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Optimising the spatial pattern of landscape revegetation

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Abstract: The spatial pattern of landscape reconstruction makes a substantial difference to environmental outcomes. We develop a spatially explicit bio-economic model that optimises the reconstruction of a heavily cleared landscape through revegetation. The model determines the spatial priorities for revegetation that minimises economic costs subject to achieving particular improvements in habitat for 29 woodland-dependent bird species. The study focuses on the Avoca catchment (330 thousand ha) in North-Central Victoria. Our model incorporates spatial pattern and heterogeneity of existing and reconstructed vegetation types. The revegetation priorities are identified as being: sites in the vicinity of existing remnants, riparian areas, and parts of the landscape with diverse land uses and vegetation types. Optimal reconstruction design is affected by opportunity costs due to the loss of agricultural production and the costs of revegetation.

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Introduction

The greatest threat to Australia's biodiversity continues to be loss of native vegetation (Australian State of the Environment Committee, 2006), especially in regions of intensive agricultural production. Since European settlement one-third of Australia's woodlands and 80% of temperate woodlands were cleared; the remaining native vegetation is highly fragmented. In areas like these, traditional conservation strategies, namely the protection of untransformed landscapes as large individual reserves, is difficult to apply (Moilanen, et al., 2005). The decline of biodiversity could be reversed by restoration of native vegetation and rebuilding functioning landscapes (Thomson, et al., 2009). The importance of landscape reconstruction is recognised in Australia's Biodiversity Conservation Strategy (Australian National Biodiversity Strategy Review Task Group, 2010). Specifically, it identifies that by 2015, 1,000 km^2 of fragmented landscapes and aquatic systems should be restored to improve ecological connectivity.

Reconstruction of natural habitat does not usually take place in a vacuum. The combination of protected areas and fragments of remnant habitat in working landscapes (especially paddock trees) might have some value for supporting biodiversity (Bennett, et al., 2006, Manning, et al., 2006). Therefore, planning landscape reconstruction should take into account spatial arrangement and characteristics of existing remnant vegetation across all land uses both inside and outside of protected areas (Thomson, et al., 2009). When resources are limited, accounting for the costs is essential for effective planning and implementation of conservation (Wilson, et al., 2009), which is reflected in the growing number of studies that utilise economics in conservation priority setting (Ando, et al., 1998, Naidoo, et al., 2006, Polasky, et al., 2005, Wilson, et al., 2007). It had been shown that under certain circumstances conservation plans could be 10 times more efficient when costs are taken into account (Polasky, et al., 2005). However, very few studies have applied an economic framework to prioritise landscape reconstruction to conserve biodiversity.

In this paper we describe a spatially explicit bio-economic optimisation model that minimises the cost of biodiversity conservation effort (including loss of agricultural production) on a catchment level subject to achieving certain biodiversity outcomes. The biodiversity outcome being sought in this study is the summed probability of occurrence of woodland-dependent birds. We apply the model to the Avoca catchment (330 thousand ha) in North-Central Victoria. By solving the model for different levels of the biodiversity outcome, we identify locations and spatial arrangements of conservation efforts that offer the best value for money, and identify combinations and arrangements of land use that meet biodiversity targets at least cost. We also compare the efficiency of targeted versus non-targeted conservation effort, as well as outcomes generated by utilising different optimality criteria.

Materials and Methods

Study site and partitioning the landscape

The study site is upper Avoca river catchment in North Central Victoria (Figure 1). The pattern of native vegetation of the study region was significantly modified by agriculture after European settlement. Currently, only about 25% of 330 thousand ha is covered by native vegetation and other woodlands. The native vegetation types are dominated by Box Ironbark Forest, Grassy Woodlands, and Grassy Dry Forest in a matrix of native pastures, modified pastures, crops, and vineyards. The region has a Mediterranean climate, with hot, dry

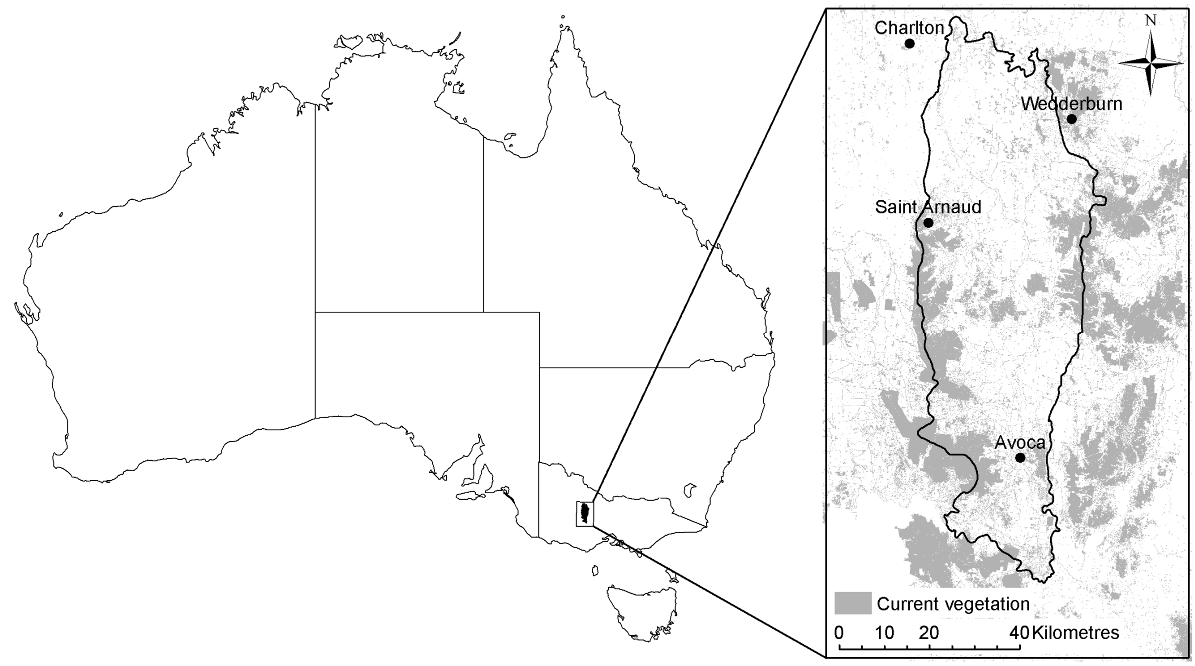


Figure 1. Avoca catchment study area.

summers, cool wet winters, and most rainfall received in winter and spring, although the average varies from 400 mm/yr in the North to 700 mm/yr in the South. The elevation ranges between 100 m in the North and 350 m in the South of the catchment.

Because land use and land cover patterns affect both biodiversity and production outcomes, it is important to design a representation of the landscape that suits both modelling biodiversity and optimisation of revegetation patterns. A traditional approach to spatially explicit modelling of landscape reconstruction is to partition each planning region into a set of distinct homogenous regular (Polasky, et al., 2001, Westphal, et al., 2007) or irregular, based on ownership, (Polasky, et al., 2008) shapes and treat the optimisation problem as binary or integer. However, for highly fragmented landscapes, the use of homogenous parcels of a relatively large size, e.g., 250×250 m or 6.25 ha, (Thomson, et al., 2009, Westphal, et al., 2007) leads to the loss of information about small remnants such as paddock trees, roadside or creek line vegetation, while the use of parcels small enough to represent small remnants, e.g., 25×25 m or 0.0625 ha, leads to a computationally hard or infeasible optimisation problem.

We use an alternative approach and partition the landscape into larger parcels, which are not treated as homogeneous. The planning region is partitioned by overlaying a regular hexagonal grid with the side length of 500 m and area approximately 65 ha over a study catchment. Each grid cell is characterised by the areas of land uses, vegetation cover types, pre-settlement ecological vegetation classes (EVCs), landforms, and individual farms.

Biological model

The biological model predicts probability of occurrence of each of 29 woodland-dependent bird species on every 2 ha of suitable habitat (woodlands) across the landscape. The models (Polyakov, et al., 2011) are developed based on the data collected by J. Radford (Radford and Bennett, 2007, Radford, et al., 2005). The explanatory variables in the logistic regression models are characteristics of the landscape such as weighted proportions of the groups of EVC and densities of the woodlands within 2 km of the survey sites. Landscape characteristics in the immediate proximity are assumed to have greater effect on suitability of habitat then the landscape characteristics further away; this is represented by applying weights proportional to the inverse of squared distance.

We use summed probability of occurrence of all 29 bird species as a biodiversity score. Summed probability of occurrence for each species is the product of habitat area and probability of occurrence summed over the landscape. Consider a landscape that is partitioned into N hexagons. Summed probability of occurrence for species s is calculated as $\sum_{N}\left(p_{s,n}\left(\mathbf{AW}\right)\div 2\times\sum_{E}a_{n,e}\right)$ where $a_{n,e}$ is the area of woodland vegetation of EVC/density group e within hexagon n, $p_{s,n}$ is the probability of occurrence of species s on 2 ha of woodland vegetation in hexagon n, $\mathbf{A}$ is the matrix of areas of woodland vegetation of EVC/density groups in hexagon n and hexagons within 2 km of the centre of hexagon n, and $\mathbf{W}$ is a weight matrix.

Economic model

The economic model is used to minimise the cost of conservation actions. It consists of a loss to agricultural production on the sites planned for revegetation and the cost of revegetation. We assume that the loss of agricultural production is equal to the per hectare land values of large agricultural properties. In the Avoca catchment, sale price of pasture land is \$990/ha and sale price of land suitable for mixed cropping is \$1730/ha (L. Ezard, pers. comm.). We assume that mixed cropping enterprises are located in the lower (flat, plain) parts of the landscape, while grazing-only lands are located in the hilly part of the landscape. We use "Landforms" attribute from LSYS250 GIS layer to assign opportunity cost to agricultural lands suitable for revegetation. Furthermore, we assume that land within land uses such as natural feature protection is not used for agricultural production and therefore revegetation of such land does not involve opportunity cost.

The cost of revegetation and management is calculated using a combination of possible management actions (revegetation with tubestock or direct seeding, fencing of revegetated sites, as well as follow-up weed management) depending on the current land use. We use the standard prices that the North Central CMA uses when costing on-ground works. We assume that croplands and modified pastures would be revegetated using a combination of tubestock (bare paddock: 400 trees/shrubs per ha at \$2,880.00/ha) and direct seeding (\$1,435.60/ha), followed by non-woody weed management (spraying: \$1,000/ha). Areas with land uses such as “grazing natural vegetation” and nature protection would be revegetated using direct seeding at \$1,435.60/ha. In all cases we assume that revegetated area will be fenced at the cost of \$7,000/km. We derived a relationship between area and perimeter of polygons from Avoca data, separately for land-use classes (grazing natural vegetation and nature protection land will have longer per hectare fences due to less regular shapes). We assume separate “re-vegetation projects” for each farm and land use within hexagon.

Optimisation model

First, The baseline summed probability of occurrence aggregated across the catchment is calculated for every species. Then the model tries to optimally allocate revegetation across the landscape. Revegetation of $a_{n,e,l,f}^{reveg}$ hectares of EVC type e in hexagon n, land use l, and farm f increases the area of suitable habitat in hexagon n for all woodland dependent birds. Furthermore, it changes the probabilities of occurrence of woodland dependent birds in suitable habitat inside hexagon n, as well as inside hexagons within 2 km radius of hexagon n.

The probabilities of occurrence of individual species change differently depending on the species response to habitat type *e* in a landscape context and the proximity to hexagon *n*. The costs of revegetation depend on the revegetation area and land use *l*.

The objective function is to minimise the cost of revegetation (1) subject to improvement of the summed probability of occurrence by a certain amount, e.g., by 10%, 20%, etc. (2a), and availability of land for revegetation (2b). Some species are more responsive than the others (their response is more elastic) to increases in vegetation. The constraints require all bird species to increase in occurrence by at least specified amount. This means that the summed probability of occurrence of most species will be increased by a greater amount. The problem is:

$$\min \quad \sum_N \sum_E \sum_L \sum_F a_{n,e,l,f}^{reveg} \times \left(c_l^{mng} + c_l^{opp} \right) \tag{1}$$

$$\text{s.t.} \quad \sum_N \sum_E \left(a_{n,e}^{curr} + \sum_L \sum_F a_{n,e,l,f}^{reveg} \right) \times p_{s,n} \left(\left(\mathbf{A}^{curr} + \mathbf{A}^{reveg} \right) \mathbf{W} \right) \div 2 \geq$$

$$\left(1+g\right) \times \sum_N \sum_E \left(a_{n,e}^{curr} \right) \times p_{s,n} \left(\mathbf{A}^{curr} \mathbf{W} \right) \div 2 \quad \forall S \tag{2a}$$

$$0 \leq a_{n,e,l,f}^{reveg} \leq a_{n,e,l,f}^{avail} \quad \forall N, E, L, F \tag{2b}$$

where $a_{n,e}^{curr}$ is the current area of woodland vegetation of EVC/density group *e* within hexagon *n*, $a_{n,e,l,f}^{avail}$ is the area available for revegetation in hexagon *n* by EVC type *e*, land use *l*, and farm *f*, c_l^{opp} is the opportunity cost of agricultural production, c_l^{mng} is the management (establishment plus maintenance) cost of revegetation per hectare in land use *l*, and *g* is the target percentage increase of biodiversity outcome.

We also tested an alternative objective function: minimising revegetation area (e.g., Thomson, et al., 2009):

$$\min \quad \sum_N \sum_E \sum_L \sum_F a_{n,e,l,f}^{reveg} \tag{1a}$$

Furthermore, to compare spatially targeted with non-targeted revegetation strategies, we ran cost minimisation scenario with an equality constraint, which required the proportion of revegetation on each farm to be equal:

$$\sum_N \sum_E \sum_L a_{n,e,l,f}^{reveg} \Big/ \sum_N \sum_E \sum_L a_{n,e,l,f}^{avail} = r \quad \forall F \text{ ,} \tag{2c}$$

where *r* is the proportion of the area available for revegetation on every farm to be revegetated.

Results

The optimal revegetation patterns that increase summed probability of occurrence for every species by at least 20% under different scenarios are shown in Figure 2. Under area minimisation and cost minimisation scenarios, the optimal solutions allocate most of the

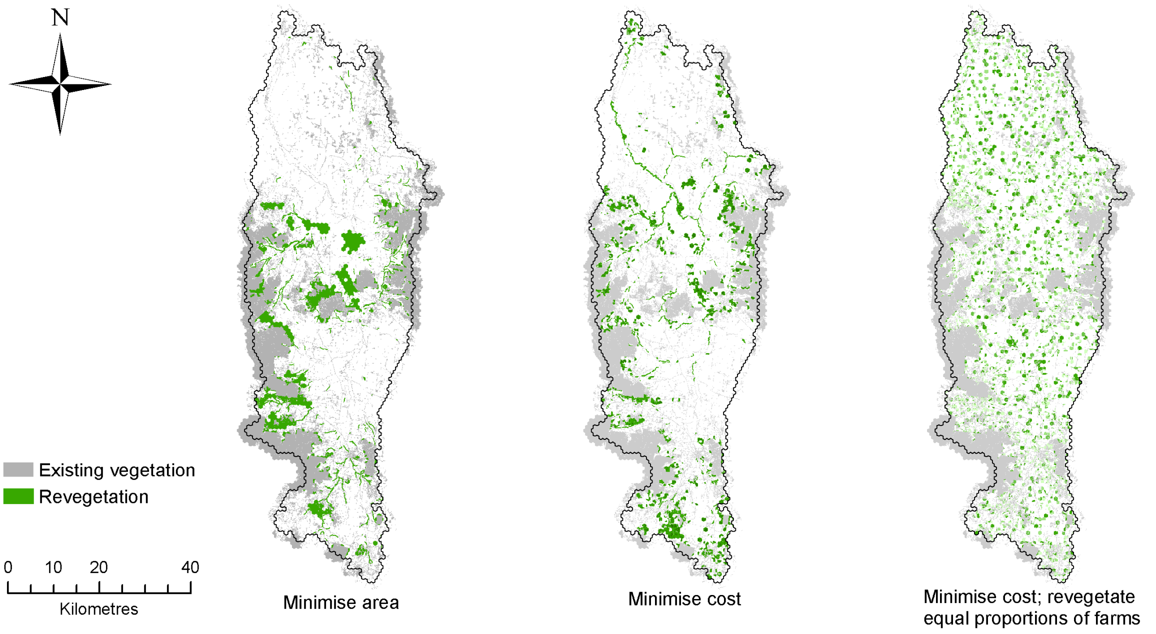
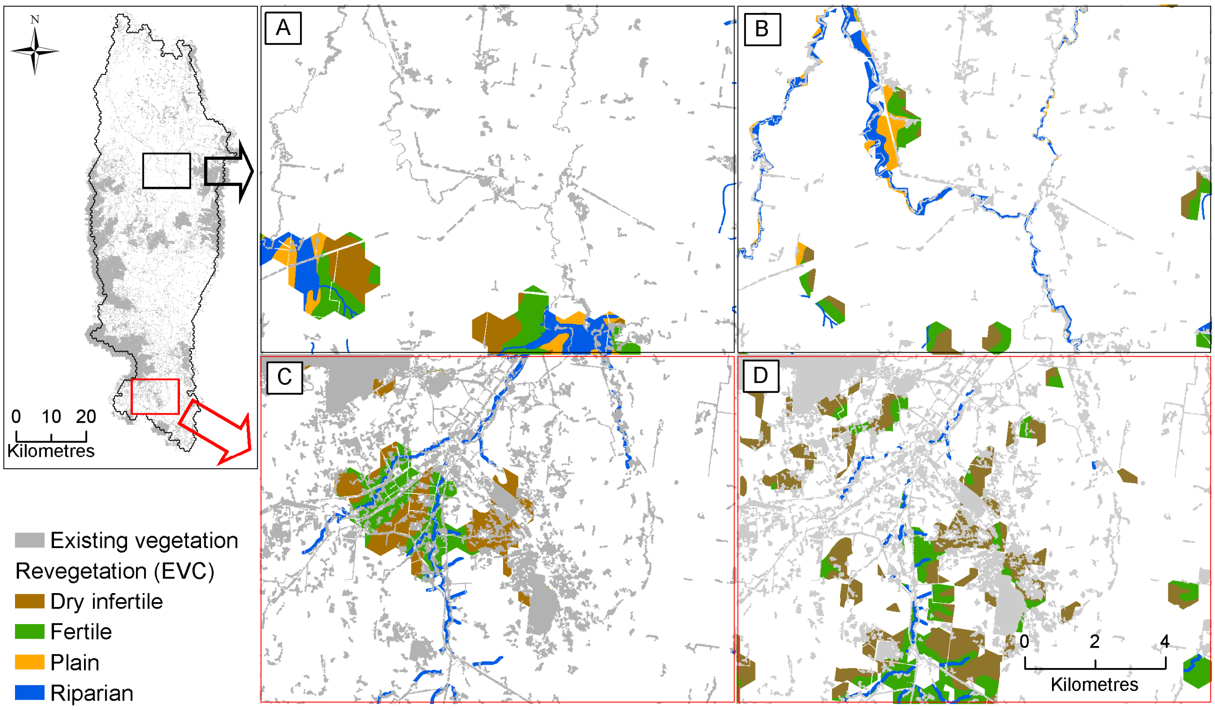


Figure 2. Optimal spatial pattern of revegetation in Avoca catchment to improves summed probability of occurrence for every species by at least 20% under different optimality targets.

revegetation in the neighbourhood of existing large patches of remnant vegetation as reported elsewhere (Thomson, et al., 2009, Westphal, et al., 2007). Under the cost minimisation with an equality constraint, the revegetation is evenly distributed over the landscape, as expected.

However, under both area minimisation and cost minimisation, some revegetation is located in parts of the landscape with lower proportions of tree cover, around smaller remnants (Figure 3). Among all locations, both in the proximity of large patches of existing vegetation and around smaller remnants, a substantially greater amount of revegetation was allocated to parts of the landscape with greater heterogeneity of existing and potential (pre-settlement) vegetation types and tree cover densities. In all parts of the landscape, revegetation of riparian sites has been given priority. This spatial arrangement of optimal revegetation patterns is caused by the heterogeneity of habitat requirements of bird species used in this analysis. While optimal revegetation patterns produced by minimising area and minimising cost scenarios are somewhat similar, the latter caused shifting of revegetation patterns toward "Natural feature protection" land uses along creeks (compare maps A and B on Figure 3) or towards hills (compare maps C and D on Figure 3) due to lower opportunity cost of revegetation on these areas.

Table 1 shows a comparison of areas and cost of optimal revegetation for two target levels of improvement: 20% and 100%. The results show that there is a small difference in terms of costs and area between minimising area and minimising cost scenarios. The area-minimising scenario achieves a 20% improvement of biodiversity outcome with 5% less area of vegetation than the cost- minimising scenario. However, the cost of the area-minimising scenario is 5% higher. For the 100% target, the area difference is smaller (only 2%) while the cost difference is greater (13%). Note that, even though the area-minimising strategy is not much more expensive than the cost-minimising strategy, it involves a very different spatial allocation of revegetation (Figures 2 and 3). This suggests that around the biodiversity optimal revegetation pattern, there are multiple near-optimal revegetation patterns. Pannell (2006) noted that this is a common feature of economic optimisation models.



Minimise area

Minimise cost

Figure 3. Optimal revegetation patterns in different parts of Avoca catchment under minimise cost and minimise area scenarios.

On the other hand, the scenario with revegetation distributed equally across all farms achieves biodiversity targets at substantially higher costs than either the area-minimising or cost-minimising scenarios. This indicates that the cost-effectiveness of biodiversity conservation effort can be improved by spatially targeting revegetation.

Table 1. Areas and costs of optimal revegetation under different scenarios and targets

Target	Scenario	Revegetation area		Revegetation cost
		1000 ha	% of existing vegetation	$1,000,000
20%	Minimise Area	14.6	17.8%	38.4
	Minimise Cost	15.3	18.7%	36.4
	Non-targeted	27.0	33.0%	54.4
100%	Minimise Area	75.9	92.5%	79.9
	Minimise Cost	77.9	95.0%	70.7
	Non-targeted	108.7	132.6%	142.2

Conclusions

This study develops a method for quantifying tradeoffs between conservation and agricultural production. Optimising the spatial pattern of landscape restoration makes a substantial difference to the biological outcome. Spatially targeted (optimised) revegetation achieves the same biodiversity outcome at a fraction (50% to 70%) of the cost or area of non-targeted revegetation. Minimising cost resulted in cost savings between 5% and 13% in comparison to minimising revegetation area.

Under the cost-minimsing strategy, revegetation is concentrated in proximity to large patches of existing vegetation, riparian areas, and parts of the landscape with diversity of land uses and vegetation types.

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