Integrating Multi-Criteria Modelling and GIS for Sugarcane Land Allocation

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Abstract: The sugar industry is a major user of natural resources on the eastern coast of Australia. While it has come under increasing pressure from competition for land use from other stakeholder groups, the sugar industry in many regions still has opportunities for expansion. However, land allocation for sugarcane must be based not only on biophysical suitability of land and economic viability, but also on stakeholder aspirations and value judgements. This paper presents a cane land allocation model which integrates multi-criteria modelling and GIS techniques. This model has been developed to assist industry and government users to explore and evaluate different land allocation scenarios for sugarcane production. It uses a multi-criteria modelling technique, SMARTER (a modified Simple Multi-Attribute Rating Technique), to help users identify those criteria that are important for cane land allocation, make subjective assessments of relative importance of those criteria, and to convert the assessments into a set of weights. GIS is used to develop map data layers to represent the identified allocation criteria and potential constraints for cane land use, combine these map layers through spatial modelling, identifying the suitable land for sugarcane production by applying the SMARTER weights, and to generate map presentations of land allocation scenarios. This model is illustrated by using an example of cane land allocation in the Lower Herbert River Catchment in Northern Queensland, Australia.

Keywords: Multi-criteria modelling; Geographical information systems; Sugarcane land allocation

1. INTRODUCTION

The sugar industry is a major stakeholder in the eastern coastal zone of Australia. While it has come under increasing pressure from competition for land use from other stakeholder groups, the sugar industry in many regions is still expanding. About 95% of Australia's sugarcane is grown in the state of Queensland, where the area assigned for sugarcane growing has increased over 40% in the last decade [CANEGROWERS, 1999]. As cane production has increased, more and more attention has been on where sugarcane is grown and how the expansion can occur without compromising sustainable development in a region [Mallawaarachchi and Quiggin, 1999; Walmsley et al., 1999]. Like many other natural resource management and planning issues, cane land allocation is essentially of a multi-objective nature, characterised by socio-political, environmental and economic value judgements [Johnson et al., 1997]. Several alternative land allocation strategies have to be considered and evaluated in terms of many different biophysical and socio-economic criteria, and also in terms of stakeholder aspirations and value judgements. A single, objectively best solution does not generally exist.

This paper describes a cane land allocation model which integrates multi-criteria modelling and geographical information systems (GIS). This model has been developed to assist industry and government users to explore and evaluate different land allocation scenarios for sugarcane production by integrating environmental information with the stakeholder values, government policies and management goals. It is illustrated by using a case study of cane land allocation in the Lower Herbert River Catchment in Queensland, Australia.

2. LAND ALLOCATION WITH MULTI-CRITERIA MODELLING AND GIS

Land allocation seeks to allocate a certain amount of feasible land for particular types of land use. It should be based on the comprehensive assessment of potentials and feasibility of land resources, taking into account the biophysical and socio-economic factors as well as stakeholders' value judgements. Multi-criteria modelling and GIS have been used for land use allocation [Diamond and Wright, 1988; Ridgley et al., 1997; Walmsley et al., 1999].

Multi-criteria modelling provides a quantitative framework that can integrate information on planning goals and objectives along with the values of stakeholders for evaluation of each land allocation scenario. GIS provides tools to manage and integrate spatially referenced data or spatial data, and offers a means of visualising resultant land allocations. The challenge is to manipulate the proportion and locations of land uses to achieve 'best possible' solutions given multiple and often conflicting objectives.

Walmsley et al. [1999] developed a spatial disaggregation algorithm for cane land allocation to meet this challenge. This algorithm utilises a multi-criteria evaluation model and GIS. It divides a region into spatial units. Each spatial unit is evaluated against five criteria, including the land suitability for sugarcane, the overall compactness of cane land, the size and area perimeter ratio of a spatial unit, and the proximity to milling facilities [Walmsley et al., 1999]. Each criterion is assigned a weight by a user. An overall score for a spatial unit is calculated by the linear value function:

$$V = \sum_{i=1}^{n} W_i * X_i \qquad (1)$$

where V is the overall score of a spatial unit, W_i is the relative weight of the ith criterion, X_i is the score of a spatial unit on the ith criterion, and n is the number of criteria. $\sum W_i = 1$.

The algorithm starts the allocation process with the selection of the spatial unit of the highest overall score. The selected spatial unit is assigned as cane land. The algorithm then recalculates the overall scores for all remaining spatial units by (1), selects the spatial units with the next highest overall score and adds them to the list of the assigned cane land. Afterwards, it recalculates the overall scores for all remaining spatial units again, and adds those with the next highest overall scores to the list of assigned cane land. This process is repeated until a set amount of land is assigned for cane.

The spatial disaggregation algorithm lacks a standardisation procedure to transform criterion values (or raw data) into comparable scores, and an elicitation process to facilitate the estimation of the weight of each criterion. We extended the land allocation model by incorporating SMARTER, a modified Simple Multi-Attribute Rating Technique, for eliciting weights based on the rank order of importance of criteria.

3. A CANE LAND ALLOCATION MODEL THROUGH THE INTEGRATION OF SMARTER AND GIS TECHNIQUES

3.1 The SMARTER Technique

SMARTER is an approximate method for multi-attribute utility measurement based on an elicitation procedure for weights, developed by Edwards and Barron [1994]. This procedure includes nine steps: (i) identifying the purpose of decision making and decision makers whose values or judgments should be elicited and whose utilities are to be maximised; (ii) eliciting a list of attributes which are relevant to the purpose of the value elicitation from the decision makers; (iii) identifying alternatives or the outcomes of possible actions to be evaluated; (iv) evaluating how well each alternative would perform on each attribute; (v) eliminating ordinally and cardinally dominated alternatives in order to reduce the total number of alternatives but without changing the range of any attribute; (vi) developing single-dimension utilities for producing scores for each of the alternatives on each attribute; (vii) eliciting rank order of the attributes; (viii) calculating the weights for each attribute based on the rank order; and (ix) calculating multi-attribute utilities for alternatives. A how-to-do-it checklist for this procedure is provided in Edwards and Barron [1994].

SMARTER uses a linear additive model as presented by the formula (1) to calculate multi-attribute utilities, which can be used as overall scores for spatial units in cane land allocation. The score X_i for a spatial unit on the ith criterion is estimated in Step 6 based on a 0-100 scale, with 0 as the minimum plausible value and 100 the maximum plausible value. For continuous variables, a straight line function can be developed. For qualitatively rated measures, scores can be assigned reflecting relative performance. W_i is derived based on the rank order of criteria obtained in Step 7. In SMARTER, after the rank order of a set of criteria or objectives is obtained, it is used to estimate the set of weights using the centroid method. The centroid method assigns weights as follows.

Assume W_1 is the weight of the most important criterion or objective, W_2 is the weight of the second most important criterion or objective, and so on. For n criteria or objectives:

$$W_1 = (1 + 1/2 + 1/3 + \ldots + 1/n)/n$$
$$W_2 = (0 + 1/2 + 1/3 + \ldots + 1/n)/n$$
$$W_n = (0 + 0 + 0 + \ldots + 1/n)/n$$

Generally, if $W_1 > W_2 > \ldots W_n$, then the weight of the ith criterion or objective is:

$$W_i = (1/n)\sum_{j=i}^{n}(1/j) \qquad (2)$$

Partial rank orders (i.e. tied and missing ranks) can be handled using methods from Kmietowicz and Pearman [1984].

SMARTER uses the strategy of heroic approximation to justify linear approximations of single-dimensional utility functions and use of an additive aggregation model, and justification of rank weights [Edwards and Barron, 1994]. The centroid method minimises maximum error by identifying the centroid of all possible weights maintaining the rank order of importance of criteria or objectives.

3.2 The Cane Land Allocation Model

The cane land allocation model proposed here integrates SMARTER and GIS modelling. SMARTER is used for evaluating the feasibility of land for sugarcane based on multiple criteria. GIS modelling is used for manipulating the data representing the land use constraints and the allocation criteria, and combining them with SMARTER derived weights to allocate a set amount of land to sugarcane production.

This model was implemented using the following steps:

Step 1: *Defining land use constraints and allocation criteria.* Land use constraints represent restrictions imposed on areas for sugarcane production. They define regions of certain biophysical and environmental conditions which are unsuitable for sugarcane. Examples of areas unsuitable for sugarcane include regions with high nature conservation values, steep slopes or poor biophysical suitability for sugarcane production.

Allocation criteria are used to measure to what degree the decision makers' objectives are achieved.

Step 2: *Preparing data for determining the land use constraints.* Each land use constraint is represented as a map data layer in the GIS. The constraint maps are created by eliminating regions characterised by attributes or certain values of attributes from consideration. They categorise the areas into two classes: feasible and infeasible. Feasible areas are assigned a value of 1, and infeasible areas are assigned a value of 0.

Step 3: *Preparing data for measuring the allocation criteria.* Each allocation criterion is also represented as a map data layer in the GIS. Criterion maps can be created according to appropriate qualitative or quantitative scales of measurements. Since criteria can be measured on a variety of scales, these scales must be commensurate in order to combine the various criterion map data layers. To achieve this, the values of the criteria need to be converted into standardised criterion scores. Here, the values of all criteria are converted into standardised scores on a 0-100 scale. The higher the value of the score is, the more attractive is the criterion value.

The following formulae are used to standardise the values for continuous variables:

If the value of a criterion is to be maximised,

$$Score_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} * 100 \qquad (3)$$

if the value of a criterion is to be minimised,

$$Score_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} * 100 \qquad (4)$$

where $Score_i$ is the standardised score for the criterion for the ith spatial object (an area on the criterion map), x_i is the value of the criterion for the ith spatial object, x_{max} is the maximum value of the criterion, and x_{min} is the minimum value of the criterion. $Score_i$ ranges between 0 – 100.

Step 4: *Combining constraint and criterion maps to create a spatial unit map.* The spatial unit map excludes the restricted areas by applying the land use constraints. Each spatial unit represents an alternative area for sugarcane production, and contains the score values for all the allocation criteria.

Step 5: *Ranking the allocation criteria in order of importance.* This is accomplished by asking decision makers: "Image you have a cane land block that had the worst possible performance on all criteria. You are selecting an alternative area. You can improve the value of one criterion to achieve the best possible attainment level of sugarcane production. Among all the n criteria, whose value would you improve to make the alternative most desirable?" The decision makers would then select one of the n criteria. This criterion would be removed from the list and the decision makers are asked to select one criterion from the remaining list, whose value would be preferred to be improved to make the alternative most desirable. This continues, with the outcome that a rank ordering of criteria is obtained. The most important criterion was the first selected in this operation, and the last selected the least important.

Step 6: *Estimating weights.* This step estimates and assigns numerical weights to the allocation criteria based on their rank order of importance obtained in the previous step by applying the formula (2).

Step 7: *Calculating overall scores for each spatial unit.* The calculation is accomplished by applying formula (1) on all spatial units on the spatial unit map.

Step 8: *Allocating the most feasible land for sugarcane production.* This is done by following the spatial disaggregation algorithm developed by Walmsley et al. [1999] as described in Section 2.

Step 9: *Generating a future sugarcane land use plan.* The allocated cane land is presented as a sugarcane allocation map. Step 1 to Step 8 can be repeated to develop different land allocation scenarios by defining different land use constraints and allocation criteria, and by providing different rank orders of the criteria. By comparing land allocation scenarios based on deriving criteria and weightings, decision makers can explore the implications of differing policies in allocation strategy in attempting to meet targets for expansion without violating constraints on expansion and minimising conflicts with other land use aspirations.

4. CASE STUDY

The Herbert River Catchment is located in northern Queensland, Australia, covering an area of about 10,000 km^2 (Figure 1). The sugar industry is the largest intensive agricultural industry in the catchment. Other important industries include forestry, beef and small crops such as pineapples, melons and pumpkins. Lands not used for arable agriculture are mainly under native vegetation or improved pastures for beef production. Small areas are utilised for mining and industrial activities. Our study area is located in the southeast of the catchment (known as the "Lower Herbert"), where sugarcane is the dominant land use.

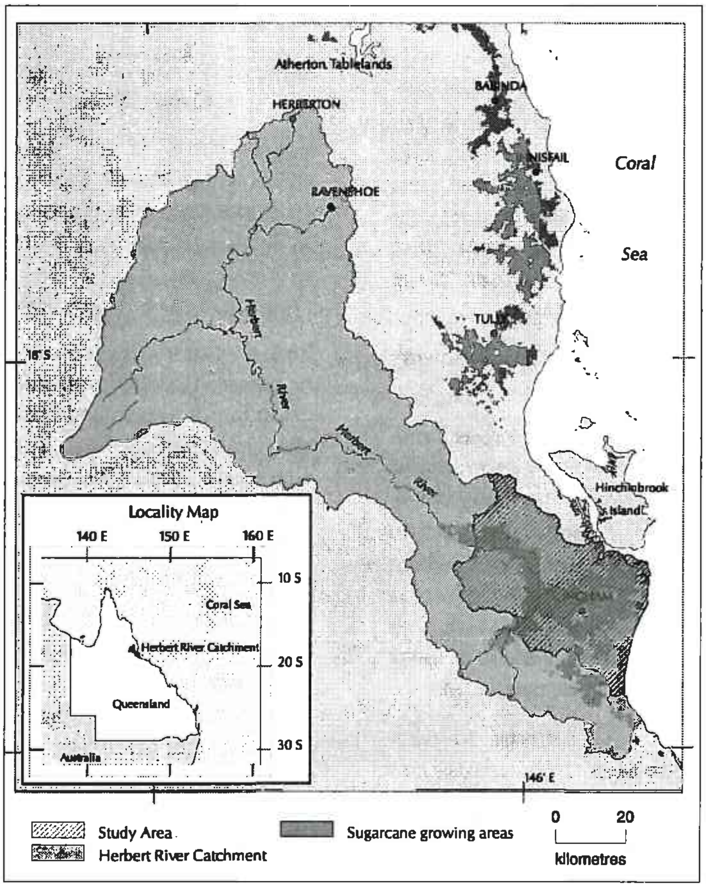

Figure 1. The Herbert River Catchment.

A detailed GIS database has been collated and contains map data layers for land cover, landuse, slope, elevation, land suitability for sugarcane, roads, rivers, mill locations, flood prone areas. All map data layers are in the Arc/Info GRID format, with a cell resolution of 100m × 100m. Land use constraint and allocation criterion maps were produced through GIS operations within ArcView. The cane land allocation model was written using the ArcView AVENUE script language.

The criteria for cane land allocation in this case study are based on those proposed by Walmsley et. al [1999] and include land suitability for sugarcane, slope, proximity to existing mills, proximity to roads, shape compactness of cane land blocks, and fragmentation of landscape.

The shape compactness of a cane land block is measured as $4\sqrt{A}/P$ [Bogaert et al., 2000], where A is the area (km^2) and P is the perimeter (km) of a cane land block. The fragmentation of landscape is measured as $2\log A/\log P$ [Milne, 1988], where A is the area (km^2) of the land allocated to cane and P is its perimeter (km).

The land use constraints may be those areas where state forests, national parks, wetlands or flood prone areas are located. The model allows users to choose a set of criteria and land use constraints for analysis.

Two hypothetical scenarios for cane land allocation in the study area are illustrated below. The criteria and weightings used are hypothetical and do not represent expressed stakeholder values.

In the first scenario, it is planned to allocate about 600km^2 of land to cane production. The selected allocation criteria include land suitability for sugarcane, slope, distance to mills, distance to roads, shape compactness of a cane land block and fragmentation of landscape. They are ranked in the order: *land suitability for sugarcane > slope > distance to mills > distance to roads > fragmentation of landscape > shape compactness of a cane land block*. National parks, state forests, and those areas with a slope of 8% or more are reserved. Figure 2 shows the result of cane land allocation under this scenario. The figure shows the new cane allocation is distributed along the major rivers due to the importance placed on the criterion "land suitability for sugarcane".

In the second scenario, the same amount of land for cane production, 600km^2, is planned. A different set of allocation criteria is selected, including land suitability for sugarcane, distance to mills, and fragmentation of landscape. They are ranked in the order: *distance to mills > fragmentation of landscape > land suitability for sugarcane*. The same land use constraints as the first scenario are imposed. The result of cane land allocation for this scenario is shown in Figure 3. In this scenario the new cane allocation is skewed towards the East due to the importance placed on the criterion "distance to mills".

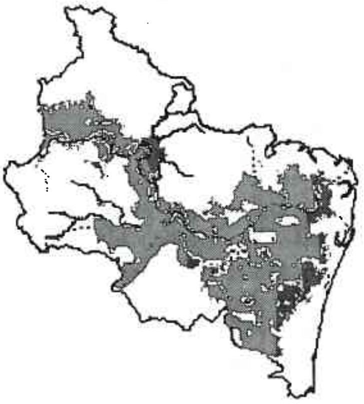

Figure 2. Cane land allocation for scenario 1.

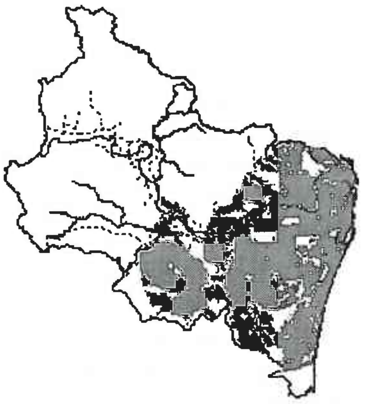

Figure 3. Cane land allocation for scenario 2.

5. CONCLUSIONS

This paper has presented a cane land allocation model which integrates multi-criteria modelling and GIS techniques. Cane land allocation involves multi-criteria analysis and integration of decision makers' value judgements with biophysical and socio-economic information. SMARTER is used in this model due to its ease of elicitation of relative importance for allocation criteria and its formally justifiable and robust weighting procedure. SMARTER does not require any difficult judgements from users. It is well suited to those multi-criteria modelling applications for which easy elicitation is useful [Edwards and Barron, 1994]. Our cane land allocation modelling is such a case.

This model aims to spatially allocate land for cane production at a landscape level, which is based on spatial data. GIS provides a powerful tool for the analysis and integration of spatial data. The integration of multi-criteria modelling and GIS allows decision makers to explore and evaluate different cane land allocation scenarios effectively and efficiently.

Through the use of the model, cane land allocation scenarios can be developed by: (a) using different sets of criteria, (b) imposing different sets of land use constraints, (c) providing different rank orders of importance of the selected criteria, and (d) setting different targets for cane production.

The SMARTER procedure involves a judgemental step of ranking criteria in order of importance. For decision making by one person, this step is fairly straightforward. It is certainly more difficult in a group environment.

Ranking order is a decision task that is easier than developing numerical weights. Using an ordinal approximation, SMARTER alleviates the discomfort that many people feel when forced to put hard numbers (weights) to subjective judgements. However, order ranking does not provide decision makers with an opportunity to carefully weigh the relative importance of criteria during which the insights could emerge. How this affects the use of the cane land allocation model remains to test.

The cane land allocation model is implemented in the NRMTools environment [Walker and Johnson, 1996] over the World Wide Web. It can be used by a single decision maker or a group of decision makers who have reasonable agreed-on values. The model is currently only applicable to a single land use allocation, sugarcane land allocation. It does not deal with the competition from other land uses. An extension to this model to support multiple land use allocation is being developed.

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