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# Quantifying and Exploring Strategic Regional Priorities for Managing Natural Capital and Ecosystem Services Given Multiple Stakeholder Perspectives

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## Abstract

A ubiquitous problem for community-based regional environmental agencies is to set strategic management priorities among a myriad of issues and multiple stakeholder perspectives. Here, we quantify the strategic management priorities for natural capital and ecosystem services using multicriteria decision analysis (MCDA) in a case study of the South Australian Murray-Darling Basin Natural Resources Management Board (the *Board*) region. A natural capital and ecosystem services framework was tailored to present decision-makers with a range of potential issues for strategic consideration as goal hierarchies in MCDA. Priorities were elicited from the Board and its four regionally based consultative groups using the Analytical Hierarchy Process and swing weights. Centered log ratio transformed weights were analyzed using multiple pairwise ANOVA comparisons (Dunnett's T3) and hierarchical cluster analysis. Substantial variation in priorities occurred between decision-makers. Nonetheless, analysis of priorities for assets and services robustly demonstrated that water was the highest priority, followed by land, then biota, with atmosphere the lowest priority. Decision-makers also considered that environmental management should not impact negatively on built or social capital. Few significant differences in priorities were found between decision-maker groups. However, clusters of manager types were found which represent distinct alternative management strategies, notably the prioritization of either intermediate or final ecosystem services. The results have implications for regional environmental decision-making and suggest that embracing variation in perspectives may be a better way forward for multistakeholder MCDA. The study operationalizes natural capital and ecosystem services by providing strategic priorities for targeting management and policy within the context of community-based, regional environmental management.

**Key words:** multicriteria decision analysis; weighting; compositional analysis; planning; environmental management; multiple objective.

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## Introduction

Identifying strategic priorities for environmental management presents community-based regional agencies with a complex decision problem. Within regions, management may be directed at multiple, complexly interacting aspects of the environment such as water, land, and biota; or processes such as erosion, salinization, energy efficiency, climate change, pollution, pest plants and animals, and native species extinction. Compounding this complexity, the decision-making structure of community-based regional agencies typically requires input from multiple stakeholders (Broderick 2005; Farrelly and Conacher 2007). Thus, the strategic challenge confronting regional agencies is the identification of those environmental issues of greatest importance and urgency for management within the context of limited resources and multiple, diverse stakeholder perspectives. Two things are required to address this challenge: (1) a comprehensive framework for considering the full range of environmental issues of potential importance for management within a region, and; (2) a structured means of quantifying and integrating the priorities of multiple stakeholders.

To identify priorities for environmental management regional decision-makers need to consider the full range of investment alternatives. The natural capital and ecosystem services framework may be used to structure the task of identifying regional priorities for environmental management. Natural capital assets are the physical aspects and organization of the environment such as the land, water, biota, and atmosphere (Costanza and others 1997; MacDonald and others 1999; Fisher and others 2009). These assets generate a range of ecosystem goods and services such as provisioning (for example, food, fresh water), regulating (for example, pest control, flood mitigation), cultural (for example, recreation, heritage), and supporting (for example, water and nutrient cycling) services (MEA 2005). Ecosystem services are aspects of ecosystems utilized and valued by people and, in conjunction with other forms of capital, contribute to human wellbeing (Boyd and Banzhaf 2007; Fisher and others 2009). Management of natural capital is required to sustain the provision of ecosystem services and resultant human wellbeing (Turner and Daily 2008; Daily and others 2009). The natural capital and ecosystem services framework provides a comprehensive enumeration of the range of environmental issues of potential import for management in a region.

Natural capital and ecosystem services frameworks have been used to inform environmental management in several ways. Most commonly, the economic value of ecosystem services has been estimated to better account for the impact of human society on nature (Costanza and others 1997; Farber and others 2006). However, economic valuation of the breadth of natural capital assets and environmental services that need to be considered for management at the regional level is prohibitively costly (Kroeger and Casey 2007). Rather, quantification of the relative priority (importance or value) of natural capital and ecosystem services may be more appropriate for strategic regional management (Cowling and others 2008).

Multicriteria decision analysis (MCDA) provides a means for structuring complex environmental management decisions and quantifying management priorities (Balasubramaniam and Voulvoulis 2005). MCDA is appropriate for supporting the quantification of regional environmental management priorities as it: incorporates multiple incommensurate, competing, and conflicting criteria; allows explicit consideration of trade-offs; does not require monetary valuation; captures a broader array of values, and; facilitates community-based collaborative decision-making through integrating the perspectives of multiple stakeholders (Prato 1999; Prato and Herath 2007). MCDA has been widely applied in identifying priorities for environmental management generally (Balasubramaniam and Voulvoulis 2005; Mendoza and Martins 2006). A few studies have specifically used MCDA to quantify strategic regional priorities for environmental management based on elements of the natural capital and ecosystem services framework and select specific projects for addressing these (Hajkowicz 2006; Hajkowicz and McDonald 2006; Hajkowicz 2008).

Inclusion of multiple stakeholder perspectives in community-based regional planning has become routine to enhance the effectiveness and acceptability of complex environmental management decisions (Schmoldt and Peterson 2000; Broderick 2005). Stakeholder priorities have often been found to vary considerably and often conflict in environmental applications of MCDA (Hajkowicz and McDonald 2006; Sell and others 2006; Balasubramaniam and others 2007; Hermans and others 2007; Hajkowicz 2008). Many multistakeholder MCDA studies aim to arrive at a final prioritization of management alternatives either through the process of facilitating debate and compromise/consensus among decision-makers (Gamboa 2006), or through the mathematical aggregation of individual weights (Lai and others 2002; Ananda and Herath 2003, 2008; Pavlikakis and Tsihrintzis 2003; Hajkowicz 2006; Regan and others 2006). However, aggregation of priorities of multiple stakeholders to a single measure of central tendency (for example, mean, geometric mean, rank aggregation) has been strongly criticized as it inevitably results in the loss of information on the variation in stakeholder perspectives (Regan and others 2006; Xenarios and Tziritis 2007). The underlying principle here, that *you can't please all of the people all of the time*, is embodied in Arrow's impossibility theorem and the social choice literature (Arrow 1950).

Rather than losing information through aggregation of diverse perspectives, a better approach is to explore the similarities and differences among stakeholders (Balasubramaniam and others 2007; Fürstenau and others 2007; Hermans and others 2007; Rezaei-Moghaddam and Karami 2008). In essence, MCDA-derived weights are a form of multivariate data that can be analyzed using classical statistics. Statistical analysis enables the robust assessment of differences in MCDA-derived weights between criteria given multiple stakeholder perspectives, or differences in weights between groups of stakeholders (Schmoldt and Peterson 2000; Sell and others 2006; Ananda and Herath 2008). Statistical techniques can also be used to explore clusters of different decision-maker types (Emtage and others 2007; Lai and others 2009) according to their priorities for managing different aspects of natural capital and ecosystem services. However, caution must be exercised as MCDA-derived weights may violate several assumptions of classical statistics, particularly through spurious bias toward negative correlations resulting from the trade-offs involved in the weighting process. *Compositional analysis* provides a suite of techniques for the robust analysis of this kind of data (Aitchison 1982, 1986; Aitchison and Egozcue 2005; Buccianti and others 2006).

In this paper, we quantify and explore strategic regional priorities for environmental management based on a natural capital assets and ecosystem services framework using a MCDA approach given multiple stakeholder perspectives. We use a case study of a community-based regional agency—the South Australian Murray-Darling Basin (SAMDB) Natural Resources Management Board (the *Board*). A qualitative interview process was used to refine a goals hierarchy for natural capital and ecosystem services. MCDA workshops were held with the Board and its four regionally based NRM advisory groups to elicit management priorities for natural capital assets and ecosystem services. Weights quantifying management priorities were described and transformed using compositional analysis. Differences in management priority between natural capital assets and ecosystem services, and differences in management priority of individual assets and services between groups were assessed. Cluster analysis was used to further explore typologies of decision-makers according to their priorities for managing natural capital and ecosystem services. The results have implications for the strategic management of natural capital and ecosystem services in the study area and more broadly.

## Regional Environmental Management and the Study Area

There is an increasing global trend for the delivery of government environmental management programs through community-based regional agencies (Peterson and others 2007; Somanathan and others 2009). In Australia, Commonwealth policy has encouraged the establishment of 56 community-based regional *natural resource management* (NRM) agencies since the inception of the Natural Heritage Trust in 1996 (Farrelly and Conacher 2007). In the past, regional agencies in Australia have largely aimed to identify key environmental assets and threats, and then set resource condition and management action targets to address them (for example, SAMDB NRM Board 2003) through a process of broad community and stakeholder consultation (Farrelly and Conacher 2007; Robins and Dovers 2007).

In the SAMDB region study area, the SAMDB Natural Resources Management Board is the community-based regional agency responsible for environmental management. The region covers around 56,000 $km^2$ with a population of 81,000 people (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, its floodplain and wetland ecosystems, the lower lakes, and Coorong estuary. The region also supports 30,748 $km^2$ (55%) of remnant native vegetation including habitat and species of conservation significance. Dryland cropping and grazing (23,304 $km^2$) and irrigated horticulture and pastures (1023 $km^2$) 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.

The Board consists of nine voting members as well as four state government agency representatives and a local government representative. Four

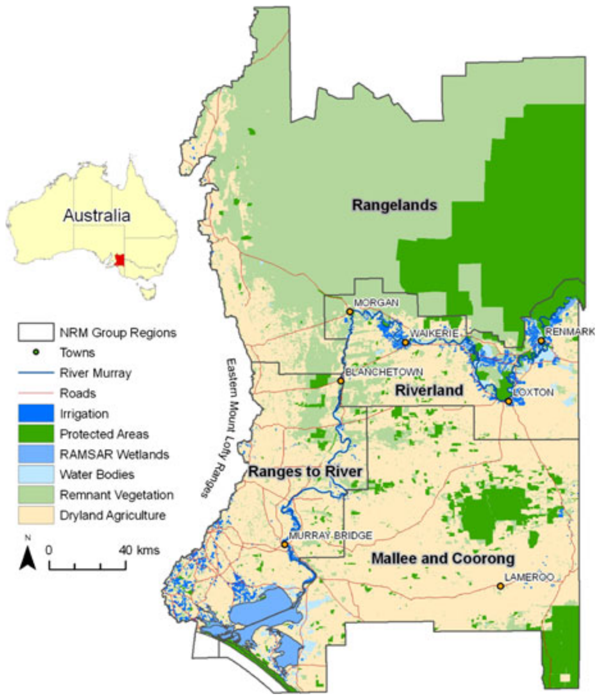


**Figure 1.** Location and broad land use in the South Australian Murray-Darling Basin study area including NRM Group boundaries.

regionally based NRM Groups (Rangelands, Ranges to River, Mallee and Coorong, Riverlands; see Figure 1) each consisting of seven community representatives and stakeholders also advise the Board. Board and group members are drawn on the basis of their expertise, 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).

# Methods

## Defining Goal Hierarchies for Natural Capital and Ecosystem Services

Goal hierarchies were developed for natural capital and ecosystem services to provide structure for the quantification of management priorities. Natural capital assets were defined by the Board as Land, Water, Biota, and Atmosphere. For ecosystem services, a number of typologies exist (Costanza and others 1997; Daily 1997; de Groot and others 2002; MEA 2005). The Millennium Ecosystem Assessment framework (MEA 2005) classified ecosystem services into provisioning, regulating, cultural, and supporting services (see also Farber and others 2006). Significant recent debate (Boyd and Banzhaf 2007; Wallace 2007; Fisher and others 2008, 2009) has distinguished between intermediate services (for example, nutrient cycling, pollination) and final services (for example, fresh water provision, recreation) largely to avoid double counting in valuation and accounting. However, management may be directed at both intermediate and final services. Hence, the full MEA (2005) framework was used as a comprehensive starting point for development of a goal hierarchy for MCDA. Modifications based on 56 qualitative ethnographic interviews with regional decision-makers (described in Cast and others 2008; Raymond and others 2009) included broadening of the natural capital framework to include both Built and Social capital (Figure 2) and by adding three new ecosystem services: Geological Resources; Energy, and; Bequest, Intrinsic and Existence values (Figure 3).

## MCDA Workshop Process

Five MCDA workshops were held across the SAMDB region—one with the Board and one with each of the regional groups. Workshops were attended by 43 decision-makers with 40 valid responses. Weights for individual participants were elicited using Logical Decisions for Groups (Smith 2007). Following the goal hierarchy structure (Figures 2 and 3), local weights were first assigned to the assets and services within each capital type and ecosystem service type, then to the higher level capital types and ecosystem service types themselves.

The Analytical Hierarchy Process (AHP; Saaty 1977, 1980) was used to derive weights for all

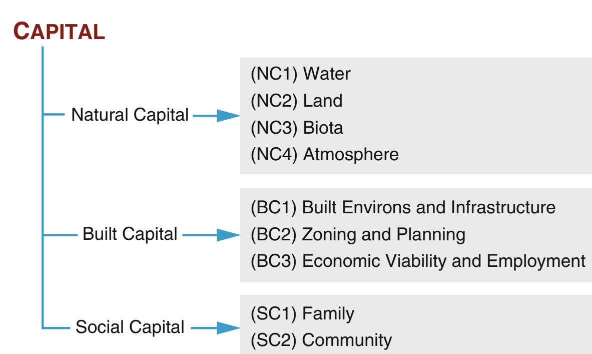


**Figure 2.** Capital-based goals hierarchy with individual assets (*right*) grouped into three capital asset types.

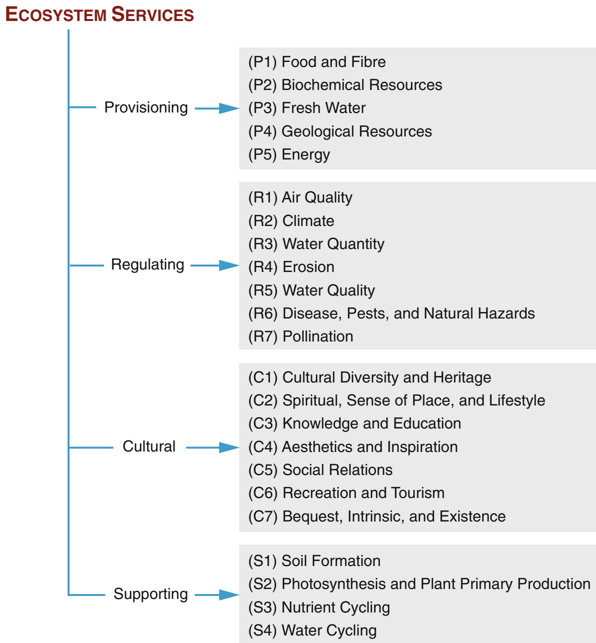


**Figure 3.** Ecosystem service-based goals hierarchy with individual services (*right*) grouped into four ecosystem service types.

capital assets, capital types, and ecosystem service types because of the intuitive nature of the pairwise comparison process. For ecosystem services, the swing weights technique (von Winterfeldt and Edwards 1986) was used to derive weights. The swing weights technique is more parsimonious than techniques that involve pairwise comparisons like AHP when many (>4) criteria need to be weighted. Both AHP (for example, Pavlikakis and Tsihrintzis 2003; Ananda and Herath 2008) and swing weights (for example, Balasubramaniam and others 2007) have been used extensively in environmental management.

Decision-makers were directed to assign weights to capital assets and ecosystem services according to their perceived importance and urgency, and hence, *priority* (Saaty 1994), for management in the SAMDB region. In pairwise comparison using AHP, participants were asked to select the criterion of highest priority for management then score the strength of this decision using the fundamental scale (Saaty 1994) of 1–9 (that is, 1 = equal, 3 = moderate, 5 = strong, 7 = very strong, and 9 = extreme). After Saaty (1980), given $D$ criteria (# capital assets, asset types, or ecosystem service types), a reciprocal $D \times D$ matrix of pairwise comparisons was then created $\mathbf{A} = (a_{ik})$ for $i,k = 1, 2, \ldots, D$, such that:

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1D} \\ 1/a_{12} & 1 & \cdots & a_{2D} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1D} & 1/a_{2D} & \cdots & 1 \end{bmatrix} \quad (1)$$

Local weights $w_i$ reflecting the management priority of individual criteria were then calculated as the normalized principal eigenvector of the matrix $\mathbf{A}$ (Saaty 1980). This was estimated by averaging over the normalized columns of $\mathbf{A}$ and the consistency ratio was calculated following Saaty (1980).

In assigning swing weights (von Winterfeldt and Edwards 1986), within an ecosystem service type, participants were asked to assign a score $w_i = 100$ to the ecosystem service $i$ they considered to be of highest priority for management in the study area. Sequentially, scores were assigned to other services within the ecosystem service type according to management priority relative to the highest priority service such that $w_i$ is less than or equal to 100. Where ecosystem services were considered of no importance for management, $w_i = 0$. Local weights $w_i'$ were then calculated as $w_i' = w_i / \sum_{i=1}^{D} w_i$, where $\sum_{i=1}^{D} w_i' = 1$ and, in this case, $D$ is the number of ecosystem services in the ecosystem service type.

Local weights on the higher level asset/service types were modified to remove bias resulting from variation in the number of assets/services they contained while still summing to 1 (Saaty 1994):

$$w_c' = \delta_c \frac{D_c w_c}{\sum_{c=1}^{C} D_c w_c}, \quad (2)$$

where $w_c$ is the local weight of the higher level asset/service type $c$, $D_c$ is the number of assets/services in asset/service type $c$, $C$ is the number of asset/service types (that is, 4), and $\delta_c$ is the ratio of the number of assets/services in type $c$ over the average number of assets/services within an asset/service type, $\delta_c = D_c/\overline{D}_c$.

Global weights were then calculated for each capital asset and ecosystem service by multiplying their local weight $w_i'$ by the modified local weight of their respective higher level asset/service type $w_c'$. Global weights sum to 1 over all capital assets and over all ecosystem services and quantify the management priorities of each decision-maker.

## Compositional and Statistical Analysis

Statistical analysis was used to explore management priorities of decision-makers for capital assets and ecosystem services. Global weights in the MCA-derived data necessarily sum to 1 (the *unit-sum* constraint) over capital assets and over ecosystem services for each decision-maker. As such, the data are *compositional* and are subject to closure effects as at least one negative correlation must exist between variables (that is, if one weight is increased, at least one other weight must decrease to preserve the unit-sum constraint not necessarily because it has been assigned lower priority). The unit-sum constraint also means that data do not satisfy the assumptions required by many classical statistical analyses. Results of statistical analyses of compositional data in raw form are clouded as it is impossible to know if any relationships in the data reflect natural processes or are an artifact of the closure effects (Aitchison 1982, 1986; Aitchison and Egozcue 2005; Pawlowsky-Glahn and Egozcue, 2006).

Aitchison (1986) described the simplex geometry of compositional data and suggested log ratio transformation for avoiding closure effects. Log ratio analysis of compositional data has been most common in fields such as mathematical geology (Buccianti and others 2006, Drew and others 2008). Centered log ratio (clr) was selected in this study because it maintains the original dimensionality ($D$) which 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 statistical analyses which rely on the covariance matrix of vectors of observations are not applicable (Pawlowsky-Glahn and Egozcue 2006).

After Daunis-i-Estadella and others (2006), let $\mathbf{X} = \{\mathbf{x}_j = [x_{1j}, x_{2j}, \ldots, x_{Dj}] \in S^D : j = 1, 2, \ldots, n\}$ define a compositional data set. In this study, the two compositional data matrices (capital assets and ecosystem services matrices) consist of 40 rows $\mathbf{x}_1$, $\mathbf{x}_2$, …, $\mathbf{x}_{40}$ with one row per decision-maker (that is, $n = 40$), and $D$ columns $X_1$, $X_2$, …, $X_D$ or *parts*. $D = 9$ for the capital assets data set (Figure 2) and $D = 23$ for the ecosystem services data set (Figure 3). Each row $\mathbf{x}_j$ captures the weights $x_{ij}$ representing the management priorities for each capital asset/ecosystem service $i$ for $i = 1, 2, \ldots, D$ of each decision-maker $j$.

The distribution of raw weights is presented in box plots based on the median interquartile range, whiskers at 10th and 90th percentiles, and outliers beyond these. The closed geometric mean of raw weights $g_i$ was calculated as a more robust measure of central tendency the management priority of each capital asset and ecosystem service $i$:

$$g_i = \left(\prod_{j=1}^{n} x_{ij}^{1/n}\right), \quad i = 1, 2, \ldots, D \qquad (3)$$

Together, the vector of closed geometric means $\mathbf{g}$ is called the center of the composition of weights:

$$\mathbf{g} = C(g_1, g_2, \ldots, g_D). \qquad (4)$$

Variance in management priorities for each capital asset and ecosystem service was calculated as the sum of the variance of the normalized log ratio of pairs of parts (Pawlowsky-Glahn and others 2007):

$$\mathrm{var}[X_i] = \frac{1}{D}\sum_{k=1}^{D} \mathrm{var}\left[\frac{1}{\sqrt{2}} \ln \frac{X_i}{X_k}\right], \quad i = 1, 2, \ldots, D \quad (5)$$

The total variance in management priorities for both capital assets and ecosystem services for each group was calculated by summing the variance over all parts:

$$\mathrm{var}[\mathbf{X}] = \sum_{i=1}^{D} \mathrm{var}[X_i] \qquad (6)$$

Global weights for both the capital assets and ecosystem services 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:

$$clr(\mathbf{x}_j) = \left[ln \frac{\mathbf{x}_j}{g_D(\mathbf{x}_j)}\right] = \left[\ln \frac{x_{1j}}{g_D(\mathbf{x}_j)}, \ln \frac{x_{2j}}{g_D(\mathbf{x}_j)}, \ldots, \ln \frac{x_{Dj}}{g_D(\mathbf{x}_j)}\right], \quad j = 1, 2, \ldots, n, (7)$$

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

$$g_D(\mathbf{x}_j) = \left(\prod_{i=1}^{D} x_{ij}\right)^{1/D}, \quad j = 1, 2, \ldots, n \qquad (8)$$

Kolmogorov–Smirnov tests confirmed that clr-transformed data generally followed a normal distribution ($P < 0.05$). Hence, a range of classical exploratory parametric statistical analyses was then performed on the clr-transformed data 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 the distributions of management priorities between individual capital assets and ecosystem services. In combination with the descriptive statistics, these analyses indicate which assets and services are of significantly higher 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 the distributions of management priority of each capital asset and ecosystem service between the five groups of decision-makers. Dunnett's T3 (Dunnett 1980) was used because it is robust to heteroscedasticity and corrects for the increased family-wise Type I error associated with multiple pairwise comparisons.

Hierarchical cluster analysis was used to create a typology of decision-makers according to similarities in management priorities. Ward's minimum distance hierarchical method (Ward 1963) was used based on the sum of squared Euclidean distances in clr-transformed weights to find clusters of decision-makers (or sum of squared *Aitchison distances*). This technique iteratively merges the two clusters which result in the smallest increase in the overall sum of squared within-cluster Euclidean distances. Inspection of dendrograms and cluster membership of a range of classifications (2–10 clusters) informed the selection of management typologies for both ecosystem services and capital assets. Typologies were used to explore the nature of decision-makers' strategic priorities for managing natural capital and ecosystem services.

## Results

### Interpretation of Capital Assets and Ecosystem Services

Decision-makers interpreted the capital assets and ecosystem services in the context of local and regional management issues (Tables 1 and 2).

### Management Priorities

Management priorities for capital assets and ecosystem services varied among the full group of 40 decision-makers. Based on the closed 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 (Figure 4). 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 (Figure 4).

Considering the variation in responses of the full group of decision-makers, ANOVA results suggested that the management priority of Water was significantly higher than all other assets except Land (Figure 4). The management priority for Land was not significantly different from 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 4).

For ecosystem services, management priorities also varied widely over the full group of decision-makers. Based on the geometric mean of raw weights, a suite of water- and production-related ecosystem services were attributed highest management priority including the provision of Fresh Water, Water Quantity regulation, Food and Fiber provision, Water Quality regulation, Water Cycling, Erosion regulation, and Disease, Pests, and Natural Hazards regulation (Figure 5). Cultural services were of lowest priority for management (Figure 5). Based on the clr-transformed data, Photosynthesis and Plant Primary Production, Geological Resources, and Biochemical Resources had the greatest variance in management priority whereas Water Quality regulation, Pollination, Erosion regulation, and Water Quantity regulation had the lowest variance (Figure 5).

The provisioning service, Fresh Water, was of significantly higher management priority than Biochemical and Geological Resources, Air Quality and Climate regulation, Pollination, Soil Formation, and all cultural services (Figure 5). Management priorities for both Water Quantity regulation and Food and Fiber provision were significantly higher than Air Quality, Pollination, and all cultural services (Figure 5). Similarly, Water Quality regulation was of significantly higher management priority than Air Quality and the cultural services. Water Cycling, Erosion regulation, and Disease, Pests, and Natural Hazard regulation were all significantly higher management priority than the three cultural services of Aesthetics and Inspiration, Social Relations, and Recreation and Tourism. Finally, Energy provision was of higher management priority than Social Relations and Recreation and Tourism. There were no other significant differences in management priority between ecosystem services (Figure 5).

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 (Figure 6) was highest in the Riverlands (var[$\mathbf{X}$] = 4.58), followed by Mallee and Coorong (var[$\mathbf{X}$] = 3.20), the Board (var[$\mathbf{X}$] = 2.83), Ranges to River (var[$\mathbf{X}$] = 1.73), and lowest in the Rangelands (var[$\mathbf{X}$] = 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 6). The Mallee and Coorong attributed significantly higher management priority

**Table 1.** Interpretation of Capital Assets by Decision-Makers

| Capital asset | Interpretation in the study area |
|---|---|
| (NC1) Water | Surface water bodies (for example, 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 |
| (NC2) Land | Soils and land resources generally under agricultural production but also supporting native habitat and pastures |
| (NC3) Biota | Native species and ecosystems such as those occurring in patches of remnant vegetation and especially those under formal protection |
| (NC4) Atmosphere | Air and climate including temperature and cloud cover affecting incoming solar radiation |
| (BC1) Built environs and infrastructure | Includes schools, roads, buildings, locks, weirs, and salt interception schemes |
| (BC2) Zoning and planning | All relevant institutions regulating land use and the environment (for example, protection for conservation) |
| (BC3) Economic viability and employment | Financial returns from agriculture, economic viability of local businesses, and job security |
| (SC1) Family | Relationships with family members (for example, parents, children, grandchildren, etc.) |
| (SC2) Community | Relationships within groups of people connected through their local area, or through activities such as schooling, fire-fighting, and land stewardship |

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, and salt interception schemes in the Riverlands.

Variance in the management priority of ecosystem services (Figure 7) was nearly twice as high in the Riverlands (var[$\mathbf{X}$] = 19.70) as in the Rangelands (var[$\mathbf{X}$] = 10.16), Mallee and Coorong (var[$\mathbf{X}$] = 10.09), and the Board (var[$\mathbf{X}$] = 9.77), with much lower variance in the Ranges to River (var[$\mathbf{X}$] = 5.63).

There were also very few (10 out of a possible 230) significant differences in the management priorities of ecosystem services between groups of decision-makers (Figure 7). Management priorities for both Fresh Water and Food and Fiber were significantly higher in the Board, Ranges to River, and the Mallee and Coorong groups than in the Rangelands. The Mallee and Coorong group attributed significantly higher management priority to Geological Resources than the Rangelands, associated with the prospect of mining of mineral sands. The Rangelands attributed significantly higher management priority to Knowledge and Education services associated with indigenous knowledge prevalent in the Rangelands region. Both the Board and the Mallee and Coorong attributed higher management priorities to Soil Formation than the Riverland. This was associated with the importance of productivity of the agricultural soils in the Mallee and Coorong region and their susceptibility to wind erosion.

## Typology of Environmental Managers

A 3-cluster hierarchical classification was selected to establish a typology of decision-makers with respect to their priorities for managing natural capital and other assets (Figure 8). Cluster 1 may be characterized as *pragmatic natural resource managers* as they attributed higher management priority to the natural capital assets of Water, Land, and Biota, moderate priority to the three built capital assets, and very low priority to social capital assets. Cluster 2 may be characterized as *community-minded managers* as they distributed management priorities fairly evenly across the range of assets with the higher priority attributed to Water and Land assets and lower priority to Biota and Atmosphere. Cluster 3 may be characterized as *deep green managers* as they attributed very high management priority to Water, Biota, and Land with very low priority associated with built and social capital assets (Figure 8). Most decision-makers fall under Cluster 1 (18) and 2 (16), with Cluster 3 consisting of only six decision-makers.

A 3-cluster hierarchical classification was also selected to establish a typology of decision-makers

**Table 2.** Interpretation of Ecosystem Services by Decision-Makers

| Ecosystem service | Interpretation in the study area |
|---|---|
| (P1) Food and fiber | Agricultural production including dryland and irrigated crops and wool production |
| (P2) Biochemical resources | A range of currently unknown but potential genetic, biochemical, and pharmaceutical resources found in native ecosystems |
| (P3) Fresh water | Availability of high quality, potable water in surface water bodies and from rainfall |
| (P4) Geological resources | A range of mineral resources extracted from land substrates (for example, mineral sands) |
| (P5) Energy | Renewable energy sources potentially generated in the region such as biofuels, wind and solar power |
| (R1) Air quality | The ability of sustainable farming techniques and native ecosystems to mitigate dust storms |
| (R2) Climate | Regulation of climate change including global warming and decreased rainfall produced by tree cover, especially native habitat. Also natural variability in rainfall (for example, drought) |
| (R3) Water quantity | Considered as environmental flows in rivers, lake levels, more ''natural'' water |
| (R4) Erosion | Predominantly wind erosion regulation from sustainable farming and native ecosystems but also some consideration of river bank erosion |
| (R5) Water quality | Water quality enhancement from wetlands and riparian buffer strips |
| (R6) Disease, pests, and natural hazards | Effect of native ecosystems in mitigating threats to agriculture and native ecosystems including both exotic (for example, goats) and native species (for example, wombats, kangaroos). The fire hazard of native vegetation was considered a major threat rather than valued for natural hazard regulation |
| (R7) Pollination | Pollination services provided by insects especially in the context of irrigated and dryland crop production |
| (C1) Cultural diversity and heritage | Relationship between indigenous people and the environment, and also European agricultural and mining heritage |
| (C2) Spiritual, sense of place, and lifestyle | Special places in the landscape tied to religious beliefs, and cultural traditions (especially indigenous). Connection o the land, and the lifestyle offered through farming |
| (C3) Knowledge and education | Educational opportunities offered by the environment such as scientific research areas, and traditional knowledge of indigenous people and other locals |
| (C4) Aesthetics and inspiration | The beauty of the landscape which may also inspire |
| (C5) Social relations | Opportunities for people to get together provided by the environment (for example, meeting places, work) |
| (C6) Recreation and tourism | Environment-based recreation such as water skiing and other water sports, fishing, hunting, camping, house-boating, hiking, and nature-based tourism |
| (C7) Bequest, intrinsic, and existence | Bequest values are associated with preserving a natural environment for future generations, intrinsic value refers to the value of an environment in and of itself, and existence values are associated with knowing that an environment is preserved irrespective of any benefit to humans |
| (S1) Soil formation | Ongoing processes of weathering of bedrock and integration of organic matter to create fertile soils |
| (S2) Photosynthesis and plant primary production | Ongoing processes of plant growth through assimilating carbon dioxide and sunlight underpinning food chains |
| (S3) Nutrient cycling | Ongoing processes of cycling of nitrogen, phosphorous and other nutrients through the lithosphere and biosphere |
| (S4) Water cycling | Ongoing processes of cycling of water in gas, ice, and liquid form through rainfall, run off and infiltration, evaporation, condensation, and so on |

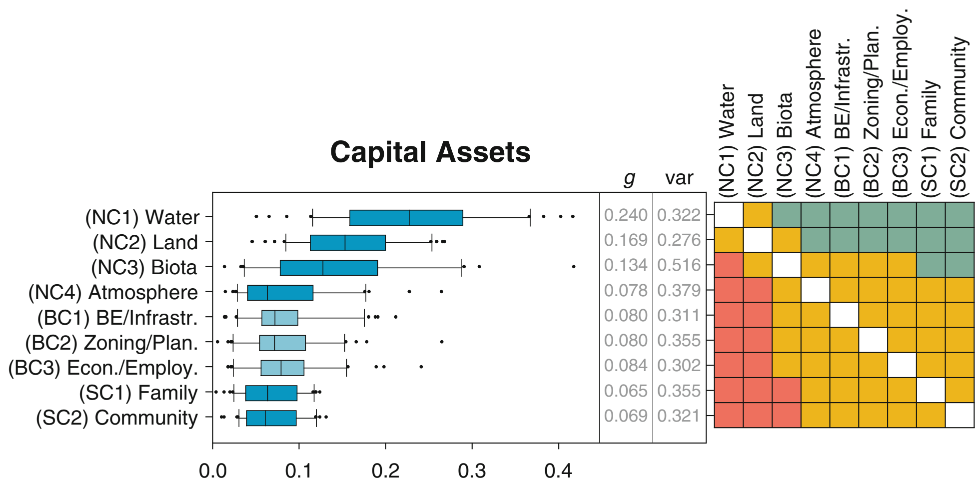


**Figure 4.** Boxplots of the raw weights representing the strategic management priority of capital assets in the study area (*left*). Descriptive statistics are also presented including the center (closed geometric mean of raw compositional weights, g) and the clr-variance (var). Together, the vector **g** forms the center of the composition of weights. On the right is the matrix of outputs of multiple pairwise ANOVA (Dunnett's T3) of clr-transformed weights based on all 40 decision-makers. *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.

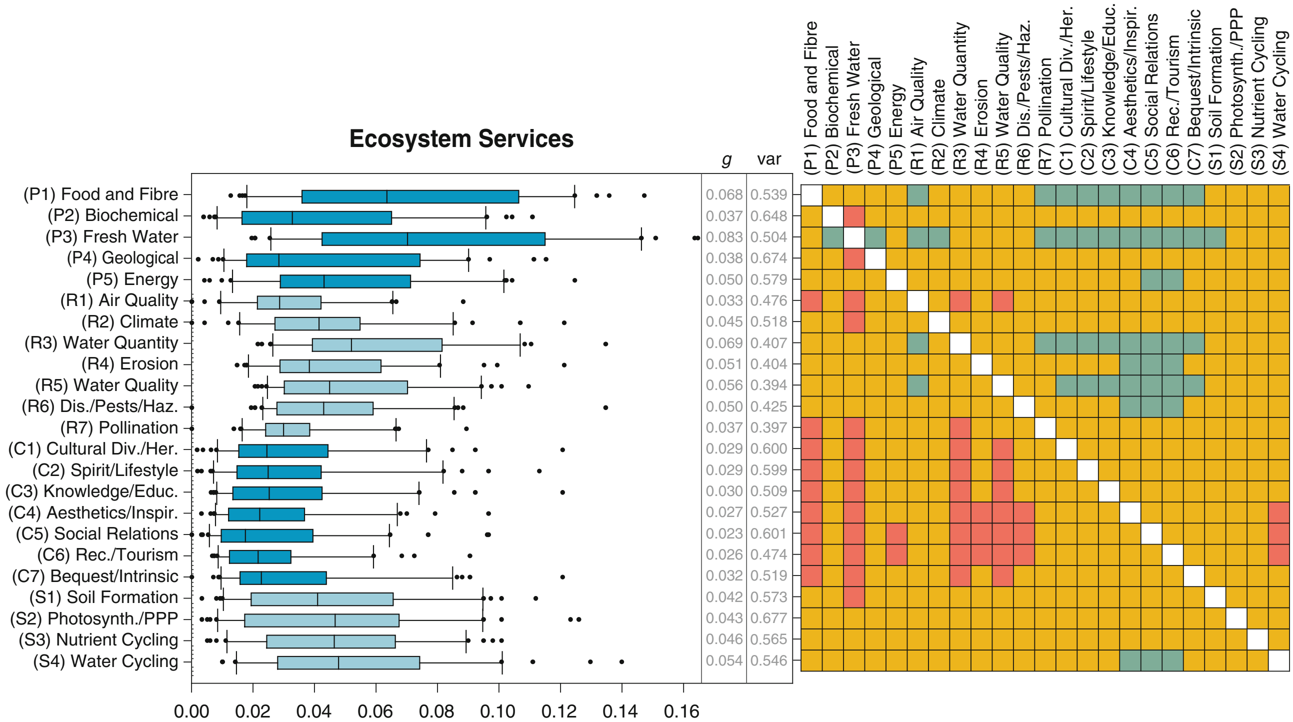


**Figure 5.** Boxplots of the raw weights of strategic management priorities of ecosystem services (*left*), descriptive statistics (*center* and variance), and results of multiple pairwise ANOVA (Dunnett's T3) of clr-transformed weights (*right*) for all 40 decision-makers. See Figure 4 caption for interpretation of colors.

with respect to their ecosystem service management priorities (Figure 8). Cluster 1 may be characterized as *farmer managers* as they attributed high priority to provisioning services and supporting services, and very low management priority to cultural services. Cluster 2 may be characterized as *final service managers* as they had a strong focus on provisioning and cultural services with very low priority associated with supporting and regulating services. Conversely, Cluster 3 may be character-

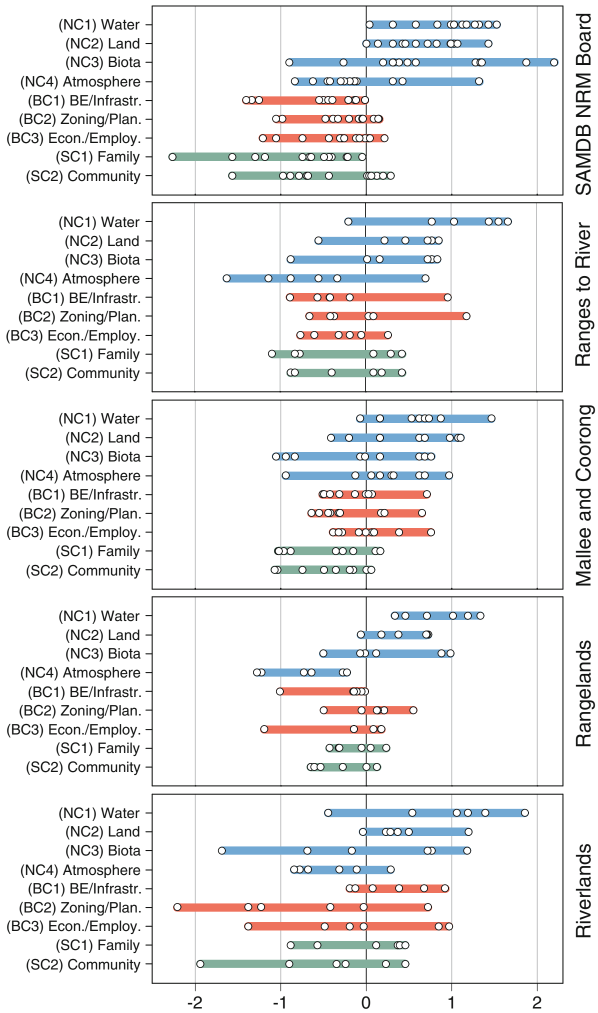


**Figure 6.** clr-transformed weights representing the relative management priority of capital assets for decision-makers in the SAMDB NRM Board and each of the four regional NRM Groups.

ized as *intermediate service managers* as they attributed higher management priority to supporting and regulating services, and lower priority to cultural and provisioning services (Figure 8). Most decision-makers fall under Cluster 1 (16), with 13 decision-makers in Cluster 2, and 11 in Cluster 3.

Decision-makers from the five groups are spread across clusters for both the capital assets and ecosystem services typologies (Table 3). However, frequencies were too low to reliably confirm this through chi-square analysis.

# Discussion

## Implications for Regional Management

The substantial diversity in priorities for managing natural capital and ecosystem services among regional decision-makers was consistent with other studies (Hajkowicz and McDonald 2006; Sell and others 2006; Balasubramaniam and others 2007; Hermans and others 2007; Hajkowicz 2008). Despite this variation, there was general agreement that natural capital assets should be managed as a priority, but not at the expense of economic or social assets. A reasonable rule of thumb for strategic regional management in the study area emergent from this analysis is to prioritize Water assets highest, followed by Land, then Biota, with Atmosphere, Built and Social Capital of lower priority:

$$\text{Water} > \text{Land} > \text{Biota} > \text{Atmosphere} \approx \text{Built Capital} \approx \text{Social Capital}$$

Management priorities for ecosystem services reinforced this with a select few water- and production-related ecosystem services of significantly higher management priority, especially compared to cultural services. Recent drought and low river flows probably contributed to the higher priority attributed to water assets and services at the time of the study.

The robust set of strategic priorities for managing natural capital assets and ecosystem services can enhance regional planning in several ways. Strategic priorities can guide the specification of targets for critical natural capital (Macdonald and others 1999) and ecosystem services (Fisher and others 2008) in a strong sustainability approach to regional environmental management. They can be used to target large scale regional investment of public money in environmental management (Bryan and Crossman 2008; Crossman and Bryan 2009; Raymond and others 2009) and inform relative levels of investment in managing specific environmental issues through processes such as fiscal equalization (Hajkowicz 2007). Strategic priorities can be also used to select a cost-effective portfolio of management actions and inform policy instruments such as payments for ecosystem services.

The few significant differences in management priority of individual assets and services that occurred between groups of decision-makers were largely a result of substantial within-group variation. Given this variation, cluster analysis was able to identify decision-maker typologies according to their individual strategic management priorities (Emtage and others 2007; Lai and others 2009). The capital assets typology shed light on the aspects of environmental organization (Fisher and others 2009) of importance for management within a

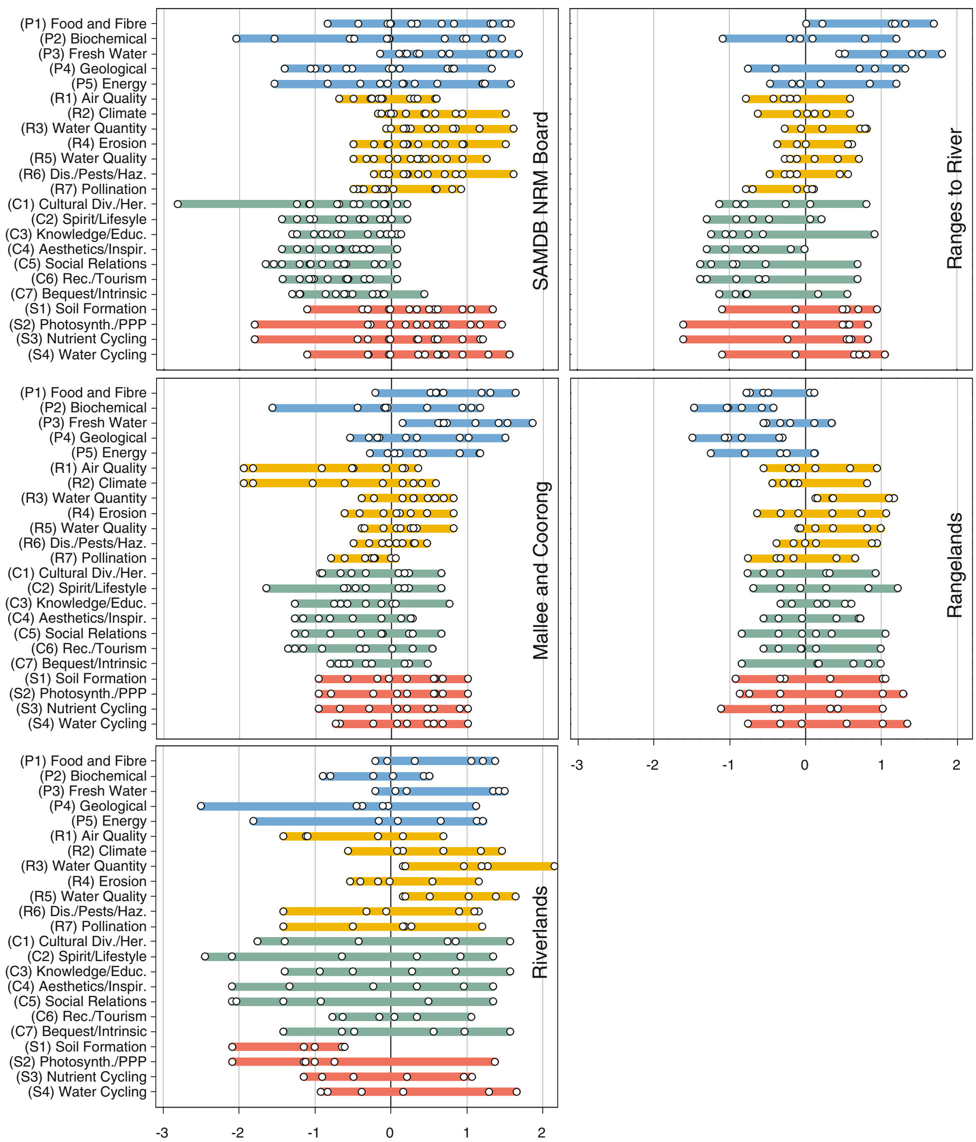


**Figure 7.** clr-transformed weights representing the relative management priority of ecosystem services for the five groups of decision-makers in the study area.

broader social and economic context. *Pragmatic natural resource managers* prioritized natural capital, then built capital, with social capital lowest. The *community-minded managers* attempt to prioritize natural, built, and social capital equally, while the *deep green managers* prioritized natural capital well above all else.

The ecosystem services typology provided more of a functional perspective on strategic management types. Aside from the distinct cluster of *farmer managers*, decision-makers were naturally divided according their priorities for managing either intermediate or final services (Boyd and Banzhaf 2007; Wallace 2007; Fisher and others 2008, 2009). To illustrate the underlying rationale, it is useful to consider a simple linear chain where intermediate services produce final services which, in turn, produce benefits to people (Fisher and others 2008, 2009). *Intermediate service managers* prioritized the management of supporting and regulating services because they considered them essential and fundamental to the production of final services and, subsequently, human benefits. They considered that as long as these underpinning services were managed, they would look after the rest. Conversely, *final service managers* perceived that intermediate services were subject to a low level of threat and hence, did not require management, and if they were threatened, there was little they could do to manage these services anyway (for example, how can they manage nutrient cycling, photosynthesis, and so on?). Rather, *final service*

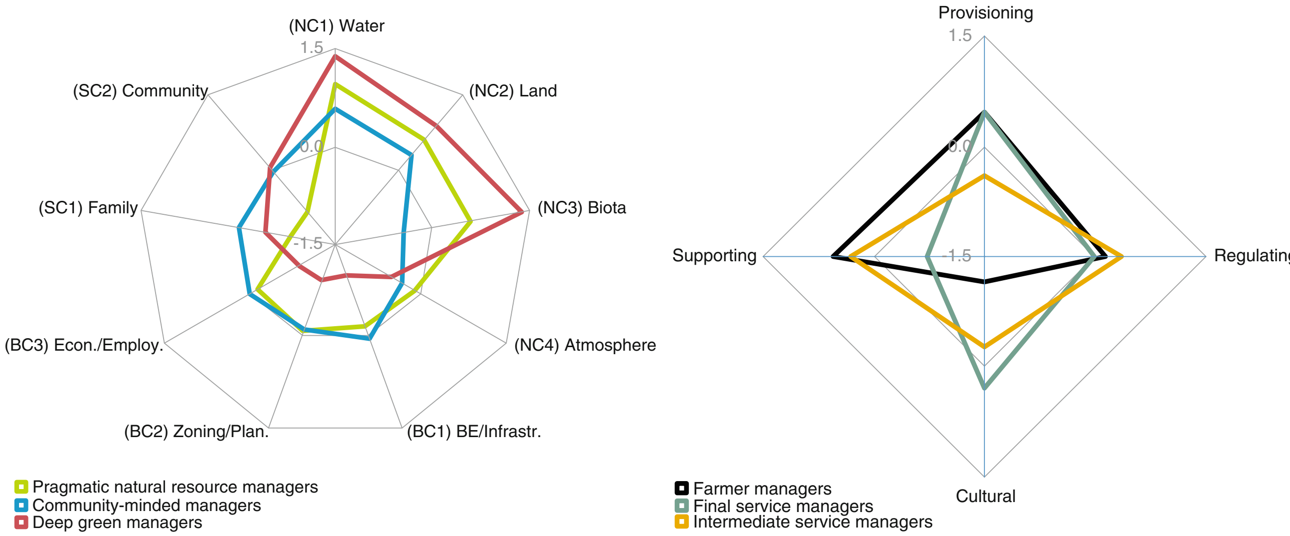


**Figure 8.** Mean clr-transformed weights of management priority typologies for capital assets (*left*) and ecosystem service types (*right*).

**Table 3.** Membership of Management Clusters from the Five Groups of Decision-Makers

| | Capital assets | | | Ecosystem services | | |
|---|---|---|---|---|---|---|
| | Pragmatic natural resource managers | Community-minded managers | Deep green managers | Farmer managers | Final service managers | Intermediate service managers |
| SAMDB NRM Board | 6 | 4 | 3 | 6 | 2 | 5 |
| Ranges to river | 3 | 2 | 1 | 4 | 2 | 0 |
| Mallee and Coorong | 4 | 5 | 0 | 4 | 3 | 2 |
| Rangelands | 2 | 3 | 1 | 0 | 2 | 4 |
| Riverlands | 3 | 2 | 1 | 2 | 4 | 0 |
| *Total* | 18 | 16 | 6 | 16 | 13 | 11 |

*managers* prioritized provisioning and cultural services which more directly affect people's wellbeing and are more tangible to manage.

These results have implications for community-based, regional decision-making structures. Geographically based NRM Groups were not particularly parochial in prioritizing the specific assets and services of concern in their local area (for example, Rangelands did not focus on biodiversity, nor Riverlands on water, and so on). Rather, each of the five groups included different manager types which contributed to significant within-group variation in priorities. This suggests that regional decision-making structures may be improved in two ways: (1) by refining the mandate of geographically based advisory groups to concentrate on local concerns, and: (2) by establishing a cross-cutting set of advisory groups consisting of similar manager types (for example, deep green managers, farmer managers, and so on). This would enable manager types to develop coherent cases for strategic management according to the various perspectives and, when combined with geographically based perspectives, can inform final decision-making at the regional level.

## Natural Capital and Ecosystem Services as a Management Framework

Several authors have commented on the importance of structuring the decision problem in MCDA (Mendoza and Martins 2006; Hajkowicz and Higgins 2008). In this study, natural capital and ecosystem services provided a structured, comprehensive, and powerful framework for capturing, communicating, and understanding the range of aspects of the environment of potential import for management. The framework simplified and clarified the complex task of setting priorities for strategic environmental management. Use of a single, comprehensive framework can also enhance the consistency and comparability of strategic priority-setting across multiple jurisdictions.

The concept of natural capital and ecosystem services has been used in environmental management in several ways (Costanza and others 1997; Macdonald and others 1999; Nelson and others 2009). However, despite significant recent research attention, the concept of natural capital and ecosystem services is yet to deliver on its substantial promise as the ''last, best hope for making conservation mainstream'' (Daily and others 2009). When rooted in the context of natural capital and ecosystem services, environmental management can then be readily valued and integrated into regular economic frameworks such as policy, national accounts, and the bottom lines of corporations (Yang and others 2010). The identification of strategic priorities for community-based regional management provides another practical way of operationalizing the concept of natural capital and ecosystem services (Cowling and others 2008).

## Multicriteria Analysis with Multiple Stakeholders

A critical issue in this and other MCDA analyses of environmental management priorities is how to make sense of multiple, diverse stakeholder priorities (Lai and others 2002; Hajkowicz and McDonald 2006; Sell and others 2006; Balasubramaniam and others 2007; Hermans and others 2007; Hajkowicz 2008). MCDA studies in the past have been quick to embrace measures of aggregation to arrive at a single set of numbers describing group priorities. In this study, using a measure of central tendency such as the closed geometric means that form the center of the composition of weights would have provided clear numerical priorities but would not have been an honest representation of the large variation in stakeholder perspectives. Statistical analysis revealed no significant difference in management priority between many assets/services and between groups. Classical statistical analysis such as pairwise ANOVA comparison provides the only robust means for the analysis of difference between distributions of multiple stakeholder priorities, and differences between groups. Monte Carlo simulation offers the potential to incorporate the variation in stakeholder priorities in further quantitative analysis through capturing the distributions as probability density functions.

A lack of statistical analysis of MCDA-derived priorities may be principally due to the typically low numbers of stakeholders. Another reason may be the complexity in analyzing compositional data. 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. Analysis of compositional data is more common in fields such as geology (Buccianti and others 2006) but seems to be absent in the MCDA literature (for example, Schmoldt and Peterson 2000; Sell and others 2006; Ananda and Herath 2008) despite data routinely of compositional form.

The major drawback of compositional analysis is that it may actually obscure the transparency of MCDA and render the decisions taken on the basis of MCDA stakeholder workshops less accessible to those involved. Further, the level of mathematical sophistication required for compositional analysis of MCDA-derived weights is usually beyond the capacity of environmental agencies. Notwithstanding, we think these trade-offs are worth the substantially increased rigor achieved by the compositional analysis of multiple stakeholder weights especially as management priority information is regularly used to inform multimillion dollar environmental investments.

# Conclusion

In this study, we confronted the challenge of identifying strategic priorities for management of natural capital and ecosystem services given multiple stakeholder perspectives typical of community-based, regional agencies. Substantial variation in management priorities occurred between decision-makers eliminating the prospect of distilling a single representative set of priorities. Statistical analysis of transformed compositional data revealed few significant differences between the management priority of assets and services given decision-maker variation. Nonetheless, it was possible to determine a robust rule of thumb for management priorities which was supported by statistical analysis of both capital assets and ecosystem services. Large variance within groups of decision-makers meant that very few significant differences in management priority of capital assets and ecosystem services were found between groups. However, cluster analysis revealed the existence of distinct types of managers distinguished by their priorities for different capital assets and ecosystem services. This suggested that regional decision-making structures could be enhanced by the establishment of cross-cutting advisory groups representing the different manager types. The results have implications for MCDA analyses where the aim is to arrive at a single set of priorities representative of diverse multistakeholder groups. We suggest that a better way is to embrace the diversity of stakeholder priorities by incorporating priority distributions as probability density functions in a Monte Carlo simulation. The results can provide a strategic basis for the planning and design of policies, programs, and projects that address the natural capital assets and ecosystem services of highest priority in regional management. The process of establishing strategic priorities can benefit community-based regional agencies by demonstrating that they are addressing high priority environmental issues, and by enhancing the transparency, accountability, and inclusiveness of regional decision-making.

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