Planning Sustainable Agro-Ecosystems: A System Dynamics Approach

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Abstract
The assessment of and planning for agricultural system sustainability is a difficult task not adequately handled by conventional methods of farm management analysis. Sustainability is appropriately considered as a multi–dimensioned phenomenon incorporating ecological, economic and sociological aspects. An holistic perspective is necessary to consider these dimensions. The inherent complexity of real world agricultural systems implies an inductive, rather than deductive analytical approach. As an inductive modelling procedure, system dynamics is able to represent the underlying feedback processes that define those ecological economic processes relevant to an understanding of sustainability. Through such an understanding, the analyst is able to facilitate change towards the ultimate goal of holistic system sustainability. A case study model is developed to indicate the relevant modelling procedure and outline some guidelines for interpretation.

The Problem of Agricultural Sustainability

Agricultural sustainability is now a central focus for agricultural research organisations and practicing farmers throughout Australia. The sustainability focus reflects the attention and concern shown for the observed degradation of agricultural land and water resources. Such concerns are sharply emphasised during periods of drought and with river system contamination episodes.

The implications of non-sustainable land use practices are now widely recognised to extend beyond landholders into the social and ecological dimensions. Support for this view is provided by the research agendas for rural industry research organisations and by governments at all levels.

Campbell and Siepen (1994) included the following summary of current land degradation problems in this country:

- Various combinations of soil erosion, salinity, acidification, soil structure decline, waterlogging and water repellency affect a significant proportion of the land used for agriculture.
- Fresh water resources (both ground water and surface water) are threatened by salinity, eutrophication, sedimentation, contamination with agricultural chemicals and municipal and industrial wastes. Riparian environments commonly suffer ecological disruption through altered flow regimes caused by regulation for irrigation and urban water supplies.
- Half of the tall and medium forests (higher than ten metres) and about 35 per cent of the woodland have been cleared or severely modified, so that, since European

settlement, the area of Australian land under forest has been reduced from ten per cent to five per cent and of woodlands from 23 per cent to fifteen per cent.

- Ninety-seven species of vascular plants are extinct and 3329 plant species (seventeen per cent of the total) are either rare or threatened.

- Twenty species of mammals and ten species of birds are extinct and a further 111 vertebrate species are considered endangered.

- At least ten per cent of Australia's flora now consists of introduced species, some of which (including Mesquite, Mimosa Pigra, Prickly Acacia, Rubber Vine, Bitou Bush, Lantana, Blackberry etc) have been ecologically disastrous.

- Similarly, rabbits, foxes, cats, pigs, donkeys, camels, horses, goats and cane toads (among others) have been deliberately introduced to Australia and have become significant pests, causing widespread land degradation and either destroying the habitat of or directly consuming native flora and fauna.

Various 'movements' have arisen to address the kind of issues listed above. One response that has attracted international interest and widespread support from the farming community is the National Landcare Program. This program involves the application of government money to producer initiated and controlled land restoration and management projects. Landcare has been a unique experiment in community/government cooperation with an emphasis on holistic or total resource management. Resource managers control projects designed to achieve maximum community impact. Both the rural economy and ecology are now integral components within the farmers' sphere of influence.

Another movement of interest that has focused attention on ecological-economic relationships and sustainable resource management is the work of the Holistic Resource Management Center based in Albuquerque, New Mexico. Savory (1988) has prepared a holistic management philosophy to guide the thoughts and practices of farmers throughout the world. Packaged as a philosophical/cultural system of management, Savory's Holistic Resource Management Model (HRM) is creating pervasive interest in this country, particularly evidenced by the widespread adoption of time control or cell grazing practices as an integral component of the model. As outlined in his contribution to the Journal of Ecological Economics (1991), the HRM model is an articulation of systems philosophy with the novel incorporation of grazing pressure, animal impact and pasture rest as management tools. The various insights presented are often controversial in at least the scientific community where the scientific validation of many key claimed ecological relationships have yet to be produced. Though many of the claims underlying the HRM model remain to be scientifically substantiated, they do seem to be at least intuitively supportable. A central problem with regard to the widespread acceptability and utility of the model is the actual process of scientific verification. It may be argued that ecologists working through a less than holistic perspective will have great difficulty in testing the relevant relationships which can only be realistically described from within an exclusively holistic viewpoint. There is evidence of impatience from the farming community with regard to the apparently slow pace of scientific verification. Adoption (particularly of cell grazing as a management process) seems to be accelerating regardless.

Views on Sustainability Planning

Perhaps the weakest link in the articulation of ecological-economic holistic principles to practical farm management is in the area of farm planning. Farm management economists generally persist with traditional analytical tools such as cash flow budgeting and partial analysis to assess and plan management routines. General characteristics of 'traditional' farm management analysis include:

- an exclusive orientation to financial outcomes;
- a partial consideration, at best, of stochastic relationships;
- a general incapacity to consider key feedback processes;
- a general unwillingness to undertake multi-disciplinary work;
- a general orientation to static rather than dynamic analysis; and
- a general orientation to determinism.

All these characteristics are features of a non-systems or non-holistic framework. The problems generated from such an approach include an unrealistic appraisal of dynamic ecological-economic interactions. A likely outcome of ill-considered system dynamics might be resource degradation and other manifestations of non-sustainability.

A theme common to both the Landcare movement and the Holistic Resource Management model is the notion that holism is a central prerequisite to sustainable production planning. Ecological and economic relationships are of equal, and linked importance. The assumption of an exclusively financial perspective for farm planning is a high-risk strategy in ecological terms. The assumption of an exclusively ecological perspective is a high risk strategy in financial terms.

Deductive and Inductive Methods for Resource Management Planning

At a fundamental level, system modelling efforts may be either inductive or deductive in orientation. Deduction has the longest tradition. Linear programming, dynamic programming and similar approaches are founded on a specified objective function (or set of objective functions) for which quantitative solutions are derived. Solutions are defined in terms of an optimal or advised arrangement of resources consistent with the derived solution. Such models are always based on a sometimes extensive set of assumptions or axioms about the behaviour of the system and its components. Many of these axioms (such as linearity and homogeneity) are generally concessions to modelling technique or capacities rather than to the reality of the situation under review. Deductive modelling may involve varying degrees of consideration of stochastic effects. A stochastic deductive model is no longer deterministic, due to the ensuing inherent uncertainties relating to outcomes. It is, however, still orientated to prediction (expressed in probabilistic terms).

Inductive modelling, alternatively, is not orientated to the prediction of future outcomes. The purpose of inductive approaches is the exploration of dynamic system relationships. The presumption is that systems can best be controlled only through an understanding of underlying processes of cause and effect. The modelling process is an end in itself. The product of such an exercise, is an understanding of dynamic system processes. Models tend to be detailed and realistic rather than abstract. Abstraction, though inevitable, must be carefully applied to avoid missing out on what might prove to be key functional relationships. Inductive models should, by definition, be holistic. Holism, in this context, means that any relationship considered to be an important component of overall system causation, should be included in the model. Strictly, all system components should be included as all components are causally relevant. Practically, some abstraction is required. There are various philosophical arguments that might be presented to suggest the impossibility of holistic modelling. In the tradition of institutional economics, for example, it might be suggested that the abstraction inherent in any formal modelling exercise implies an unacceptable truncation of reality. The more pragmatic approach of those in the system dynamics area would, alternatively, suggest a carefully managed approach to the degree of abstraction allowed. It is reasonable to suggest that a formal model without abstraction is an impossibility. Without abstraction, formal analysis becomes an exclusively qualitative exercise.

The Nature of Farming Systems

Socioeconomic–ecological systems, including farming systems, invariably consist of non–linear relationships. Feedback processes may, for example, describe a non–linear pattern of change. Feedback may promote an accelerating rate of progress (described by increasing returns) or a tendency towards stability (defined as negative feedback). One of the fundamental tenets of the institutional perspective is that an investigator's capacity to appreciate the nature of system causation will depend on his or her capacity to conceptualise underlying non–linear relationships of this nature. It follows that to adequately portray such a system with a mathematical model will involve the use of non–linear equations. To quote from Gleick (1987, p.24),

> *'Nonlinearity means that the act of playing the game has a way of changing the rules. ...Analysing the behaviour of a non–linear'... system...'is like walking through a maze whose walls rearrange themselves with each step you take.'*

Since a non–linear system is unlikely to yield an exact analytical solution, simulation is an appropriate methodology where the focus of the investigation is on the behaviour of the system over time. Non-linear dynamics is an observable phenomenon in most farming systems.

The behaviour of such a system is not amenably investigated through the application of an orthodox deductive 'reductionist' approach. If the pieces of the system are abstracted and investigated in isolation, the analyst will lose sight of those relationships which bind the system components together. In accordance with the holistic perspective, it is those binding relationships that are the primary focus of interest. An understanding of these is fundamental to deriving an appreciation of system causality.

System Dynamics as an Approach for Sustainability Planning

System dynamics is the application of feedback control systems principles and techniques to managerial, organisational, socioeconomic and ecological economics problems (Roberts 1978). The approach may be traced to the engineering area as a systematic methodology for the analysis of information feedback systems. The application of feedback control systems to management–related applications became focused within Forrester's Industrial Dynamics program at the MIT School of Industrial Management. Forrester (1961) was the first major publication associated with the area to become known later as system dynamics. Essentially, Systems Dynamics is an extension of the case study approach to planning (Forester 1961).

Under the system dynamics approach, planning problems are represented in dynamic causal flow diagrams that represent organisational relationships as a sequence of levels and rates. Levels represent accumulations of resources such as physical stock inventories, pools of employees and so on. Rates include all activities within a system such as flows of effort, streams of information and payments for expenses. Once a system is represented in this way, it could be transcribed into a dynamic, continuous–systems simulation routine for analysis. The simulation approach can involve entirely endogenous, non–linear causation within a dynamic framework. In other words, the approach can be successfully employed to analyse holistic, dynamic systems in an inductive way. Various commercial implementations of system dynamics are available for micro computers. Examples are DYNAMO, STELLA II and POWERSIM.

In his review of the system dynamics framework, Wolstenholme (1982) emphasised the distinction between qualitative and quantitative analysis. He claimed that this distinction was most important for the analysis of 'soft' systems which involve at least some hard–to–measure relationships or may involve a purely qualitative pattern of causality. The descriptive or qualitative modelling phase could, '...particularly in the case of very soft systems...', be considered '...as an end in itself, or as a forerunner to simulation analysis' (Wolstenholme 1982, p.554). The quantitative modelling phase could focus on specific follow–up areas of inquiry:

> *'...the process of diagram examination facilitates identification of critical factors or restrictions and leverage points where the biggest impact on performance might be achieved. This can often lead to implications concerning the use of more specific and detailed modelling techniques to further understand individual links of the diagram. In other words, systematic guidance to the application of more formal system techniques is facilitated.' (Wolstenholme 1982, p. 554)*

Like all inductive modelling approaches, system dynamics modelling is not directly useful for predictive purposes. Forrester (1961) claimed that the prediction of future values of variables in a complex socio-ecological-economic system composed of numerous interacting feedback loops is impossible. The main application of the system dynamics methodology is to the specification of system structure and behaviour. The main focus is on the explanation of observable behavioural phenomena. Even if the system dynamics approach could be applied to predictive purposes, the results may well be rendered meaningless given the continual state of flux inherent within dynamic systems. This is not, however, to say that such approaches are without application to problems involving an intertemporal aspect. There can be little doubt that a sound basis for any predictive purpose is a thorough appreciation of existing causal structures. This is the nature of prediction through the application of inductive analytical methods.

An Example Application of Planning for Sustainability with System Dynamics

"Gumflat" is a 400 hectare block of unimproved grazing country located in the Northern Tablelands area of New South Wales, Australia. The owners are contemplating a development program for the block to generate income. Over the past twenty years, the main return has been in the form of environmental amenity (the owners derive considerable satisfaction from owning an essentially natural ecosystem). The property is heavily timbered. The traditional development for properties of this nature is extensive clearing and pasture improvement to support either a sheep and/or cattle production. Extensive clearing, however, is inconsistent with the owners' aesthetic goals, and, probably the ultimate ecological economic sustainability of the system (this assumption is an hypothesis to be tested in the subsequent modelling exercise). Sustainability (defined in a collective ecological economic context) is an explicit goal of the owners. Consistent with their perceptions relating to the nature of a sustainable system, an agroforestry operation in conjunction with a sheep grazing enterprise is their most favoured development option.

A system dynamics model was developed using the STELLA program. The ensuing model comprises six interrelated parts or sub-models as outlined in the high level map presented in Figure 1. The model attempts to integrate the ecological, economic, financial and aesthetic aspects of the system under review. All these components are linked together in the model. Causality is represented as a circular or feedback-driven process.

The ecological sector is described by three key measures of sustainability. Soil biota populations, soil compaction and soil moisture level are three interrelated accumulations that together, are indicative of the overall ecological sustainability of the system over time. A key feature of these sustainability relationships is the application of system dynamics 'table functions'. Table functions are a mechanism employed in system dynamics modelling to incorporate non-linear and/or difficult to specify influence relationships for 'soft system' variables such as aesthetic returns and difficult–to–quantify variables like operator bias or willingness to innovate. An important table function describes the impact of grazing pressure on soil compaction. Based on the concepts presented by Savory (1988), grazing impact from medium to high stocking rates may be consistent with a reduction in soil compaction. The relevant table function relationship employed in the model is illustrated in Figure 2. Another describes the relationship between rainfall and soil biota populations (Figure 3). As with many of the table functions in the model, these relationships are non-linear. These, and other similar ecology-related relationships are based only on an intuitive understanding of the effects represented. A major imperative for subsequent analysis is to validate the various relationships through scientific research. To the extent that many relationships represented in the model are effectively hypotheses to be tested, the model, at this stage, presents an agenda for subsequent research rather than a definitive statement of system cause and effect.

Figure 1 High Level Map of an Holistic Management Model

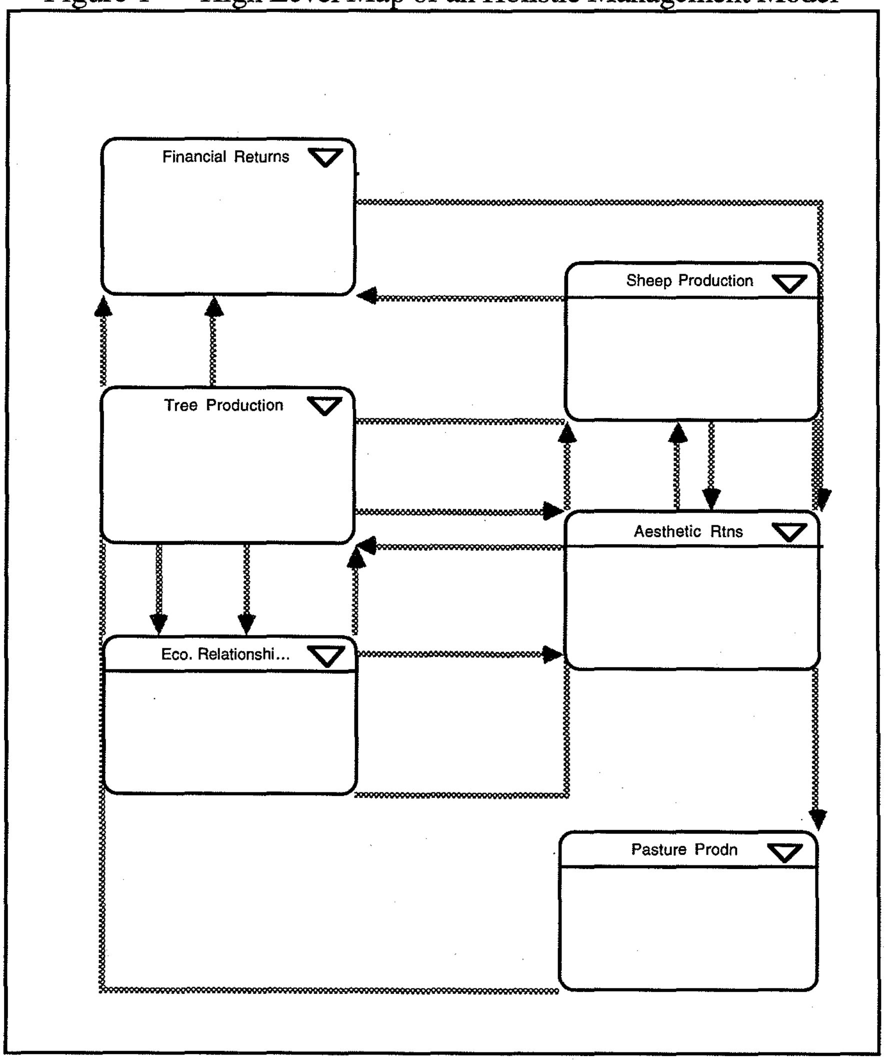


Figure 2 Grazing Pressure/Soil Compaction Table Function

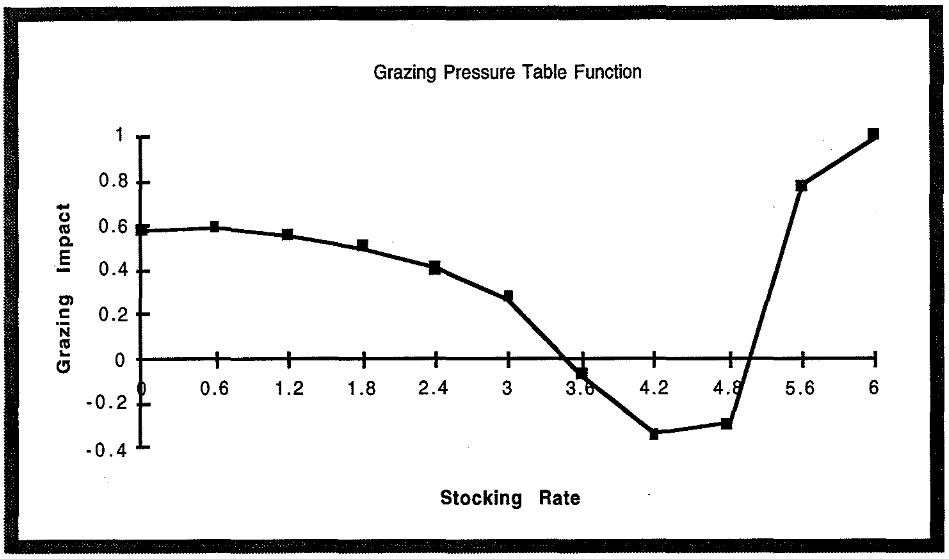
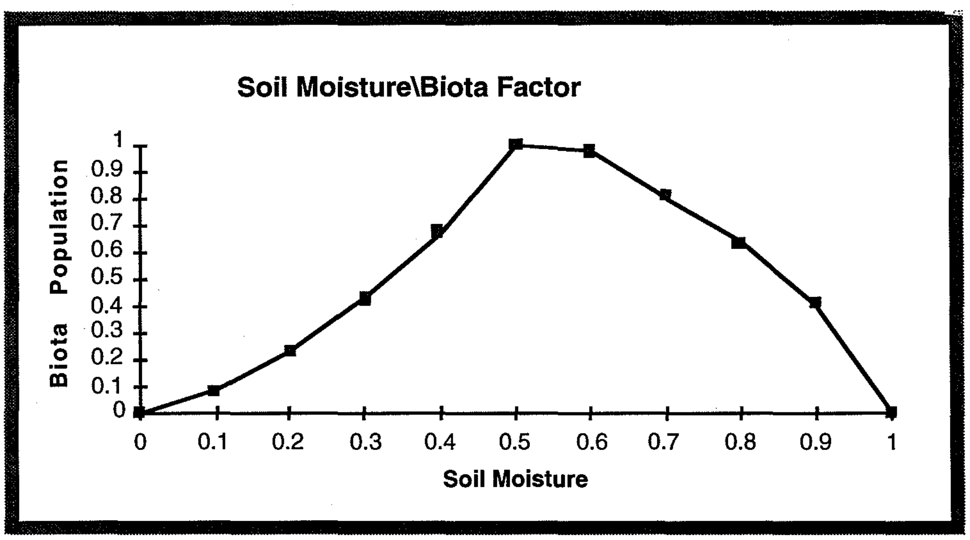


Figure 3 Soil Moisture\Biota Factor Table Function



The most important feature of the model, as specified, is the significance of ecological–economic interactions. These are described through various complex feedback arrangements that extend throughout the model, as would be the case in reality. All sectors of the model, for example, are linked through the influence of the overall Sustainability Index. Sustainability influences pasture carrying capacity and tree harvesting rates. These production rates, in turn, influence the rate of change in financial returns. Sustainability also influences the time path of aesthetic system goals. Production rates, financial and aesthetic returns, in turn, feedback to influence overall sustainability thus completing a circular path through the system.

Simulation results are presented in Figures 4 to 6. Financial returns from sheep, timber and in aggregate are presented in Figure 4. As all relevant price and yield components are described stochastically, the returns are variable, with a significant relationship to season quality (described by rainfall). Timber returns are relatively more stable than those from sheep, thus constituting a useful risk management strategy for the farm. Total net cash flow ranges from around a $50 000 loss at the outset of the development to around $20 000 depending on season. From the plot for cumulative balance, the development covers its costs, including loan servicing charges, within 22 years.

Figure 4 Financial Simulation Results

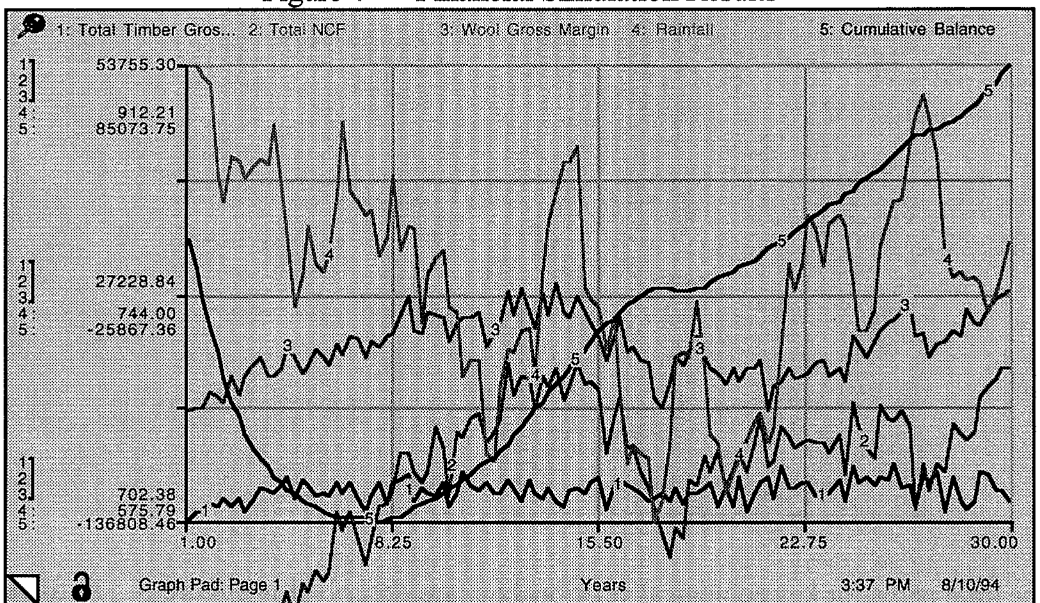


Figure 5 Ecological Sustainability Results

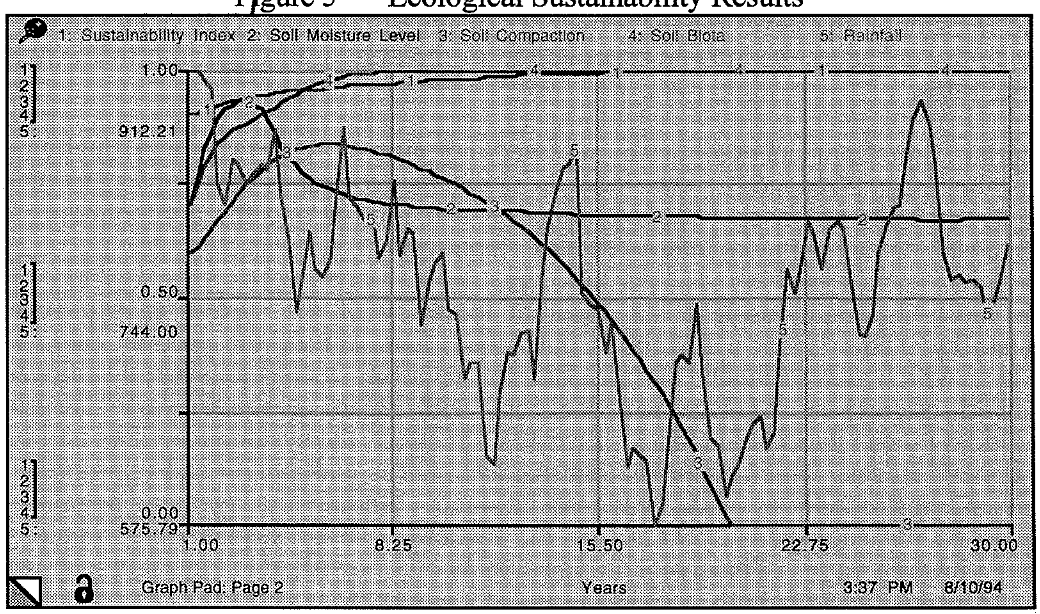
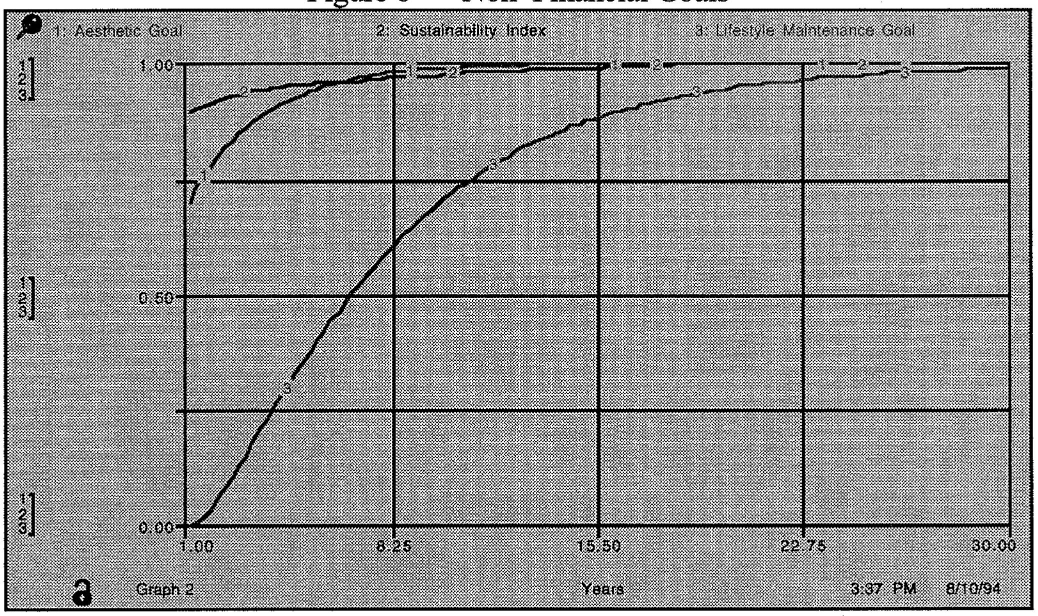


Figure 6 Non–Financial Goals



The time paths for key ecological relationships are described in Figure 5. In the early years of the development, soil moisture rises to a maximum, and, combined with a low initial stocking rate, contributes to an increase in soil compaction. As stocking rates increase and soil moisture levels decrease to a more acceptable lower level, the overall sustainability index increases to a peak in year 15 and remains at that level for the remainder of the simulation. The achievement of ecological sustainability enhances the income generated from the system through improved (higher) livestock stocking rates.

Operator non–financial goals are represented in Figure 6. All goals are gradually realised in time (as sustainability is reached). The lifestyle maintenance goal is the slowest to realise given the inherent variability of sheep–related production and returns and the compounding effect of loan service costs (set at an annual interest rate of 12 per cent).

The most important result is the apparent tendency of the system to self–organise towards sustainability. This is not a fortuitous outcome. It is, rather, the product of in–built feedback processes which automatically compensate for adverse stochastic system influences (such as drought) through time. Management decisions with regard to stocking and harvesting rates are controlled by these internal feedback processes. In effect, the system describes an ideal sustainable management process which assumes that management is continually and appropriately responsive to the ecological condition of the resources at hand. Should management response be less than attuned with the ecological dynamics of the system, overall sustainability could just as easily decrease through time. The major implication is that sustainable management requires a high degree of empathy with both ecological and economic system influences. Such a notion is in complete accord with the philosophy of Savory's HRM model and with the general concepts of Landcare.

The specific results presented in Figures 4 to 6 must be regarded as indicative only. The performance of the system is highly dependent on rainfall patterns and commodity prices. Given a virtually unlimited array of possibilities for the key sensitive parameters, a similarly infinite array of outcomes are also possible. This is the nature of inductive modelling. The results are not realistically useful for predictive purposes. In combination with the model, they are, however, meaningful as a mechanism with which to undertake sensitivity testing and to explore the nature of system cause and effect. A modelling exercise such as this will reveal patterns of influence that might otherwise be obscured within the complexity of the system.

Conclusions

Planning for sustainability in agricultural systems must be approached from an holistic perspective. The dimensions of any planning process will extend to economic, ecological and sociological interactions. Sustainability is a broad–dimensioned goal best considered through a collective process of multi–disciplinary consultation. Such a process imposes some heavy demands on the organisational capacities of the investigator. Formal system dynamics modelling is a workable and effective mechanism to enable the systematic exploration of system sustainability. As an inductive modelling process, a model is constructed for the insights it might yield with regard to inherent processes of cause and effect. It is strongly recommended that models of this nature be constructed as a collective exercise between individuals with specialised knowledge encompassing the range of economic, ecological and sociological influences inherent within the system under review. In this regard, system dynamics modelling may be considered as a mechanism through which the necessary multi–disciplinary research might be organised and articulated.

The major strengths of system dynamics modelling as an approach to sustainability planning are in its capacities to explicitly model dynamic, non–linear feedback processes and the various 'soft system' components that are inevitably relevant as explanators of overall system behaviour. As a bonus, programs such as STELLA employ a modelling procedure that is straight–forward for non–expert users and generates results that require little prerequisite knowledge to guide interpretation.

The system dynamics procedure has other capacities not extensively discussed in the preceding analysis. Most important of these is its capacity to represent complex, potentially chaotic, system behaviour. The ultimate challenge is to represent learning processes within a model structure. A model with the capacity to re–write its own internal rules (or feedback relationships) would be one step closer to observed reality and one step further from the now distant partial/reductionist abstract modelling that unfortunately remains at the centre of 'traditional' farm management analysis. This last challenge is a centrepiece of the Centre for Agricultural and Resource Economic's research agenda and is an appropriate focus for the ecological economics movement in general.

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