Integration of Spatial Land Use Allocation and Economic Optimisation Models for Decision Support

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Abstract This paper presents a land use allocation tool which integrates economic assessment of alternate land allocation strategies with spatial land use allocation technologies to generate simulated and spatially disaggregated land use patterns on the basis of economic optima and land use constraints and objectives. The allocation model developed generates spatial scenarios of land use allocation based on a range of strategies for allocation of land to alternate uses. Strategies for land use are evaluated using a weighted cumulative algorithm which alternately allocates to competing land uses. Targets for the spatial allocation are set from an economic optimisation model developed by Mallawaarachchi and Quiggin (1999). The resulting decision support simulation model has been implemented within the NRMtools decision support framework. The feasibility and usefulness of the simulated land use allocation is examined using sugarcane production and habitat conservation as an example of competing land uses. The model is applied to the Herbert River district cane production area to investigate its suitability for assisting resource managers and planners in exploring the implications of a set of policy criteria in the allocation of land to competing uses. The method fosters the ability of decision makers to quantify and visualise the implications of land allocation strategies, thereby facilitating informed debate across stakeholder groups.

1. INTRODUCTION

The 1992 Inter-governmental Agreement on the Environment commits all levels of government in Australia to achieving a balance between economic development and environmental integrity through Ecologically Sustainable Development (ESD). Primary industries, government and community need to debate and negotiate priorities that achieve an appropriate balance efficiently and equitably at property and landscape scales. Catchment scale natural resource management must address complex ecological, social and economic interactions. This involves incorporation of long time frames, the ability to deal with often considerable separation between cause and effect, and the potential for irreversible outcomes. Uncertainty must be managed as part of the decision making process. Decision Support Systems can support the representation of a wide range of data and information, including local and expert knowledge, and spatial and non-spatial data, and can therefore be effective in informing and focussing mediation and negotiation processes for regional resource use planning.

The simulation of land use allocation presented here combines an economic optimisation model for multiple land use allocation with an iterative, multiple rule-based technique using geographic information system (GIS) technology to generate scenarios of land use allocation. The resulting tool allows the user to visualise the implications of alternative criteria for land use allocation. Connected reserve networks and cane production areas that minimise transportation costs are used as allocation criteria in this example. This ability to explore implications has the potential to mitigate conflicts that otherwise arise through ill-informed planning decisions. The decision support tool is delivered to regional resource use planners via NRMtools, an Internet-based decision support environment (Walker and Johnson 1996). This 'toolkit' approach to decision making is designed to provide the flexibility to users and deliver research outcomes and knowledge directly to the decision makers.

2. METHODS

2.1 Spatial disaggregation of land use

Most land use changes are analysed at a higher level of geographic aggregation, such as national, regional or catchment levels. Yet, land use allocation decisions are taken at best at the landscape level or below, making the availability of spatially disaggregated land use information at a landscape level an important aid to local area planning.

Various methods have been developed to address the problem of spatial disaggregation (see for example, Walker and Mallawaarachchi (1998)). These approaches use GIS tools, optimisation techniques and rule-based algorithms to allocate statistical aggregates over a range of lower level target zones. Recent developments in landscape modelling extend these approaches to incorporate social preferences to come up with allocations consistent with biophysical, economic and social criteria (Thornton and Jones 1998).

Linking economic criteria and other decision rules in allocation algorithms requires careful planning if they are to be useful for decision making. The Cane Land Allocation Model (CLAM) used in the work presented here has been developed to seek allocations that provide greatest economic returns at the catchment level, while meeting resource use constraints and social objectives for natural area preservation as a means of facilitating strategic planning at a catchment scale (Mallawaarachchi and Quiggin 1999). At the catchment scale addressed by CLAM, the objective was to maiximise net social benefits by considering both economic and environmental imperatives. However land use allocation policies at a catchment scale need to be understood in terms of their operational implementation at the property scale in order for the criteria applied to be considered in terms of their operational feasibility. Furthermore, there are many landscape management imperatives associated with the specific distributions of the areas allocated at a catchment scale.

The approach used in this paper has been to develop a tool to evaluate the operational feasibility of strategic objectives through a constraint satisfaction algorithm. As illustrated in Figure 1, we used the output from the optimisation model CLAM, at a regional level to disaggregate the land uses at a landscape level using a weighted criterion set. This process is described in the following section.

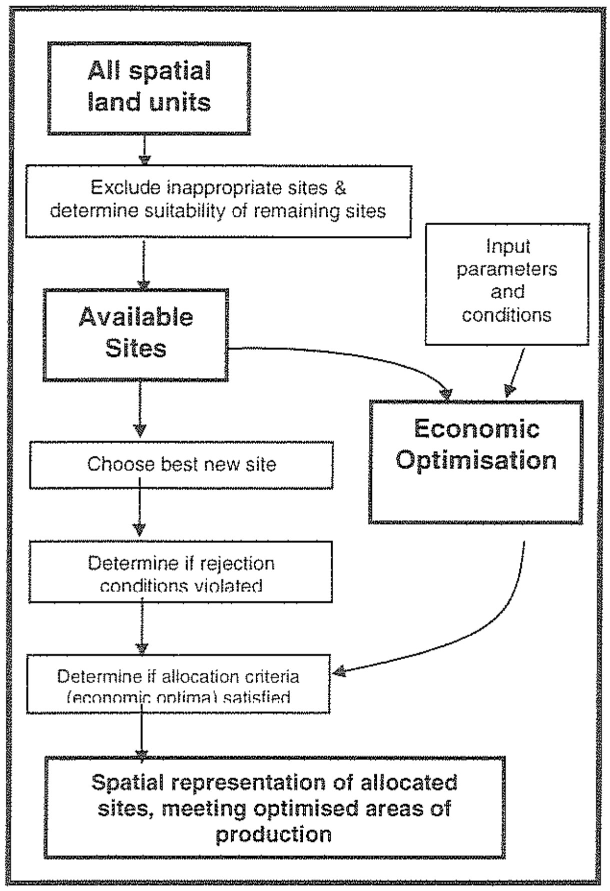

Figure 1. Simulation procedure, the economic analysis results become targets for the spatial selection algorithms.

2.2 Economic Optimisation Model

Mallawaarachchi and Quiggin (1999) developed an economic modelling framework to determine the joint environmental and economic net benefits of different land allocation strategies.

This model determines the joint economic and environmental net benefits of alternative land allocation strategies in the Australian sugar industry. The model combines the marginal physical productivity of cane production and environmental values estimated through a multi-attribute choice experiment. The regional analysis employs allocation rules based on land use suitability attributes that differentiate land parcels of varying potential productivity. Technological options to augment land quality under different states of nature are modelled using a dynamic formulation under alternative assumptions for sugar price and mill quota. The model captures the interdependency between area expansion and intensification of production, as a behavioural response of canegrowers to an increasing demand for cane output. Given these inputs (areas of land in different land use suitability classes, technological inputs, commodity prices and production costs as well as the environmental opportunity cost of loss of habitat) the model determines an economically optimal expansion and allocates the total sugar cane area of a catchment across different land use classes.

Mallawaarachchi and Quiggin (1999) applied the model to Herbert river district cane production region to analyse the tradeoffs between environmental preservation and sugar cane area expansion at a regional scale. The research reported in this paper extends this land use allocation model to a lower level of disaggregation to identify an spatially disaggregated land use allocation that satisfies the economic optima specified by the CLAM model while complying with operational constraints in terms of tenure and desired characteristics of the landscape.

2.3 Spatial Disaggregation Algorithms

Geographic Information System (GIS) technology was used to allow the study area to be divided into unique land units. The individual spatial and aspatial characteristics of the land parcels were then used as input data to the multiple criteria analysis algorithm.

The algorithm developed to implement the multiple criteria analysis evaluates the suitability of individual land parcels for allocation to competing land uses. The algorithm allows users to interactively assign weights to particular strategies for allocation, hence making the resultant decision support tool flexible and interactive and thereby an appropriate vehicle for exploring aspirations, opportunities and constraints across stakeholder groups.

In the case study application described, the algorithm implements strategies for allocation to both cultivation and conservation purposes, based on the sugar cane assignment process in the Herbert River catchment (Johnson *et al.* 1997a; Johnson *et al.* 1997b; Shrubsole 1997), and principles of landscape ecology and reserve design (Margules & Nicholls 1993; Noss & Cooperrider 1994). Users can assign weights to reflect their preference towards these particular strategies in the allocation of land. These weights are multiplied by a measure representing each of the strategies and a cumulative score is calculated for each land unit. From this cumulative score, the most suitable unit is selected and allocated. A re-calculation of the cumulative score is then conducted, given the changes in spatial relationships incurred through the last allocation. The algorithm then repeats the allocation process to select another unit for allocation. The algorithm is finished when two, user assigned, mandates are accomplished, they are:

1. Achieving a set level of sugar cane production, and
2. Capturing a representative reserve network.

The algorithm alternately selects the most appropriate land unit for allocation to cane and conservation, progressively building the catchment landscape. In order to compare all possible additions to either the reserve system or to cane cultivation, each spatial unit was evaluated in relation to its suitability for selection for both land use types. This evaluation is achieved through the use of two valuation functions, the terms of which were chosen to reflect the land-allocation strategies, modified by weights applied by the user.

2.2.1 Algorithm implementation

<u>1 - Sugar cane assignment procedures</u>

Proximity to sugar cane processing facility
The proximity criteria provides a measure of the cost of transport encountered in the process of transporting harvested cane from the field to the cane processing facility. The location of land relative to milling facilities influences the suitability of a site for allocation to cane productivity.

Size
Economies of scale mean that the contiguous area of land available for allocation will have a major influence on the potential selection of land for assignment to cane.

Agricultural suitability classification
The agricultural land suitability classification used was conducted by Wilson and Baker (1990). This classification of suitability integrates a range of biophysical factors and covers the entire catchment area.

Perimeter minimisation

The areal compactness of a land unit impacts on the efficiency of cane production. Perimeter minimisation reduces the potential for damage during bad weather, and maximises efficiency in planting and harvesting periods.

Overall cane compactness
Compactness of the entire cane producing region focuses upon the selection of spatial units which have the greatest percentage of their perimeter adjoining an existing cane area. Consequently, the entire cane producing area will be as large and contiguous as possible. This measure is important in terms of the machinery and infrastructure required for cane cultivation at catchment scale.

<u>2 - Representative reserve network</u>
A key component for biodiversity management is the regional reserve network. Reserve networks should encompass a complement of regional biota, and sustain that sample into the future. This research focuses on the need for preservation of biological diversity through the development of a representative reserve network that aims to minimise conflict in the Herbert River catchment. The simulation model uses several strategies for selection of areas for reserve, as outlined below.

Representativeness
The primary objective of biodiversity conservation is to retain the evolutionary diversity, flexibility, and hence the long term viability of a region (Baverstock *et al.* 1993; McKenzie *et al.* 1989). This study used maps of pre-European vegetation communities as a surrogate for biodiversity. The vegetation communities were mapped through an extrapolation of existing vegetation mapping, a correlation of soils and vegetation types and interpretation of aerial photographs and satellite imagery.

Reserve size
The number of species encountered increases as the size of the area increases (Margules & Usher 1981). The viability of a reserve area therefore increases as a function of its area. Conservation literature has engaged in significant discussion surrounding the ideal size and shape of reserves. A preference for larger reserve areas is identified as a useful, and common approach to reserve design.

Reserve continuity
Connectivity between areas of reserve protection counteracts fragmentation of a landscape. Many conservation strategies focus attention on the spatial configuration of important habitat across the landscape. Despite uncertainty surrounding the optimal width of corridors, mortality risks, and other issues, the fundamental need for populations of many species to be connected in order to be viable is widely recognised (Noss & Cooperrider 1994). In this research, connectivity is implemented by providing the opportunity for greater importance to be placed on reserve areas which are adjacent to another reserve.

Overall reserve compactness
Compactness of reserve areas is a strategy which addresses the issues of reserve size, representativeness, and connectivity. Compactness focuses upon the selection of reserve units which have the greatest percentage of their perimeter adjoining an existing reserve area. Consequently, reserve areas will be as large and continuous as possible, and have a minimal perimeter for their size. Compactness is ultimately a measure of ecological edge and minimisation of this edge decreases the interaction of the reserve unit with surrounding land uses. Although any effective reserve network is likely to consist of both large continuous areas and smaller discrete sites, protection of biodiversity is more probable within a large area with minimal perimeter, than within a series of smaller reserves, or a single large reserve with many incursions.

Riparian protection
Riparian environments are important to conservation issues in north Queensland, and have been connected to issues of water quality and erosion. Maintenance of quality riparian areas can help ensure the viability of the ecosystem balances in freshwater and marine areas. This strategy aims to allow for the capture of riparian zones into reserve areas in the Herbert.

The valuation algorithms for allocation to reserve and to sugar cane areas are given in equations 1 and 2.

Equation 1 : A valuation function for reserve areas:

$$(w_1 RV + w_2 CN + w_3 RI + w_4 SI + w_5 RC)$$

Where w_i are the user assigned weights, and:
RV - Is the representative value of the spatial unit,
CN - Is the potential connectivity of a spatial unit,
RI - Is the riparian value of the spatial unit,
SI - Is the size of the spatial unit, and
RC - Is the contribution to reserve compactness.

Equation 2 : A valuation function for cane areas:

$$(w_6 AG + w_7 CC + w_8 SI + w_9 CP + w_{10} PM)$$

Where w_i are the user assigned weights, and:

AG - Is the agricultural suitability classification,

CC - Is the contribution to cane compactness value,

SI - Is the relative size of each spatial unit,

CP - Is a measure of perimeter minimisation, and

PM - Is the proximity of a spatial unit to milling facilities.

2.2.2 Iterative selection process

The iterative approach developed seeks the first allocation that satisfies user specified objectives, thereby enabling the visualisation of the consequences of a set of user specified criteria and weights. This can provide direction to land use managers on the implications of a particular preference (Pressey & Nicholls 1989a; Pressey & Nicholls 1989b).

Iterative selection procedures begin their selection with the site which contributes most to a certain criteria (eg. most species rich site, or site containing unique occurrences of species) and then add, successively, sites which contribute to this criteria until a target is achieved (eg. all species are sampled) (Margules & Nicholls 1993). These algorithms are applicable where there are complete lists of attributes for all candidate sites.

This research developed an algorithm which identifies the most suitable spatial unit for allocation. After the selection and allocation of a spatial unit the algorithm iterates to re-calculate all necessary measures again. The advantages of an iterative approach to land allocation is that the most suitable spatial units, based upon different strategies, are selected for allocation at each and every stage of the simulated allocation process.

2.3 Integration

The land use allocation model presented combines an economic analysis framework and a spatial allocation algorithm producing a method which simulates a spatially disaggregated landscape representing the regional economic optima and a nominated set of other land allocation strategies.

The common strand between the two model components outlined above is the spatially disaggregated agricultural suitability classification which covers the entire study area. The economic framework uses the suitability classification to determine agricultural production potential as a parameter in the optimisation, while the selection algorithms uses the output from the economic model as the basis to set the targets for simulated allocation.

The economic framework specifies for each land suitability class a specific area which should be allocated to the competing land uses of sugar cane production. The areas of land specified are used as targets in the selection of land for allocation to competing uses using the selection algorithms described previously. The land use suitability classification used in this research has four classes, however any number of suitability classes can be used. The spatial allocation selects land and progressively allocates it to competing uses. A set of completion and termination criteria are used to monitor the progress of the allocation.

The completion criteria identify when the allocation procedure reaches the targets set by the economic framework. As the land allocated in each suitability class accumulates the completion criteria identify when each of the target areas is achieved. The simulation termination criteria, which can be selected by the user, include criteria such as the maintenance of a specific percentage of vegetation in protected areas or ensuring the landscape does not become fragmented beyond a specified degree.. The termination criteria are used by the simulation to establish if the spatial landscape pattern exceeds any of the users specified limitations.

This simulation capability is delivered through NRMtools, an Internet-based decision support environment (Walker and Johnson, 1996; nrmtools.tag.csiro.au). The simulation was developed specifically to enable regional resource use planners and decision makers to explore the implications of various land allocation strategies. This model requires a substantial amount of user input in the selection of, and direction of preferences towards, allocation strategies as well as the selection of termination criteria.

3. CONCLUSION

The simulation algorithm presented in this research provides decision-makers with the capacity to visualise and synthesise the ramifications of their decision making strategies at a catchment scale.

The method allows the use of decision-makers preferences for allocation to derive quantified outcome that can also be viewed as a spatial map.

Using this facility in the initial stages of planning of cane production area allocation may assist decisions to be made from a common and informed basis.

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