Rangelands Monitoring:

Developing an Analytical Framework for Monitoring Biodiversity in Australia's Rangelands.

Background paper 4.
Approaches to broad scale monitoring of biological diversity – a brief review of international experience

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The report was coordinated by the Tropical Savannas Cooperative Research Centre, and written by Kerry Beggs.

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Contents

1. Introduction

The main purpose of this review is to report on international approaches to biological diversity (biodiversity) monitoring. The review is not intended to be exhaustive. It aims to cover the general frameworks and methods of biodiversity monitoring and, in particular, how the issues of broad scale monitoring have been addressed. The review will also discuss some specific international examples of broad scale programs in place and their implications for monitoring biodiversity in Australian rangelands.

Effort has been made to focus specifically on biodiversity monitoring, however, in some areas the review draws on the more general and extensive environmental and natural resource monitoring literature. Biodiversity monitoring in the context of this review generally refers to monitoring at the species level or higher taxon levels (e.g. genus or family).

2. General monitoring frameworks and methods

Environmental monitoring is generally undertaken in association with ecosystem management. Ecosystem management has been defined as "management driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure and function" (Christensen et al. 1996). Monitoring provides the information for making appropriate management decisions. Through repeated measurement monitoring is usually designed to reveal changes in particular parameters. More specifically, the purpose of biodiversity monitoring is to assess change in the variety of living things, and obviously this can be measured at many levels.

Recent reviews make some common recommendations regarding frameworks of successful monitoring programs. Most state that a monitoring program must first and foremost be designed in accordance with specific objectives and to provide the information needed to progress towards the achievement of those objectives (Stork & Samways 1995; Ringold et al. 1996; Gibbs et al. 1999). Objectives should describe the desired state of an appropriate indicator that management is intended to meet, and they should also drive what, where and how often measurements should be made. However, many management programs initiate monitoring without first defining what they hope to accomplish (Gibbs *et al.* 1999). Failure to define explicit objectives may lead to mismatches between monitoring design and hypotheses of interest and this may ultimately result in reduced confidence in conclusions (Rose & Smith 1992). Furthermore, spatial and temporal scales of investigation must be carefully considered when designing a monitoring program, to ensure that monitoring objectives are actually addressed and the program is also operationally feasible (Stork & Samways 1995).

The other important issue stressed in the literature is that monitoring programs must be designed with a sound methodological and statistical foundation. Standardized and repeatable methods of measurement or assessment will provide the most useful data, by facilitating comparisons with other monitoring undertaken locally or regionally (Stork & Samways 1995). Similarly, in order to produce the most meaningful and reliable results, data should be collected in accordance with a statistically sound design (Rose & Smith 1992; Stork & Samways 1995; Lougheed et al. 1999). This is achieved by following accepted experimental design principles that generally recommend random, independent and replicated samples with stratified sampling where appropriate, from various experimental treatments including before and after (treatment or impact), and control and impact sites (Krebs 1989; Green 1993).

However, this sort of design would rarely be achievable in a broad scale biodiversity monitoring program because of problems such as a lack of "before impact" sites, and logistic constraints on the selection of site locations and number of sites assessable (Skalski 1990; Rose & Smith 1992; Green 1993; Schlesinger et al. 1994; Dixon et al. 1998). Consequently, there is much criticism in the ecological literature regarding shortcomings in the statistical design of many monitoring programs, but authors offer little in the way of specific recommendations for improvement, or methods for drawing generalizations applicable at large spatial scales, or extending sampling of the quality of design and execution achievable at small scales to larger scales.

A common recommendation for improving monitoring programs is to use statistical power analyses. Statistical power is a measure of the confidence with which a statistical test can detect a particular effect when an effect does exist (failing to detect a true effect is called a Type II error) (Taylor & Gerrodette 1993; Steidl et al. 1997; Burgman & Lindenmayer 1998). Power is proportional to the magnitude of the effect, sample size and the significance level of the statistical test being used (α), and inversely proportional to variability in the data (Fairweather 1991; Burgman & Lindenmayer 1998; Lougheed *et al.* 1999). Many statistical texts (e.g. Zar 1984; Sokal & Rohlf 1995) provide more detailed information on the definition and methods of calculating power.

Many authors suggest power analyses precede the design of monitoring programs, to provide estimates of the number of samples needed to achieve an acceptable probability of detecting an environmental change of a specified magnitude (e.g. Fairweather 1991; Rose & Smith 1992; Burgman & Lindenmayer 1998; Gibbs et al. 1998; Gibbs *et al.* 1999; Lougheed *et al.* 1999). Others advocate retrospective power analyses to aid the interpretation of results by assessing the probability of a Type II error (Fairweather 1991; Thomas 1997; Lougheed *et al.* 1999). However, in the context of broad scale biodiversity monitoring, power analyses during the planning stage may be of limited practical use. This is because the analyses require reliable estimates of sample variability (e.g. obtained from a pilot study) in order to calculate the number of samples required (Green 1993; Gibbs *et al.* 1998). Such estimates of variability are rarely available. Furthermore, the estimated number of samples required may be substantially more than is logistically feasible for the majority of broad scale monitoring programs.

Although most monitoring programs attempt to "do the best they can" with limited resources, the result is often inadequate design, suffering from such common problems as too few sites, or possibly numerous sites, but sites lacking temporal and spatial independence. Lack of independent replicate sites, that are necessary for most forms of statistical analysis, is a major criticism of many monitoring programs. Sites are often not temporally independent, as is the case for much forest monitoring, which often involves repeated assessment of permanent plots (Skalski 1990; Green 1993; Schlesinger *et al.* 1994). Sites located in close proximity may suffer from spatial autocorrelation and hence may not be independent (Hulbert 1984; Krebs 1989; Green 1993). Some authors recommend sampling with partial replacement, or rotation sampling, as a way of overcoming this breach of assumptions underpinning statistical methods (e.g. Skalski 1990; Scott 1998). Such sampling schemes make use of permanent and temporary plots, with only a proportion of plots revisited and other plots added or removed, during each assessment (Skalski 1990; Scott 1998). Sampling with partial replacement enables an assessment to be more spatially extensive increasing confidence that sites are truly independent, without increasing the total sample size and hence effort and cost of the monitoring program. Skalski (1990) argues that no other sampling scheme combines an adequate statistical foundation, precision and flexibility for monitoring trends and status.

Clearly, designing a broad scale biodiversity monitoring program that will both address objectives of the sort that might reasonably be demanded (e.g. to track changes in the distribution and abundance of a number or rare or cryptic species and reveal change over relatively short time spans) and also be statistically sound represents a substantial challenge. Matching public expectations to an affordable sampling regime can not be achieved by simply scaling up the standard approaches used in small scale environmental monitoring. It is impractical to routinely sample a range of taxa in a statistically robust way over huge areas and over long time spans. Modifications to the design of monitoring programs may lead to some improvement in statistical robustness for a given level of sampling effort and intensity. However, it is unlikely that tinkering with design alone will result in an adequate broad scale biodiversity monitoring program. All examples that we have been able to examine have apparently accepted this conclusion (e.g. Breckenridge et al. 1995, Bricker and Ruggiero 1998). Searches for alternative to the maintenance of the sampling intensity considered appropriate for small areas to larger areas is one of the defining features of the monitoring literature.

3. Alternative approaches to broad scale biodiversity monitoring

A number of options have been proposed for monitoring at the broad scale. Heywood (1995) suggests two main ways: (i) point-sampling of many localized sites, and (ii) landscape level assessment. However, field-based point-sampling methods must be streamlined in order to achieve broad scale monitoring. This has largely been done by restricting the range of phenomena monitored. Rather than directly monitor all of the phenomena of interest, sampling is focused on a small number of carefully chosen attributes that are thought to be adequate surrogates or indicators of the processes or attributes for which no process is known or assumed identified in the study objectives. The second approach, landscape level assessment, has been examined, mainly using remote sensing methods and measures. These two different approaches are discussed below.

3.1. Rapid assessment using indicators

Environmental monitoring has the potential to be substantially accelerated by reducing the comprehensiveness of assessment to just a few key features – indicators. These indicators are simply measurable surrogates for broader environmental conditions (Noss 1990). In the context of biodiversity monitoring, the presence or condition of a particular indicator is presumed or demonstrated to reflect some pattern in overall biodiversity (Noss 1990; Saunders et al. 1998). Importantly, indicators do not necessarily bear any direct or cause and effect relationship to the factor of interest; they are simply *indicators* (Landres et al. 1988).

Various types of indicators have been widely used as part of rapid assessment methods in environmental monitoring. Many have been used for the purpose of detecting environmental impacts from particular forms of pollution, and the use of indicators has also broadened to general assessments of "ecosystem health" and "ecological integrity" (Patton 1987; Landres *et al.* 1988; Noss 1990; Breckenridge *et al.* 1995). There are many well-documented examples in which faunal communities or assemblages have been used to assess environmental change or ecological integrity in terrestrial systems (e.g. birds: Bradford et al. 1998, Kremen 1992, Morrison 1986, O'Connell et al. 1998, Whitford et al. 1998; ants: Andersen 1990, Whitford et al. 1998; butterflies: Lawton et al. 1998) and also in aquatic systems (e.g. macroinvertebrates: Plafkin et al. 1989; Rosenberg & Resh 1993; Chessman 1995; Resh 1995; fish: Karr 1981; Plafkin *et al.* 1989; Fausch et al. 1990; Harris 1995).

The use of indicators for biodiversity monitoring is a more recent trend. Nevertheless, there have been several reviews and discussions of the issue (e.g. Landres *et al.* 1988; Noss 1990; Faith & Walker 1996; Saunders *et al.* 1998; Caro & O'Doherty 1999; Lindenmayer 1999; Simberloff 1999). The review of Noss (1990) is particularly detailed. Biodiversity indicators have generated substantial interest at an international level and the United Nations Environment Program, in the context of the Convention on Biological Diversity, has commissioned the development of a "core set of biodiversity indicators" (Anonymous 1997; Anonymous 2000).

Criteria for selection of indicator taxa is a central topic in most of the comprehensive treatments. Although differences exist among the authors' recommendations, most stress the importance of a well-established (statistical) relationship between the indicator and biodiversity generally, or a process threatening biodiversity. Some information is also available regarding the relative suitability of particular indicators. For example, Landsberg et al. (1999) provide a comparison of the indicator potential of different taxonomic groups (arthropods, vertebrates and plants) in the rangelands. Other authors report on the potential utility of higher level taxonomic biodiversity (e.g. family or order) as an indicator of lower level diversity (e.g. species) (Oliver & Beattie 1993; Williams & Gaston 1994; Andersen 1995).

Most of the literature on biodiversity indicators refers to species or other taxonomic groups as the indicators. However, an alternative approach has been suggested as potentially useful – measures of ecosystem function as indicators of biodiversity (Mooney et al. 1995a, Mooney et al. 1995b). Ecosystem function can be defined as the collective services provided by biological communities and their associated non-living environments (ecosystems), and includes processes such as water and energy flows, primary production, nutrient cycling, competition and predation (after Mooney *et al.* 1995; Burgman & Lindenmayer 1998). The idea of monitoring ecosystem function as an indicator of biodiversity is centered on the concept that there is a strong link between the two and hence changes in one will be reflected in the other. Therefore, if a readily interpretable relationship were to be demonstrated between a measurable aspect of ecosystem function and biodiversity, this attribute could be assessed as another indirect way of monitoring biodiversity.

Interest in the relationship between biodiversity and ecosystem function has grown substantially in the past decade and several recent publications have addressed the issue (e.g. Schultze & Mooney 1993; Huston 1994; Naeem et al. 1994; Tilman & Downing 1994; Cushman 1995; Mooney et al. 1996). The United Nations Environment Program's "Global Biodiversity Assessment" provides a particularly thorough discussion (see Mooney *et al.* 1995; Mooney *et al.* 1995). Underlying assumptions are many, and include the intuitively reasonable belief that the continued functioning of ecosystems is dependent on their constituent species and their distribution, the genetic variation within those species and on the dynamics of the interactions that exist between different species and between them and the physical environment (Mooney *et al.* 1995). However, there have been few experimental studies investigating the relationship (but see Naeem *et al.* 1994; Tilman & Downing 1994; Tilman & Knops 1996; van der Heijden et al. 1998). These studies claim to have shown that plant diversity is important for ecosystem functioning, but Huston (1997) and Wardle (1999) have questioned the validity of the results of some of these studies because of problems with experimental design. The strength of debate in the relevant literature indicates that there is still a very poor understanding of how ecosystem function and biodiversity are related and, at the extremes, whether they are related at all. Most working in this field acknowledge that much additional research is needed (Mooney *et al.* 1995; Mooney *et al.* 1995; Doherty et al. 1998; Simberloff 1999; Wardle 1999). In light of this, use of measures of ecosystem function seems an unrealistic option, at present, as surrogates for, or indicators of the status of biodiversity.

In summary, the use of indicators offers an attractive way of maximizing returns from plot-based assessments and increasing the spatial and temporal scales over which robust systems of biodiversity monitoring can be implemented. However, the fundamental principle behind the use of indicators is that there is a strong and consistent relationship between the state of an indicator and the condition is it supposed to index. Unfortunately, few indicators have been validated, (but see Bradford et al. 1998, who examined bird assemblages as indicators of ecosystem integrity).

Another problem with choice of indicators is the issue of scale. It is unlikely that any one indicator will be appropriate for monitoring at multiple spatial and temporal scales (Noss 1990). No single level of organization (e.g. gene, population, or community) is fundamental, and different levels of resolution are appropriate for different questions (Noss 1990). Various authors have suggested using suites of indicators for monitoring (e.g. Noss 1990; Croonquist & Brooks 1991; Bradford *et al.* 1998; Brooks et al. 1998; O'Connell *et al.* 1998), but Noss (1990) is the only author to specifically address the issue of scale. Noss (1990) argues that a hierarchical approach is necessary for the use of indicators in biodiversity monitoring. He has proposed a comprehensive framework and recommended several indicator variables appropriate for monitoring different components of biodiversity (composition, structure and function) at a range of ecological levels of organization (genetic, population-species, community-ecosystem and regional landscape level) (Noss 1990). Indicators proposed by Noss (1990) include species diversity and evenness (for biodiversity composition at the community-ecosystem level), distribution, richness and proportions of patch (habitat) types and patterns of species distributions (for biodiversity composition at the regional landscape level), and landscape pattern characteristics (for biodiversity structure at the regional landscape level) (Noss 1990). The indicators and overall approach to biodiversity monitoring proposed by Noss (1990) would certainly be appropriate for broad scale biodiversity monitoring in the Australian rangelands.

3.2. Landscape scale assessment

Landscape level assessment, using remote sensing, is perhaps the most obvious way of undertaking broad scale biodiversity monitoring. Remote sensing encompasses aerial photography and videography, satellite imagery captured by multispectral scanners, as well as radar and laser systems. This technology has long been used for mapping but only recently for natural resource monitoring, analysis of landscape structure and biodiversity mapping (e.g. Conroy & Noon 1996; Scott et al. 1996; Fuller et al. 1998).

The rationale behind the use of landscape level analysis for biodiversity monitoring is that there is a strong relationship between habitat/landscape characteristics (heterogeneity) and biodiversity (Noss & Harris 1986; Dunn et al. 1990; Faith & Walker 1996; Doherty *et al.* 1998; Nichols et al. 1998). The importance of landscape structure to biodiversity is now well accepted, largely because of the voluminous literature on habitat fragmentation (e.g. Verner 1986; Wiens 1990; Hansson & Angelstam 1991; Soulé et al. 1992). Landscape features such as patch size, heterogeneity, perimeter-area ratio and connectivity have been found to be major controllers of species composition and abundance and of population viability for individual species (Noss & Harris 1986). Characteristics of landscape composition (i.e. proportions and arrangement of particular habitats) may also be critical determinants of the distribution and persistence of species (Noss 1990).

In addition, landscape ecologists have developed many landscape pattern indices to summarize important characteristics of spatial structure (e.g. patch size, interpatch distance, connectivity, fractal dimension) (Forman & Godron 1986; O'Neill et al. 1988; Turner & Gardner 1990; Trani & Giles 1999). Time series analysis of remotely sensed data and indices of landscape pattern may therefore offer powerful broad scale methods of monitoring temporal changes in landscape structure and hence elements of biodiversity (Dunn *et al.* 1990; Noss 1990; Pastor & Johnston 1992).

Another important advantage that this sort of assessment offers is the ability to examine past landscape structure. Aerial photographs dating back decades may be available for many areas, and satellite imagery is now available at some resolutions for periods exceeding 15 years. Detailed information collected on the ground will most often be less obtainable and cover only small portions of the landscape. Furthermore, landscape assessment using remote sensing has the added attraction that it can provide these measures of landscape structure at relatively low cost, in comparison with field based monitoring on a similar spatial scale. Although the initial cost of equipment (i.e. computers, software) and data (e.g. satellite imagery) is often substantial, remote sensing assessments avoid many of the labour and other operational costs associated with extensive fieldwork.

On the surface, landscape level assessment seems to be an ideal way to monitoring biodiversity at a broad scale. However there is a number of constraints. Firstly, although landscape structure is generally well accepted as important for biodiversity, there is little evidence of a strong association between landscape pattern metrics derived from remotely sensed data, and other, direct measures of biodiversity values (Doherty et al. 1998, Noss 1999; but see Schumaker 1996, Stoms and Estes 1993). Relationships between diversity and existing landscape indices need to be examined, and perhaps new indices formulated specifically in the context of biodiversity assessments (Stoms & Estes 1993).

Secondly, remotely sensed data is not error free. Errors may arise from image classification problems such as those caused by poor spatial resolution, variable illumination of topography, and atmospheric interference (Lillesand & Kiefer 1994; Johnston 1998). Despite the improved availability of high-resolution satellite imagery, it remains difficult to differentiate between some superficially similar but ecologically distinct habitats or environments (e.g. areas with similar structures and densities of vegetation cover but different floristics, or areas of low topographic relief) (Stoms & Estes 1993). Advances in both quality of imagery and in image classification techniques will be required before they will be able to discriminate among a sufficiently wide range of habitat types, for remote sensing and landscape assessment to replace on-ground sampling of biodiversity values (Goward and Williams 1997, Scott et al. 1996, Stoms and Estes 1993).

Other types of errors may be present because of low spatial accuracy or problems during data acquisition. Related to this issue is a third problem – remotely sensed data alone is not sufficient. Field-based work to ground-truth the information derived from remotely sensed images is also required in order to validate conclusions drawn from landscape assessments. Lastly, many species respond to threatening processes that cannot be detected by remotely-sensed imagery of any resolution (e.g. densities of cryptic, nocturnal, introduced predators – may determine population trends for native animals).

In conclusion, both indicators and landscape level assessment are potentially valuable approaches to broad scale biodiversity monitoring, but more research is needed before either approach can be applied with confidence. In particular, further investigation and testing is required of the relationships between indicators, landscape pattern indices at various resolutions, and more direct and comprehensive measures of biodiversity.

4. Examples of broad scale biodiversity monitoring programs

Natural resource and environmental monitoring programs are underway in a number of countries. Some of these specifically include biodiversity monitoring. However there are fewer examples of overseas programs designed specifically to monitor biodiversity at very large scales. This section provides a brief overview of some of these programs.

The most comprehensive overseas environmental monitoring programs are probably those underway in, or proposed for, the USA. Although they are not exclusively biodiversity monitoring programs, a couple of these warrant detailed discussion. Firstly, the USA Environmental Protection Authority's Environmental Monitoring and Assessment Program (EMAP) was set up in the late 1980s (Anonymous 2000). EMAP was initiated to address the need for coherent ecological resource information on a regional and national scale and its primary goal was to provide an integrated set of monitoring designs that could be adapted to sampling any ecological resource (Stevens 1994).

The EMAP organizational structure is composed of resource groups charged with specific responsibilities for several resource categories (e.g. forests, agro-ecosystems, surface waters, etc) which are administratively grouped into inland aquatic systems, terrestrial systems and near-coastal systems (Stevens 1994). The sampling design developed for EMAP is based on a triangular grid system which yields a point density of about 1 grid point per 635km2, and the grid of sample points is randomly located in a manner that provides uniform coverage probability over the entire US mainland (Stevens 1994). The grid can be used in several ways to sample a resource, depending on the specific monitoring objectives, the nature of the resource and its associated environment. Detailed information on the sampling design of EMAP is given by Messer et al. (1991) and Stevens (1994).

EMAP does not have a specific biodiversity monitoring project. However the work of the Rangeland Resource Group is relevant to this review. The goal of this group is to provide an assessment of the current and changing conditions of natural resources in arid, semi-arid and subhumid ecosystems and their extent at the regional and national level (Breckenridge et al. 1995). This program is particularly interested in assessing the ability of such systems to sustain biotic potential relative to exposure to anthropogenic stressors such as livestock grazing, urbanization, aquifer depletion, as well as natural phenomena such as climate variability. Breckenridge et al. (1995) provide a detailed account of how the Group has addressed the issue. In short, they recommend that a sample-based approach in association with the selection and measurement of ecologically-based indicators is the best strategy for determining the status and trend of ecological condition on a regional and national scale. The Group also acknowledges that remote sensing technology offers a powerful tool and shows promise for rangeland monitoring (Breckenridge *et al.* 1995).

Little information is available on the overall progress of EMAP and, in particular, how far the program has gone towards meeting its original objectives. However, EMAP has undergone 20 separate peer reviews of individual components of the program and a program-wide review by a panel under contract between the US EPA and the National Research Council (Anonymous 1997). These reviews highlighted several concerns about aspects of EMAP, which, if not addressed, may lead to diminished success of the program. The key recommendations from the reviews were (i) the inclusion of nonrandomly selected sentinel sites with intensive data collection; (ii) further integration of effects-oriented and stressor-oriented monitoring approaches; (iii) more analysis of variability and its relationship to sampling design and power to describe status and detect trends; and (iv) the initiation of a major research program on indicator development (Anonymous 1997). EMAP's new research strategy has acknowledged these recommendations and has also recognised that EMAP will not provide the entire national monitoring network but will contribute components to it (Anonymous 1997). Importantly, EMAP acknowledges the need for increased collaboration with other federal monitoring programs and agencies (Anonymous 1997).

Another broad scale environmental monitoring initiative has recently been developed in the USA, in response to recognised shortcomings in existing monitoring and research programs. In 1995, the USA National Science and Technology Council's Committee on Environmental and Natural Resources (CENR) established an interagency team (the Environmental Monitoring Team) to recommend a framework for an integrated monitoring and research network that allows regular evaluation of the nation's environmental resources. (National Science and Technology Council 1997). The Monitoring Team, made up of representatives from 12 federal agencies, developed a national framework for integration and coordination of environmental monitoring and related research through better collaboration and building upon existing networks and programs (National Science and Technology Council 1997). Although this framework addresses the more general issue of environmental monitoring, aspects of its approach are also relevant for broad scale biodiversity monitoring. Bricker and Ruggiero (1998) provide a concise overview of the framework, and the following excerpt from their paper provides a good summary of a carefully-considered design based on long experience. The emphases are ours.

"The key concept in this framework is the necessity for a long-term continuous program that will integrate monitoring and related research across environmental resources and spatiotemporal scales. **A single approach to monitoring, at one scale, is not sufficient for all questions**. In addition, **monitoring must be linked with predictive modelling and process research to be most effective**. The proposed framework consists of three general levels of monitoring activities or networks, integrated across spatial scales and sampling intensities. Level 1 represents inventories and remote sensing programs which characterize a few specific properties over large regions with simultaneous and spatially intensive measurements. Level 2 represents national and regional resource surveys, which are designed to characterize specific properties of a region by sampling a subset of total area, rather than the entire area. Levels 1 and 2 are essential for quantifying the regional extent, distribution, condition, and rate of change of specific environmental properties and for identifying processes that occur over large areas. **Level 3 represents intensive monitoring and research sites. At these sites, a larger number of variables are measured, at a higher frequency and on a continuing basis, but at far fewer locations than in levels 1 and 2.** This level is essential for understanding processes that occur at local scales, for integrating the effects of multiple processes, for understanding the causes of changes detected at levels 1 and 2, and for developing and testing predictive models of environmental response. Measurements at this level also provide information for determining the level of uncertainty associated with inventory, remote sensing and survey results, and model predictions. Each level contains a research component essential to keeping the program current with new developments in monitoring and research at the respective levels."

The framework acknowledges that full cooperation among federal, state, indigenous, private and nongovernmental bodies is required in order to implement the program (National Science and Technology Council 1997). The framework also seeks to link with existing monitoring programs such as EMAP (National Science and Technology Council 1997) and the National Biological Service, which is responsible for the coordination of biodiversity inventorying and monitoring in the USA (National Research Council 1993, cited in Stork and Samways 1995). To date, the process of implementation has involved workshops between federal and non-federal stakeholders, the establishment of working groups, and the planning of a regional pilot demonstration project of the framework. EMAP is undertaking its first regional-scale assessment in the mid-Atlantic region of the USA and this will serve as the pilot to evaluate the effectiveness and usefulness of the CENR framework (Anonymous 1997; Pryor et al. 1998). Furthermore, the adoption by EMAP of the CENR's three-tiered monitoring approach is evidence that key aspects of the framework are already being incorporated into existing monitoring programs (Anonymous 1997; Pryor *et al.* 1998).

Similar national environmental or resource monitoring programs have been proposed or are already underway in other countries. These include Canada's Environmental Monitoring and Assessment Network (Royal Society of Canada 1995); the United Kingdom's Environmental Change Network (National Environmental Research Council 1994); and the United Nations Economic Commission for Europe's Integrated Monitoring Program (United Nations Economic Commission for Europe 1993) (all cited in National Science and Technology Council 1997). Specific details of these programs are not discussed here. However it is useful to note that the common threads connecting these monitoring and research programs are (i) integration across all facets of the environment (from driving variables to responding systems and across temporal and spatial scales) and (ii) the commitment to develop long-term databases (National Science and Technology Council 1997).

There are several examples of other less comprehensive overseas biodiversity monitoring programs. Some of these are aimed at monitoring specific taxa including birds (Furness et al. 1993; Link & Sauer 1998), invertebrates (butterflies, moths, aphids), mammals (otters, badgers, bats, squirrels) and rare plants (Anonymous 1994 cited in Stork and Samways 1995). Birds, in particular have received much attention, with long running monitoring programs in place in North America and the UK. The bird monitoring programs are somewhat unique and warrant further discussion.

The North American Breeding Bird Survey (BBS) was initiated in 1966 to monitor bird population change (Link & Sauer 1998). The BBS scheme incorporates a large number of permanent monitoring sites, most of which are surveyed annually using standardized methods by skilled volunteers (Thomas 1996). It is unique in its geographical extent and the large number of species it surveys. Presently, the BBS monitors more than 400 species of birds, using data obtained on an annual basis at more than 3500 roadside survey routes in the continental US, southern Canada and northern Mexico (Link & Sauer 1998). For Neotropical migrants and other land bird species in North America, the BBS is the primary source of population information at the regional and continental scales (Thomas 1996; Link & Sauer 1998). Nevertheless, several factors have been identified that, at best, complicate analysis of BBS data and, at worst, limit its usefulness as a source of information on population change. These include general problems associated with count data (i.e. count are only indices to population size, not censuses or density estimates), variable detectability of individual bird species, and other issues concerning differences in observer ability (Thomas 1996; Link & Sauer 1998).

Similar avian monitoring schemes exist in the United Kingdom. The British Trust for Ornithology's (BTO) began the Common Bird Census 1961 and Waterways Bird Survey in 1974 (Furness *et al.* 1993; Greenwood et al. 1994). In these programs, annual changes in population size are calculated as percentages from summed territory counts for all plots that are surveyed in the same way in consecutive years (Furness *et al.* 1993). Additional monitoring programs such as the Integrated Population Monitoring Programme and Breeding

Bird Survey, have recently been developed by the BTO to provide the more detailed demographic information required to understand changes in bird populations (Furness *et al.* 1993; Greenwood *et al.* 1994).

There are also several examples of general biodiversity inventory programs operating on a regional or national scale overseas. Examples include the Mexican National Commission for the Knowledge and Use of Biodiversity (CONABIO), which was set up by the Mexican government in 1992 to promote and coordinate biodiversity studies in universities and other research bodies (Stork & Samways 1995), and Costa Rica's national biodiversity institute (INBio), is an all taxa biodiversity inventory program with activities mainly concentrated in the country's national system of protected areas (about 25% of the country) (Stork & Samways 1995).

In addition, yet another biodiversity monitoring initiative has been proposed for the USA – a national biodiversity observatory network (BON) (Anonymous 1998; Dalton 1999). This proposed network will consist of three elements – observatories, a program to support research across the network, and to coordinate the network, conduct research and training, and provide technical services (Anonymous 1998). The BON appears to be another attempt to coordinate US biodiversity monitoring and research efforts, but it is unclear whether it has progressed much beyond the planning stage.

Efforts have been made to develop biodiversity monitoring guidelines and efforts at a multinational or global scale. For example, The Montréal Process is an initiative launched in 1994 by several non-European countries (Argentina, Australia, Canada, Chile, China, Japan, Republic of Korea, Mexico, New Zealand, Russian Federation, USA and Uruguay), to develop and implement internationally agreed criteria and indicators for the conservation and sustainable management of temperate and boreal forests (Anonymous 2000). The Montréal Process Working Group agreed on a framework that identifies seven key criteria and 67 associated indicators that are to be monitored, with a fundamental criterion being the conservation of biodiversity at multiple levels (i.e. from genetic diversity to ecosystem diversity) (Anonymous 2000). Another program operating at a multinational level is the United Nations Environment Program's Convention on Biological Diversity. As mentioned earlier, the aim of this program is to develop a core set of country-specific biodiversity indicators to be used in conjunction with standardized methods of biodiversity monitoring in local and national programs (Anonymous 1997; Anonymous 2000). Yet another UNEP initiative is the comprehensive Global Biodiversity Assessment (Heywood 1995), which addresses many, if not all of the important issues concerning broad scale biodiversity assessment.

Lastly, even though they do not represent national scale biodiversity monitoring programs, some additional examples worth discussing are research projects that have addressed the issue of integrating remote sensing with field based assessment. Fuller et al. (1998) used satellite imagery to produce land cover maps and undertook ground based flora and fauna surveys to provide biodiversity data for tropical forests and wetlands in the Sango Bay area, Uganda. The authors were able to identify patterns in land cover and biodiversity and consequently produce a biodiversity map suitable for conservation planning and management in the area (Fuller *et al.* 1998). Similarly, Nagendra and Gadgil (1999a, 1999b) integrated remotely sensed data with biodiversity field data, collected at multiple spatial scales, in areas of India. The results of these projects suggest localized field investigations of biodiversity can be effectively linked with remotely sensed information to permit extrapolations at progressively larger scales.

In summary, a number of countries have instigated or proposed broad scale, comprehensive environmental and/or natural resource programs. Biodiversity monitoring is probably included in many of these programs. However there appear to be no overseas examples of well-developed and comprehensive programs set up specifically to monitor biodiversity. The biodiversity monitoring programs that do exist mostly target particular taxonomic groups or simply provide inventories. Nevertheless, there are many positive elements to most of the programs discussed and some may be of relevance to the development of an Australian rangelands biodiversity monitoring framework. In particular, the CENR framework's three tiered strategy appears a well-considered and sensible approach to the twin challenges of broad scale natural resource monitoring and improved understanding of the dynamics of ecological change and its implications for biodiversity.

5. Conclusions

In conclusion, designing a broad scale biodiversity monitoring program that will both address objectives and be statistically sound represents a significant challenge. Simply scaling up the standard approaches used in small scale monitoring is not a realistic option as it is impractical to routinely sample a range of taxa in a statistically robust way at broad spatial and temporal scales. Some improvement in statistical robustness may be achievable though modification of the design of monitoring programs, however, these changes alone will not result in an adequate broad scale biodiversity monitoring program – alternative approaches are required. Such alternatives may include rapid assessment methods using indicators and landscape level assessment. Both these approaches are potentially valuable for biodiversity monitoring in the Australian rangelands, but more research is needed before either approach can be applied with confidence. In particular, further investigation and testing is required of the relationships between indicators, landscape pattern indices at various resolutions, and more direct and comprehensive measures of biodiversity. Logistic and economic issues must also be considered when evaluating broad scale monitoring approaches. Although it is difficult to find any actual estimates of cost for monitoring using remote sensing versus on-ground methods, an extensive field-based broad scale monitoring program would almost certainly be the more expensive option.

Although there are few overseas examples of broad scale programs designed specifically for monitoring biodiversity, many lessons can be learned from some of the more general environmental monitoring initiatives. In particular, the three-tiered, integrated monitoring and research network framework developed by the USA's Committee on Environmental and Natural Resources (National Science and Technology Council 1997), is an example of a well-designed monitoring program based on long experience. Aspects of this approach are relevant for biodiversity monitoring in the Australian rangelands. However, the adaptation of any overseas program to biodiversity monitoring in Australia's rangelands would not be straightforward because of the nature of these environments. Environmental conditions in the Australian rangelands are highly variable and unpredictable, especially rainfall. Another issue which will complicate rangelands monitoring is that it represent an extremely large area that is ecologically poorly known and has limited infrastructure. Consequently, methods used elsewhere will not simply be able to be adopted and applied here; additional research will be needed to modify existing or develop new methods to suit Australian conditions here. Nevertheless, existing overseas environmental programs provide an excellent starting point.

There is one overwhelming message from all of the overseas examples discussed and the theoretical and operational questions with which they grapple in various ways. There are no obvious shortcuts that do not require either a relaxation of accepted standards of sampling design, or other forms of risk-taking with regard to the utility of indicators or surrogates for important components of biological diversity. The evidence for decline in many rangeland plants and animals demands that Australia adopt a risk-averse strategy for its national framework for monitoring rangeland biodiversity.

Compromising design standards is the antithesis of risk-averse behaviour. Outputs from flawed monitoring programs may incorporate unpredictable bias of unknown and perhaps unknowable severity. We argue that all of the monitoring programs that are implemented within a rangeland framework should be designed to the highest standards, even if this is achieved at the expense of the range of phenomena that can be measured. It is better to be confident about a few key results than to substitute a larger collection of flawed, potentially biased indices. Elsewhere, we examine the options for making this tradeoff between quality and quantity, and the manner in which both may be maintained or increased through time.

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7. References

Andersen, A. N. 1990, 'The use of ant communities to evaluate change in Australian terrestrial ecosystems: a review and a recipe', *Proceedings of the Ecological Society of Australia,* vol. 16, pp. 347-357.

Andersen, A. N. 1995, 'Measuring more of biodiversity: genus richness as a surrogate for species richness in Australian ant faunas.', *Biological Conservation,* vol. 73, pp. 39-43.

Anonymous 1994, *Biodiversity, the UK action plan,* HMSO, London.

Anonymous 1997, *Environmental monitoring and assessment program (EMAP) research strategy,* United States Environmental Protection Agency, Office of Research and Development, Washington.

Anonymous 1997, *Recommendations for a core set of indicators of biological diversity,* Subsidiary Body on Scientific, Technical and Technological Advice. Convention on Biological Diversity, United Nations Environment Programme,

Anonymous 1998, 'A national biodiversity observatory network. Final Report: Biodiversity Monitoring Workshop', in , 10--11 September 1998, Blandy Experimental Farm, University of Virginia, pp.

Anonymous 2000, 'About EMAP', United States Environmental Protection Agency, 10/10/2000, http://www.epa.gov/emap/html/about.html.

Anonymous 2000, *Development of indicators of biological diversity*, Subsidiary Body on Scientific, Technical and Technological Advice. Convention on Biological Diversity, United Nations Environment Programme,

Anonymous 2000, 'The Montreal Process', 01/06/2000, http://www.mpci.org/home_e.html.

Bradford, D. F., Franson, S. E., *et al* 1998, 'Bird species assemblages as indicators of biological integrity in Great Basin rangeland', *Environmental Monitoring and Assessment,* vol. 49, pp. 1-22.

Breckenridge, R. P., Kepner, W. G. & Mouat, D. A. 1995, 'A process for selecting indicators for monitoring conditions of rangeland health', *Environmental Monitoring and Assessment,* vol. 36, pp. 45-60.

Bricker, O. P. & Ruggiero, M. A. 1998, 'Toward a national program for monitoring environmental resources', *Ecological Applications,* vol. 8, pp. 326-329.

Brooks, R. P., O'Connell, T. J., Wardrop, D. H. & Jackson, L. E. 1998, 'Towards a regional index of biological integrity: the example of forested riparian ecosystems', *Environmental Monitoring and Assessment,* vol. 51, pp. 131-143.

Burgman, M. A. & Lindenmayer, D. B. 1998, *Conservation Biology for the Australian Environment,* Surrey Beatty and Sons Pty Limited, Chipping Norton NSW.

Caro, T. M. & O'Doherty, G. 1999, 'On the use of surrogate species in conservation biology', *Conservation Biology,* vol. 13, pp. 805--814.

Chessman, B. C. 1995, 'Rapid assessment of rivers using macroinvertebrates: A procedure based on habitat-specific sampling, family level identification and a biotic index', *Australian Journal of Ecology,* vol. 20, pp. 122-129.

Christensen, N. L., Bartuska, A. M., *et al* 1996, 'The report of the Ecological Society of America Committee on the scientific basis for ecosystem management', *Ecological Applications,* vol. 6, pp. 665-691.

Conroy, M. J. & Noon, B. R. 1996, 'Mapping of species richness for conservation of biological diversity: conceptual and methodological issues', *Ecological Applications,* vol. 6, pp. 763--773.

Croonquist, M. J. & Brooks, R. P. 1991, 'Use of avian and mammalian guilds as indicators of cumulative impacts in riparian-wetland areas', *Environmental Management,* vol. 15, pp. 701--714.

Cushman, J. H. 1995, 'Ecosystem-level consequences of species additions and deletions on islands', in *Islands*, eds P. M. Vitousek, Springer-Verlag, Berlin.

Dalton, R. 1999, 'Monitoring system planned for US biodiversity drive', *Nature,* vol. 398, pp. 738.

Dixon, P. M., Olsen, A. R. & Kahn, B. M. 1998, 'Measuring trends in biological resources.', *Ecological Applications,* vol. 8, pp. 225-227.

Doherty, M., Kearns, A., *et al* 1998, *The interaction between habitat conditions, ecosystem processes and biodiversity - A review.*, CSIRO Wildlife and Ecology. Institute of Wildlife Research, Dunn, C. P., Sharpe, D. M., *et al* 1990, 'Methods for analyzing temporal changes in landscape pattern', in *Quantitative methods in landscape ecology*, eds M. G. Turner & R. H. Gardner, Springer-Verlag, New York.

Fairweather, P. G. 1991, 'Statistical power and design requirements for environmental monitoring', *Australian Journal of Marine and Freshwater Research,* vol. 42, pp. 555-567.

Faith, D. P. & Walker, P. A. 1996, 'Environmental diversity: on the best-possible use of surrogate data for assessing the relative biodiversity of sets of areas', *Biodiversity and Conservation,* vol. 5, pp. 399--415.

Fausch, K. D., Lyons, J., Karr, J. R. & Angermeier, P. L. 1990, 'Fish communities as indicators of environmental degradation. In: Biological indicators of stress in fish', *American Fisheries Society Symposium,* vol. 8, pp. 123-144.

Forman, R. T. T. & Godron, M. 1986, *Landscape ecology,* John Wiley and Sons, New York.

Fuller, R. M., Groom, G. B., *et al* 1998, 'The integration of field survey and remote sensing for biodiversity assessment: a case study in the tropical forests and wetlands of Sango Bay, Uganda', *Biological Conservation,* vol. 86, pp. 379--391.

Furness, R. W., Greenwood, J. J. D. & Jarvis, P. J. 1993, 'Can birds be used to monitor the environment?', in *Birds as monitors of environmental change*, eds R. W. Furness & J. J. D. Greenwood, Chapman and Hall, London.

Gibbs, J. P., Droege, S. & Eagle, P. 1998, 'Monitoring populations of plants and animals', *BioScience,* vol. 48, pp. 935-940.

Gibbs, J. P., Snell, H. L. & Causton, C. E. 1999, 'Effective monitoring for adaptive wildlife management: lessons from the Galapagos Islands', *Journal of Wildlife Management,* vol. 63, pp. 1055-1065.

Goward, S. N. & Williams, D. L. 1997, 'Landsat and earth systems science: development of terrestrial moitoring.', *Photogrammetric Engineering & Remote Sensing.,* vol. 63, pp. 887--900.

Green, R. H. 1993, 'Application of repeated measures designs in environmental impact and monitoring', *Australian Journal of Ecology,* vol. 18, pp. 81--98.

Greenwood, J. J. D., Baillie, S. R., *et al* 1994, 'Some new approaches to conservation monitoring of British breeding birds.', *Ibis,* vol. 137, pp. S16--S28.

Hansson, L. & Angelstam, P. 1991, 'Landscape ecology as a theoretical basis for nature conservation', *Landscape Ecology,* vol. 5, pp. 191-201.

Harris, J. H. 1995, 'The use of fish in ecological assessments', *Australian Journal of Ecology,* vol. 20, pp. 65-80.

Heywood, V. H. (ed.) 1995, *Global Biodiversity Assessment,* Cambridge University Press. Published for the United Nations Environment Programme, Cambridge.

Hulbert, S. H. 1984, 'Pseudoreplication and the design of ecological field experiments', *Ecological Monographs,* vol. 54, pp. 187--211.

Huston, M. A. 1994, *Biological diversity: the cooexistence of species on changing landscapes,* Cambridge University Press, Cambridge.

Huston, M. A. 1997, 'Hidden treatments in ecological experiments: re-evaluating the ecosystem function of biodiversity', *Oecologia,* vol. 110, pp. 449--460.

Johnston, C. A. 1998, *Geographic information systems in ecology,* Blackwell Science Ltd, Oxford.

Karr, J. R. 1981, 'Assessment of biotic integrity using fish communities', *Fisheries,* vol. 6, pp. 21-27.

Krebs, C. 1989, *Ecological methodology,* HarperCollins, New York.

Kremen, C. 1992, 'Assessing the indicator properties of species assemblages for natural areas monitoring', *Ecological Applications,* vol. 2, pp. 203--217.

Landres, P., Verner, J. & Thomas, J. 1988, 'Ecological uses of vertebrate indicator species: a critique', *Conservation Biology,* vol. 2, pp. 316-328.

Landsberg, J., Morton, S. & James, C. 1999, 'A comparison of the diversity and indicator potential of arthropods, vertebrates and plants in arid rangelands across Australia', in *The other 99%. The Conservation and Biodiversity of Invertebrates.*, eds W. Ponder & D. Lunney, Royal Zoological Society of New South Wales, Mosman.

Lawton, J. H., Bignell, D. E., *et al* 1998, 'Biodiversity inventories, indicator taxa and effects of habitat modification in tropical forest.', *Nature,* vol. 391, pp. 72-76.

Lillesand, T. M. & Kiefer, R. W. 1994, *Remote sensing and image interpretation,* John Wiley and Sons, Inc., New York.

Lindenmayer, D. B. 1999, 'Future directions for biodiversity conservation in managed forests: indicator species, impact studies and monitoring programs', *Forest Ecology and Management,* vol. 115, pp. 277--287.

Link, W. A. & Sauer, J. R. 1998, 'Estimating population change from count data: Application to the North American breeding bird survey.', *Ecological Applications,* vol. 8, pp. 258--268.

Lougheed, L. W., Breault, A. & Lank, D. B. 1999, 'Estimating statistical power to evaluate ongoing waterfowl population monitoring', *Journal of Wildlife Management,* vol. 63, pp. 1359--1369.

Messer, J. J., Linthurst, R. A. & Overton, W. S. 1991, 'An EPA program for monitoring ecological status and trends', *Environmental Monitoring and Assessment,* vol. 17, pp. 67--78.

Mooney, H. A., Cushman, J. H., *et al* (ed.) 1996, *Functional roles of biodiversity: a global perspective,* John Wiley, Chichester.

Mooney, H. A., Lubchenco, J., Dirzo, R. & Sala, O. E. 1995, 'Biodiversity and ecosystem functionaing: basic principles', in *Global Biodiversity Assessment*, eds V. H. Heywood, Cambridge University Press. Published for the United Nations Environment Programme, Cambridge.

Mooney, H. A., Lubchenco, J., Dirzo, R. & Sala, O. E. 1995, 'Biodiversity and ecosystem functionaing: ecosystem analyses', in *Global Biodiversity Assessment*, eds V. H. Heywood, Cambridge University Press. Published for the United Nations Environment Programme, Cambridge.

Morrison, M. L. 1986, 'Bird populations as indicators of environmental change', *Current Ornithology,* vol. 3, pp. 429-451.

Naeem, S., Thompspn, L. J., *et al* 1994, 'Declining biodiversity can alter the performance of ecosystems', *Nature,* vol. 368, pp. 734--737.

Nagendra, H. & Gadgil, M. 1999, 'Biodiversity assessment at multiple scales: linking remotely sensed data with field information', *Proceedings of the National Academy of Sciences USA,* vol. 96, pp. 9154--9158.

Nagendra, H. & Gadgil, M. 1999, 'Satellite imagery as a tool for monitoring species diversity: an assessment.', *Journal of Applied Ecology.,* vol. 36, pp. 388-397.

National Environmental Research Council 1994, *The United Kingdom Environmental Change Network,* Institute of Terretrial Ecology, Cumbria.

National Research Council 1993, *A biological survey for the nation,* National Academy Prress, Washington D. C.

National Science and Technology Council 1997, *Integrating the nation's environmental monitoring and research networks and programs: a proposed framework,* The Environmental Monitoring Team, Committee on Environment and Natural Resources, National Science and Technology Council, Washington D. C.

Nichols, W. F., Killingbeck, K. T. & August, P. V. 1998, 'The influence of geomorphological heterogeneity on biodiversity II. A landscape perspective', *Conservation Biology,* vol. 12, pp. 317--379.

Noss, R. F. 1990, 'Indicators for monitoring biodiversity: a hierarchical approach', *Conservation Biology,* vol. 4, pp. 355-364.

Noss, R. F. 1999, 'Assessing and monitoring forest biodiversity: a suggested framework and indicators', *Forest Ecology and Management,* vol. 115, pp. 135--146.

Noss, R. F. & Harris, L. D. 1986, 'Nodes, networks, and MUMs: preserving diversity at all scales', *Environmental Management,* vol. 10, pp. 299--309.

O'Connell, T., Jackson, L. & Brooks, R. 1998, 'A bird community index of biotic integrity for the mid-Atlantic highlands', *Environmental Monitoring and Assessment,* vol. 51, pp. 145-156.

Oliver, I. & Beattie, A. J. 1993, 'A possible method for the rapid assessment of biodiversity.', *Conservation Biology,* vol. 7, pp. 562-568.

O'Neill, R. J., Krummel, J. R., *et al* 1988, 'Indices of landscape pattern', *Landscape Ecology,* vol. 1, pp. 153--162.

Pastor, J. & Johnston, C. A. 1992, 'Using simulation models and geographic information systems to integrate ecosystem and landscape ecology', in *Watershed management.*

Balancing sustainability and environmental change, eds R. J. Naiman, Springer-Verlag, New York.

Patton, D. R. 1987, 'Is the use of "Management Indicator Species" feasible?', *Western Journal of Applied Forestry,* vol. 2, pp. 33-34.

Plafkin, J. L., Barbour, M. T., *et al* 1989, *Rapid bioassessment protocols for use in streams and rivers. Benthic macroinvertebrates and fish*, US Environmental Protection Agency. Office of Water Regulations and Standards, Washington DC.

Pryor, D., Bierbaum, R. & Melillo, J. 1998, 'Environmental monitoring and research initiative: a priority activity for the Committee on Environmental and Natural Resources', *Environmental Monitoring and Assessment,* vol. 51, pp. 3-14.

Resh, V. H. 1995, 'The use of benthic macroinvertebrates and rapid assessment procedures for water quality monitoring in developing and newly industrialized countries', in *Biological Assessment and Criteria: Tools for Water Resource Planning and Decision-making*, eds W. S. Davis & T. Simon, Lewis Publishers, Chelsea, MI, USA.

Ringold, P., Alegria, J., *et al* 1996, 'Adaptive monitoring design for ecosystem management', *Ecological Applications,* vol. 6, pp. 745-747.

Rose, K. A. & Smith, E. P. 1992, 'Experimental design: the neglected aspect of environmental monitoring', *Environmental Management,* vol. 16, pp. 691--700.

Rosenberg, D. M. & Resh, V. H. 1993, *Freshwater Biomonitoring and Benthic Macroinvertebrates,* Chapman and Hall, New York.

Royal Society of Canada 1995, *Looking ahead: Long-term ecological research and monitoring in Canada*, Technical report No. 95-1, Canadian Global Change Program, Ottawa, Ontario.

Saunders, D., Margules, C. & Hill, B. 1998, *Environmental indicators for national State of the Environment reporting - biodiversity,* Environment Australia, Canberra.

Schlesinger, R., Funk, D., Roth, P. & Myers, C. 1994, 'Assessing changes in biological diversity over time.', *Natural Areas Journal,* vol. 14, pp. 235-240.

Schultze, E.-D. & Mooney, H. A. (ed.) 1993, *Biodiversity and ecosystem function*, Springer-Verlag, Berlin.

Schumaker, N. H. 1996, 'Using landscape indices to predict habitat connectivity', *Ecology,* vol. 77, pp. 1210--1225.

Scott, C. T. 1998, 'Sampling methods for estimating change in forest resources', *Ecological Applications,* vol. 8, pp. 228--233.

Scott, J. M., Jennings, M., Wright, R. G. & Csuti, B. 1996, 'Landscape approaches to mapping biodiversity', *BioScience,* vol. 46, pp. 77--78.

Simberloff, D. 1999, 'The role of science in the preservation of forest biodiversity', *Forest Ecology and Management,* vol. 115, pp. 101--111.

Skalski, J. R. 1990, 'A design for long-term status and trends monitoring', *Journal of Environmental Management,* vol. 30, pp. 139-144.

Sokal, R. R. & Rohlf, F. J. 1995, *Biometry,* Freeman and Company, New York.

Soulé, M. E., Alberts, A. C. & Bolger, D. T. 1992, 'The effects of habitat fragmentation on chaparral plants and vertebrates', *OIKOS,* vol. 63, pp. 39--47.

Steidl, R. J., Hayes, J. P. & Schauber, E. 1997, 'Statistical power analysis in wildlife research.', *Journal of Wildlife Management,* vol. 61, pp. 270-279.

Stevens, D. 1994, 'Implementation of a national monitoring program', *Journal of Environmental Management,* vol. 42, pp. 1-29.

Stoms, D. M. & Estes, J. E. 1993, 'A remote sensing agenda for mapping and monitoring biodiversity', *International Journal of Remote Sensing,* vol. 14, pp. 1839--1860.

Stork, N. E. & Samways, M. J. 1995, 'Inventorying and monitoring', in *Global Biodiversity Assessment*, eds V. H. Heywood, Cambridge University Press. Published for the United Nations Environment Programme, Cambridge.

Taylor, B. L. & Gerrodette, T. 1993, 'The uses of statistical power in conservation biology: The Vaquita and Northern Spotted Owl.', *Conservation Biology,* vol. 7, pp. 489-500.

Thomas, L. 1996, 'Monitoring long-term population change: why are there so many analysis methods ?', *Ecology,* vol. 77, pp. 49--58.

Thomas, L. 1997, 'Retrospective power analysis.', *Conservation Biology,* vol. 11, pp. 276-280.

Tilman, D. & Downing, J. A. 1994, 'Biodiversity and stability in grasslands', *Nature,* vol. 367, pp. 363--365.

Tilman, D. W., D. & Knops, J. 1996, 'Productivity and sustainability influenced by biodiversity in grassland ecosystems', *Nature,* vol. 379, pp. 718--720.

Trani, M. K. & Giles, R. H. J. 1999, 'An analysis of deforestation: metrics used to describe pattern change', *Forest Ecology and Management,* vol. 114, pp. 459--470.

Turner, M. G. & Gardner, R. H. (ed.) 1990, *Quantitative methods in landscape ecology*, Springer-Verlag, New York.

United Nations Economic Commission for Europe 1993, *Manual for integrated monitoring. Programme Phase 1993-1996.*, UN ECE Convention on Long-Range Transboundary Air Pollution, International Co-operative programme on Integrated Monitoring on Air Pollution Effects, Environment Data Centre, National Board of Waters and the Environment, Helsinki.

van der Heijden, M. G. A., Klironomos, J. N., *et al* 1998, 'Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity', *Nature,* vol. 396, pp. 69--72.

Verner, J. 1986, 'Summary: predicting effects of habitat patchiness and fragmentation -- the researcher's viewpoint', in *Wildlife 2000: Modeling habitat relationships of terrestrial vertebrates*, eds J. Verner, M. L. Morrison & C. J. Ralph, University of Wisconsin Press, Madison.

Wardle, D. A. 1999, 'Is "sampling effort" a problem for experiments investigating biodiversity--ecosystem function relationships?', *OIKOS,* vol. 87, pp. 403--407.

Whitford, W. G., De Soyza, A. G., *et al* 1998, 'Vegetation, soil, and animal indicators of rangeland health', *Environmental Monitoring and Assessment,* vol. 51, pp. 179-200.

Wiens, J. A. 1990, 'Habitat fragmentation and wildlife populations: the importance of autecology, time, and landscape structure', in *Transactions of the19th IUGB Congress, Trondheim.*, eds .

Williams, P. H. & Gaston, K. J. 1994, 'Measuring more of biodiversity: can higher-taxon richness predict wholesale species richness?', *Biological Conservation,* vol. 67, pp. 211-217.

Zar, J. H. 1984, *Biostatistical analysis,* Prentice-Hall Inc, Englewood Cliffs, New Jersey.