null deviance	12971.6	9597	9597
Best deviance	7261	5329	5308
Deviance explained	49%	44%	44%
Input layers and number of predictors selected	56, 33	56, 34	57, 35

We carried out three runs of GDM modelling: (1) GDM area with 56 predictors where the grazing pressure predictor was not available, (2) GP area with 56 predictors where the grazing pressure predictor was excluded, and (3) GP area with 57 predictors including grazing pressure. The first two runs were included to see if using the same predictors gave consistent results when used over a restricted area. The analyses revealed similarities and differences in the selected predictors.

Table 4 shows the results from the GDM modelling for each of the runs. Using the 57 predictors (run 3), the model selected 35 predictors to explain the species turnover of persistent, native plant species. Grazing pressure, although selected as an influential predictor, tended to influence species turnover where grazing pressure was low to medium in the landscape but had little influence overall (Figure 12). This was further supported by the small increase in explained deviance when the GDM analysis was run without grazing pressure (run 2). Similarly, there was virtually no change in the plots and the selection of significant predictors (Table 5).

As part of the GDM modelling process, I-spline functions are fitted to each predictor, using the environmental data (sites and grid layers). The GDM output includes a set of plots showing these smoothed functions fitted to each predictor. Ferrier et al. (2007) provide the following description:

> *The maximum height reached by each function provides an indication of the total amount of compositional turnover associated with each environmental gradient, holding all other variables constant. The slope of the functions provides an indication of the rate of compositional turnover, and how this rate varies along the gradient concerned.*

An example plot of a function fitted using GDM modelling is shown in Figure 12.

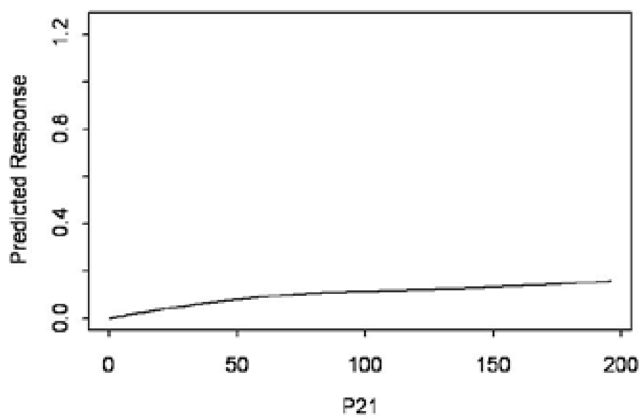


Figure 12: The relationship of grazing pressure and predicted compositional dissimilarity of persistent, native plant species

Thirty-four significant predictors of persistent, native plant species turnover were identified for the GP area (run 2). Of these, 12 predictors appear to have a high total amount of compositional dissimilarity and to be highly influential (Table 5, Figure 13).

The plots of climate variables indicate that compositional dissimilarity reaches a threshold over small scales (X-axis) with little change over broader scales.

A similar pattern occurs for the physical predictors. For example, compositional dissimilarity of plant species changed noticeably along drainage lines where wetness is sporadically higher. Uranium count tends to influence compositional dissimilarity in specific areas where counts are high. This could be indicating isolated areas on hills, rises or plateaux that are environmentally different from the dunefields and the gibber pavements.

The reflectance in TM band 2 is likely to be signalling ferric material of sand dunes and the gibber pavement. Its importance in determining compositional dissimilarity in 2002 (wet) and not 2000 (dry) is not clear. In wetter years with higher cover, TM2 values tend to be lower. The rain in 2001 and early 2002 was higher but very patchy as mentioned in the methods for land use pressure data. It is possible then that TM2 reflectance values will be variable across the landscape, with some being high where there is little cover but other areas lower where more rain stimulated more vegetation cover. It is possible that the rain in 2000 (dry) produced little cover through the region and, therefore, the predicted compositional dissimilarity response was fairly even and insignificant.

Analysis for the GDM area revealed that only three of the selected predictors substantially influenced compositional dissimilarity; these were log catchment size (p2), elevation diversity at 300 m (p7) and temperature seasonality as measured by its coefficient of variation (e4l) (Table 5, Figure 13). Log catchment size and temperature seasonality were also influential predictors for the smaller spatial extent of the GP area, suggesting that these two predictors may be valid surrogates of biodiversity compositional dissimilarity of plant species. However, they vary little at high resolutions and only marginally at low resolutions, so they may not be that realistic as surrogates for monitoring biodiversity.

Table 5: Layers used in three runs of GDM modelling

Predictor	GDM-selected influential predictors			
Code	**Layer**	**GDM area**	**GP area**	**GP area**
		1	2	3
Eucl	Geographic distribution between sites (GDM output)	1	1	1
p1	DEM from SRTM	1	S	S
p2	Log catchment size	S	S	S
p3	Wetness	1	S	S
p4	Potassium – Radiometrics			
p5	Thorium – Radiometrics	1	1	1
p6	Uranium – Radiometrics	1	S	S
p7	Elevation diversity 300 m	S	1	1
p8	Elevation diversity 3000 m	1	1	1
p9	PD54 2000		1	1
p10	PD54 2002	1		
p11	Texture: contrast 2000 from PD54		1	1
p12	Texture: variance 2000 from PD54	1	1	1
p13	Texture: contrast 2002 from PD54	1	S	S
p14	Texture: variance 2002 from PD54		S	S
p15	Landsat TM 2000 Band2	1	1	1
p17	Landsat TM 2000 Band4	1	1	1

Predictor	GDM-selected influential predictors			
Code	**Layer**	**GDM area**	**GP area**	**GP area**
p18	Landsat TM 2002 Band2	1	S	S
p19	Landsat TM 2002 Band3			
p20	Landsat TM 2002 Band4	1		
p21	Grazing pressure	N/A	N/A	1
e1l	Annual mean temperature		1	1
e2l	Mean diurnal range (mean (period max-min))	1	S	S
e3l	Isothermality (P2/P7)	1	1	1
e4l	Temperature seasonality (coefficient of variation)	S	S	S
e5l	Max temperature of warmest period			
e6l	Min temperature of coldest period	1	S	S
e7l	Temperature annual range (P5–P6)			
e8l	Mean temperature of wettest quarter			
e9l	Mean temperature of driest quarter	1	S	S
e10l	Mean temperature of warmest quarter	1		
e11l	Mean temperature of coldest quarter	1		
e12l	Annual precipitation	1		
e13l	Precipitation of wettest period	1	1	1
e14l	Precipitation of driest period			
e15l	Precipitation seasonality (coefficient of variation)			
e16l	Precipitation of wettest quarter			
e17l	Precipitation of driest quarter	1	1	1
e18l	Precipitation of warmest quarter	1		
e19l	Precipitation of coldest quarter			
e20l	Annual mean radiation	1	1	1
e21l	Highest period radiation	1	S	S
e22l	Lowest period radiation			
e23l	Radiation seasonality (coefficient of variation)	1	1	1
e24l	Radiation of wettest quarter	1	1	1
e25l	Radiation of driest quarter		1	1
e26l	Radiation of warmest quarter		1	1
e27l	Radiation of coldest quarter		1	1
e28l	Annual mean moisture index		1	1
e29l	Highest period moisture index			
e30l	Lowest period moisture index	1		
e31l	Moisture index seasonality (coefficient of variation)			
e32l	Mean moisture index of highest quarter MI			
e33l	Mean moisture index of lowest quarter MI			
e34l	Mean moisture index of warmest quarter	1	1	1
e35l	Mean moisture index of coldest quarter	1	1	1

Note: Value of 1 indicates the layer is a predictor (not in order of importance). S=predictor that has a relatively higher amount of compositional dissimilarity. A blank cell indicates the layer has all three fitted coefficients zero, so has not been included in the model.

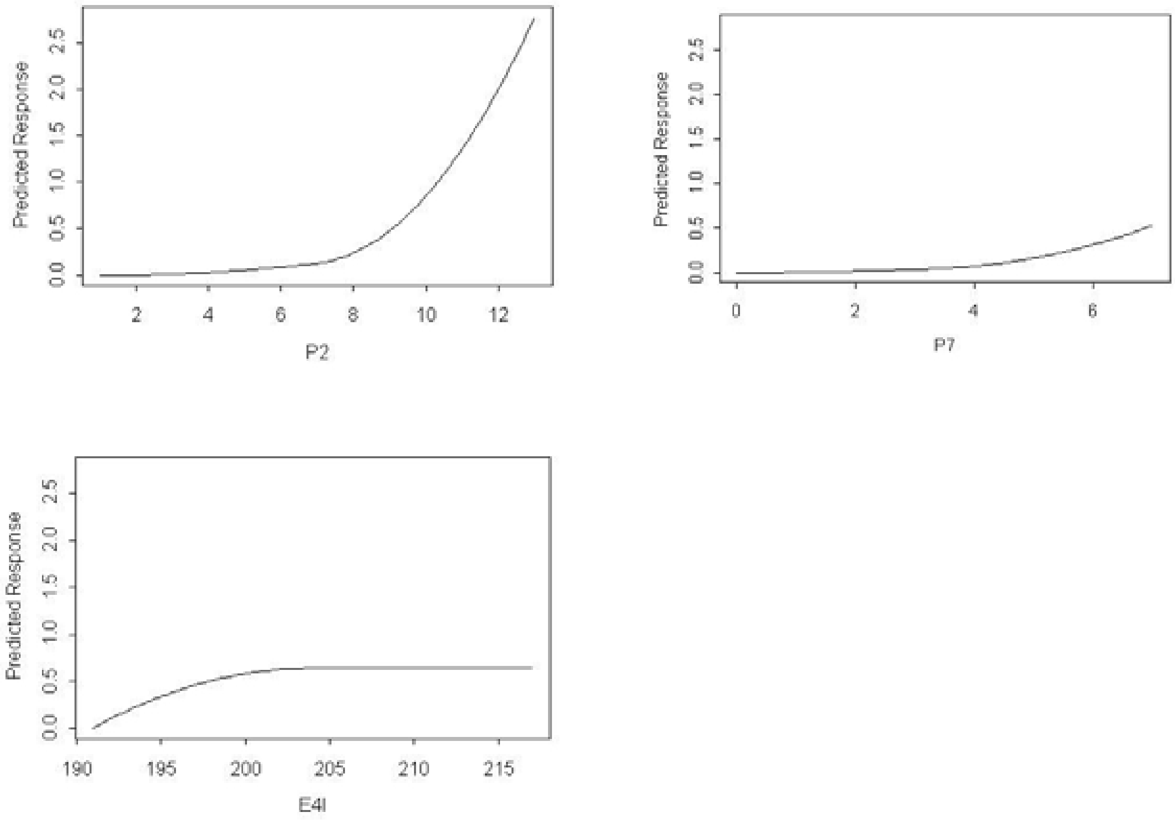


Figure 13: Plots of individual modelled functions between environmental predictor (X-axis) and compositional dissimilarity (Y-axis) for persistent, native plants in the larger GDM area

Notes: see Table 5 for predictor names

X-axis represents the locations on an environmental gradient

Y-axis shows the function fitted, holding other variables constant

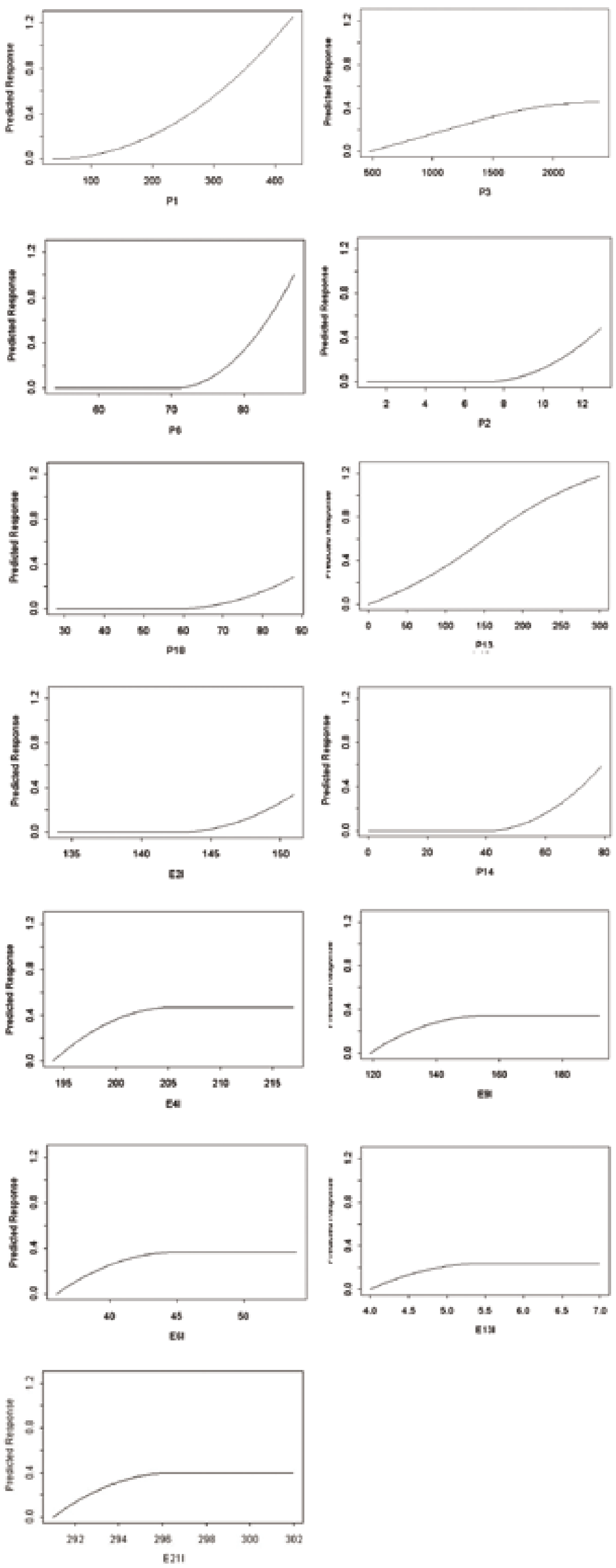


Figure 14: Plots of individual modelled functions between environmental predictors (X-axis) and compositional dissimilarity (Y-axis) for persistent, native plants in the GP masked area

Notes: see Table 5 for predictor names

X-axis represents the locations on an environmental gradient

Y-axis shows the function fitted, holding other variables constant

3.3 Interpreting biodiversity condition

We propose presenting the values of the selected individual indicators for each desired outcome separately instead of using a single, aggregate score. One of our indicators – total grazing pressure – is probably best derived using an index, which is discussed later. However, all values for the other indicators will be presented as normalised values to a number of condition states. These are: (1) value when degraded, irrespective of rainfall patterns – that is, no resilience; (2) intact, ecologically functioning under 'dry and wet' conditions; and (3) intact, ecologically functioning under 'wet' conditions.

Rather than have one condition state representing the ecologically sustainable, natural and complex state of the indicator, we propose all three.

For each desired outcome, we recommend producing radar plots to communicate the value of the selected indicators being monitored. This will show the effects of policy and management actions over time towards achieving biodiversity outcomes in each of the different land types of the Stony Plains case study region (Figure 15). Each arm of a plot could be used to indicate the relative value of a selected indicator to its three condition states for land types of interest (Figure 15). The condition state would be depicted as three circular-like lines where their relative positions depend on the expected threshold values of high and poor quality measurements (see % native vegetation cover versus occurrence of non-native invasive weeds in Figure 15A cf. Figure 15D). Results of the long-term monitoring sites per land types are compared relative to the condition state sites to inform policy and management actions. In the hypothetical example, land types 8 and 15 appear to be severely degraded, while 4 and 5 seem to be in the early stage of a decline.

Alternatively, each arm of a plot could be used to depict the relative value of all selected indicators to each of its three condition states (Figure 16). However, as measurements differ, it cannot be used to compare among the indicators. An additional benefit would be to show increases and decreases of indicators at each monitoring milestone so that achievement towards meeting biodiversity outcomes is tracked.

Measuring total grazing pressure is a challenge, and we recommend using a metric based on information already obtained by pastoral assessors when undertaking lease assessments and on additional information gained from the producer about the site during the field assessment. Information should include:

- numbers of domestic and feral stock and kangaroos on the waters of the site
- historical numbers of domestic and feral stock, rabbits and kangaroos on the waters of the site
- preferred grazing locations, for most of the time or at particular times on the site, marked on a map
- productive value of areas within the site, marked on a map
- the age of all permanent waters on site where permanency is greater than 12 months.

From this information it will be possible to estimate present stocking density, the intensity of grazing and how long the preferred grazing areas of the proposed site have been exposed to grazing. This information could also be supported by feral animal survey information.

In proposing this approach we assume that a well-designed, risk-based monitoring system is in place.

Figures 15A–E show hypothetical radar plots of six indicators monitored at reference and long-term monitoring sites for the native vegetation desired outcome:

- Hypothetical regional average native vegetation cover under dry conditions by land type (1–15), 1985–2000
- Hypothetical regional % cover of *Abutilon halophilum* by land type (1–15), 1985–2000
- Hypothetical regional frequency of *Abutilon halophilum* by land type (1–15), 1985–2000
- Hypothetical regional non-native invasive weeds by land type (1–15), 1985–2000
- Hypothetical regional total grazing pressure land type (1–15), 1985–2000

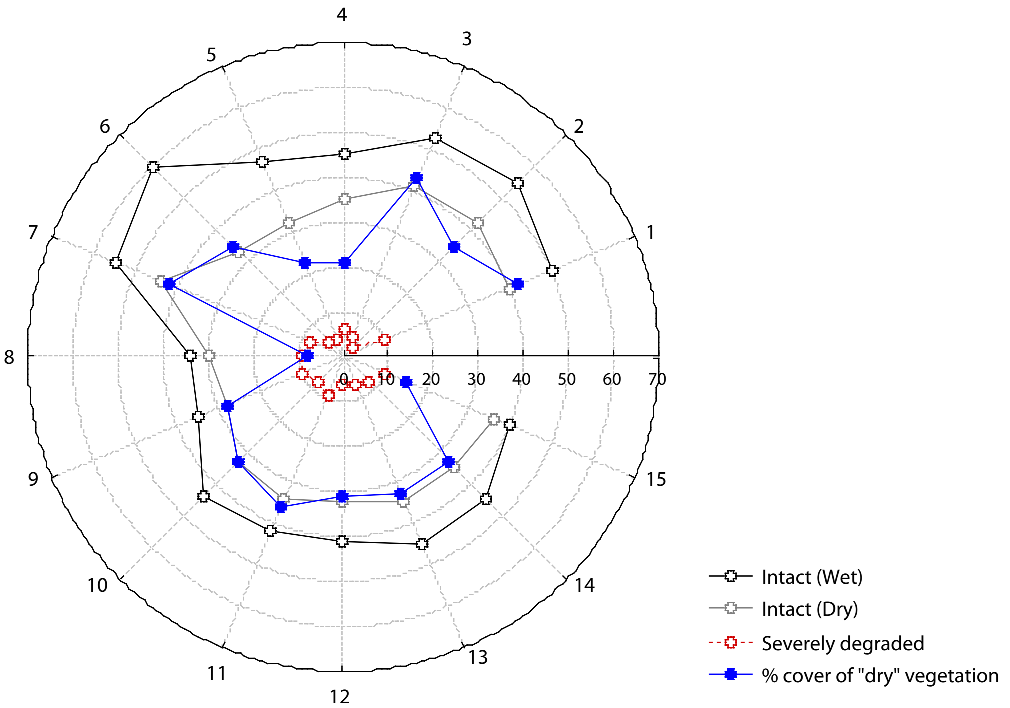


Figure 15A: Hypothetical regional average native vegetation cover under dry conditions by land type (1–15), 1985–2000

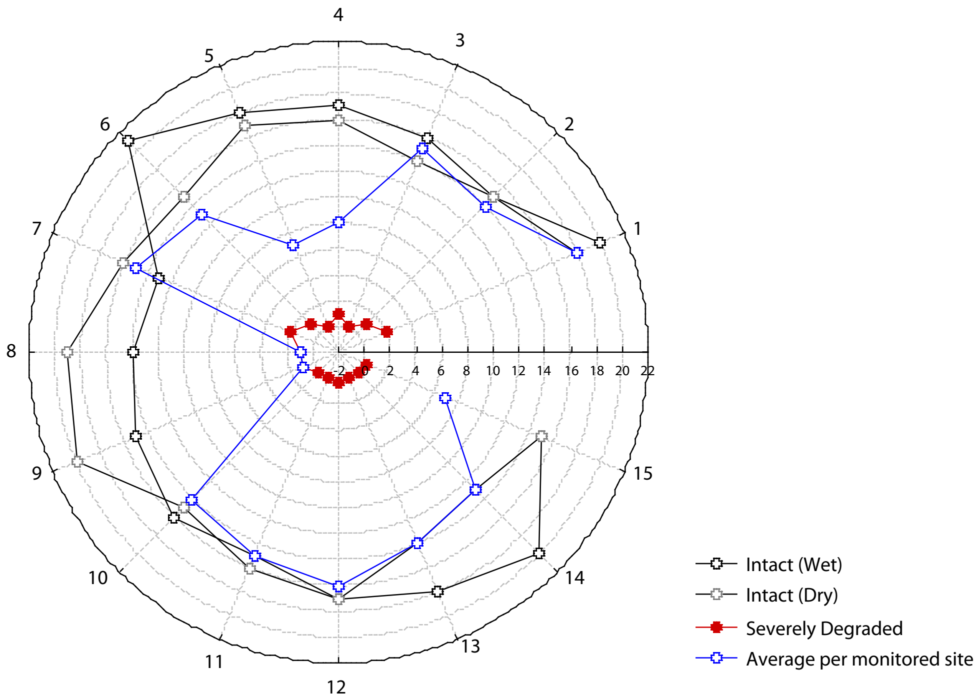


Figure 15B: Hypothetical regional % cover of Abutilon halophilum *by land type (1–15), 1985–2000*

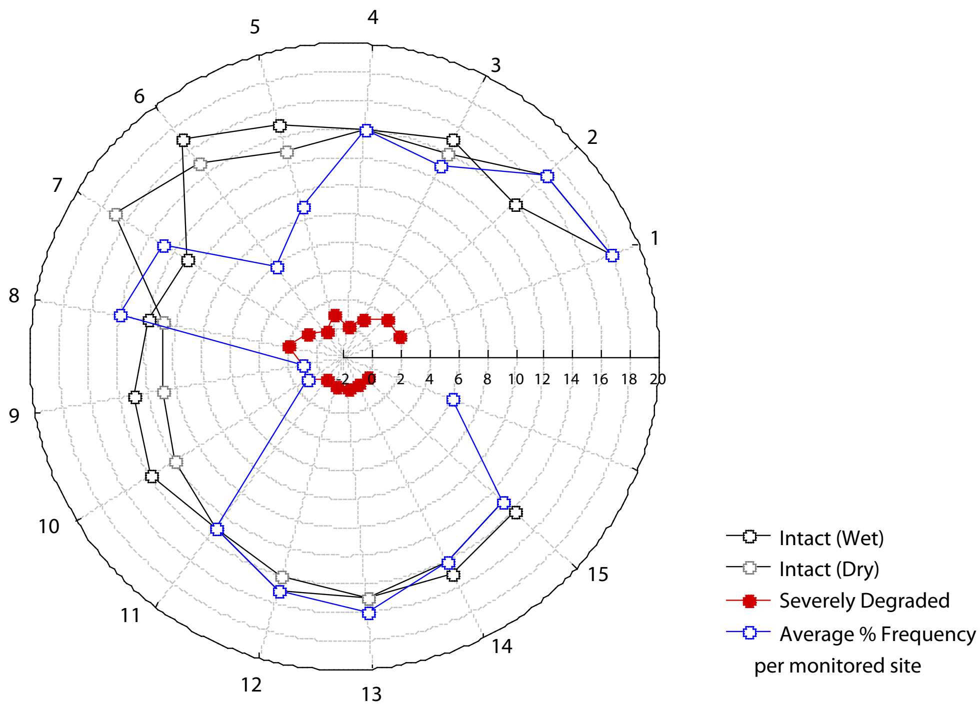


Figure 15C: Hypothetical regional frequency of Abutilon halophilum *by land type (1–15), 1985–2000*

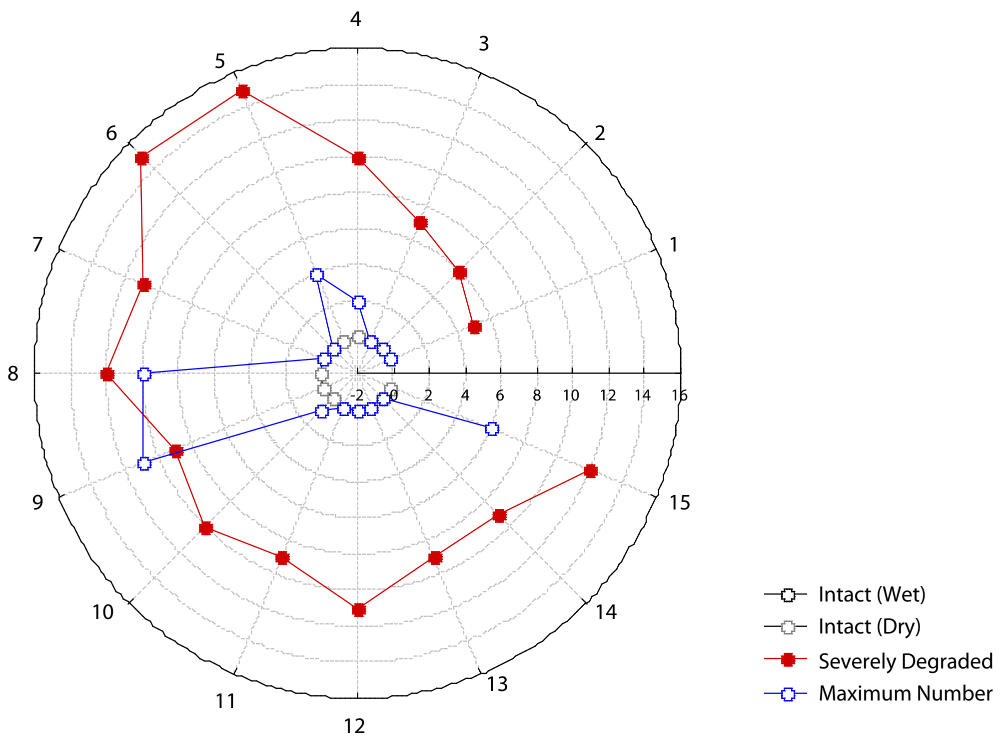


Figure 15D: Hypothetical regional non-native invasive weeds by land type (1–15), 1985–2000

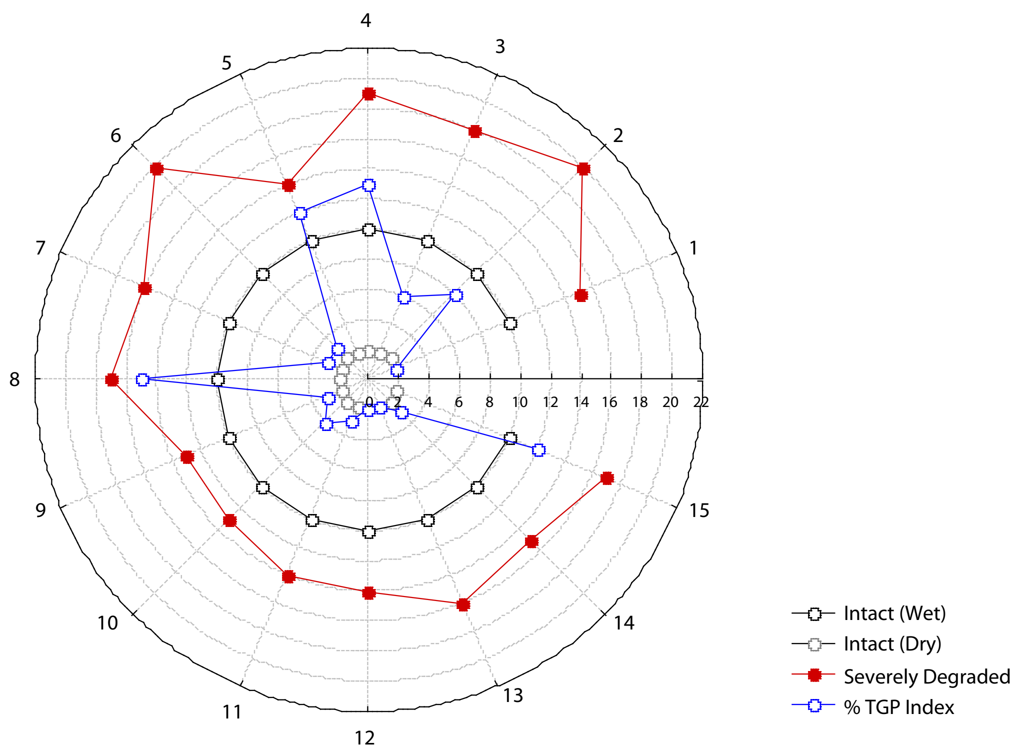


Figure 15E: Hypothetical regional total grazing pressure land type (1–15), 1985–2000

Figure 16 below shows hypothetical radar of six indicators monitored at reference and long-term monitoring sites to meet outcomes for native vegetation, where the horizontal axis is a numerical scale with no specific units.

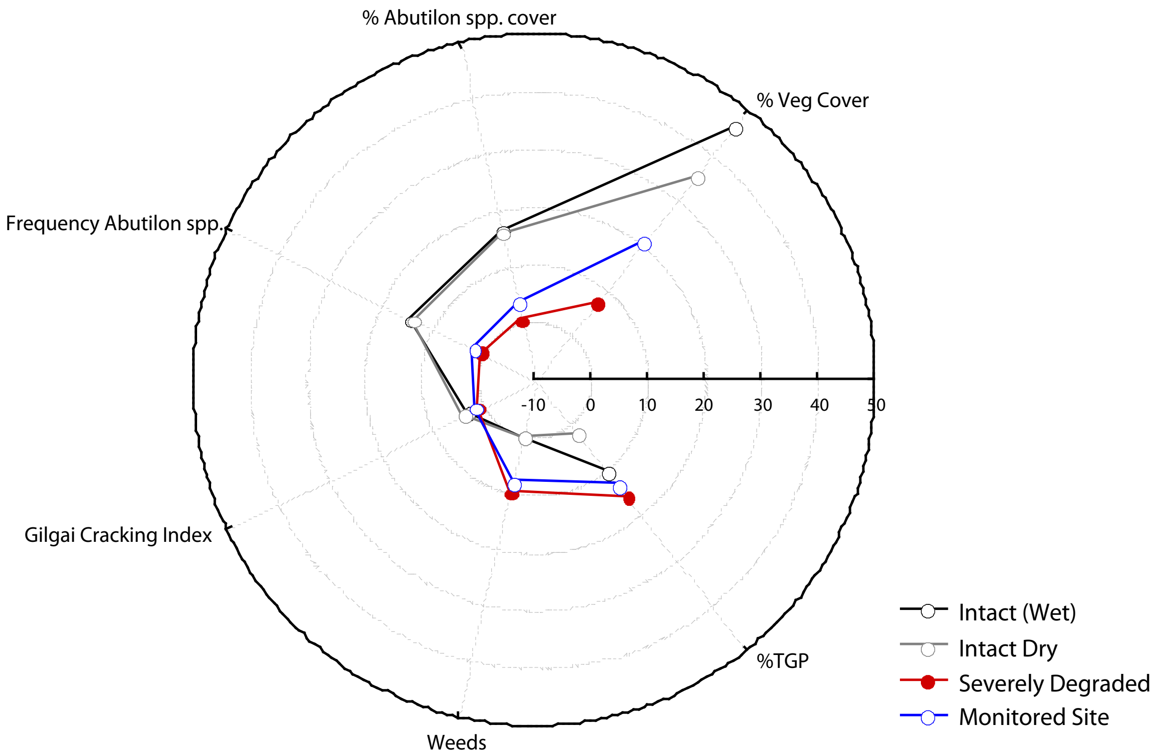


Figure 16: Hypothetical condition of native vegetation indicators for monitored sites within a land type, 1985–2000

4. Discussion

4.1 Identifying outcome-based indicators

We undertook a biodiversity risk assessment of the case study region in order to select indicators that were linked to the regional management objectives. This approach provided a foundation for prioritising which indicators to assess in the first instance by clearly stating a set of key desired outcomes. We looked at the feasibility of including both field and remote indicators in the assessment of biodiversity condition because both types are of interest to potential customers.

Using a set of criteria based on recommendations by several authors in the scientific literature, we were able to identify a necessary and sufficient set of field-based and remotely derived indicators for each of the desired outcomes for managing biodiversity in the Stony Plains bioregion. For the first two desired outcomes, three of the indicators for total grazing pressure were the same, which is a cost savings, but almost all of the indicators for achieving the other desired outcomes were different. This result has implications for policy effectiveness if resources are limited – biodiversity conservation managers may need to prioritise desired outcomes so that work towards achieving outcomes is phased.

In most cases, the selected field indicators met over two-thirds of the selection criteria (see Table 1) including measurement qualities, feasibility of implementation and policy and management utilities. The potential indicators that had conceptual relevance tended to be biotic and were grounded in natural history. However, these were most costly and difficult to collect, and there was considerable uncertainty about their reliability, predictability and anticipatory functions. With these kinds of indicators, it will be necessary to accept biodiversity indicators that meet fewer criteria, especially when the endpoint concerns conserving threatened species. Alternatively, investing in research that leads to resolution of some of these issues to do with causality between the stressors and biological attributes could improve their value.

In assessing indicators, we have not identified any particular taxon guild as an 'impact' type of indicator as described by Suter (2001). Potential guild indicators were reptiles or ants, but experimental field studies undertaken in the arid South Australian rangelands by Read and co-workers strongly suggest that these taxa are not reliable indicators of the impacts on ecosystems from total grazing pressure (Read 1999, 2002; Read & Andersen 2000).

We adopted a different approach to determine the regional indicators. While many other regional indicators have been developed (Bastin & Ludwig 2006, Ludwig et al. 2007), most are questionable predictors of biodiversity patterns as they have yet to be shown to be highly correlated with biological patterns (see Ludwig et al. 2007). As an alternative, we hoped to identify indicators where the remote predictors did this. We expected that grazing pressure, resilience and other predictors would predict biodiversity patterns, but our model failed to show this. The likely reasons for this are outlined below.

GDM modelling relied on climate, surrogates of landform, soils and geology, and pressure datasets. Although our information was derived from 100 x 100 m grids, some of the data showed little variation over the modelled areas of the Stony Plains. This is understandable as climate information is collected at very few stations (see Hutchinson et al. 2005) and is extrapolated to the whole region. The paucity of information was particularly evident when deriving the resilience predictor for the region. The patchiness of the rainfall in 2001 meant that there was not a consistent vegetation response, so we were unable to calculate grazing gradients for the whole area. Similarly, uranium of the radiometrics airborne data was a significant predictor but it was mainly picking up the extensive areas of gibber pavements on the rises in the region. This predictor for the region was primarily dominated by one response signature and did not provide information useful for prediction. TM Band 2 was a predictor for the 2000 mosaics and early 2002 mosaics in both GDM area and the GP subset area. It may reflect a signature of red soil and could be an indication of bare ground. However, without ground truthing, it is difficult to know whether this is due to land degradation or natural openness of different communities under variable conditions.

The results for grazing pressure were a surprise, as there was a definite gradient occurring in the different land types and we were puzzled as to why grazing pressure did not influence compositional dissimilarity of persistent, native plants. An explanation may be that some land types, especially SPT1, are reasonably resilient to grazing activity because the gibber landscapes are dynamic and thought to form far more rapidly than expected (Waclawik 2006). If this is true, then it is possible that soil is being turned over at faster rates and the effects of compaction may be less pronounced in these areas. Preliminary plant survey data, with cross-fence comparisons and at distances near to and remote from water points, tend to confirm this impression (Smyth and colleagues, unpublished data).

A major problem with this approach is significant variation in time for collecting biological survey data and taking imagery – the survey date was collected in different years and much earlier than when the imagery was taken. This is a fundamental problem when comparing imagery acquired at different times with ground data. Jafari et al. (2007) compared field estimates of ground cover from the DWLBC database during 1990–1991 with a number of multispectral vegetation indices derived from Landsat TM. This was done to see if image-based vegetation indices could be used as an adjunct to field methods for the assessment of land condition. The authors were able to use a satellite scene collected during dry conditions similar to the field conditions and they obtained promising results with some indices. In our case, we were including field data that spanned 30 years in the GDM modelling, while the Landsat imagery and derived indices were for only two dates. As yet, the results of GDM modelling have not been ground-truthed and even if we had identified some interesting and significant relationships, GDM modelling is still a development product for this region as we do not fully understand environmental processes that drive compositional patterning of vegetation. Therefore, for this project it was not useful for identifying regional estimator surrogates that had a strong relationship to biological patterns.

A challenge with using remotely derived indicators is that it does not facilitate the involvement of landholders in the process of monitoring stressors that affect biodiversity condition. To this end, the response-type indicators play an important role in landholders accepting and implementing policy. However, because these response-type indicators tend to drop out during the selection criteria assessment, it may be necessary for land and biodiversity conservation planners to include them just to encourage adoption (Andreasen et al. 2001, Niemeijer & de Groot 2007). Jafari et al. (2007) also suggest that there might be uncertainty by landholders in how to interpret remotely sensed indices in relation to conventional field data.

Assembling the spatial information required to run GDM modelling over the project area took a number of months. It is unlikely that agencies would have the capacity to commit these resources on an ongoing basis.

4.2 Assessing biodiversity condition

Assessing biodiversity condition is a monitoring exercise to determine the status and trends in indicators to help all managers decide whether biodiversity is being maintained or improved (Suter 2001). Indicators are often expressed in terms of metrics, which are then aggregated to give a single score (e.g. IBI by Karr & Dudley 1981, IBI by Majer & Beeston 1996, Oliver & Parkes 2003). These scores often obscure the actual condition of biodiversity. To minimise this problem, we proposed four different condition charts to help achieve each of the four different desired outcomes. More importantly, we proposed the novel idea of having three different reference conditions by which to gauge and interpret changes.

These reference conditions attempt to capture, in a qualitative sense, the variability in arid environmental conditions. Ideally, it would be beneficial to index the variability in the indicators and reference conditions quantitatively over time (e.g. Coulson & Joyce 2006, Howe et al. 2007) but we were not able to adopt this approach for this project as it would require a detailed study. Such complexity, while scientifically valid, may be less beneficial if policy makers and planners reject it because they do not sufficiently understand it.

Successful application of this approach hinges on a well-designed monitoring program with secure, long-term condition state and monitoring sites (Andreasen et al. 2001, Suter 2001).

4.3 Feasibility of identifying indicators for assessing biodiversity condition

Indicators have not had favourable treatment in the scientific literature for the past 15 years (see Smyth et al. 2000 for a summary of issues). The main reason for this is that different types, especially focal species, have sometimes been used in isolation to represent extraordinary ecological complexity without first formulating the problem or identifying the desired outcomes and the most pertinent indicators (Andreasen et al. 2001). We avoided this problem by adopting a risk-based approach to identify outcome-based indicators.

With a series of participatory workshops and a review of existing resources, it is feasible to adopt the problem formulation framework to identify appropriate indicators. At present, it is not feasible to use GDM, at least in landscapes similar to the Stony Plains, to quantitatively predict reliable indicators of ecological communities as measured by species dissimilarity. Once remotely derived indicators are calibrated and tested on the ground relative to biological attributes, the power of regional monitoring to inform regional biodiversity risks will increase substantially.

The merit of the approach that we propose largely depends on having a regional monitoring program to address regional biodiversity conservation issues. This approach is only feasible if it is supported by a long-term monitoring program that has guaranteed funding and institutional support similar to the role that the Australian Bureau of Statistics has in managing socio-economic statistics.

4.4 Next steps

This work has advanced the process for selecting indicators for assessing biodiversity condition in the arid rangelands. Using the Stony Plains bioregion as a case study, we:

- developed a problem formulation framework that links indicator selection to desired achievement in biodiversity
- established an integrated, comprehensive set of selection criteria
- identified a set of theoretically credible and practical field and remote indicators that measure information to address each desired outcome, but are yet to be tested
- developed a novel technique specific to the arid rangelands that helps managers to interpret the condition of biodiversity relative to the desired outcomes
- increased understanding about the generic nature of GDM modelling and data requirements
- identified knowledge gaps with using remotely derived indicators that offer promise.

The next steps leading from this work are to:

- establish a pilot monitoring program in the Stony Plains bioregion to identify condition states and monitoring sites to test the merit of and showcase the methods and selected indicators

- conduct research on the relationship between remotely derived indicators and ecological field indicators
- publish a paper on ‘Application of the problem formulation framework to identify meaningful indicators of biodiversity condition in arid Australia’.

4.5 Conclusions

We conclude that a problem formulation framework is essential in identifying a potential set of indicators for assessing biodiversity condition. By using selection criteria, it is feasible to identify a small subset of field and remote indicators pertaining to the nominated endpoints for managing biodiversity. These indicators are complete in that they collectively cover the complexity of biodiversity as well as the causal relationship between driving forces, stressors, condition, impact and response.

It is not feasible to use regional spatial modelling techniques to identify the relationship between biophysical explanatory variables and biodiversity patterns. We recommend more research to comprehensively test the merit of the indicators to identify changes in biodiversity condition and to understand the relationship of remotely derived indicators to biological patterns.

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Appendices

Appendix 1: Key principles for development of a biodiversity monitoring system

- Identify the reasons for monitoring and how the information is to be used (i.e. will it be used to support or inform management and decision making, or to demonstrate a level of environmental performance? See above.)
- Seek expert advice on biodiversity management and monitoring.
- Identify who is responsible for monitoring, collating, analysing and storing the data.
- Obtain basic information on the natural resources of the area (e.g. vegetation associations, soils, fauna, and, if available, identified biodiversity values).
- Identify and prioritise the risks to biodiversity values (including the changes that may be occurring in the environment). This should focus on the land uses that are occurring and potentially driving the changes in biodiversity values.
- Identify what changes are happening that have implications for biodiversity values.
- Define what is to be monitored. Ideally this will include at least one aspect of each of the structural, compositional and functional elements. It is clearly impossible to attempt to monitor all aspects of biodiversity. Instead, it is commonsense to monitor the abundance of a mix of attributes from at least each of the three components of biodiversity.
- Identify appropriate indicators (i.e. what will be monitored and how) considering the above questions.
- Consider the appropriate scales (temporal and spatial) for assessing these indicators. This will also involve identifying the scale of information that is required and what resources (time and money) are available to conduct the monitoring.
- Consider the locations most appropriate for monitoring (e.g. river banks, areas of grazing use, areas of important habitat or concentrations of species – areas that provide something important for the taxa of concern).
- Use monitoring methods that are objectively repeatable, have reliable ability to be re-counted and are informative.
- Conduct a regular, formal review of the monitoring system to ensure it is meeting the intended needs, and/or whether the needs have changed.

Source: Hunt et al. 2006

Appendix 2: Method used by Hunt et al. (2006) to develop a biodiversity monitoring program at the regional scale for a worked example

The purpose for monitoring biodiversity in the worked example of Hunt et al. was to assess 'improved condition of regional biodiversity assets', so the method used in this example is analogous to the problem being addressed in our study. The method involved undertaking two broad activities that can be separated into conceptual and operational aspects of monitoring biodiversity. The key conceptual issues addressed in the early stages of planning were:

- purpose of monitoring
- scale of the issue (i.e. the size and complexity of the area to be monitored)
- elements of biodiversity (as measured by surrogates) to monitor and the best indicators to measure them
- complementarity of interdependent indicators versus the value of a single surrogate indicator
- amount of sampling effort versus data quality
- analyses and evaluation
- adoption and uptake of change management practices arising from monitoring
- post hoc responsibility by monitoring agencies.

The steps used to design the biodiversity program were:

1. Obtain existing mapping and biodiversity data for the region.
2. Identify significant biodiversity components.
3. Identify significant pressures.
4. Select and measure 'pressure-type' and 'response-type' indicators.

Appendix 3: Participants of stakeholder, technical expert and producers workshops during 2005 and 2006

Participants	Affiliation
Amanda Brook	Knowledge and Information, DWLBC, South Australia
Robert Brandle	Biological Survey and Research, DEH, South Australia
Greg Campbell	S. Kidman & Co.
John Chappel	Pastoral Program, DWLBC, South Australia
Vanessa Chewings	CSIRO Sustainable Ecosystems, Alice Springs
Ken Clark	The University of Adelaide
Anthea Coggan	CSIRO Sustainable Ecosystems, Canberra
Phil Cullen	Producer
Jocelyn Davies	CSIRO Sustainable Ecosystems, Alice Springs
Rick Davies	CSIRO Sustainable Ecosystems, Alice Springs
Mike Fleming	Knowledge and Information, DWLBC, South Australia
Anthony Freebairn	DEH, South Australia
John Gavin	South Australian Arid Lands Natural Resources Management Board
Russell Gorddard	CSIRO Sustainable Ecosystems, Canberra
Charlie Jackson	Aboriginal Arid Lands Natural Resources Management (now Alinytjarra Wilurara NRM Board)
Paul Jupp	CSIRO Land and Water, Adelaide (formerly Pastoral Program, DWLBC, South Australia)
Megan Lewis	The University of Adelaide
John Maconochie	Pastoral Program, DWLBC, South Australia
Jo Maloney	Tangentyere Council, Alice Springs
Michael McBride	McBride Pastoral Company and Pastoral Board of South Australia
Geoff Mills	Producer
Sharron Oldfield	Cowarie Station, South Australia
John Read	Formerly BHP Billiton, Olympic Dam
Anita Smyth	CSIRO, Sustainable Ecosystems, Adelaide
Dionne Walsh	Centralian Land Management Association
Stuart Whitten	CSIRO, Sustainable Ecosystems, Canberra

Appendix 4: Sources and image processing details of datasets modelled as potential estimator surrogates of biodiversity as measured by plant compositional dissimilarity

Datasets	Source	Processing
Biological survey data		
Flora records	DWLBC & DEH	Records from the Pastoral Monitoring Information System (PMIS) database and Biological Survey (BS) database were checked and combined. Sites without persistent species were removed. Sites had been surveyed between 1974 and 2004.
Environmental data		
Land types	DWLBC	Some areas were identified as not being suitable for further analysis due to cloud in satellite imagery or dark gibber.
Digital Elevation Model (DEM) derived from Shuttle Radar Topography Mission	NASA, Geoimage (2006)	Images were mosaicked then processed by CSIRO's Division of Mathematical Information Science for Mapping and Monitoring Group to smooth and fill missing holes and pits (Caccetta 1999). This process was undertaken to produce a hydrologically sound DEM. Ouput products included slope and catchment size.
DEM derived layers	CSIRO	Slope, aspect, wetness, position in the landscape, elevation diversity and log of the catchment size calculated as output from the CMIS process or in Arcinfo software (ESRI 2006). Wetness is a measure of soil moisture at each cell, Wetness = LN(1 + (Catchment size/Slope)).
Climate layers of temperature, radiation and moisture	ANUCLIM/BIOCLIM http://cres.anu.edu.au/outputs/anuclim.php	Thirty-five layers were derived.
Satellite data Landsat TM mosaics bands 2 (green),3 (red) ,4 (infrared) for 1988, 1989, 1997, 2000, 2002	Australian Greenhouse Office and DWLBC (Brook et al. 2001)	Processing including cloud removal, masking of Lake Torrens and calibration of the NLWRA imagery (1988, 1989, 1997) to the AGO imagery (2000). Note that the AGO 2000 mosaic consists of images acquired September 1999 – January 2000. The 2002 mosaic consists of images acquired during January–March 2002.
PD54 (index of vegetation cover)	CSIRO, Pickup et al. (1994)	The development of the PD54 images was iterative, based on previous calculations done for the NLWRA. Highly variable seasonal conditions (Fig. 2) resulted in large variations in cover throughout the imagery so fitting a soil line in a consistent way was problematic. Consequently PD54 parameters were derived for the smaller NLWRA area.
Variance and contrast (derived using Landsat TM 2000 and 2002 data)	CSIRO	Measures of variance and contrast were calculated in a 3x3 window using the algorithm of Haralick et al. (1973) implemented in the ENVI image processing system (ITT 2006).
Radiometrics – potassium, thorium, uranium	Department of Primary Industries and Resources, South Australia (PIRSA)	Images for potassium, thorium and uranium were mosaicked and projected to Lamberts Conformal.
Land use pressure data		
Distance to water	DWLBC	Layer developed in Brook et al. (2001) was updated.
Grazing gradients	DWLBC and CSIRO	Calculated using distance to water and land type layers using CSIRO WPAC software for selected individual land types, combinations of land types and subregions for 5 mosaic dates (1988, 1989, 1997, 2000 and 2002).
Grazing pressure	DWLBC and CSIRO, unpublished	Derived from distance to water, land types and grazing gradient results for particular land types.

Appendix 5: Systematic assessment and prioritisation of biodiversity at risk issues for the Stony Plains bioregion

In this appendix, we identify the terrestrial biodiversity conservation priorities associated with total grazing pressure (TGP). We focused on TGP because it is the most widespread and significant disturbance that is pressuring terrestrial biodiversity of the Stony Plains bioregion (SADEH 2005). But first, we briefly summarise the key biodiversity assets and the biodiversity values of the region, and the threats and pressures affecting them.

1. Biodiversity assets and values

The significant biodiversity values that influenced the identification of indicators are listed below:

Key biodiversity values of the Stony Plains bioregion based on assets described in Brandle (1998), Neagle (2003) and SADEH (2005).

- Connected mosaics of extensive ecological communities/habitats across land types enabling genetic flows and species re-establishment across the landscape to maintain resilience of species and communities (i.e. compositional and structural attributes of biodiversity at the regional scale)
- Connectivity of minor and island ecological communities/habitats to neighbouring ecological communities to maintain resilience of significant ecological communities (i.e. structural attributes of biodiversity in significant ecological communities at the regional scale)
- Relatively uninterrupted surface water flows across resource source and sink patches within land types to support highly dynamic flora and fauna assemblages (i.e. maintain functional biodiversity at the regional scale)
- The diversity of plant and animal assemblages across and within land types (i.e. compositional attributes of biodiversity at a subregional scale)
- Endemic species and species for which the Stony Plains bioregion represents the largest area of suitable habitat for the species (i.e. compositional attributes of biodiversity at local scales)
- Threatened species
- Significant ecological communities (i.e. specific biodiversity attributes at local scales)
    - mound springs – internationally recognised heritage sites – geology and endemic species
    - gypsum clay plains – endemic and threatened plant species and important areas for native small mammal species including nationally vulnerable plains mouse
    - breakaway hills – endemic and threatened plant species, distinctive flora and fauna assemblages, endemic reptile species including nationally vulnerable bronze-backed legless lizard
    - drainage lines and floodplains – high plant and bird species richness, critical for most frog and fish species in the region
    - swamps – high periodic productivity provides important breeding habitat for aquatic fauna and waterbirds
    - waterholes – enable the survival of aquatic vertebrates (particularly fish) and sustain many bird species through dry periods
    - arid ranges – provide habitat for plant and animal species that have specialised for rocky range habitats and contribute to an archipelago of ranges that spans from the MacDonnell to the Flinders Ranges
    - areas of stony plains with gilgais – provide productive areas for native and non-native species following relatively minor rainfall events through the concentration of water and nutrients within the gilgais – important for the continuous existence of most small mammals in the region and low shrub dependent birds (e.g. thick-billed grasswren *Amytornis textilis*)
    - areas of stony tableland with sand mounds – important habitat for small mammals adapted to hopping (e.g. kultarr *Antechinomys laniger*, kowari *Dasyuroides bynie)* ground roosting birds (e.g. gibber bird *Ashbyia lovensis*) that are susceptible to nocturnal predation in better vegetated areas.

Appendix 6: Threats and pressures affecting biodiversity of the Stony Plains bioregion (after SADEH 2005)

Of these, excessive TGP and related mechanical disturbances are recognised as the most significant pressures on biodiversity at a regional level (SADEH 2005, Neagle 2003). At the paddock and station level, introduced predators are an equally significant threat and pressure on some native animals (Brandle 1998, Neagle 2003). Climate change and the other factors listed below are all added pressures that no doubt have a combined impact on the persistence of biodiversity. However, we did not consider them as indicators because:

- other government initiatives (e.g. GABSI programs) are facilitating the duty of care
- the threats and pressures require management actions beyond the capacity of the bioregion (e.g. climate change)
- the pressure is so localised that special management action would need to be developed (e.g. altered fire regimes).

After a more detailed assessment of the threats and pressures of TGP plus related mechanical disturbance and introduced predators in the Stony Plains bioregion at the October 2005 and March 2006 workshops, we identified a list of key threats and pressures that underpinned the identification of indicators.

Pressure	Description	Disturbance
Excessive total grazing pressure (TGP) and related mechanical disturbances	• Combined effects of grazing pressure from domestic stock, feral and native herbivores • Changes to the natural flow and/or flooding regimes of a watercourse due to diversions or the construction of artificial flow barriers and storage areas, tracks, dams and other infrastructure	• Loss of vegetation cover • Increased land degradation through soil erosion • Reduction in recruitment of grazing-intolerant native plant species • Increase in the recruitment of some unpalatable, grazing-favoured native plants • Loss of native animals due to competition for resources • Habitat loss or reduction in habitat quality • Invasion of weeds and disease • Degradation of ecosystem functioning • Disruption of dispersal mechanisms of aquatic species, • Loss of refuges • Increased land degradation through erosion and salinity
Introduced predators	• Densities of introduced carnivores increase the predation and mortality rate of native animal populations to levels beyond natural recruitment rates	• Decline/loss in local populations of native animals • Loss of species at the region level • Change in local ecosystem dynamics and composition
Climate change	• Changes in rainfall patterns and temperatures at rates greater than those to which species can adapt	• Contraction of species distributions • Shifts in the location of habitat and its quality • Threatened species become extinct • Increase in invasive species
State infrastructure	• Changes to the natural flow and/or flooding regimes of a watercourse due to, for example, diversions or the construction of artificial flow barriers and storage areas, roads, highways and seismic lines	• Degradation of ecosystem functioning • Loss of refuges • Increased land degradation through erosion and salinity
Altered fire regimes	• Changes in the intensity, season and frequency of fire is so rapid that species cannot adapt to the new regimes	• Changes in ecosystem structure and habitat value • Decline/loss in local populations of plants and animals
Pollution	• Poor quality of ground and/or surface water cause by human interventions	• Loss of local native species • Decline in the habitat value in and surrounding waterholes

Appendix 7: List of key threats and pressures affecting the persistence of terrestrial biodiversity in the Stony Plains bioregion that underpinned the identification of indicators

Key threats and pressures on terrestrial biodiversity of the Stony Plains bioregion

1. Loss, fragmentation and degradation of ecological communities

- High total grazing pressure
  - intensification of watered areas
  - development of new waters in areas historically remote from water
  - overgrazing
    - domestic stock
    - camels (only some land types)
    - donkeys (only some land types)
    - horses
    - rabbits (only some land types)
    - kangaroos

2. Species loss

- Increased predation of fragmented or rare native fauna populations by introduced predators, e.g. fox and cat
- Impact of reducing dingo populations
- Alteration of habitat structure by large herbivores (overgrazing and trampling)
- Loss of adult plants and their recruitment (refer to total grazing pressure)
  - to maintain some species populations no grazing pressure may be required
  - competition from invasive introduced plants

3. Change in natural surface water flows

- Construction of dams and drainage networks to fill dams affect the resources of downstream run-on areas.
- Construction of tracks with substantial windrows across gibber flats will alter water flow patterns.

Appendix 8: Desired outcomes, key biodiversity values and potential indicators for assessing biodiversity condition to meet the desired outcomes for the Stony Plains bioregion

Goal	**Retain or restore (if possible) the resilience of ecological communities/habitats for land types of the stony plains**			
Desired outcomes	**Native vegetation typical of the Stony Plains bioregion communities maintained or restored**	**Maintain and increase existing complement of rare and regionally significant native species, populations and ecological communities**	**Natural surface water flows of natural drainage lines maintained or restored**	**Mosaic of water remote areas**
Key biodiversity surrogates	• Vegetation cover • Plant diversity • Structural complexity • Naturalness (i.e. negligible rabbits, donkeys, camels, feral horses, pre-settlement kangaroo densities)	• Endemic and threatened species and communities • Species that are vulnerable to grazing • Significant ecological communities (gypsum clay plains, stony plains with gilgais, breakaway hills, drainage lines and flood plains, arid ranges, stony tableland with sand mounds) • Pre-settlement densities of dingos • Negligible foxes and cats • Negligible introduced weeds	• Landscape function	• Interconnected tracts of functioning ecological communities

Goal	Retain or restore (if possible) the resilience of ecological communities/habitats for land types of the stony plains			
Potential indicators	Within land types: • average % dry-period vegetation cover[1] • change in composition of persistent, palatable native perennial plant taxa[2] • frequency and cover of *Abutilon halophilum* at 1.5 km from water sources • diversity of age classes for dry-period vegetation[1] • landscape function[3, 4], resilience[5], leakiness score[6,7,8] • cracking index of gilgais • presence of non-native (terrestrial/aquatic) invasive weeds • presence of feral herbivores • change in composition of resident ground-dependent fauna (birds, small mammals, crickets) • insect numbers in dry conditions • kangaroo abundance • preferred grazing area of all stock most of the time • productive value of grazed areas • number of domestic stock per water • historical numbers of all stock and kangaroos per water • number of active rabbit warrens • change in waterpoint closure frequency and interval • property environmental plans • infrastructure to change grazing behaviour	Within land types: • register of potential threats and impacts affecting conservation-related species and significant communities in property plan • infrastructure to mitigate threats • preferred grazing area of all stock most of the time • number of domestic stock per water • number of active rabbit warrens • presence of feral herbivores • composition of terrestrial fauna • presence of dingos • presence of non-native (terrestrial/aquatic) invasive weeds • presence of terrestrial endemic and threatened species • status of regionally significant terrestrial ecological communities • change in composition and abundance of mound spring fauna specifically fly-specked hardyhead (*Craterocephalus stercusmuscarum*), hardyhead (C. eyresii), desert goby (Chlamydogoblus eremius) and endemics • change in composition and distribution of mound spring vegetation specifically pigface *Hemichroa* (*Hemichroa mesembryanthemum*), *Utricularia dichondra*, salt pipewort (*Eriocaulon carsonii*) • presence of aquatic endemic and threatened fauna • status of regionally significant aquatic communities of drainage lines an floodplains • water quality • CUMSUM for rainfall • seasonality of temperature and rainfall	Within catchments: • change in extent and distribution of floodwaters • average % cover of riparian and wetland vegetation, especially *Enteropogon ramosus, Eragrostis setifloia, Eulalia aurea, Santalum lanceolatum, Erompholia longifloia, Cyprus* spp. of riparian communities after wet conditions • change in composition of aquatic and semi-aquatic vegetation • presence of non-native (terrestrial/aquatic) invasive weeds • presence of native saplings below 2 m in height • composition and abundance of waterbird fauna • no artificial earthworks in drainage lines • reduced estimated number of erosion gullies and central windrows on tracks per km	Within land types: • % area remote from water by length of time • density of artificial waterpoints by age

[[1] Dry period vegetation cover is the vegetation cover that is typical after long periods of little or no rain; [2]Native plant taxa that are detectable and identifiable after long dry periods of little or no rain (e.g. a subset of the persistent taxa listed in Appendix 11) and palatable where palatable flora are those species favoured by domestic stock and feral herbivores; [3]Tongway & Hindley 2004; [4]Bastin et al. 2002; [5]Pickup et al. 1994; [6] Ludwig et al. 2002; [7]Ludwig et al. 2006; [8]Ludwig et al. 2007]

Appendix 9: Ecological function of biodiversity surrogates as identified by a panel of technical experts

Biodiversity surrogates	Function
Vegetation cover, floristic diversity, structural complexity, negligible feral animals (rabbits, donkeys, camels, feral horses) Pre-settlement kangaroo densities	Vegetation provides food for herbivores, cover for resource retention and habitats for animals. Feral animals and high densities of kangaroos add to the total grazing pressure of already disturbed plant ecosystems.
Endemic and threatened species, grazing-intolerant species, significant ecological communities (gypsum clay plains, stony plains with gilgais, breakaway hills, drainage lines and flood plains, arid ranges, stony tableland with sand mounds), pre-settlement densities of dingos, negligible foxes, cats and non-native invasive weeds	Grazing-intolerant plant species that are an iconic complement of the floristic diversity and contribute to ground cover for retaining resources, and provide habitat for fauna. Also, a direct measure of significant components of biodiversity. Dingos are meso-predators of cats and foxes, and weeds homogenise natural ecosystems by out-competing native vegetation especially when it is subject to excessive grazing pressure. (NB. Significant ecological communities were considered special cases of conservation that needed a different suite of indicators for monitoring condition. As a result the function was not considered further.)
Landscape function of natural surface water flow and drainage lines	Landscape-scale habitats for aquatic life cycle development, source subpopulations of meta populations, breeding and dispersal, and important sources of water for terrestrial wildlife and livestock.
Interconnectedness of tracts of ecological communities	Preserve the natural heritage values and provide source populations for genetic connectivity.

Appendix 10: Description of potential outcome-based indicators, with comments on relevance, acceptance and applicability to each desired management outcome

Note: Desired management outcome = DO

Indicator (Type) Note that items in bold are the indicators that were selected in the final indicator set	Description	Relevant to whom?	Potential acceptance	DO 1	DO 2	DO 3	DO 4
Preferred grazing area of all stock for most of the time (Driving force)	**Property management plan. Indicates intensity of grazing in the ecological communities favoured by stock**	**Landholders, government land and biodiversity conservation managers**	**High: all stakeholders**	✓	✓		
Productive value of grazed areas (Driving force)	**Property management plan. Indicates intensity of potential pressures on ecological communities**	**Landholders, government land and biodiversity conservation managers**	**High: all stakeholders**	✓			
Number of domestic stock per water (Pressure)	**Property management plan. Directly indicates total grazing pressure when combined with feral herbivores and kangaroos**	**Landholders, government land and biodiversity conservation managers**	**High: all stakeholders**	✓	✓		
Presence of feral herbivores (camels, donkeys, horses) (Pressure)	**Aerial assessment across property boundaries. Indicates, in combination with stock and kangaroos, total grazing pressure on ecological communities**	**Pest managers**	**High: some landholders, land and biodiversity conservation managers** **Low: Some Aboriginal landholders**	✓	✓		
Historical numbers of all stock and kangaroos per water (Pressure)	**Government records and property management plans. Directly indicates intensity of grazing and exposure to total grazing pressure**	**Landholders, land managers, biodiversity conservation managers**	**High: biodiversity conservation managers** **Low: landholders and land managers**	✓			
Number of active rabbit warrens (Pressure)	**Field assessment. Indicates total grazing pressure in combination with feral herbivores and stock**	**Landholders, government land and biodiversity conservation managers**	**High: all stakeholders**	✓	✓		
Change in waterpoint closure frequency and interval (Pressure)	Property management plan or remotely derived. Indicates grazing pressure and land-use intensity	Landholders, biodiversity conservation and land managers, mining companies	High: biodiversity conservation and land managers Low: landholders	✓			
Presence of non-native (terrestrial/aquatic) invasive weeds (Pressure)	**Field assessment. Indicates invasion and spread through formal reporting of new presences**	**Landholders, land and biodiversity conservation and pest managers**	**High: land and biodiversity conservation managers** **Medium: landholders**	✓	✓	✓	

Indicator (Type) Note that items in bold are the indicators that were selected in the final indicator set	Description	Relevant to whom?	Potential acceptance	DO 1	DO 2	DO 3	DO 4
Mean % dry-period vegetation cover (State)	**Field assessment or remotely derived using MODIS imagery (e.g. Bastin et al. 2006) and GIS. The later maps cover at nominated times for paddock/ property scaled between the historically lowest and highest values of cover for the paddock, property or region. Time traces could be used to track average cover for dry times. Indicates total grazing pressure in different terrestrial ecological communities**	**Landholders, government land and biodiversity conservation managers, mining companies and tourists of the outback**	**High: all stakeholders**	✓			
Diversity of age classes for dry-period vegetation (State)	Field assessment. Indicates maintenance of pastorally productive plant species and habitat for other elements of biodiversity during common climatic conditions.	Biodiversity conservation managers	High: biodiversity conservation managers Low: landholders, other land managers	✓			
Composition of palatable, persistent native plant taxa (State)	Field assessment. Indicates maintenance of pastorally productive plant species and habitat for other elements of biodiversity during common climatic conditions	Landholders, land and biodiversity conservation managers, mining companies	High: Land and biodiversity conservation managers Low: landholders	✓			
Frequency and cover of *Abutilon halophilum* at 1.5 km from water (State)	**Field assessment. Indicates maintenance of pastorally productive plant species for other elements of biodiversity during common climatic conditions**	**Landholders, government land and biodiversity conservation managers, mining companies**	**High: All stakeholders**	✓			
Change in composition of resident ground-dependent fauna (birds, small mammals, crickets) (State)	Field assessment. Presence of certain species indicates the level of disturbance to environment, hence the presence of some specific species in least pressured areas of the landscape is desirable for persistence	Biodiversity conservation managers, tourists	High: biodiversity conservation managers Low: landholders and land managers	✓			
Landscape function (State)	Field assessment. Indicates the loss of water and soil resources in ecosystems	Landholders, land managers, mining companies	High: landholders, land mangers Medium: biodiversity conservation managers	✓			

Indicator (Type) Note that items in bold are the indicators that were selected in the final indicator set	Description	Relevant to whom?	Potential acceptance	DO 1	DO 2	DO 3	DO 4
Resilience (State)	Remotely derived. Indicates the impact of total grazing pressure and correlates with vegetation cover	Land managers, landholders, biodiversity conservation managers	High: landholders, land mangers, Medium: biodiversity conservation managers	✓			
Leakiness index (State)	Remotely derived. Indicates the impact of total grazing pressure and correlates with vegetation cover	Land managers, landholders, biodiversity conservation managers	High: landholders, land mangers, Medium: biodiversity conservation managers	✓			
Cracking index of gilgais	**Field assessment. Indicates the impact of total grazing pressure on vegetation and animals.**	**Biodiversity conservation managers, landholders, land managers, mining companies**	**High: All stakeholders**	✓			
Insect numbers in dry conditions (State)	Rapid field assessment. Indicates condition of ecological communities when present in large numbers during dry times	Biodiversity conservation managers	High: biodiversity conservation managers Low: landholders and land managers	✓			
Kangaroo abundance **(Impact)**	**Field assessment by rapid assessment. Confidence in sustainability of harvest and to set quota to maintain pre-settlement densities. Indicates total grazing pressure**	**Government pest managers, and managers, biodiversity conservation mangers**	**High: All stakeholders**	✓			
Property environmental plans (Response)	Indicates landholders responsiveness to ecologically sustainable grazing land management practices	Landholders, land managers	High: landholders, land managers Low: biodiversity conservation managers	✓			
Infrastructure to change grazing behaviour (Response)	Fencing diversions. Indicates landholders responsiveness to ecologically sustainable grazing land management practices	Landholders, land managers	High: landholders, land managers Low: biodiversity conservation managers	✓	✓		
Presence of dingos or foxes **(Driving force)**	**Field assessment. Indicates control for sheep production but a lack of policy control of feral predators (e.g. foxes, cats)**	**Biodiversity conservation and pest managers**	**High: biodiversity conservation managers** **Low: landholders and land managers**		✓		
Presence of terrestrial endemic and threatened fauna **(State)**	**Field assessment. Indicates improving the environment if species are delisted locally or not listed ever**	**Biodiversity conservation managers, mining companies**	**High: Biodiversity conservation managers, Aboriginal custodians, some landholders** **Low: land managers**		✓		
Composition of terrestrial fauna (State)	Field assessment. Indicates improving the environment if species are delisted locally or not listed ever	Biodiversity conservation managers, mining companies	High: Biodiversity conservation managers, Aboriginal custodians, some landholders Low: land managers		✓		

Indicator (Type) Note that items in bold are the indicators that were selected in the final indicator set	Description	Relevant to whom?	Potential acceptance	DO 1	DO 2	DO 3	DO 4
Status of regionally significant terrestrial ecological communities (Impact)	Field assessment. Indicates improving the environment if species are delisted locally	Biodiversity conservation managers, Aboriginal landholders mining companies	High: Biodiversity conservation managers, Aboriginal custodians, some landholders Low: land managers		✓		
Change in composition of mound spring fauna specifically fly-specked hardyhead (*Craterocephalus stercusmuscarum*), hardyhead (*C. eyresii*), desert goby (*Chlamydogoblus eremius*) and endemics (State)	**Field assessment. Indicates improving the environment if species are delisted locally or not listed ever**	**Biodiversity conservation managers, Aboriginal landholders**	**High: Biodiversity conservation managers, Aboriginal custodians, some landholders Low: land managers**		✓		
Change in composition and distribution of mound springs vegetation specifically pigface Hemichroa (*Hemichroa mesembryanthemum*), *Utricularia dichondra*, salt pipewort (*Eriocaulon carsonii*) (State)	**Field assessment. Indicates improving the environment if species are delisted locally or not listed ever**	**Landholders, land and biodiversity conservation managers, mining companies**	**High: Land and biodiversity conservation managers Low: landholders**		✓		
Presence of aquatic endemic and threatened fauna (drainage lines and flood plains) (State)	**Field assessment. Indicates improving the environment if species are delisted locally or not listed ever**	**Biodiversity conservation managers, Aboriginal landholders, mining companies**	**High: Biodiversity conservation managers, Aboriginal custodians, some landholders Low: land managers**		✓		
Status of regionally significant aquatic communities of drainage lines and floodplains (Impact)	Field assessment. Indicates improving the environment if species are delisted locally	Biodiversity conservation managers, Aboriginal landholders mining companies	High: Biodiversity conservation managers, Aboriginal custodians, some landholders Low: land managers		✓		
Water quality (State)	Indicator of aquatic and riparian habitat condition	Landholders, land and biodiversity conservation managers, mining companies	High: land and biodiversity conservation managers Low: landholders		✓		
Register of potential threats, impacts and mitigation affecting significant species and ecological communities (enterprise level) (Response)	Indicates landholders' responsiveness to ecologically sustainable grazing land management practices	Landholders, biodiversity conservation mangers	High: biodiversity conservation managers Low: landholders, land managers		✓		
CUMSUM[2] rainfall	**Remotely and field assessment. Indicates climate change**	**Landholders, biodiversity conservation managers, land managers, mining companies, regional communities**	**High: all stakeholders**		✓		
Seasonality of temperature and rainfall	**Remotely and field assessment. Indicates climate change pressure**	**Landholders, biodiversity conservation managers, land managers, mining companies, regional communities**	**High: all stakeholders**		✓		

2 Cumulative sum of the standard deviations from the long-term mean

Indicator (Type) Note that items in bold are the indicators that were selected in the final indicator set	Description	Relevant to whom?	Potential acceptance	DO 1	DO 2	DO 3	DO 4
Average % cover of riparian and wetland focal plant species (especially *Enteropogon ramosus*, *Eragrostis setifloia*, *Eulalia aurea*, *Santalum lanceolatum*, *Erompholia longifloia*, *Cyprus* spp. of riparian communities) (State)	Field assessment. Indicates total grazing pressure and magnitude of impact	Land and biodiversity conservation managers, tourists of the outback	High: biodiversity conservation and land managers, tourists Low: landholders			✓	
Presence of native saplings below 2 m in height (State)	**Field assessment. Indicates maintenance of pastorally productive long-lived riparian vegetation and habitat for other elements of biodiversity**	**Landholders, land and biodiversity conservation managers, mining companies**	**High: all land managers and ecologists**			✓	
Change in composition of aquatic and semi-aquatic vegetation (State)	Field assessment. Directly measures the effect of changed flow regimes and riparian vegetation and wetland health	Biodiversity conservation managers	High: biodiversity conservation managers, ecologists Low: landholders, land managers			✓	
Composition and abundance of waterbird fauna (State)	Sensitive to changes in water quality and pollution. An integrating indicator because they are at the top of the food chain	Biodiversity conservation managers, tourists	High: biodiversity conservation managers Low: landholders and land managers			✓	
Change in the extent and distribution of floodwaters (Impact)	**Remotely-derived. Directly measures the effect of changed flow regimes by monitoring seasonality, duration, extent, and frequency**	**Landholders, biodiversity conservation and land managers, mining companies**	**High: biodiversity conservation managers Medium: land mangers and landholders**			✓	
No artificial earthworks in drainage lines (Response)	**Field assessment. Directly restores natural flow patterns**	**Landholders, land managers, biodiversity conservation managers**	**High: biodiversity conservation managers Low: land mangers and landholders**			✓	
Reduced estimated no. of erosion gullies and central windrows on tracks per km (Response)	**Field assessment. Directly restores natural flow patterns**	**Landholders, land managers, biodiversity conservation managers**	**High: land mangers and landholders Low: biodiversity conservation managers**			✓	
Density of artificial waterpoints by age (Pressure)	**Remotely derived. Indicates grazing pressure and land-use intensity but also directly correlated with changes in water-dependent species**	**Landholders, biodiversity conservation and land managers, mining companies**	**High: all managers and ecologists**				✓
% area remote from water by length of time (State)	**Remotely derived. Indicates the sustainability, naturalness and intactness of ecological communities**	**Landholders, biodiversity conservation and land managers, mining companies, tourists**	**High: biodiversity conservation managers Low: land managers, landholders**				✓

Appendix 11: Desired outcome 1 – Native vegetation condition

Assessment of appropriate indicators based on Conceptual relevance and Historical dimensions of selection criteria (Table 1)

Indicator Note that items in bold are the indicators that were selected in the final indicator set	**Criterion**							
	Conceptual relevance						**Historical dimension**	
	1.1 Biotic	**1.2 Naturalness**	**1.3 Biodiversity Complexity** **C – composition** **S – Structure** **F – Function**	**1.4 Multi-scaled**	**1.5 Land-water link**	**1.6 Ecosystem function** **D – Driving force** **P – Pressure** **S – State** **I – Impact** **R – Response**	**2.1 Historical records**	**2.2 Reliability**
1. Mean % dry-period vegetation cover	**✓**	**✓**	**S**	**✓**	**✓**	**S**	**✓**	**✓**
2. Composition of palatable, persistent native plant taxa	✓	✓	C	X	✓	S	✓	?
3. Diversity of age classes for dry-period vegetation	✓	✓	S	X	X	S	X	✓
4. Frequency and cover of *Abutilon halophilum* at 1.5 km from water	**✓**	**✓**	**C**	**X**	**X**	**S**	**✓**	**X**
5. Landscape function[2, 3]	X	X	?	✓	✓	S	X	✓
6. Resilience[4]	X	X	?	X	✓	S	X	X
7. Leakiness index[5,6]	X	X	?	X	✓	S	X	✓
8. Cracking index of gilgais	**X**	**✓**	**F**	**X**	**✓**	**S**	**X**	**X**
9. Presence of non-native (terrestrial/aquatic) invasive weeds	**✓**	**X**	**F**	**X**	**✓**	**P**	**✓**	**✓**
10. Presence of feral herbivores	**✓**	**X**	**F**	**X**	**✓**	**P**	**✓**	**✓**
11. Change in composition of resident ground-dependent fauna	✓	✓	S	X	X	S	X	X
12. Insect numbers in dry conditions	✓	✓	S	X	X	S	X	X
13. Kangaroo abundance	**✓**	**✓**	**S**	**✓**	**✓**	**I**	**✓**	**✓**
14. Preferred grazing area of all stock most of the time	**✓**	**✓**	**X**	**X**	**✓**	**D**	**X**	**✓**
15. Productive value of grazed areas	**X**	**X**	**X**	**X**	**X**	**D**	**X**	**✓**
16. Number of domestic stock per water	**✓**	**X**	**F**	**X**	**✓**	**P**	**✓**	**✓**
17. Historical numbers of all stock and kangaroos per water	**✓**	**X**	**F**	**X**	**✓**	**P**	**✓**	**X**
18. Number of active rabbit warrens	✓	½	F	X	X	P	X	✓
19. Change in waterpoint closure frequency and interval	X	X	X	✓	X	P	X	X
20. Property environmental plans	X	X	X	X	✓	R	X	X
21. Infrastructure to change grazing behaviour	X	X	X	X	✓	R	X	X

[1] See Table 1 for descriptions of criteria

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

[2] Tongway & Hindley 2004 [3] Bastin et al. 2002 [4] Pickup et al. 1994 [5] Ludwig et al. 2002 [6] Ludwig et al. 2007

Appendix 12: Desired outcome 1 – Native vegetation condition

Assessment of appropriate indicators based on Measurement qualities dimension of selection criteria (Table 1)

Indicator	Criterion										
	Measurement qualities										
	3.1 Anticpatory	3.2 Predictable	3.3 Robust	3.4 Sensitive to pressures	3.5 Space-bound	3.6 Time-bound	3.7 Measurable	3.8 Portable	3.9 Specificity	3.10 Statistical properties	3.11 Universality
1. Mean % dry-period vegetation cover	✓	X	X	✓	✓	✓	✓	✓	✓	X	✓
2. Composition of palatable, persistent native plant taxa	✓	X	X	✓	✓	✓	✓	✓	✓	✓	✓
3. Diversity of age classes for dry-period vegetation	✓	X	X	✓	✓	✓	✓	✓	✓	✓	✓
4. Frequency and cover of *Abutilon halophilum* at 1.5 km from water	✓	✓	✓	✓	✓	✓	✓	½	✓	✓	X
5. Landscape function[2, 3]	X	X	✓	½	✓	✓	½	✓	✓	X	✓
6. Resilience[4]	½	X	X	?	✓	✓	✓	✓	✓	X	✓
7. Leakiness index[5,6, 7]	½	X	X	✓	✓	✓	✓	✓	✓	X	✓
8. Cracking index of gilgais	✓	?	✓	✓	✓	✓	✓	✓	✓	✓	✓
9. Presence of non-native (terrestrial/aquatic) invasive weeds	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
10. Presence of feral herbivores	✓	✓	✓	X	X	X	✓	✓	✓	X	✓
11. Change in composition of resident ground-dependent fauna	✓	X	X	✓	✓	✓	✓	X	X	X	✓
12. Insect numbers in dry conditions	✓	X	X	✓	X	✓	✓	X	X	X	✓
13. Kangaroo abundance	X	X	X	✓	✓	✓	✓	✓	✓	X	✓
14. Preferred grazing area of all stock most of the time	✓	✓	X	✓	✓	✓	✓	✓	✓	X	✓
15. Productive value of grazed areas	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓
16. Number of domestic stock per water	✓	✓	X	X	✓	✓	✓	✓	✓	✓	✓

Indicator	Criterion										
	Measurement qualities										
	3.1 Anticpatory	3.2 Predictable	3.3 Robust	3.4 Sensitive to pressures	3.5 Space-bound	3.6 Time-bound	3.7 Measurable	3.8 Portable	3.9 Specificity	3.10 Statistical properties	3.11 Universality
17. Historical numbers of all stock and kangaroos per water	✓	✓	✓	X	✓	✓	✓	X	✓	✓	✓
18. Number of active rabbit warrens	✓	✓	X	X	✓	X	X	X	✓	✓	✓
19. Change in waterpoint closure frequency and interval	½	✓	X	X	X	✓	✓	✓	✓	✓	✓
20. Property environmental plans	X	X	X	X	X	✓	X	X	X	X	✓
21. Infrastructure to change grazing behaviour	X	X	X	X	X	✓	X	X	X	X	✓

[1] See Table 1 for descriptions of criteria

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

[2] Tongway & Hindley 2004

[3] Bastin et al. 2002

[4] Pickup et al. 1994

[5] Ludwig et al. 2002

[6] Ludwig et al. 2006

[7] Ludwig et al. 2007

Appendix 13: Desired outcome 1 – Native vegetation condition

Assessment of appropriate indicators based on Feasibility of implementation and Policy and management utility dimensions of selection criteria (Table 1)

Indicator	Criterion													
	Feasibility of implementation						Policy and management utility							
	4.1 Cost-effective	4.2 Data	4.3 Technical skills	4.4 Operational simplicity	4.5 Resource needs	4.6 Time needs	5.1 Compre-hensible	5.2 Compatibility	5.3 Societal links	5.4 Mgt links	5.5 NRM targets	5.6 Noticeable Significance	5.7 Acceptance	5.8 Facilitative
1. Mean % dry-period vegetation cover	✓	✓	✓	½	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2. Composition of palatable, persistent native plant taxa	X	✓	X	X	✓	✓	✓	X	X	✓	X	✓	½	X
3. Diversity of age classes for dry-period vegetation	X	X	X	✓	X	X	✓	✓	X	✓	X	✓	½	X
4. Frequency and cover of *Abutilon halophilum* at 1.5 km from water	**X**	✓	✓	✓	✓	✓	✓	**X**	✓	✓	**?**	✓	✓	✓
5. Landscape function[2, 3]	X	X	½	X	X	X	✓	✓	X	½	X	✓	✓	✓
6. Resilience[4]	✓	X	X	X	✓	X	X	✓	X	½	X	✓	½	X
7. Leakiness index[5,6, 7]	✓	✓	X	X	✓	✓	X	✓	X	✓	X	✓	½	X
8. Cracking index of gilgais	✓	✓	✓	✓	✓	✓	✓	✓	**X**	✓	**X**	✓	✓	✓
9. Presence of non-native (terrestrial/ aquatic) invasive weeds	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
10. Presence of feral herbivores	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
11. Change in composition of resident ground-dependent fauna	X	X	X	X	✓	X	✓	X	X	✓	X	✓	½	X
12. Insect numbers in dry conditions	✓	✓	✓	✓	✓	X	✓	✓	✓		X	✓	½	✓
13. Kangaroo abundance	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Indicator	Criterion													
	Feasibility of implementation						Policy and management utility							
	4.1 Cost-effective	4.2 Data	4.3 Technical skills	4.4 Operational simplicity	4.5 Resource needs	4.6 Time needs	5.1 Compre-hensible	5.2 Compatibility	5.3 Societal links	5.4 Mgt links	5.5 NRM targets	5.6 Noticeable Significance	5.7 Acceptance	5.8 Facilitative
14. Preferred grazing area of all stock most of the time	✓	✓	✓	✓	✓	✓	✓	**X**	✓	✓	**X**	**X**	✓	✓
15. Productive value of grazed areas	✓	✓	✓	✓	✓	✓	✓		✓	✓	**X**		✓	✓
16. Number of domestic stock per water	✓	✓	✓	✓	✓	✓	✓	✓	**X**	✓	✓	✓	✓	✓
17. Historical numbers of all stock and kangaroos per water	✓	✓	✓	✓	✓	✓	✓	✓	**X**	✓	✓	✓	½	✓
18. Number of active rabbit warrens	X	X	X	X	X	X	✓	✓	X	✓	✓	✓	✓	✓
19. Change in waterpoint closure frequency and interval	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	X	✓	½	X
20. Property environmental plans	✓	X	✓	✓	✓	✓	✓	X	X	✓	✓	X	½	✓
21. Infrastructure to change grazing behaviour	X	X	✓	✓	✓	✓	✓	X	X	✓	X	X	½	X

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

[2] Tongway & Hindley 2004

[3] Bastin et al. 2002

[4] Pickup et al. 1994

[5] Ludwig et al., 2002

[6] Ludwig et al. 2006

[7] Ludwig et al. *2007*

Appendix 14: Desired outcome 2 – Significant species and ecological communities

Assessment of appropriate indicators based on Conceptual relevance and Historical dimensions of selection criteria (Table 1)

Indicator	Criterion							
	Conceptual relevance						Historical dimension	
	1.1 Biotic	1.2 Naturalness	1.3 Biodiversity Complexity C – composition S – Structure F – Function	1.4 Multi-scaled	1.5 Land-water link	1.6 Ecosystem function D – Driving force P – Pressure S – State I – Impact R – Response	2.1 Historical records	2.2 Reliability
1. Presence of dingoes or foxes	✓	✓	F	X	X	D	½	✓
2. Presence of feral herbivores	✓	X	F	X	✓	P	✓	✓
3. Preferred grazing area of all stock most of the time	✓	✓	X	X	✓	D	X	✓
4. Number of domestic stock per water	✓	X	F	X	✓	P	✓	✓
5. Number of active rabbit warrens	✓	½	F	X	X	P	X	✓
6. Composition of terrestrial fauna	✓	✓	C	X	X	S	✓	½
7. Presence of terrestrial endemic and threatened fauna	✓	✓	C	X	X	S	✓	✓
8. Status of regionally significant terrestrial ecological communities	✓	✓	C	X	X	I	X	✓
9. Change in composition of mound springs fauna	✓	✓	C	X	✓	S	✓	✓
10. Change in composition and distribution of mound springs vegetation	✓	✓	C,S	X	✓	S	✓	✓
11. Presence of non-native (terrestrial/aquatic) invasive weeds	✓	X	F	X	✓	P	✓	✓
12. CUMSUM[3] rainfall	X	X	X	✓	X	P	✓	✓
13. Seasonality of temperature and rainfall	X	✓	X	✓	X	P	✓	✓
14. Register of potential threats	X	X	X	X	X	R	X	X
15. Infrastructure to change grazing behaviour	X	X	X	X	X	R	X	X
16. Presence of aquatic endemic and threatened fauna	✓	✓	C	X	✓	P	✓	✓
17. Status of regionally significant aquatic communities of drainage lines an floodplains	✓	✓	C	X	✓	P	✓	✓
18. Water quality	X	X	F	X	✓	P	✓	✓

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

3 Cumulative sum of the standard deviations from the long-term mean

Appendix 15: Desired outcome 2 – Significant species and ecological communities

Assessment of appropriate indicators based on Measurement qualities dimension of selection criteria (Table 1)

Indicator	Criterion										
	Measurement qualities										
	3.1 Anticipatory	3.2 Predictable	3.3 Robust	3.4 Sensitive to pressures	3.5 Space-bound	3.6 Time-bound	3.7 Measurable	3.8 Portable	3.9 Specificity	3.10 Statistical properties	3.11 Universality
1. Presence of dingoes or foxes	✓	x	✓	x	x	✓	✓	✓	✓	x	✓
2. Presence of feral herbivores	✓	✓	✓	x	x	x	✓	✓	✓	x	✓
3. Preferred grazing area of all stock most of the time	✓	✓	x	✓	✓	✓	✓	✓	✓	x	✓
4. Number of domestic stock per water	✓	✓	x	x	✓	✓	✓	✓	✓	✓	✓
5. Number of active rabbit warrens	✓	✓	x	x	✓	x	x	x	✓	✓	✓
6. Composition of terrestrial fauna	½	x	x	✓	✓	✓	✓	✓	✓	x	x
7. Presence of terrestrial endemic and threatened fauna	½	x	x	✓	✓	✓	✓	✓	✓	✓	✓
8. Status of regionally significant terrestrial ecological communities	½	x	x	✓	✓	✓	x	✓	✓	✓	x
9. Change in composition of mound springs fauna	✓	x	x	✓	✓	✓	✓	✓	✓	x	x
10. Change in composition and distribution of mound springs vegetation	✓	x	x	✓	✓	✓	✓	✓	✓	x	x
11. Presence of non-native (terrestrial/aquatic) invasive weeds	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12. CUMSUM[4] rainfall	½	x	✓	x	✓	✓	✓	✓	✓	✓	✓
13. Seasonality of temperature and rainfall	✓	½	✓	x	½	✓	✓	✓	✓	✓	✓

4 Cumulative sum of the standard deviations from the long-term mean

Indicator	Criterion										
	Measurement qualities										
	3.1 Anticipatory	**3.2 Predictable**	**3.3 Robust**	**3.4 Sensitive to pressures**	**3.5 Space-bound**	**3.6 Time-bound**	**3.7 Measurable**	**3.8 Portable**	**3.9 Specificity**	**3.10 Statistical properties**	**3.11 Universality**
14. Register of potential threats	X	X	X	X	X	✓	X	X	X	X	✓
15. Infrastructure to change grazing behaviour	X	X	X	X	X	✓	X	X	X	X	✓
16. Presence of aquatic endemic and threatened fauna	✓	X	X	✓	✓	✓	✓	X	✓	X	X
17. Status of regionally significant aquatic communities of drainage lines an floodplains	✓	X	X	✓	✓	✓	✓	X	✓	X	X
18. Water quality	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓

✓ - mostly met, ½ – partially met, X – not met, ? – unknown

Appendix 16: Desired outcome 2 – Significant species and ecological communities

Assessment of appropriate indicators based on Feasibility of implementation and Policy and management utility dimensions of selection criteria (Table 1)

Indicator	Criterion													
	Feasibility of implementation						Policy and management utility							
	4.1 Cost-effective	4.2 Data	4.3 Technical skills	4.4 Operational simplicity	4.5 Resource needs	4.6 Time needs	5.1 Compre-hensible	5.2 Compat-ibility	5.3 Societal links	5.4 Mgt links	5.5 NRM targets	5.6 Noticeable Significance	5.7 Acceptance	5.8 Facilitative
1. Presence of dingoes	✓	✓	X	X	X	✓	✓	✓	✓	✓	?	✓	½	X
2. Presence of feral herbivores	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Preferred grazing area of all stock most of the time	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	X	X	✓	✓
4. Number of domestic stock per water	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓
5. Number of active rabbit warrens	X	X	X	X	X	X	✓	✓	X	✓	✓	✓	✓	✓
6. Composition of terrestrial fauna	X	✓	X	X	X	X	X	X	X	✓	?	✓	½	X
7. Presence of terrestrial endemic and threatened fauna	✓	✓	X	X	X	X	✓	X	½	✓	?	✓	½	X
8. Status of regionally significant terrestrial ecological communities	✓	✓	X	X	X	X	X	X	X	✓	?	✓	½	X
9. Change in composition of mound springs fauna	X	✓	X	X	✓	X	½	X	X	✓	?	✓	½	X

Indicator	Criterion													
	Feasibility of implementation						Policy and management utility							
	4.1 Cost-effective	4.2 Data	4.3 Technical skills	4.4 Operational simplicity	4.5 Resource needs	4.6 Time needs	5.1 Compre-hensible	5.2 Compat-ibility	5.3 Societal links	5.4 Mgt links	5.5 NRM targets	5.6 Noticeable Significance	5.7 Acceptance	5.8 Facilitative
10. Change in composition and distribution of mound springs vegetation	X	✓	X	X	✓	X	½	X	X	✓	?	✓	½	X
11. Presence of non-native (terrestrial/ aquatic) invasive weeds	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12. CUMSUM[5] rainfall	✓	✓	X	X	✓	✓	X	✓	✓	✓	?	✓	✓	X
13. Seasonality of temperature and rainfall	✓	✓	X	X	✓	✓	X	✓	✓	✓	?	✓	✓	X
14. Register of potential threats	½	X	✓	✓	✓	✓	✓	X	X	✓	X	X	X	✓
15. Infrastructure to change grazing behaviour	✓	X	✓	✓	✓	✓	✓	X	X	✓	X	X	X	X
16. Presence of aquatic endemic and threatened fauna	X	✓	½	✓	✓	✓	✓	X	X	✓	?	✓	X	X
17. Status of regionally significant aquatic communities of drainage lines an floodplains	X	✓	½	✓	✓	✓	✓	X	X	✓	?	X	X	X
18. Water quality	✓	✓	½	✓	✓	✓	✓	✓	✓	✓	?	✓	X	✓

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

5 Cumulative sum of the standard deviations from the long-term mean

Appendix 17: Desired outcome 3 – Natural surface water flows and Desired outcome 4 – Water remote areas

Assessment of appropriate indicators based on Conceptual relevance and Historical dimensions of selection criteria (Table 1)

Indicator	Criterion							
	Conceptual relevance						Historical dimension	
	1.1 Biotic	1.2 Naturalness	1.3 Biodiversity Complexity C – composition S – Structure F – Function	1.4 Multi-scaled	1.5 Land-water link	1.6 Ecosystem function D – Driving force P – Pressure S – State I – Impact R – Response	2.1 Historical records	2.2 Reliability
Desired outcome 3								
1. Change in extent and distribution of floodwaters	X	✓	**F**	✓	✓	**I**	✓	✓
2. Change in composition of aquatic and semi-aquatic vegetation	✓	✓	C	X	✓	S	✓	✓
3. Average % cover of riparian and wetland focal plant species	✓	✓	S	X	✓	S	✓	X
4. Presence of native saplings below 2 m in height	✓	✓	**S**	**X**	✓	**S**	**X**	**X**
5. Presence of non-native (terrestrial/aquatic) invasive weeds	✓	**X**	**F**	**X**	✓	**P**	✓	✓
6. Composition and abundance of waterbird fauna	✓	✓	C	X	✓	S	✓	X
7. No artificial earthworks in drainage lines	**X**	**X**	**F**	**X**	✓	**P**	**X**	✓
8. Reduced estimated no. of erosion gullies and central windrows on tracks per km	**X**	**X**	**F**	**X**	✓	**P**	**X**	✓
Desired outcome 4								
1. Density of artificial waterpoints by age	✓	✓	**S**	✓	✓	**S**	✓	✓
2. % area remote from water by length of time	**X**	**X**	**C**	✓	✓	**P**	✓	✓

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

Appendix 18: Desired outcome 3 – Natural surface water flows and Desired outcome 4 – Water remote areas

Assessment of appropriate indicators based on Measurement qualities selection criteria (Table 1)

Indicator	Criterion										
	Measurement qualities										
	3.1 Anticipatory	3.2 Predictable	3.3 Robust	3.4 Sensitive to pressures	3.5 Space-bound	3.6 Time-bound	3.7 Measurable	3.8 Portable	3.9 Specificity	3.10 Statistical properties	3.11 Universality
Desired outcome 3											
1. Change in extent and distribution of floodwaters	X	X	✓	✓	✓	✓	✓	X	✓	X	X
2. Change in composition of aquatic and semi-aquatic vegetation	✓	X	X	✓	✓	✓	✓	X	✓	X	X
3. Average % cover of riparian and wetland focal plant species	✓	X	X	✓	✓	✓	✓	X	✓	X	X
4. Presence of native saplings below 2 m in height	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓
5. Presence of non-native (terrestrial/aquatic) invasive weeds	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
6. Composition and abundance of waterbird fauna	X	X	X	✓	✓	✓	✓	X	✓	X	X
7. No artificial earthworks in drainage lines	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
8. Reduced estimated no. of erosion gullies and central windrows on tracks per km	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓
Desired outcome 4											
1. Density of artificial waterpoints by age	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2. % area remote from water by length of time	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

Appendix 19: Desired outcome 3 – Natural surface water flows and Desired outcome 4 – Water remote areas

Assessment of appropriate indicators based on Feasibility of implementation and Policy and management utility of selection criteria (Table 1)

Indicator	Criterion													
	Feasibility of implementation						Policy and management utility							
	4.1 Cost-effective	4.2 Data	4.3 Technical skills	4.4 Operational simplicity	4.5 Resource needs	4.6 Time needs	5.1 Compre-hensible	5.2 Compat-ibility	5.3 Societal links	5.4 Mgt links	5.5 NRM targets	5.6 Noticeable Significance	5.7 Acceptance	5.8 Facilitative
Desired outcome 3														
1. Change in extent and distribution of floodwaters	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	?	✓	½	X
2. Change in composition of aquatic and semi-aquatic vegetation	X	✓	X	X	X	X	X	X	X	✓	?	✓	X	X
3. Average % cover of riparian and wetland focal plant species	X	✓	X	X	X	X	X	X	X	✓	X	✓	X	X
4. Presence of native saplings below 2 m in height	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	✓
5. Presence of non-native (terrestrial/ aquatic) invasive weeds	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Indicator	Criterion													
	Feasibility of implementation						Policy and management utility							
	4.1 Cost-effective	**4.2 Data**	**4.3 Technical skills**	**4.4 Operational simplicity**	**4.5 Resource needs**	**4.6 Time needs**	**5.1 Compre-hensible**	**5.2 Compat-ibility**	**5.3 Societal links**	**5.4 Mgt links**	**5.5 NRM targets**	**5.6 Noticeable Significance**	**5.7 Acceptance**	**5.8 Facilitative**
6. Composition and abundance of waterbird fauna	X	✓	X	X	✓	✓	½	X	X	✓	?	✓	✓	X
7. No artificial earthworks in drainage lines	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	½	✓
8. Reduced estimated no. of erosion gullies and central windrows on tracks per km	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	½	✓
Desired outcome 4														
1. Density of artificial waterpoints by age	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	½	✓
2. % area remote from water by length of time	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	½	✓

✓ – mostly met, ½ – partially met, X – not met, ? – unknown

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