Use of Models in Ecologically Sustainable Forest Management and Decision-Making

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Abstract: Use of models in ecologically sustainable forest management is fraught with problems of lack of data, accuracy of individual models, integration of individual models and interpretation of results. There seems to be no clear universal paradigm for over-coming these problems as each case is unique and requires a different approach. This paper expounds on some of these problems and uses two Australian examples in forest management. In each case suggestions are made as to how to tackle these ensuing problems. It is our firm belief that mathematical/statistical rigour in models combined with professional judgement will go a long way in developing management strategies that can be applied in the field. However, a real test of our affirmation will only be possible when the consequences of the applied management strategies are measured over-time and compared to the model predictions.

Keywords: Ecologically sustainable forest management; Professional judgement; Harvest scheduling; Spectrum; ALEX

1. INTRODUCTION

Ecologically sustainable forest management (ESFM) is intended to achieve 'multiple-use' of a forest resource within constraints imposed by ecological and socio-economic processes. Although it might be easy to understand the goals or intended outcomes of ESFM, it is a challenging task to analyse and subsequently translate the findings of the analysis into operational practice. The analysis normally involves the cause-and-effect assessment of ecological, economic and social processes. Although review of the details of each process is possible, problems arise when an attempt is made at assessing the interactions of these processes. As in all cases of these types of analyses, the data and subsequent model development are always inadequate, a situation that is too often exacerbated by not knowing what parameters (from the data) to model. If inventories and surveys are still to be carried out, there is also a problem of understanding which parameters to measure. In forestry, inventories can go on for long periods of time. For example, useable tree growth data might not be available until after 10-15 years, where the measurement interval is 1or 2 years. It is vital to speculate on how these data will be used such that all parameters that need to be measured are actually measured during the measurement period.

Forest planners are typically in a situation where they have to use models that are inadequately documented in terms of their limitations, to develop management strategies supporting sustainability. Sustainability in this context means managing a forest system such that production is maintained through time without severe or permanent deterioration of resources and forest values, whilst subject to long-term constraints and socio-economic pressures.

Forest management problems considering sustainability have become complex because of the extensive and large datasets, and the programming required to represent the complexity in parameterisation of goals, values and constraints. Validation now requires new and innovative ways since common sensitivity analysis is becoming inadequate since interaction of parameters is becoming far more important and more difficult to understand. Amidst all this complexity of dealing with large integrated models and their associated problems of validation, practical management strategies can still be derived using the currently available models, information and hardware. Inadequacies in model integration and validation process are bound to show up and these need to be highlighted so that research can be directed towards those areas of weakness.

Criticisms of models used for forest management have also targeted the use of 'professional judgement' to fill in the gaps in management decision-making where models are not available or are clearly inadequate. It is important to realise what professional judgement is all about. Many models are used to speculate an outcome in a multi-dimensional system that in no way any person can visualise. In the field of artificial intelligence, it has been found that the human-being is generally unable to hold more than six or seven pieces of information simultaneously in short-term memory [Peters and Waterman, 1982]. The implications of this finding are that to understand fully the working of a system model we are constrained to six or seven prime state variables (ideas). This constraint, however, can be overcome by introducing sub-models containing six or seven state variables. Thus an effective planning tool for forest management should consist of a hierarchy of constituent sub-models. It can be argued that the greater the number of levels in the hierarchy, with greater detail contained in the sub-models, the better (in terms of reliability) the model is, but at a cost of more complexity.

Therefore professional judgement, in a multi-dimensional problem where the above hierarchal model is used, is an ability to determine a suitable strategy from an extensive sensitivity analysis. The type of sensitivity analysis in this case would result in scenarios that may be compared until an outcome is agreed upon. If the short-coming of the sub-models are fully documented, it gives an insight into the level of sensitivity analysis to be carried out. Consequently models are not done away with where professional judgement takes precedence, but interpretation of results will rely heavily on sensitivity analysis. Even in a politically driven environment, it is still essential that a sensitivity analysis be done because foresters should always anticipate the consequences of their forest resource resulting from any of the applied management strategies.

So models are here to stay but how do we ensure their correct use and also leave room for refinement of the 'good' models and improvement of the 'bad' ones? The following aspects if strictly adhered to, would minimise a lot of the confusion and criticism that surround forest management models and interpretation of their results:

- regardless of the inadequacy of the data used for developing a sub-model, a statistical validation and cross validation should be carried out specifying clearly the limitations of use and sensitivity of the sub-model;
- The size and consequently the cost of model analysis should be reduced without loss in accuracy of results;
- Validation of the model (integrated models) should also be on the basis of the effectiveness of the management strategy derived from the model output; and
- An understanding of how professional judgement comes into play in the event of uncertainty is essential.

2. INDIVIDUAL MODELS AND VALIDATION

A model can be defined as a representation with a few degrees of freedom and it explains trends found in large and small data sets. A model can also be looked at as an efficient way of storing data that may be retrieved quickly when required. If the trends found in a data set are adequately represented in a model, including the stochastic element that influences change, a model can be used to predict the future. Note that all these definitions are based on the dataset and not on the actual system from which the data were collected. It can obviously be concluded from this, that data collection should always be preceded by a careful definition of model use and application. Appropriate data are then collected and at time intervals that will correspond with the application. Because of other pressing issues, little or no data are available. In other cases lots of data are available but cannot be appropriately utilised to develop the desired model.

The components essential to the development of models are closely linked and can be summarised as follows [Ljung, 1987]:

- a good knowledge of the processes or relationships of the system being modelled;
- modelling insight and mathematical/statistical intuition of the developer/modeller; and
- good quality data from an experiment or survey.

Forest analysts have had this list upside down, where large data have been collected without a clear knowledge of what to model and how [Adlard, 1995]. As a result there are lots of permanent sample plot measurements that do not span over a measurement period long enough to have sufficient information for model identification. Even if the former criterion is satisfied, there is not enough representativeness of different geographical areas. Where does this leave the forest analyst? The problem can be tackled in 2 stages:

- Identify the areas of weakness of the existing databases by using very simple graphical procedures and plan remedial sampling; and
- Develop models from existing databases by employing appropriate mathematical and statistical techniques dictated by nature of the data and the intended use of the models. However, validation of such models becomes tricky.

This last stage is the most stressful one because there is no universal paradigm to apply to it. We will elaborate on that to find out why. As stated earlier a good knowledge of the system is essential and in addition, the objectives of any modelling of a system should be clear at the outset so that the effort spent in developing the model is related to its intended application. Forest analysts develop models for physiological understanding of individual trees or stand characteristics, and forest management. In both cases the aim is to simulate, predict, optimise (or more specifically 'control') or to reconstruct inventory measurements.

Suppose a model has been developed and found to be satisfactory in terms of representing the data that were used for the modelling procedure, it is imperative that a cross validation be carried out. Cross validation is concerned with evaluating the model as a whole in addition to checking its performance when applied to a different dataset than was used for the estimation. To quote Forrester [1960]:

> "The defence of a model rests primarily on the individual defence of each detail and policy, all confirmed when the total behaviour of the model system shows the performance characteristics associated with the real system".

More material on model validation can be found in a paper by Goulding [1979].

3. INTEGRATED MODELS

It should be borne in mind that ESFM implies utility of a resource that is part of an ecosystem whole, without disrupting the dynamics of that ecosystem which functions as a single unit. That is difficult to model, because, as pointed out earlier, one never has sufficient data, parameter interaction and representation within the system being modelled are complex and the decision to include the components that make the ecosystem whole is subjective and therefore open to criticism. However, in all cases that decision is largely determined by industry or community objectives or political pressure. To integrate different components and simulate the ecosystem requires that data, that focuses on 'interaction' of these components be collected, management strategies (inputs to control) that directly influence the ecosystem be modelled (requires experimental data of the form input-output or input-state-output). Here is how the modelling system, at a simulation level, would work:

- select a management option (which generates an ecosystem output);
- this ecosystem output then triggers a series of events in other components of the ecosystem (the interactions); and
- the analyst then decides whether or not to adopt a management option based on some criteria providing the other ecosystem outputs are desirable.

Looking at the modelling system at an optimisation level would work as follows:

- provide a suite of management options (that generate different ecosystem outputs);
- define an objective criteria/criterion (that enable(s) a selection of a management option to be adopted);
- define the constraints (which shape the solution landscape, and these constraints can be budgetary, biophysical or social); and
- by choosing an appropriate search technique for a formulated optimisation problem, determine optimal or near-optimal management options.

The optimisation problem may become complex when adjoining land parcels that differ in land use and geographic properties are considered. A decision made for one land parcel, may affect the decisions that have to be made to the neighbouring land parcels.

4. EXPERIENCE IN THE STATE OF NEW SOUTH WALES, AUSTRALIA

Australia's forests are the subject of intense debate that encompasses wide-ranging issues of forest tenure, land use, and management. Nationally, the Commonwealth Government coordinated the preparation of a National Forest Policy Statement [Commonwealth of Australia, 1992], which was agreed to by the Commonwealth, State and Territory Governments to provide a long term framework for balancing the competing demands of conservation and industry. This policy, *inter alia*, established a process for joint Commonwealth/State Comprehensive Regional Assessments of forests. The process considered resource, economic, social, national and world heritage values, ecologically sustainable forest management, environmental impacts, and obligations relating to international conventions such as those for protecting endangered species and biological diversity.

To undertake assessments in the state of NSW, scientific technical committees were established to collate available data and develop models for the different components of the environment, namely, social, economic, biological diversity for fauna and flora, forest resource assessment, and ecologically sustainable forest management. The idea was to integrate these models and information in some decision support system, and make informed decisions on utility of the forest whilst maintain its vitality through ecologically sustainable management. However, the integration process had not been well thought through and problems showed up with time.

A steering committee was established to manage Federal and State government policy requirements and money allocated to the different scientific technical committee projects. The objective of government and stakeholder negotiations[1] were to arrive at a regional forest agreement that provided a comprehensive, adequate and representative reserve system, a twenty year strategic plan securing the resource base for industry and ecologically sustainable forest management. It became clear that strategic level modelling tools would not adequately address the sustainability issues that were being raised.

The different scientific technical committees did not adequately develop tools to integrate their information and models to help fully address the issues of sustainability or maintaining ecological vitality. Ecological vitality implies that the forest remains dynamic or self-sustaining and self repairing in the face of harvesting or anthropogenic disturbances.

An approach was to follow a step-wise process that obviously did not consider the dynamic nature of the forest system. The process was to:

- determine a reserve design that would stay static for the rest of the analysis;
- determine a strategic timber harvest scheduling for a forest resource; and
- determine the economics (using a separate model) of the scheduled timber
- guess the consequential results in terms of sustainable forest management.

Different stakeholder groups used this process and their professional judgement to come up with their ideal forest management strategy. The integration process left a lot to be desired despite providing a way forward.

The consequences of the management strategies agreed upon in negotiations are subject to a 5 yearly review and with time it will be possible to assess the benefits of the models and whether professional judgement had any impact to the whole process, negative or positive.

A more scientifically based integration modelling process was later demonstrated [Chikumbo et al., 2000], targeted at reflecting the impact of harvesting and utility of non-timber values in the forest whilst maintaining ecological vitality. This process provided considerable insights into how the forest ecosystem may respond to changes in goals, constraints and parameter settings and resulting issues affecting sustainability. A review of forest sustainable management can be found in Chikumbo et al., [2001].

5. EXPERIENCE IN THE STATE OF VICTORIA, AUSTRALIA

In the state of Victoria, Australia, allocation and harvest scheduling for the native forests have been simultaneously and successfully dealt with by integrating spatially referenced data from geographic information systems (GIS) to an optimisation formulation. The GIS enables the ability to explore different spatial strategies. For example, the effect on timber production due to changes in stream buffer widths on the operationally effective areas can be explored [Turner, 1995]. Linear programming (LP) is then used to identify an optimal solution on how these effective areas should be managed over a planning period [Gijsbers et al., 1992]. The integration of data from GIS to an LP formulation is made possible by using a matrix builder called SPECTRUM. This is used to formulate an LP matrix that is solved by a 'simplex method' algorithm. In SPECTRUM, the unit of the effective area is defined by the planner, usually through the overlaying of appropriate thematic maps in a GIS. The regulation of cut is accomplished through the planner nominating a series of constraints on the production of timber [Turner, 1995].

Problems have arisen in trying to seamlessly integrate environmental objectives in the planning process, especially wildlife concerns [Burgmann,

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[1] Negotiations included representatives from non-government organisations, state and federal governments, industry, state forest managers, parks and wildlife managers, and scientists from federal and state government departments and independent specialists.

1993]. The addition of a population viability analysis (PVA) to the planning process was going to enable harvest scheduling to take into account the conservation of endangered animal species. Moreover, if an indicator species for most endangered animals is identified, management strategies can be made sensitive to this species and also benefit the other animals.

Since the PVA model had to merge spatial information for habitat description and the animal 'population dynamics', it had to be modelled as a separate entity but with an interface that would directly link with the spatial representation ('visualised' results) from the allocation and scheduling planning processes [Lau et al., 1996].

5.1 Current Model and Problems of Application

Lindenmayer and Possingham [1994] developed a population modelling tool for estimating the probability that Leadbeater's Possum will become extinct under current timber harvesting strategies in the Central Highlands. This PVA model is called ALEX (Analysis of the Likelihood of Extinction) and is essentially a Monte Carlo simulation model. Each scenario is run many times to gather statistics on the likelihood of extinction. The variables used in the model were as follows: the numbers, location and age-class of animals; mortality of each age-class; and a finite number of patches (habitat areas) with the associated population distribution.

There have been problems with incorporating ALEX into the Victorian planning process:

- The management options that were determined from the use of ALEX are as follows: increasing the rotation time between timber harvesting operations; modifying existing clearfelling practices; and varying the size, spatial arrangement and number of areas that are exempt from timber harvesting.

This information did not explicitly specify these management options for the forest planners. Forest planners need to know the specific increment in rotation length, the alternative silvicultural strategies and how to vary the size and spatial arrangement of the habitat area. This can only be achieved in an integrated planning framework (that allows for spatial representation of the allocation and scheduling of timber harvesting with the associated impact on Leadbeater's Possum habitat) for full exploration.

- The constant habitat quality (i.e. without anthropogenic disturbances) hypothesised in ALEX for old growth forest seemed over-simplistic given that one major component of the habitat quality, the wattle understorey, has a life span of 80 years and requires a fire disturbance regime for its perpetuation. Generally the requirement for maintenance of the wattle understorey is successive fires within the period represented by the life span of the acacia component plus the length of time their seeds remain viable in the soil [Gill et al., 1981].
- It seemed likely that Leadbeater's Possum would thrive on the fringes of old growth forests (where shelter would be maximised) and regrowth forests (where the food would be maximised). Therefore, the concept of suitable patches as modelled in ALEX may need to be revised.
- Once the patch size was defined in ALEX, it stayed the same to the end of a simulation run. Therefore ALEX did not take into account suitable habitat that became available with time, during any simulation run.
- There were a number of hypotheses built into ALEX and the results of the Monte Carlo simulations were based on conditions of expectations that had not been validated. These hypotheses and available data were used to determine variables such as fecundity and mortality in ALEX. Lindenmayer and Possingham [1994] did not indicate the significance of the estimates of these variables.
- The problem of migration was not adequately modelled in ALEX because very little is known about the dispersal biology of Leadbeater's Possum and how vacant suitable habitat is colonised by this species [Lindenmayer and Possingham, 1994].

Because of these problems a different theoretical modelling approach is proposed that will enable hypothesis testing and a seamless link to the allocation and scheduling planning process incorporating the frameworks of Davey and Stockwell [1991] and Davey et al., [1995]. The objective is to make available a grid-based PVA model that may be directly linked with the visualised results (also in grid format) from allocation and scheduling of timber harvesting. The benefit (to visualise any management option) would be a feedback process that allows for the determination of alternative spatial constraints that favour, for example, the survival of endangered animal species.

5.2 Population Dynamics and Model Development

Population dynamics is the study of populations as dynamic systems. To reflect this dynamic character, a population dynamics model is needed that can take into account the activities and the interrelationships of a population. These characteristics would be represented in a set of equations compiled as a computer program to enable simulation. Solomon [1969] expounded on the general definition of population dynamics to include the environmental influences upon populations, e.g.:

- the effects of climate;
- the quantity of food;
- availability of shelter and other species that compete for the same necessities;
- natural enemies;
- micro-organisms causing disease; and
- various other combinations of such factors.

He also included the influence of members of a population upon each other, which can be negative or positive. Sexual reproduction and rearing the young were among the positives and the negatives included competition for a limited supply of food, shelter or other requisites, mutual disturbance and fighting or even predation (cannibalism).

The procedure to build the model would be as follows:

- gathering of information on the biology and habitat of Leadbeater's Possum;
- development of an algebraic model and testing of the general population dynamics hypotheses using the gathered information;
- sensitivity analysis to identify the significant hypotheses and non-significant hypotheses;
- further developing the significant hypotheses using field data, so that parameters, directly related to the hypotheses, can be used in the final model;
- validation tests with long-term data records or if not available with synthetic data generated to simulate real life scenarios; and
- determining the reliability of the model (variance) and its sensitivity to wrong input data.

The approach in the initial stages would be to develop a theoretical model of Leadbeater's Possum and its environment. This model would be developed based on information from the current model (ALEX) and likely scenarios that are typical of this animal's population and habitat dynamics.

The success of this deductive approach will depend on the availability of data to closely analyse the validity of the assumptions and relationships that set the stage for the theoretical model. Data will provide a basis for estimating the numerical values for various parameters in the algebraic model. Developing a mathematical model and testing some of its implications in practical applications would follow. The implications would be analysed in the light of decisions (conscious choices made between alternatives) and events (occurrences over which little or no control is exercised).

5.3 Proposed Model

The approach in section 5.2 may result in complex models because experimental data for population dynamics (no matter how good the data records are) will always reflect perturbations by unexpected and uncontrollable influences. This complexity has become a major area of research in the field of mathematical biology.

A theoretical grid-based algebraic model for the population dynamics is suggested here. As pointed out earlier there were problems with the migration in ALEX and in the proposed model, movement (due to emigration and immigration) is accounted for from cell to cell. Each 1 hectare cell is represented by a habitat quality value derived from a GIS for the forest area under study. The preferred habitat is expressed in terms of the vegetation classification normally used for timber utilisation, e.g. an ecological land classification that describes vegetation structure and floristics [Burgmann, 1993]. The habitat quality variable is modelled as a function of time (a dynamical model). Influenced by the adopted forest management option, this habitat quality will in turn affect the population dynamics for Leadbeater's Possum. The bushfire occurrence model developed by MIRA Consultants [Neuhaus and Playford, 1995] can be integrated in the habitat quality model. Population distribution will be directly related to the habitat. The habitat characteristics will be used to predict populations [Burgmann, 1993].

To illustrate the model, let us consider a single cell problem where migration is not considered. A basic Leslie model [Usher, 1966] can be represented by a matrix equation that shows the population changes at successive times. A transition matrix, **R**, for the three female age-classes namely, young, juvenile and adult, drives the equation:

$$\begin{bmatrix} f_1 & f_2 & f_3 \\ p_1 & 0 & 0 \\ 0 & p_2 & p_3 \end{bmatrix} \begin{bmatrix} Y_{t,1} \\ J_{t,2} \\ A_{t,3} \end{bmatrix} = \begin{bmatrix} Y_{t+1,1} \\ J_{t+1,2} \\ A_{t+1,3} \end{bmatrix} \quad (1)$$

where

$Y_{t,1}$ = population of young in cell at time t

$J_{t,2}$ = juvenile population in cell at time t

$A_{t,3}$ = adult population in cell at time t

t = time (years)

$\begin{bmatrix} f_1 & f_2 & f_3 \\ p_1 & 0 & 0 \\ 0 & p_2 & p_3 \end{bmatrix}$ = transition matrix, **R**.

The first row of the transition matrix, $f_i (i = 1,2,3)$ and the second and third rows with the probabilities p_i $(i=1,2,3)$ indicate fecundity and age-class population dynamics of the young, juvenile and adult respectively. Only the female population is considered in this case because it limits the reproductive capacity of the total population.

The data concerning the population is used to model the elements of **R**:

$$p_1 = Y(t+1) = \alpha A(t) \quad (2)$$
$$p_2 = J(t+1) = \beta Y(t) \quad (3)$$
$$p_3 = A(t+1) = \lambda J(t) - \sigma A(t) \quad (4)$$

where

$\alpha, \beta, \lambda, \sigma$ = parameters dependent on the habitat quality.

To investigate migration from cell i to cell k at least 2 cells have to be considered and the matrix equation (1) becomes:

$$\begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} x_{t,1} \\ x_{t,2} \end{bmatrix} = \begin{bmatrix} x_{t+1,1} \\ x_{t+1,2} \end{bmatrix} \quad (5)$$

where

$x_{t,k}$ = the age-class population vector (see equation (1)) in cell k at time t

R_{11} = reproduction and age-class recruitment of population in cell 1, less emigration

R_{12} = migration from cell 2 to cell 1

R_{21} = migration from cell 1 to cell 2

R_{22} = reproduction and age-class recruitment of population in cell 2, less emigration.

The population dynamics that include migration can thus be generalised as follows:

$$Y(k,t+1) = \alpha A(k,t) \quad (6)$$
$$J(k,t+1) = \beta Y(k,t) \quad (7)$$
$$A(k,t+1) = \lambda J(k,t) + \sum_i m_{ik} A(i,t) - \sum_i m_{ki} A(k,t) - \sigma A(i,t) + \sum_i n_{ik} J(i,t) - \sum_i n_{ki} J(k,t) \quad (8)$$

where

$m_{ik}; m_{ki}$ = migration parameters of the adult population from cell i to cell k and vice versa

$n_{ik}; n_{ki}$ = migration parameters of the juvenile population from cell i to cell k and vice versa.

Since the dynamics are modelled as time functions, the transition matrix, **R**, is time-dependent. Any initial population of the 3 age-classes in each cell (including migration between cells), can be simulated over a specified time. The algorithm allows for any size of grid to be defined (that will only be limited by long processing time on a computer for a big grid size). The initial population is estimated from habitat quality values in each cell. Such a model, validated with experimental data, would provide integration with the allocation and scheduling planning process in a grid-based framework. This would enable the determination of spatial harvesting options that favour the survival of Leadbeater's possum.

6. CONCLUSION

Modelling is based on mathematics/statistics and knowledge of the processes at work in a system. Note that mathematics/statistics only deal with the abstract reasoning and the axioms are carefully formulated such that any one using them (or doing the reasoning) need not have any knowledge of the system in order to deduce new conclusions in the same language.

Forest management and planning (FMP) is not mathematics/statistics and neither is the reverse. For FMP interpretation, one must have an understanding of the connection between models developed from mathematics/statistics and the real world. It is essential though, for a forest analyst to translate model outputs into management strategies applicable to the real forest. Only in this way may the use of models be evaluated by observing the consequences of the management strategies in the post-application period.

Mathematical reasoning, which is the whole basis of models, is not being discounted here and it would be quite naive to underestimate its great power and use. But then again the forest analyst's reasoning and interpretation is highly essential to the analyses. Analysts use these tools based on general reasoning and apply professional judgement to interpret the results. Extensive sensitivity analysis is necessary where different scenarios are simulated from a model or integrated models. This is a process that has to be done until a sufficient understanding of the connection of that model and the real world has been acquired. In other words the forest analyst only stops the process when they have developed enough confidence to derive a practical management strategy from that model. The real test, however, will be the monitoring of the consequences of the applied management strategies over-time and comparison with the model predictions.

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