18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Quantifying strategic regional priorities for managing natural capital: Compositional exploration of MCA-derived weights

Bryan, B.A. [1], **A. Grandgirard** [2] **and J.R. Ward** [1]

[1] *CSIRO Sustainable Ecosystems, Urrbrae, South Australia*
[2] *Cemagref, France*
Email: brett.bryan@csiro.au

Abstract: Demand for natural resource management (NRM) exceeds supply. In Australia, under Commonwealth policy, the responsibility for investment of substantial amounts of public money falls largely to the 56 regional agencies. A ubiquitous problem for these agencies is to set strategic priorities for management amongst a myriad of complex, competing, and urgent issues. What types of environmental assets, values, and threats should regional agencies devote scarce management resources to? Regional agencies need to quantify strategic priorities for management. However, this is often difficult due to the complexity of environmental processes and the diversity of opinions amongst decision makers.

In this study we quantify the strategic management priorities for the South Australian Murray-Darling Basin Natural Resources Management Board (the *Board*). We use a natural capital framework to present regional environmental decision-makers with a range of potential issues for strategic consideration. The Board defined Water, Land, Biota, and Atmosphere as natural capital assets of interest and these formed the basis of a goal hierarchy for Multi-Criteria Analysis (MCA). This goal hierarchy was modified after 56 qualitative ethnographic interviews revealed that people also cared about built and social capital assets in the context of environmental management.

MCA offers a potential tool for quantifying relative management priorities of a diverse range of natural capital assets. Five decision conferences were held with the Board and its four regionally-based, consultative NRM Groups. Decision conferences were held across the study area and included a total of 40 people. Using the Analytical Hierarchy Process from the field of MCA the relative management priorities of natural capital assets were quantified as weights. The unit-sum constraint (i.e. weights sum to 1 for each participant) renders the data *compositional*. As such, at least on negative correlation must exist (if one weight increases, other must decrease to maintain the unit-sum). This renders the data unfit for classical statistical analysis. Rather, a range of compositional analysis techniques were used to explore the management priorities for natural capital assets in the study area.

Compositional measures of central tendency and variance were calculated to describe management priorities for natural capital assets. Compositional weights were then transformed using a centred log ratio approach and analysed using classical statistical methods. ANOVA with Dunnett's T3 *post hoc* test was used to test for between-variable differences in the management priorities of natural capital assets. Similarly, Dunnett's T3 was also used to test for between-group differences in the management priority of each capital asset between the Board and the four NRM Groups.

Substantial variation in management priority occurred between decision makers. Decision makers identified water, followed by land and biota as the highest priority natural capital assets for management but they also considered that the impact on both built and financial capital, and social capital was important in making environmental management decisions. Despite the variation in management priorities of decision makers, water was of significantly higher priority than all other assets except land. Likewise, management of land was of significantly higher management priority than all other assets except water and biota, and biota was significantly higher than family and community. There was no significant difference in management priority between any other assets. Very few significant differences in management priority of capital assets were found between the Board and NRM Groups. The variance in the priorities of decision makers implies that investment analyses should be based on the distribution of weights in MCA rather than single measures of central tendency. The results can provide a basis for the design of programs and projects that address the natural capital assets of highest priority in strategic planning for regional NRM.

Keywords: *Multi-Criteria Analysis, Compositional Analysis, natural resource management, planning*

1. INTRODUCTION

Many environmental problems require urgent management. The limited funds available for natural resource management (NRM) means that hard decisions need to be made about what aspects of the environment are addressed by management and what is left to continue to degrade. In Australia, regional agencies are charged with the investment of significant amounts of public money in management and restoration programs and to mitigate and reverse further environmental degradation. Hence, regional agencies need to strategically plan for investment in NRM.

At the regional level, management may be directed at many different aspects of the environment such as water, soils, and biota, or processes such as erosion, salinisation, climate change, and species extinction. The decision-making structure of regional agencies often includes input from multiple stakeholders each with varying perspectives on management priorities. There is a need to identify strategic priorities for regional NRM within the context of multiple diverse perspectives.

In identifying environmental management priorities for supporting regional investment decisions by multiple stakeholders, the decision criteria need to cross the full range of environmental issues and processes that may be important to decision makers. Natural capital assets are the tangible aspects of the environment such as the land, water, and biota. These generate ecosystem goods and services that are utilised and valued by people (MEA 2005). The concept of natural capital can enumerate aspects of the environment which may require management as a basis for strategic NRM decisions. Natural capital has been used as a basis for regional NRM planning (Crossman and Bryan 2009, Nelson et al. 2009, Raymond 2009)

Multiple criteria analysis (MCA) is a suitable tool for quantifying the relative level of importance of multiple incommensurate criteria (Prato 1999). MCA can also capture variability between decision makers in complex environmental settings typical of those associated with strategic NRM planning.

In this paper we identify the relative priorities for managing natural capital assets using MCA to support strategic regional NRM planning. We use a case study of the South Australian Murray-Darling Basin (SAMDB) region. The SAMDB Natural Resources Management Board (the *Board*) is charged with investing public money in conservation and environmental management in the study area. The Analytical Hierarchy Process (AHP) and swing weights techniques are used to elicit weights reflecting managing priorities for individual natural capital assets. Weights were elicited using a decision conferencing approach with the Board and its four regionally-based, consultative NRM Groups. Compositional analysis was used to assess significant differences between in management priorities of natural capital between groups of decision-makers.

2. STUDY AREA DESCRIPTION

The study area covers around 56,000 km^2 (Figure 1). Topography is mostly flat apart from the hilly eastern Mt. Lofty Ranges. Climate ranges from Mediterranean in the south to semi-arid in the north. Key natural capital assets in the region include the River Murray including its floodplain and wetland ecosystems, the lower lakes, and Coorong estuary. The region also supports 30,748 km^2 (55%) of remnant native vegetation. Vegetation communities vary from open mallee *Eucalyptus* woodland communities in the south to shrubland communities in the drier north. Twenty-one fauna species are of conservation significance

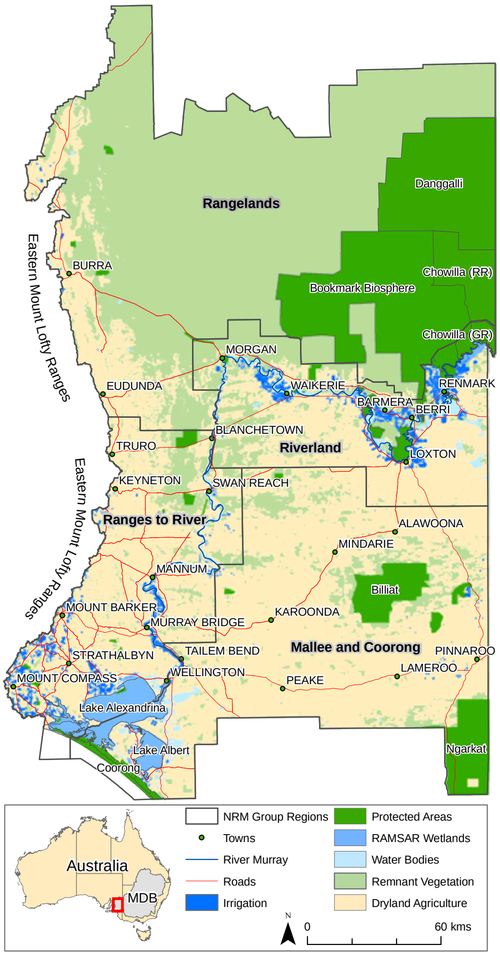

Figure 1. The South Australian Murray-Darling Basin study area including NRM Group regions.

in the region.

Dryland cropping and grazing (23,304 km^2) and irrigated horticulture and pastures (1,023 km^2) are the dominant land uses. Agricultural development has caused increased soil erosion, increased dryland and river salinity, and biodiversity decline, especially in the southern half of the region. Riparian ecosystems have been further impacted over the past decade by reduced environmental flows.

3. METHODS

3.1. Regional decision-makers

The SAMDB NRM Board is principally responsible for allocating investment in natural resource management over the study area. Four regionally-based NRM Groups (Rangelands, Ranges to River, Mallee and Coorong, Riverlands, see Figure 1) advise the Board. Board and group members are drawn from a range of backgrounds including primary production (dryland famers and irrigators), soil conservation, local government, animal and plant control, salinity mitigation, indigenous issues, and the management of biodiversity and water resources (SAMDB NRM Board, 2009).

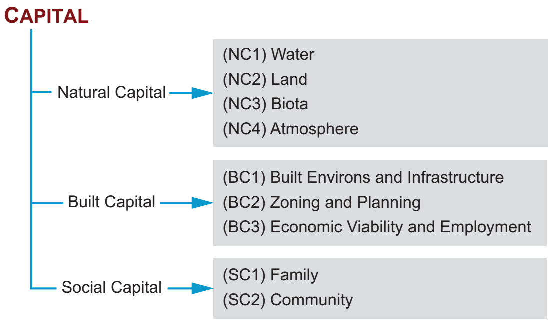

Figure 2 – Capital-based goals hierarchy with individual assets (right) grouped into three capital asset types.

3.2. Defining a goal hierarchy for natural capital

A goal hierarchy was developed for natural capital assets to provide structure for the quantification of management priorities. Natural capital assets were defined by the Board as Land, Water, Biota, and Atmosphere. This was extended for the study area based on the results of 56 qualitative ethnographic interviews with members of the Board, the four NRM Groups, and community representatives (see Cast et al., 2008). The natural capital goal hierarchy was broadened to include both Built and Social capital, each with specific assets (Figure 2).

3.3. MCA decision conference process

Five decision conferences were held across the SAMDB region, one with the Board and one with each of the regional groups, attended by 40 decision makers. Weights were elicited using the Logical Decisions for Groups software. For each decision task, weights were entered on paper first then electronically. Responses for each decision were instantly collated and projected on the screen. Following discussion, decision makers were given the opportunity to revise their scores.

Following the goal hierarchy structure (Figure 2), local weights were first assigned to the assets within each capital type. Second, local weights were assigned to the higher level capital types. Higher level local weights on asset types were modified to remove bias resulting from variation in the number of assets they contained whilst still summing to 1:

$$w'_c = \lambda_c \frac{K_c w_c}{\sum_{c=1}^{C} K_c w_c} \tag{1}$$

where w_c is the local weight of the asset type c, K_c is the number of assets in asset type c, C is the number of asset types (i.e. 4), and λ_c is the ratio of the number of assets in type c over the average number of assets within an asset type such that $\lambda_c = K_c / \bar{K}_c$.

Global weights were then calculated for each capital asset by multiplying their local weight by the modified weight of their respective asset type. Global weights sum to 1 over all capital assets and quantify the management priorities of each decision maker.

In this study, AHP was used to derive weights because of the logical validation available through application of the consistency index to pairwise comparisons (Saaty 1980). Decision makers were directed to assign weights to capital assets according to their perceived importance and urgency, and hence, *priority*, for management in the SAMDB region. In assigning weights using AHP, pairwise comparisons were made between criteria. For each pair of criteria, participants were asked to select the criterion of highest priority for management then score the strength of this decision. A standard pairwise comparison scale (Saaty 1980) was used where the relative importance of one criteria over another is scored on a scale of 1 - 9 (i.e. 1 = equal, 3 = moderate, 5 = strong, 7 = very strong, and 9 = extreme). In AHP, local weights on individual criteria are then calculated as an eigenvector of the matrix of pairwise comparisons (Saaty 1980).

3.4. Compositional Analysis

Statistical analysis was used to explore management priorities for capital assets of decision makers in this study. Global weights in the MCA-derived data necessarily sum to 1 (the *unit-sum* constraint) over capital assets for each decision maker. Hence, the data is subject to closure effects as at least one negative correlation must exist between variables. The unit-sum constraint defines the data as *compositional* (Aitchison 1986). Compositional data does not satisfy the covariance assumptions required by standard statistical analyses and clouds the outputs of such analyses. It is impossible to know if any relationships in the data reflect natural processes or are an artefact of the closure effects (Pawlowsky-Glahn and Egozcue, 2006).

In describing the compositional analysis in this study we adopt standard notation after Daunis-Estadella et al. (2006). Let $\mathbf{X} = \{\mathbf{x}_j = [x_{1j}, x_{2j}, ..., x_{Dj}] \in S^D : j = 1, 2, ..., n\}$ define a compositional data set. In this study, the compositional data matrix consist of 40 rows $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{40}$ with one row per decision maker (i.e. n = 40), and D columns $X_1, X_2, \ldots, X_D$ or *parts* (here D = 9). Each row $\mathbf{x}_j$ captures the weights x_{ij} representing the management priorities for each capital asset i for i = 1, 2, …, D of each decision maker j.

The distribution of raw weights is presented in boxplots. The geometric mean g_i of raw weights was calculated as a more robust measure of central tendency the management priority of each capital asset and ecosystem service i:

$$g_i = \left(\prod_{j=1}^{n} x_{ij}\right)^{1/n},\ i = 1, 2, ..., D \tag{2}$$

Variance in management priorities for each capital asset was calculated as the sum of the variance of the normalised log ratio of pairs of parts (Pawlowsky-Glahn et al., 2007):

$$\text{var}[X_i] = \frac{1}{D}\sum_{m=1}^{D} \text{var}\left[\frac{1}{\sqrt{2}}\ln\frac{X_i}{X_m}\right],\ i = 1, 2, ..., D \tag{3}$$

The total variance in management priorities for capital assets for each group of decision makers was calculated by summing the variance over all assets:

$$\text{var}[\mathbf{X}] = \sum_{i=1}^{D} \text{var}\left[X_i\right] \tag{4}$$

A centred log-ratio (clr) transformation was selected in this study because it maintains original number of columns (D) and provided more interpretable results for our case study. A drawback of clr transformation is that rows in the transformed data sum to zero. The implications of this are that the covariance matrix is singular and does not have a normal inverse (Pawlowsky-Glahn and Egozcue, 2006). Statistical analyses insensitive to this limitation were used in this study.

Global weights for both the capital assets were subject to clr-transformation calculated, for each participant i, as the natural log of the raw scores over the geometric mean of the raw scores:

$$\text{clr}(\mathbf{x}_j) = \left[\ln\frac{\mathbf{x}_j}{g_D(\mathbf{x}_j)}\right] = \left[\ln\frac{x_{1j}}{g_D(\mathbf{x}_j)}, \ln\frac{x_{2j}}{g_D(\mathbf{x}_j)}, ..., \ln\frac{x_{Dj}}{g_D(\mathbf{x}_j)}\right],\ j = 1, 2, ..., n \tag{5}$$

where $g_D(\mathbf{x}_j)$ is the geometric mean of the raw weights across all assets for decision maker (row) j calculated as:

$$g_D(\mathbf{x}_j) = (\prod_{i=1}^{D} x_{ij})^{1/D},\ j = 1, 2, ..., n \quad (6)$$

All compositional data analysis and transformation in this study was performed with CodaPack3D (Thió-Henestrosa and Martín-Fernández 2005).

Kolmogorov-Smirnov tests confirmed that clr-transformed data generally followed a normal distribution. Hence, a range of classical exploratory parametric statistical analyses was then performed on the clr-transformed data. All testing was done using a significance level of $p < 0.05$.

Multiple pairwise comparisons within a one-way analysis of variance (ANOVA) were used to test for differences in management priority between capital assets. In combination with the descriptive statistics, these analyses indicate which assets and services are of highest priority for management given the variation between individual decision makers. Similarly, multiple pairwise comparisons within an ANOVA were also used to test for differences in management priority of each capital asset and ecosystem service between the five groups of decision makers. Dunnett's T3 was used because it is robust to heteroscedasticity and corrects for increased family-wise Type I errors associated with multiple pairwise comparisons.

4. RESULTS

4.1. Interpretation of Capital Assets

Decision makers made specific interpretation of capital assets in the decision conferences. Interpretations were made in the context of their own knowledge and decision making responsibilities. The interpretation of each capital asset (Table 1) determines the nature of the management actions required. Generally, decision makers considered that their job was to direct proactive management actions towards sustaining and enhancing natural capital assets but not at the expense of built and social capital in the region.

Capital Asset	Interpretation in the Study Area
Water	Surface water bodies (e.g. rivers, creeks, estuaries, lakes) including associated ecosystems especially those along the River Murray, lower lakes, and Coorong. Also includes rainfall, and other sources of fresh water
Land	Soils and land resources generally under agricultural production but also supporting native habitat and pastures
Biota	Native species and ecosystems such as those occurring in patches of remnant vegetation and especially those under formal protection
Atmosphere	Air and climate including temperature and cloud cover affecting incoming solar radiation
Built Environs and Infrastructure	Includes schools, roads, buildings, locks, weirs, and salt interception schemes
Zoning and Planning	All relevant institutions regulating land use and the environment (e.g. protection for conservation).
Economic Viability and Employment	Financial returns from agriculture, economic viability of local businesses, and job security
Family	Relationships with family members (e.g. parents, children, grandchildren etc.)
Community	Relationships within groups of people connected through their local area, or through activities such as schooling, fire-fighting, and land stewardship

Table 1 – Interpretation of capital assets in the context of natural resource management by decision makers in the study area.

4.2. Management Priorities

Management priorities, as represented by weights, for capital assets varied amongst the full group of 40 decision makers. Based on the geometric means of raw weights, Water was the asset of highest management priority in the study area followed by Land and Biota. The three Built Capital assets and Atmosphere were in the middle, with Family and Community of lower priority for management (). Based on clr-transformed data, the greatest variance in management priorities of decision makers occurred within Biota and Atmosphere and least variance occurred within the Land and Economic Viability and Employment assets ().

Statistical analysis of mean difference between the weights assigned by decision makers suggested that the management priority of Water was significantly higher than all other assets except Land (). High priorities for Water may have been emphasized by recent ongoing drought and low river flows. The management priority for Land was not significantly different to Water or Biota but was significantly higher than all other assets. Management priority for Biota was significantly higher than both Family and Community. There was no significant difference in management priority of any other combination of assets ().

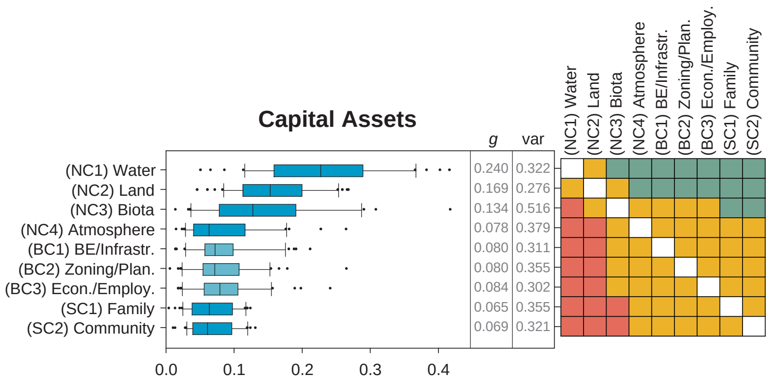

Figure 3 – Boxplots of the raw weights representing the relative management priority of natural, built, and social capital assets in the study area (left). Median and quartiles are presented with whiskers at 10th and 90th percentiles and outliers. Descriptive statistics are also presented including the geometric mean of raw compositional asset weights (*g*) and the clr-variance (var). Pictured on right is the matrix of outputs of the ANOVA (Dunnett's T3) on clr-transformed weights for all participants. Green means that the management priority of the row asset is significantly higher than that of the column asset, orange represents no significant difference between the row and column assets, red means that the management priority of the row asset is significantly lower than the column asset.

Substantial variation in management priorities for capital assets occurred within the SAMDB NRM Board and each of the four regional NRM Groups. Variance in management priorities (**Error! Reference source not found.**) was highest in the Riverlands (4.58), followed by Mallee and Coorong (3.20), the Board (2.83), Ranges to River (1.73), and lowest in the Rangelands (1.26).

There were very few (2 out of a possible 90) significant differences in the management priorities of capital types between groups of decision makers (Figure 4). The Mallee and Coorong attributed significantly higher management priority to Atmosphere than did the Rangelands due to the greater problem with dust storms in the Mallee and Coorong NRM Group region. The Riverlands attributed significantly higher management priority to Built Environs and Infrastructure than the Board associated with the larger towns, irrigation infrastructure, locks, weirs, salt interceptions schemes in the Riverlands.

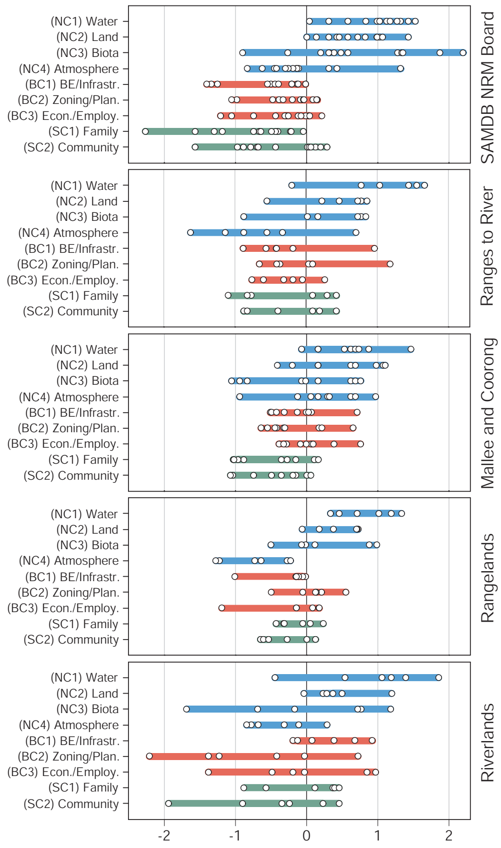

Figure 4 – clr-transformed weights representing the relative management priority of capital assets for decision makers (dots) in the SAMDB NRM Board and each of the four regional NRM Groups.

5. DISCUSSION AND CONCLUSIONS

Substantial variation exists in the management priority assigned to natural capital and other capital assets by the 40 NRM decision makers in the study area. This illustrates the diversity of opinions on management priorities that can exist among NRM decision makers.

Despite variation between individuals, significant differences in management priority exist between some capital assets. Hence, there was some agreement on management priority amongst decision makers. Given the variation in management priorities of decision makers in the region there is good reason to prioritise the management of water assets over all other assets except land. Likewise, management of land assets should be prioritized over all other assets except water and biota, and biota should be prioritized over family and community assets. However, there is no justification in these results for prioritizing the management of any other assets.

Few significant differences in management priority of individual capital assets occurred between groups of decision makers. This may be interpreted in one of two ways. Firstly, we may suggest that this reflects very good agreement in management priorities between groups. Alternatively, this may simply be a product of the large variation in management priorities that occurs between individuals both within groups and between groups. What is certain is that geographically-based NRM Groups did not tend to prioritise the specific capital assets in their region (e.g. Rangelands did not focus on Biota, nor Riverlands on Water, etc). Rather, their priorities tended to capture the broader issues of concern over the entire region.

The results also have important implications for MCA studies. First, when multiple decision makers are involved, it may not be sufficient to take a single measure of central tendency to represent the range of weights ascribed by decision makers. Rather, simulation studies are required which use the full distribution of weights by decision makers and quantify the potential impacts of variation in weights on outputs. Second, when analysing weights derived from MCA, compositional analysis is required. Compositional analysis provided for a more robust assessment of central tendency and variance in the data, and enabled the statistical analysis of management priorities free of bias from spurious correlations produced by the unit-sum constraint. We don't know of any MCA studies that have analysed the data using compositional analysis.

ACKNOWLEDGMENTS

The authors are grateful to the South Australian Murray-Darling Basin Natural Resource Management Board and CSIRO's Sustainable Regional Development theme for funding the research. The authors are also very grateful to Juan Jose Egozcue and Vera Pawlowski-Glahn for their kind advice on compositional analysis.

REFERENCES

Aitchison, J. (1986) *The Statistical Analysis of Compositional Data*. Monographs on Statistics and Applied Probability. Chapman & Hall Ltd., London (UK). 416p.

Cast, A., D. Hatton MacDonald, A. Grandgirard, T. Kalivas, S. Strathearn, M. Sanderson, B.A. Bryan and D. Frahm. 2008. South Australian Murray Darling Basin Environmental Values Report. Water for a Healthy Country National Research Flagship Report, CSIRO.

Crossman, N.D. and Bryan, B.A. (2009), Identifying cost-effective hotspots for restoring natural capital and enhancing landscape multifunctionality. *Ecological Economics*, 68, 654 – 668.

Daunis-i-Estadella, J., Barceló-Vidal, C. and Buccianti, A. (2006). Exploratory compositional data analysis. In: Buccianti, A., Mateu-Figueras, G. and Pawlowsky-Glahn, V. (eds) Compositional Data Analysis in the Geosciences: From Theory to Practice, Geological Society, London, Special Publications, 264, 161 - 174.

MEA (2005), *Ecosystems and Human Well-being: Synthesis.* Millennium Ecosystem Assessment, Island Press, Washington DC.

Nelson, E. Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D.R., Chan, K.M.A., Daily, G.C., Goldstein, J., Kareiva, P.M., Lonsdorf, E., Naidoo, R., Ricketts, T.H., and Shaw, M.R. (2009), Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*, 7, 4-11.

Pawlowsky-Glahn, V. and Egozcue, J.J. (2006). Compositional data and their analysis: an introduction. In: Buccianti, A., Mateu-Figueras, G. & Pawlowsky-Glahn, V. (eds) *Compositional Data Analysis in the Geosciences: From Theory to Practice*, Geological Society, London, Special Publications, 264, 1 - 10.

Pawlowsky-Glahn, V., Egozcue, J.J., and Tolosano-Delgado, R. (2007). *Lecture Notes on Compositional Analysis*. http://ima.udg.edu/Recerca/EIO/inici_eng.html

Prato, T. (1999), Multiple attribute decision analysis for ecosystem management. *Ecological Economics*, 30, 207–222.

SAMDB NRM Board (2009), SAMDB NRM Board website. http://www.samdbnrm.sa.gov.au/ 11/05/2009.

Raymond, C.M., Bryan, B.A., Hatton MacDonald, D., Cast, A., Strathearn, S., Grandgirard, A. and Kalivas, T. (2009), Mapping community values and risks towards natural capital and ecosystem services for environmental management. *Ecological Economics*, 68, 1301-1315.

Saaty, T.L. (1980), *The Analytical Hierarchy Process*. McGraw-Hill.

Thió-Henestrosa, S., Martín-Fernández, J.A. 2005. Dealing with compositional data : The freeware CoDaPack. *Mathematical Geology*, 37, 773-793.