An Interactive Spatial Optimisation Tool for Systematic Landscape Restoration

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Abstract: This paper describes the design and construction of a prototype spatial decision support system (SDSS) for an interactive evaluation of integrated landscape restoration planning using spatial information technology. Landscape planning involves spatially explicit decisions about the types of landuses allowable, and the extent and location of these landuses. This decision-making needs to be supported by accurate and detailed information about the spatial distribution of numerous parameters affecting the distribution of landuse. The SDSS that we present in this paper comprises a geographic information system (GIS) tightly coupled with an analytical optimisation module by means of an interactive interface. The GIS is used for storage, manipulation and visualisation of spatial data, and for assessing the results of the analytical module computing optimal spatial pattern. Several user-selectable parameters allow consideration of management objectives related to planning for landscape restoration.

Keywords: decision support systems; integer programming; GIS; landscape restoration; priority setting.

1. INTRODUCTION

1.1 Landscape Planning and Optimisation

Typically, and with some notable exceptions, landscape restoration efforts tend to occur on the scale of the individual property/landowner. As such, the restoration efforts are rarely planned so as to be of maximum benefit to the regional ecology and biodiversity. Systematic conservation planning (SCP) [Margules and Pressey, 2000] involves selecting the areas and environments to conserve in order to maximise the chances for biodiversity sustainability. SCP is a difficult problem [Margules et al., 2002] and involves consideration of an established suite of principles such as comprehensiveness, adequacy, representativeness, efficiency, flexibility, irreplaceability, and complementarity [Margules and Pressey, 2000]. Using SCP principles and with the coupling of Integer Programming (IP) and Geographic Information Systems (GIS) the potential now exists for landscape restoration activities to be systematically planned using a range of spatial databases. Thereby, maximum ecological value can be gained from current restoration efforts. Whilst the principles of systematic conservation planning are reasonably well established, the methods for implementing these principles are many and varied. The methods can be classed according to whether they can guarantee an optimal solution or not.

The nature of spatial problems amenable to solution by optimisation approaches is diverse. So too are the models used for their solution. An optimisation paradigm used in spatial planning is integer or *zero-one* (0-1) programming. The major advantage of this technique is that it guarantees the optimal solution [Haight et al., 2000] (if the problem is tractable of course), thereby removing ambiguity about just how *good* the solution is. The biggest drawback to IP problems is that they are *NP-complete* [Karp, 1972]. In other words, the time taken for the models to run is a polynomial function of the number of inputs. Previous studies exploring problems of only modest size have proven to be intractable. Studies of spatial phenomena, especially those using GIS, typically involve large databases covering wide areas often at high resolution. It is not uncommon to work with raster databases of 20 million cells or more. The data-intensive nature of GIS has been fundamentally at odds with the data-restrictive nature of the IP paradigm. However, new proprietary algorithms have greatly increased the tractability of IP problems [Rodrigues and Gaston, 2002a]. Thereby, fast algorithms have bridged the data requirements gap between IP and GIS, and opened up these techniques to widespread application in the spatial domain.

Many studies have used IP for conservation planning, particularly reserve selection [Cocks and Baird, 1989; Church et al., 1996; Williams and ReVelle, 1996; Haight et al., 2000; ReVelle et al., 2002; Rodrigues and Gaston, 2002a], but IP has not been used for systematic landscape restoration. Several other methods that do not guarantee an optimal solution [Underhill, 1994] have been used in systematic reserve design including scoring approaches [Pressey and Nicholls, 1989a], heuristic algorithms [Pressey and Nicholls, 1989b; Csuti et al., 1997], and simulated annealing [Possingham, et al. 2000]. Optimality is not everything in reserve design of course [Csuti et al., 1997], but it does provide certainty when negotiating for conservation in areas of high landuse demand.

1.2 Spatial Decision Support Systems

A spatial decision support system (SDSS) is an intelligent information system that reduces decision making time as well as improving the consistency and quality of the decisions [Cortes et al., 2000]. A SDSS can be either problem specific or situation and problem specific [Rizzoli and Young, 1997]. Both are tailored to a specific problem, but the latter is limited to one specific spatial location.

Amongst Rizzoli and Young’s [1997] six desirable features of an SDSS is the ability to deal with spatial data and ability to be used effectively for diagnosis, planning, management and optimisation.

In this paper we describe the design and construction of a prototype SDSS combining IP and GIS to solve a landscape planning problem. This SDSS is not location specific and can be applied to any area of interest at any spatial scale. We present a brief demonstration of the SDSS with the aim of identifying high priority areas for the restoration of an adequate and representative landscape ecological system in the Carrickalinga Creek catchment, South Australia.

2 METHODS

The Carrickalinga Creek catchment forms the study area for this analysis. The study area covers 5,586 ha and is located in the southern Mt. Lofty Ranges, some 60 km south of Adelaide, the capital city of South Australia (Figure 1). The Mt. Lofty Ranges is a highly fragmented agricultural region with less than 10% of the native forests and woodlands remaining. Remnant vegetation is mostly located in the upper reaches of the catchment. The remaining area is cleared land under mixed use, predominantly agriculture and grazing (Figure 1).

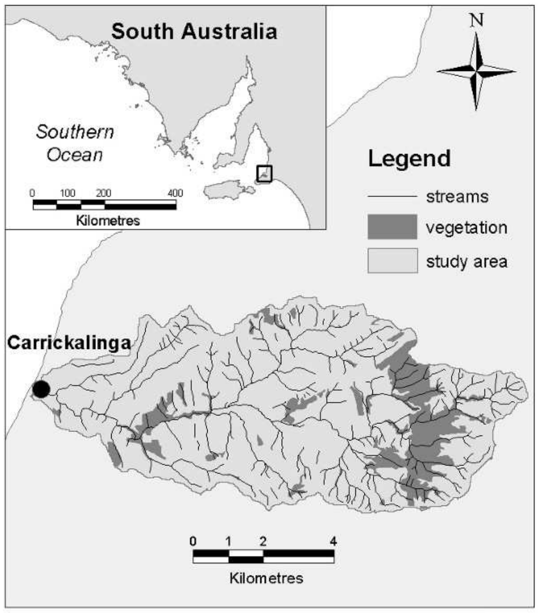

Figure 1: Location of the Carrickalinga Creek catchment in the Mt. Lofty Ranges, South Australia.

Topography of the catchment is undulating to hilly with elevation ranging from sea-level at the mouth of the creek to 420m ASL toward the upper reaches of the catchment. The climate of the catchment is a typical coastal Mediterranean regime characterised by a strong seasonal demarcation of moderate to warm dry summers and cool, wet winters.

2.1 The Data

This optimisation analysis is based on six physical environmental variables and a mapped Soil Landscape Units (SLUs) variable. These variables act as surrogates for species distributions. The use of surrogates is preferable when there has been removal of extensive areas of native habitat. The environmental variables (Table 1) are a subset of those available in BIOCLIM (variables 1 to 4) [Nix, 1986] and the TAPES-G (variables 5 and 6) suite of topographic modelling tools [Gallant and Wilson, 1996]. Bryan [2003] should be consulted for a detailed description of methods used to derive the variables. Each of the six continuous physical environmental variables was categorised into 5 classes.

Table 1. List of variables used in this study.

1. Annual Mean Temperature
2. Temperature Annual Range
3. Annual Mean Precipitation
4. Annual Mean Moisture Index
5. Net Radiation
6. Steady-state Wetness Index
7. Soil Landscape Units

The soils data was derived from a long-term soil survey by the South Australian Department of Primary Industries and Resources (PIRSA). Interpretation of aerial photography and field surveys are used to identify polygons representing homogeneous areas of soil. These homogenous areas are termed Soil Landscape Units. The Carrickalinga Creek study area is comprised of 36 Soil Landscape Units. All data were converted to 50m resolution grid layers. All GIS analyses were performed in ESRIs ArcGIS suite of tools.

2.2 Integer Programming

The classic set-covering/minimum representation IP model is used in this study to identify the minimum number of sites required to meet the conservation targets defined by proportional and area constraints. The model was written in ILOG's Optimisation Programming Language (OPL), a high-level scripting language part of the OPLStudio software. OPLStudio uses the CPLEX optimiser to solve linear IP problems. CPLEX has been found to be efficient in its solution of linear IP problems in conservation planning [Ando et al., 1998; Church et al., 1996; Rodrigues and Gaston, 2002b]. The software comes with its own application programming interface (API), thus allowing the solvers to be accessed through a variety of programming languages. The set-covering/minimum representation model is described below [adapted from Possingham et al., 2000].

The number of grid cells or sites (m) of 50m resolution in the Carrickalinga Creek catchment study area totalled 22,336. The total number of classes (including 5 classes of each environmental variable and the Soil Landscape Units) (n) equalled 66. An m x n matrix **A** (22,336 rows x 66 columns) was created whose elements a_{ij} were attributed a binary value according to the class of each site. Sites are given a value of one if they exhibit a particular environmental class or soil group, zero otherwise such that:

$$a_{ij} = \begin{cases} 1 \text{ if site } i \text{ occurs in class } j \\ 0 \text{ otherwise} \end{cases}$$

for $i = 1 \ldots m$ and $j = 1 \ldots n$

Next, a variable is defined that reflects whether or not a site is selected for restoration, as the vector **X** with dimension m and elements x_i, given by

$$x_i = \begin{cases} 1 \text{ if site } i \text{ is selected for restoration} \\ 0 \text{ otherwise} \end{cases}$$

for $i = 1 \ldots m$

In words, the set-covering/minimum representation problem strives to minimise the number of sites in the reserve system subject to areal and proportional constraints for each class (c_j). Areal constraints are a function of the area of the class, the proportional target ((p), the minimum percentage of each class to be restored), and the minimum area target ((t), the minimum number of sites in each class to be restored). For each class, the areal constraint is equal to the proportional target multiplied by the number of sites in the class if this value is greater than or equal to the minimum area target. Otherwise, the areal constraint for the class equals either the total number of sites in the class or the specified minimum area target, whichever is the lesser value. Mathematically, the optimisation techniques attempt to [adapted from Possingham et al., 2000]:

$$\text{minimise } \sum_{i=1}^{m} x_i$$

$$\text{subject to } \sum_{i=1}^{m} a_{ij} x_i \geq c_j \quad \text{for } j = 1 \ldots \text{n}$$

$$\text{where } a_{ij}, x_i \in \{0,1\}, \; A_j = \sum_{i=1}^{m} a_{ij}$$

$$\text{and } c_j = \begin{cases} pA_{\text{j}} \text{ if } pA_{\text{j}} \geq t \\ \min(A_{\text{j}}, t) \text{ otherwise} \end{cases}$$

2.3 Spatial Decision Support System Development

Our SDSS, the **C**onservation **R**eserve **E**valuation and **D**esign **O**ptimisation **S**ystem (CREDOS; Figure 2), is formed by the combination of the GIS, the CREDOS interface, and the IP analytical module. The interface provides the coupling between the GIS and the analytical module, and was written in *Microsoft Visual Basic* 6.0 (VB) using an *ActiveX* Dynamic Link Library (DLL) project. Functionality for manipulation of the spatial datasets was incorporated by means of ESRI *ArcObjects*, the development platform for the *ArcGIS* family of applications. ESRI is a proponent of the interoperability protocols expounded by the OpenGIS consortium (OGC), and *ArcObjects* is therefore built using *Microsoft Component Object Model* (COM) technology that allows applications using such technology to be written in any COM compliant programming language.

The *ActiveX* project was compiled into an executable file (a DLL), thereby allowing portability between GIS sessions. Because CREDOS is a spatial analysis tool, the command to execute the CREDOS DLL was seamlessly included as an additional toolbar in the GIS.

3 RESULTS

CREDOS (Figure 2) consists of a set of input windows that allow the user to select the working directory, sites (zone) layer, input variables, optimisation model, constraints and outputs. These can be changed any time prior to, or after, running the model. During run time the user is informed of progress via a window that is updated as each CREDOS modelling procedure is completed. This assist the user in debugging input data and in determining the existence of any related procedural problems. Final output of CREDOS is a grid layer of sites identified as an optimal solution to the imposed proportional and areal constraints (Figure 3), and a tabular summary of identified sites and the corresponding values of the input variables. The tabular summary can be used to validate the model by confirming that solutions meet the areal and proportional targets.

In the demonstration presented here, output consists of 4,495 50m cells (1,123.8 ha; 20% of the study area), providing at least 10 cells of each physical environmental type and soil class. The complete process (data preparation and IP problem solving) took approximately 15 minutes to solve on a P4, 3.0 GHz, 1.0Gb RAM. However the majority of this time (90%) was allocated to CREDOS data preparation (binary conversion of input variables) in the GIS.

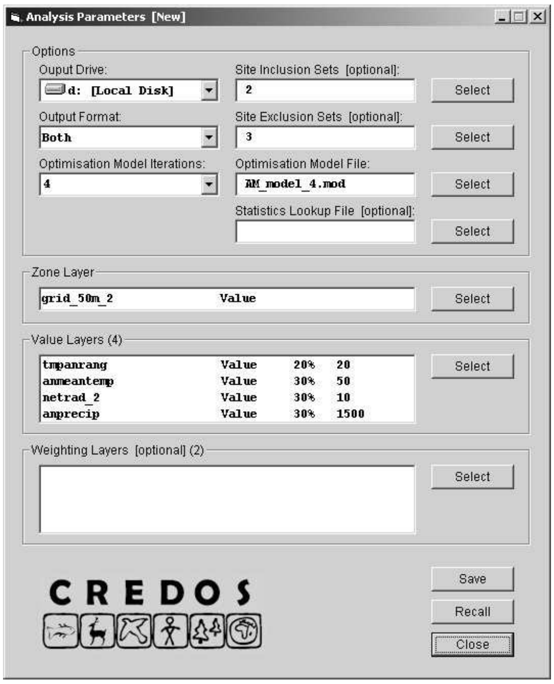

Figure 2: The prototype Spatial Decision Support System, CREDOS.

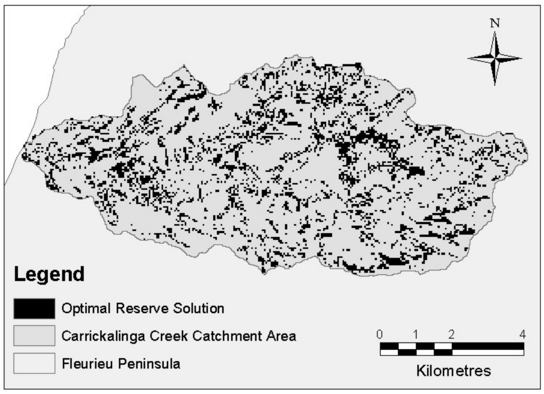

Figure 3: Optimal sites for revegetation in the study area based on the 20% proportion and 10 cell area constraints.

4 DISCUSSION AND CONCLUSION

The IP optimisation models implemented in this study were successful in finding efficient, adequate and representative combinations of sites for landscape restoration given the specified parameters. The prototype SDSS facilitated and simplified the modelling procedure by providing a user-friendly interface to find optimal solutions. Our prototype SDSS can be applied across any study area and any scale to solve user-selected optimisation constraints for landscape planning.

The solutions found by the IP models are maximally efficient. Maximally efficient solutions simply strive to find the fewest cells capable of satisfying conservation targets – in this case a minimum area and proportional targets. If more area is required, then it is a simple task to increase either of the areal targets in the SDSS. Restoration can always be increased beyond that recommended if required, or preferred, by landowners. This simply requires re-application of the SDSS with different choices of constraints.

There are many agricultural regions in Australia that have been subjected to extensive clearing and fragmentation of the native biological communities. In these regions, reserve selection, alone, will not facilitate the conservation of the natural biodiversity, and restoration is required [Bryan, 2002]. Land in these regions is usually in high demand from a variety of land uses, and restoration effort is precious. Hence, areas and environments must be judiciously planned and prioritised for restoration to gain maximum ecological benefit, whilst having minimal adverse economic impact through conversion from productive landuse. The major benefit of systematic landscape restoration is that it can be used to coordinate and gain maximum ecological benefit from all restoration initiatives within a region. The restoration initiatives may come from the local landholder, major regional scale government programs, or anywhere within this spectrum. Such planning is often in the hands of natural resource management professionals who are often not technically proficient in complex GIS and modelling procedures. The prototype SDSS presented in this paper bridges the gap between those professionals and the modelling community.

IP models have considerable potential in landscape restoration and other conservation planning problems. The study presented here is a proof of concept. Significant advances in our SDSS functionality and model algorithm sophistication are currently under development to make our results truly useful in planning for landscape restoration. If, for whatever reason, a site cannot be restored, the network of sites will no longer meet conservation targets. There are possibly very many optimal solutions and very many slightly sub-optimal solutions to the problems. Given the short run time for the models, it is relatively simple to modify the SDSS so each model can be processed many times, each time adding the previous solution as a constraint, and thereby finding many options and providing flexibility in restoration design.

The underlying IP model is naïve to current landuse and economic cost except for the assumption that each site costs the same amount and the objective is to minimise the total cost of the system. Inclusion of landuse and cadastral information in the models will enhance the applicability of the model because the assumptions made become more realistic. We are investigating other improvements in the CREDOS by incorporating spatial effects. Such spatial effects are being integrated into the model to improve the landscape structure of the resultant habitats. For example, sites are weighted that are close to existing reserves, riparian habitats, and/or transport corridors. Alternatively, constraints are set that force the model to select *n* replications of classes, separated by a certain distance, for replication and enhanced insurance against local catastrophes. The results to this work will become available at a later date.

The spatially-explicit, GIS-based IP optimisation approach taken in this research is an innovative approach to landscape restoration. The development of a prototype SDSS is not novel in itself. However, the application of CREDOS facilitates solving of complex optimisation algorithms by non-modelling professionals. The case study presented in this paper demonstrates the utility of IP in planning for landscape restoration. Ecological restoration is essential in many fragmented agricultural landscapes to sustain ecological, environmental and human systems. Geographic priorities are required to guide restoration activities that are based on sound science to gain the maximum benefit from these activities for the conservation of biodiversity. Systematic landscape restoration can be of great benefit in planning for the long term ecological, environmental, economic and social sustainability of other fragmented agricultural regions in Australia and overseas. The success of IP in this application reflects its potential in many allied areas. Current work is adding functionality to the prototype SDSS, thus allowing more complex optimisation problems to be solved by non-technical professionals.

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