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Integration of landscape-scale and site-scale metrics for prioritising investments in natural capital

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Abstract: The maintenance of natural capital for ecosystem service provision is crucial to humankind. Natural capital is being exhausted at a rapid rate, manifest as loss of biodiversity, declining water quality and quantity, soil erosion and atmospheric changes leading to climate change. The investment required to ameliorate the rate and scale of degradation of natural capital exceeds available financial resources. A decision process comprised of evidence based planning and transparent decisions, coupled with prioritised investment, provides the greatest environmental benefits. Multi-criteria decision analysis (MCDA) and analytic hierarchy process (AHP) are two decision analysis tools to inform investment planning and decision-making. The strength of these decision-analysis tools lies with their ability to integrate complex and disparate data and model outputs into a simple framework for ranking and prioritisation among a series of alternatives. However there are few integrative case studies at either catchment or individual site scales.

The metrics used to quantify the natural capital and ecosystem services benefits provided by investments at the scale of identified hotspots are typically those deployed for regional and landscape analysis. However, site-scale metrics are important to consider when estimating the efficacy, and therefore priority, of investment because landscape scale metrics may not sufficiently represent the fine-scale variation inherent in complex ecosystems.

This study applies AHP to quantify a series of weights within a MCDA framework to integrate numerous landscape-scale and site-scale metrics for the region managed by the Adelaide and Mt Lofty Ranges Natural Resource Management Board, South Australia. The landscape-scale metrics describe management priorities for various elements of natural capital, namely biodiversity, soil, water and the atmosphere. The site-scale metrics value the relevant assets that enhance natural capital and the threats to those assets. The metrics describe the health, integrity and value of aquatic habitat and terrestrial remnant vegetation at a site. AHP was used to derive weights in a workshop setting with stakeholders and field experts. The AHP was used to assess the relative importance of each metric against every other metric within the branch of a decision tree. Weights were derived using a 3-stage process: first the relative values of the landscape-scale metrics were quantified. Second, the process was repeated with the site-scale metrics. Finally, the importance of the landscape-scale metrics was weighed against the site-scale metrics. The result was a series of global weights describing the relative management priority of each regional- and site-scale factor.

The decision model was applied to a dataset of sites under consideration by the Adelaide and Mt Lofty Ranges Natural Resource Management Board for funding for on-ground works that enhance natural capital for improved provision of ecosystem services. In this case the on-ground activity being funded is the improved management and protection of remnant vegetation. The model was used to calculate investment prioritisation for: i) landscape-scale hotspots; ii) fine-scale on-ground works, and iii) integration of the two scales. The inclusion of site metric in the decision model had a large bearing on the ranking of sites for investment, demonstrating the influence of site scale metrics in the decision process.

Keywords: *Natural capital; multi-criteria decision analysis; analytical hierarchy process; conservation investment; GIS*

1. INTRODUCTION

Funding for Agro-environmental programs is contingent on scarce, finite financial resources, in turn subject to competing and diverse public investment demands. Numerous approaches are used to identify priority locations for public investment in protecting and restoring elements of natural capital. Recent attention has focussed on the spatial targeting of payments for ecosystem services at 'hotspot' locations that offer the greatest environmental benefits per unit of currency invested (van der Horst, 2006; Wünscher et al., 2008; Crossman and Bryan, 2009). The metrics used to quantify the natural capital and ecosystem services benefits provided by investments at the scale of identified hotspots are typically those deployed for regional and landscape analysis. However, site-scale metrics are important to consider when estimating the efficacy, and therefore priority, of investment because landscape-scale metrics may not sufficiently represent the fine-scale variation inherent in complex ecosystems (Wainger et al., 2004; Blaschke, 2006; Hein et al., 2006). This paper presents a decision analysis methodology that integrates landscape and site-scale metrics for prioritising investment in the protection and restoration of natural capital.

Recent studies prioritising investment in the protection and restoration of natural capital and the improved provision of ecosystem services have relied upon many different spatial landscape-scale metrics to quantify the various elements and services. For example, Wünscher et al. (2008) use six landscape metrics to describe four ecosystem services. Crossman and Bryan (2009) use nine metrics to quantify four elements of natural capital and Chan et al. (2006) use approximately 18 metrics to represent six ecosystem services. Many site-scale metrics are available for prioritising investment in restoring natural capital. The ecological management and restoration sciences are rich with metrics of ecosystem integrity and disturbance. They include local species diversity, terrestrial and aquatic habitat condition and presence and density of invasive species, water-borne nutrient and pathogen loads, ungulate grazing pressure, and soil structure and fertility (Parkes et al., 2003; Magurran, 2004; Dorrough et al., 2007; Oliver et al., 2007). Actions that can be applied to enhance these metrics at a site are generally limited to land use change and alternative land management practices.

The natural capital and ecosystem service investment prioritisation problem proposed in this study involves the compilation and synthesis of many idiosyncratic metrics measured at the two different scales. Multiple criteria decision analysis (MCDA) is a decision tool that is well suited to this problem. An MCDA involves ranking and/or scoring the performance (i.e. efficacy) of alternative decisions (i.e. natural capital investments) against multiple criteria (i.e. metrics). Each investment decision is rated against each metric with performance measures, which collectively form an evaluation matrix. The metrics are weighted to represent their importance. The weighted scores are combined with the evaluation matrix to attain an overall rank or score for each investment. A common technique for deriving weights is the Analytic Hierarchy Process (AHP; Saaty 1980).

This paper applies an AHP to weight and integrate a bundle of landscape-scale and site-scale metrics across the Adelaide and Mt Lofty Ranges Natural Resource Management Region, South Australia. The landscape-scale metrics describe management priorities for various elements of natural capital, namely biodiversity, soil, water and the atmosphere. The site-scale metrics value the relevant assets that enhance natural capital and the threats to those assets. These metrics describe the health, integrity and value of aquatic habitat and terrestrial remnant vegetation at a site. The AHP was applied in a workshop setting with stakeholders and field experts to assess the relative importance of each metric against every other metric within the branch of a hierarchical decision tree.

2. METHODS

2.1. Study Area

The focus of this study is the non-urban area that encompasses the Adelaide and Mt Lofty Ranges Natural Resource Management Board and the southern Mt Lofty Ranges bioregions. Land use across this 8,500 km^2 landscape is a mixture of conservation, high value horticulture, forestry and grazing, with 13% of native vegetation remaining. Climate in the study area is Mediterranean with average annual rainfall ranging from 500 mm in the lowest elevation eastern and western flanks, to over 1,000 mm in central and southern parts.

2.2. Landscape-scale metrics

Recent work (Crossman and Bryan 2006, 2009; Bryan and Crossman 2008) has identified the utility of taking a landscape-scale approach to planning for investments in on-ground works that enhance elements of natural capital (e.g. biodiversity, the atmosphere, and stocks of soil and water). This approach typically involves modelling the spatial distribution of various metrics or indicators that quantify management priority as informed by the disciplines of landscape ecology and catchment hydrology. The landscape-scale regional GIS layers modelled here are scaled low to high priority for undertaking on-ground works based on the relative importance of investment in enhancing natural capital. For example, all else being equal, efficacy of investment in on ground works such as weed control and stock removal would be higher in larger patches within intact landscapes (McIntyre and Hobbs, 1999). The metrics included here address flora and fauna species richness, species response to climate changes, landscape context, pre-European vegetation remnancy, vegetation patch management, protected area representativeness, carbon sequestration, water provision, and soil health and stability. Details of these GIS layers can be found in Table 1. Each spatially explicit GIS layer was linearly rescaled in the range 1 to 5, with 5 the highest priority for investment, to give each metric commensurate values.

Table 1. Descriptions of the landscape-scale metrics.

Metric Name	Description
Biodiversity	
Flora Species Richness	Total number of native (896 species) and conservation-rated (145 species) flora species and predicted using habitat suitability modelling.
Species & Climate Change	Landscape priorities for vegetation management and restoration for mitigating against flora species range shift impacts driven by a severe 2030 (1.2 degree warming, 15% drying) climate change scenario.
Dispersal Distance	Distance from patches of remnant vegetation using a negative exponential transformation. Locations closer to remnant vegetation have exponentially greater importance.
Fragmentation	Percentage of vegetation cover within fixed 1km radius circular neighbourhoods
Core Fragmentation	Percentage of core habitat vegetation cover within fixed 1km radius circular neighbourhood. Calculated for a 200m edge distance.
Road Density	Density of road segments within a fixed circular neighbourhood of 1km radius.
Vegetation Remnancy	Percentage of each pre-European class, soil class and climate zone remaining under remnant vegetation.
Vegetation Protection	Percentage of each remnant vegetation community, soil class and climate zone formally protected under a conservation agreement.
Shape	An index of patch shape complexity calculated for all contiguous patches of remnant vegetation. Values closer to 1 indicate lower shape complexity.
Area	Total area (ha) of contiguous patches of remnant vegetation.
Atmosphere	
Carbon Sequestration	Total carbon sequestered. Modelled using the tree productivity model 3PG Spatial. Tree parameter set is for *Eucalyptus globulus*.
Water Quality and Quantity	
Hillslope Erosion	Modelled hillslope erosion using RUSLE, scaled up to sub-catchment level. Three estimates were modelled: erosion under natural (pre vegetation clearance) conditions; erosion under current land use; percentage difference between natural and current conditions.
Gully Erosion	Proportion of land affected by gully erosion. Higher values indicate higher proportion of the landscape affected by gully erosion.
Catchment Vegetation Cover	Proportion of sub-catchment that is covered by woody vegetation.
Environmental Flows	Proportion of flow intercepted by farm dams.
Aquifer Recharge	Groundwater recharge potential. Higher values indicate higher proportion of the landscape with moderate to high recharge potential.
Soil	
Soil Salinity Risk	Risk posed to soil from water table induced salinity.
Water Erosion Risk	Risk posed to soil from surface water erosion.

2.3. Site-scale metrics

The aim of compiling site-scale metrics for site assessments was not motivated by the need to undertake a comprehensive ecological survey but rather to enable a rapid site assessment to be completed by experienced individuals. Site-scale metrics were therefore selected for their ability to be collected rapidly in the field and for their ability to determine the comparative natural capital value of a set of sites potentially receiving investment for on-ground works that improve the management and protection of remnant native vegetation and aquatic habitat. Complete vegetation or macro-invertebrate surveys offer a level of detail beyond that required to make objective comparisons between sites. The selection of site-scale metrics were designed to balance the need for accuracy and time efficiency. Each metric represents an element of natural capital that cannot be measured through remote means such as from biophysical modelling or remote sensing. The site metrics are grouped into four classes describing various elements of: vegetation community composition and structure; vegetation condition; riparian type and condition, and; aquatic habitat. Details of each metric are found in Table 2. Each site metric is scored in the range of 1 to 5 in the field, with 5 the highest priority for investment. The site metrics then have values commensurate with the landscape-scale metrics.

2.4. Hierarchical decision tree and weights

Developing the hierarchical decision tree is paramount for the MCDA model of investment prioritisation. The decision tree provides a visual representation and structure for integrating and synthesising all landscape- and site-scale metrics into a natural capital investment prioritisation framework. Many metrics and datasets are needed to quantify both the extent and condition of elements of natural capital, with each one potentially a decision choice when prioritising investment. For example, should investment be prioritised toward locations of greatest species richness, in largest patches, in climate zones under-represented in the protected area network, where there is low presence of exotic plants or in unhealthy riparian zones, or some combination of these and the many other metrics listed in tables 1 and 2. The decision tree simplifies this complex decision-making process and produces a single solution of investment priority.

The decision tree is central to the process of deriving weights using AHP. The AHP was applied in a workshop with Adelaide and Mt Lofty Ranges Natural Resource Management Board program staff. The AHP was used to assess the relative importance of metric against metric within the branch of the decision tree, and branch against branch. The relative values were determined for the landscape-scale metrics, site-scale metrics and then landscape-scale metrics against the site-scale metrics.

The workshop participants were able to use the decision tree to arrive at a consensus on what was important and to understand how to alter the weightings should priorities change in the future. The decision tree weightings guided conversations and provided a consistent understanding of what was measured through each metric and the investment prioritisation solutions that could be expected.

Table 2. Descriptions of the site-scale metrics.

Metric Name	Description
Vegetation	
Conservation Status	Conservation status of the mapped vegetation community that contains the site.
Condition	Level of intactness, stability and functionality of remnant vegetation
Weed Invasion	Cover and distribution of common weed species
Riparian Zone	Categorisation of the riparian zone based on intactness and integrity
Livestock	
Stock Damage	Score of the effects of grazing on vegetation and soil stability and riparian habitat.
Stock Type	Type of hard-hoofed stock and the level of accessibility to vegetation
Aquatic Habitat Condition	
Geomorphology	Geomorphology scores provide an indication of the sites potential to support a diverse aquatic community, the rarity of that structure and its risk or capacity to change.
Permanence	Whether the aquatic habitat is permanent or ephemeral.
Channel Condition	The rate of active erosion/sedimentation occurring within the reach.
Debris	Snags, logs, or branches are excellent habitat structures, providing shelter, safety, predation and navigation points.
Abiotic Substrate	Type of substrate present within the watercourse.
Organic Substrate	Presence of organic substrates in the watercourse.
Macrophytes	Abundance of aquatic plants in the watercourse
Toxic Inputs	Presence and type of toxic inputs in the watercourse

2.5. Application of decision model

The decision model was applied at two scales. The model was applied at the coarsest scale by calculating a weighted sum of all landscape-scale metric scores P_L using the weights derived in the AHP workshop:

$$P_L = \sum_{i=1}^{n} w_i L_i \qquad (1)$$

Where w_i is the weight for each landscape-scale metric L_i. The result is a map of heterogeneous spatial priority for investment in on-ground works within remnant native vegetation that best enhances natural capital.

The model was applied at the fine scale to rank private properties eligible for conservation investment funding through an on-ground works program in the study area. Experienced field staff of the Adelaide and Mt Lofty Ranges Natural Resource Management Board conducted site assessments across 25 private properties whose owners bid for funding under a trial market-based instrument program. The details of the program are reported elsewhere (Bryan et al., 2008). The site assessment scores for each site metric S_i were input into the decision model and the weighted sum of landscape and site scores P_S were calculated to rank bids according to priority for investment:

$$P_S = \sum_{i=1}^{n} w_i L_i + \sum_{i=1}^{n} w_i S_i \qquad (2)$$

3. RESULTS

The hierarchical decision tree and global weights for each metric is presented in Figure 1. Workshop participants considered landscape-scale metrics to be approximately 2.5 times more important than site-scale metrics when prioritising investment. Biodiversity was considered as the most important element of natural capital for prioritising investment among the landscape-scale elements of natural capital, weighted five times more importantly than its nearest rival, water. Patch area was considered the most important metric across the full set, at approximately three times more important than the next most important metrics. The next most important are the site-scale metrics livestock damage and conservation status of the vegetation community.

The map of spatial investment priorities for enhancing natural capital in the study area is shown in Figure 2. The map in Figure 2 is the weighted sum of all landscape-scale metrics using the weights derived in the AHP workshop. It is evident that the highest priorities are in locations where there are large patches of remnant vegetation. This result demonstrates the influence of the high global weight for the patch area landscape metric (Figure 1).

The inclusion of site-scale metrics into the decision model for ranking properties to receive investment has a noticeable influence on the overall natural capital benefits rank (Figure 3). The rank of each property if considering only the landscape-scale metrics is given by the left hand number of each point in figure 3. The rank changes for every property after inclusion of the site-scale metrics, as shown by the right hand number in figure 3. Not one property is on the 45 degree line, which indicates no change in rank. Many properties are a large distance from the 45 degree line because their rank changes by a large amount (Figure 3). At one extreme end, one property ranks 2nd for landscape-scale metrics, but its overall natural capital benefit rank falls to 17th after inclusion of the site metrics. At the other extreme, one property ranks 10th for landscape-scale metrics, but rises to an overall 2nd place for natural capital benefits after the site metrics are included.

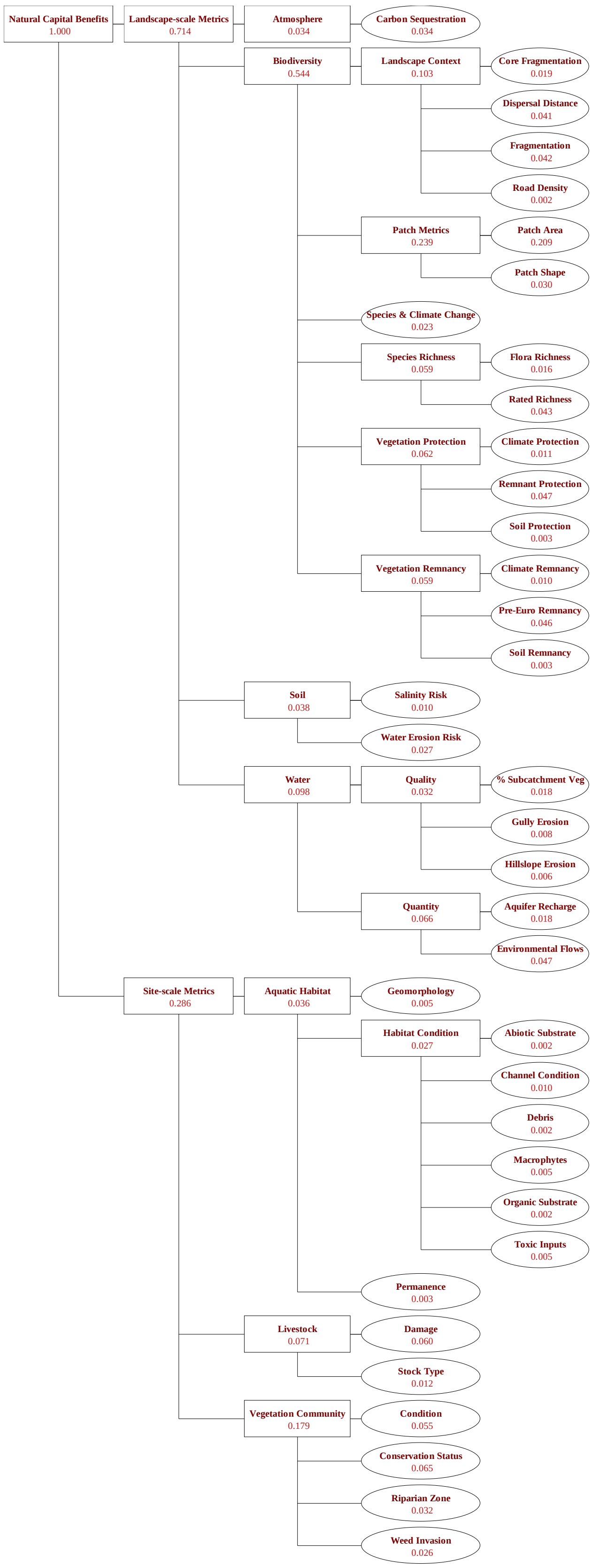

Figure 1. Hierarchical decision tree for landscape scale indicators and site scale metrics. Each oval is a metric. Global weights are shown.

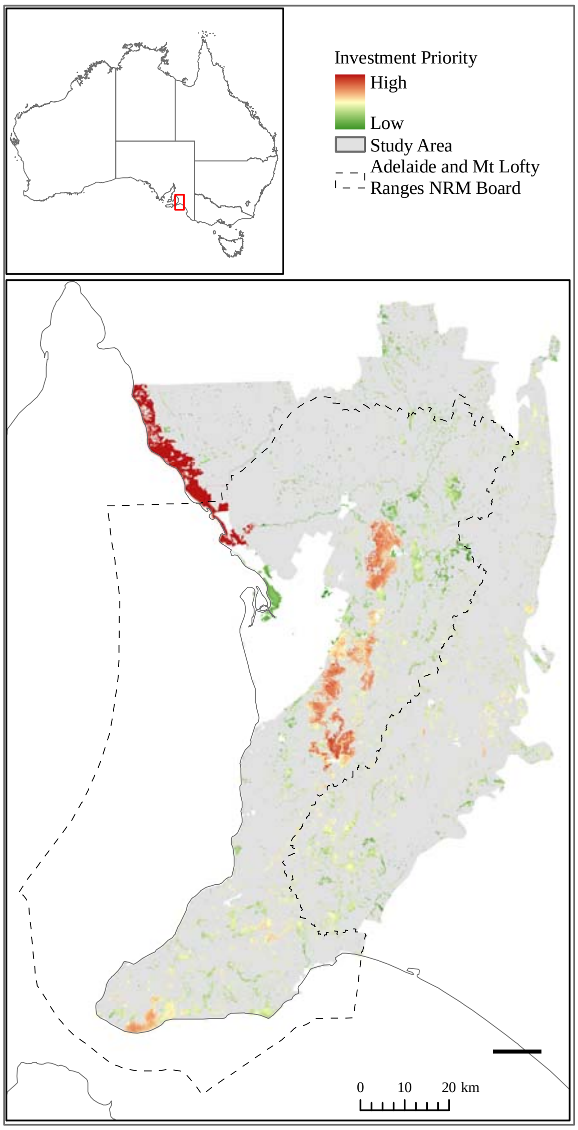

Figure 2. Spatial priorities for investment in remnant vegetation management and restoration that enhance natural capital. Calculated using landscape-scale metrics.

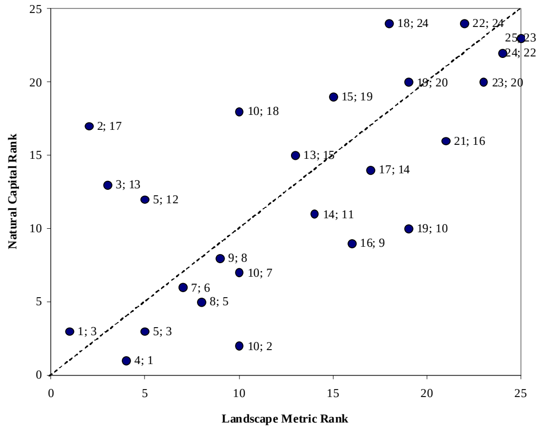

Figure 3. Rank of properties for landscape-scale metrics only (left number) and natural capital benefits rank after inclusion of site-scale metrics (right number).

4. DISCUSSION AND CONCLUSION

Inclusion of site-scale metrics has a noticeable influence on the decision model for prioritising investment in on ground works that protect and enhance natural capital. This is despite the relatively low weighting attributed to the site-scale metrics. The individual properties whose rank changes by a large amount (figure 3) demonstrates that the site-scale metrics are capturing the fine-scale heterogeneity present in natural systems. The inclusion of the fine-scale metrics is consistent with other studies that recommend multi-scale measurements to capture ecosystem complexity (Wainger et al., 2004; Blaschke, 2006; Hein et al., 2006).

The integration and synthesis of metrics from the two scales provides a methodological advance on existing methods that assess the extent and condition of natural capital assets for prioritising investment. Existing Australian methodologies such as the Victorian Habitat Hectares (Parkes et al., 2003) and Index of Stream Condition (Victorian Government Department of Sustainability and Environment, 2006), and the South Australian Nature Conservation Society Bushland Condition Monitoring Manual (Croft et al., 2005) are limited to the measurement of single elements of natural capital, especially biodiversity, and are generally skewed toward site-scale metrics. The present decision model encompasses a greater number of natural capital assets and includes a larger number of landscape-scale metrics. The decision to include the landscape metrics is strongly supported by the large weighting ascribed to the metrics by the AHP workshop participants.

There are several potential applications of the decision model presented here. Most prominently is the use of the model to rank landholder bids within a conservation tender/auction program increasingly common across Australia (Stoneham et al 2003; Windle and Rolfe, 2008) and the USA (Latacz-Lohmann and van der Hamsvoort, 1997). The model can also be used to quantify natural capital for trade under an ecosystem services market (e.g. Gibbons et al 2009) and to quantify condition of natural capital for conservation planning purposes (e.g. Zerger et al., 2009).

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REFERENCES

Blaschke, T., 2006. The role of the spatial dimension within the framework of sustainable landscapes and natural capital. Landscape and Urban Planning 75, 198–226.

Bryan, B.A., Crossman, N.D., Ward, J.R., King, D. and Cast, A.S., 2008. Environmental Auctions and Beyond. . National Market Based Instruments Pilot Program - Round 2. Final Report for the Project. Policy and Economic Research Unit, CSIRO Land and Water.

Bryan, B.A. and Crossman, N.D., 2008. Systematic landscape planning for multiple objective natural resource management. Journal of Environmental Management, 88, 1175-1189.

Chan, K.M.A., Shaw, M.R., Cameron, D.R., Underwood, E.C. and Daily, G.C., 2006. Conservation Planning for Ecosystem Services. PLoS Biology, 4, 2138-2152.

Croft S., Pedler J. and Milne T., 2005. Bushland Condition Monitoring Manual: Southern Mount Lofty Ranges. Volume 1: Field Guide to Bushland Monitoring. Nature Conservation Society of South Australia.

Crossman, N.D. and Bryan, B.A., 2006. Systematic landscape restoration using integer programming. Biological Conservation 128, 369–383.

Crossman, N.D. and Bryan, B.A., 2009. Identifying cost-effective hotspots for restoring natural capital and enhancing landscape multi-functionality. Ecological Economics 68, 654-668.

Dorrough, J., Ash, J.E., Bruce, S. and McIntyre, S., 2007. From plant neighbourhood to landscape scales: how grazing modifies native and exotic plant species richness in grassland. Plant Ecology 191, 186–198.

Gibbons, P., Briggs, S.V., Ayers, D., Seddon, J., Doyle, S., Cosier, P., McElhinny, C., Pelly, V. and Roberts, K., 2009. An operational method to assess impacts of land clearing on terrestrial biodiversity. Ecological Indicators 9, 26-40.

Hein, L., van Koppen, K., de Groot, R.S. and van Ierland, E.C., 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecological Economics 57, 209-228.

Latacz-Lohmann, U. and der Hamsvoort, C.V., 1997. Auctioning conservation contracts: a theoretical analysis and an application. American Journal of Agricultural Economics 79, 407-418.

Magurran, A.E. 2004. Measuring Biological Diversity. Blackwell Publishing, Australia.

McIntyre, S., Hobbs, R., 1999. A framework for conceptualizing human effects on landscapes and its relevance to management and research models. Conservation Biology 13, 1282–1292.

Oliver, I., Jones, H. and Schmoldt, D.L., 2007. Expert panel assessment of attributes for natural variability benchmarks for biodiversity. Austral Ecology 32, 453-475.

Parkes, D., Newell, G. and Cheal, D., 2003. Assessing the quality of native vegetation: the ‘habitat hectares’ approach. Ecological Management and Restoration 4, S29-S38.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.

Stoneham, G., Chaudhri, V., Ha, A. and Strappazzon, L., 2003. Auctions for conservation contracts: an empirical examination of Victoria's BushTender trial. Australian Journal of Agricultural and Resource Economics 47, 477 – 500.

van der Horst, D., 2006. Spatial cost-benefit thinking in multi-functional forestry; towards a framework for spatial targeting of policy interventions. Ecological Economics 59, 171–180.

Victorian Government Department of Sustainability and Environment, 2006. Index of Stream Condition User’s Manual 2nd Edition. Victorian Government Department of Sustainability and Environment, Melbourne.

Wainger, L.A., King, D.M., Cantrell, J.A. and Bird, S.L., 2004. Development of indicators to assess economic vulnerabilities to changes in ecosystem services: Case study of counties in Maryland, USA. Environmental Management 34, 730-747.

Windle, J. and Rolfe, J., 2008. Exploring the efficiencies of using competitive tenders over fixed price grants to protect biodiversity in Australian rangelands. Land Use Policy 25, 388-398.

Wünscher, T., Engel, S. and Wunder, S., 2008. Spatial targeting of payments for environmental services: A tool for boosting conservation benefits. Ecological Economics 65, 822-833.

Zerger, A., Gibbons, P., Seddon, J., Briggs, S. and Freudenberger, D., 2009. A method for predicting native vegetation condition at regional scales. Landscape and Urban Planning 91, 65-77.