Simulating the Feedback Between Land Cover Configuration and Ecohydrological Functioning in Complex Adaptive Landscapes

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EXTENDED ABSTRACT

Within Australia, excessive clearing of native vegetation has resulted in many landscapes becoming increasingly dysfunctional with respect to the retention of water and nutrients, and the maintenance of biodiversity. Natural Resource Management (NRM) groups are now engaging in 'on-ground activities' based upon their respective regional plans to address many of the issues that have arisen from the inappropriate or excessive removal of native vegetation across the landscape. From a land manager's perspective, the performance of alternative landscape designs that incorporate native vegetation as a key functional component to address processes that aid soil structure and stability, fertility, and water available for plant growth. Catchment managers must deliver considerable improvements in soil erosion, riparian vegetation condition, water quality, and environmental flows. The multiple functions of native vegetation and their affects upon hydrology throughout the landscape over time are termed ecohydrology in this paper.

Under varying management and seasonal influences, differing amounts and spatial configurations of native vegetation and other land covers, can result in numerous possible feedbacks to local micro-climates. This subsequently affects the flows of water, nutrients, and sediments across the landscape. Landscape designs that use native vegetation or other vegetative covers to improve ecohydrological functioning within production landscapes, must equally address environmental, economic, and social values. This should be considered across a continuum of spatial scales and through time. This is of particular importance in the face of climate change.

The reciprocal feedbacks between physical and biophysical processes as well as the multitude of human land use modifications to these systems, results in bottom-up, non-linear, complex adaptive landscapes. Such incessant adaptations within and between landscape components and their supporting systems may result in landscapes residing in one of a number of multiple quasi-stable states which depends upon historical conditions and current positive and negative feedback mechanisms between components. The use of historical data to infer likely future responses may therefore, lead to erroneous inferences. Complex adaptive systems offers a means by which landscape complexity can be reduced to common component types, and their possible states, via feedback mechanisms captured in a much simplified form.

The paradigm of complex adaptive systems also lends itself to comparable modelling approaches that utilise bottom-up organisation based upon simple rules and a large number of components. One such example introduced in this paper is agent based models. This method develops a coupled simulation model that integrates an agent rule based optimization process with the outputs from ANSWERS-2000 (Dillaha *et al.* 1998).

ANSWER-2000 is a distributed parameter hydrological process model that generates both climatic inputs in the form of variable frequencies, durations, and intensities of precipitation, as well as probable runoffs of water, nutrients, and sediments from various land cover types. Using the output files generated at each iteration as inputs into the agent based model, numerous possible configurations of land cover types are tested in order to find optimised soil and water outputs across the landscape.

Farmer expert knowledge is used to generate the initial rule set, while successive iterations alter the rules to find possible alternatives that may lead to designs for rehabilitating dysfunctional catchments. The focus is on understanding which parts of the landscape native vegetation provides a key role in regulating ecohydrological functions, and which configurations may lead to more sustainable production outcomes.

1 INTRODUCTION

Rapid transitions from native vegetation systems to predominantly cleared production landscapes comprised of exotic annuals has been partly responsible for the loss of resilience within Australian landscapes. Maximising production at the cost of adverse landscape function has been cited as the principle causes of greater water and nutrient leakiness, as well as significant losses to biodiversity (NLWRA 2001; Williams and Gascoigne 2003). As Australia's rural industries are underpinned by the natural resource base (Reuter 1998), we need to continually improve our understanding of the feedbacks of primary production on landscape function (Ernoult *et al.* 2003).

One aspect of landscape function that is of high priority, are the potential effects of native vegetation configurations for the capture and use of water within the headwaters of catchments, and for the enhancement of water quality and environmental flows (CSIRO 2004). Potential landscape designs must recognise and manage a landscape as an integrated dynamic system comprised of complex natural and modified components that together constitute landscape structure (Reuter 1998; Veldkamp *et al.* 2001; Williams and Gascoigne 2003).

Native vegetation is a fundamental structural and functional component of the landscape that promulgates self-organisation across scales, such that its modifications or replacement at the patch and landscape scales has direct and indirect affects on the capacity of landscapes to cycle nutrients, to retain sediments and nutrients, and to produce food, fibre, and wood (Rapport *et al.* 1998). Understanding these complex interactions within and between landscape systems and human land use is a prerequisite for instilling confidence in predictions of the likely landscape response to a given set of modifications (Barrett *et al.* 2001). To achieve this, we must translate landscape complexity to models that capture the components, interactions, and scope of the particular systemic dynamics that are appropriate to focal processes (Pickett and Cadenasso 2002).

To simplify real-world landscapes to relative and tractable models, the inherent complexities of landscapes must be reduced to fewer and more simple component types, which includes explicit recognition of the reciprocal non-linear feedback mechanisms that operate between components of landscape systems, which in turn give rise to emergent levels of organisation across a continuum of scales. Such organisational attributes may be approximated using the paradigm of Complex Adaptive Systems (CAS).

Holland (1995) suggests that CAS result from the simple local interactions of a large number of interacting components, which are diverse in both form and function. Of marked importance however, is that at any given level of complexity or at any hierarchical level within CAS, there are emergent properties that cannot be readily explained by reference to lower levels (Clayton and Radcliffe 1996; Parker *et al.* 2003).

Once we achieve a suitable approximation of the key feedbacks between physical, biophysical, and human land use systems using the CAS paradigm, we may further explore the possible effects of modifying components and their configurations within a simulated environment. By necessity, models would best be suited to capture bottom-up processes as in their real world counterparts. The term 'bottom-up' refers to the emergence of behaviours and patterns, as opposed to 'top-down' prescribed rules or requirements.

An example of a bottom-up modelling approach are multi agent systems or agent based models, which have generated considerable interest in recent years as a tool for exploring numerous types of bottom-up processes (Box 2002). These modelling approaches have the potential to link several levels of organisation in simulations (Le Page *et al.* 2004), enabling macro-scale behaviours/patterns to emerge from the aggregate interactions between component 'agents' and their environment (Torrens 2004). As landscape pattern or land use decision making are emergent phenomena, agent based systems may be particularly well suited to capture both biophysical processes and socio-economic decision making (Parker *et al.* 2003).

In this paper, we present a simulation model based upon a coupled hydrological process model and agent based system configured as a constrained optimisation process. The principle aim is to explore two important questions related to native vegetation management in production landscapes:

1. components types – how does the type of vegetation cover in different locations affect landscape ecohydrological functions (water, nutrient, and sediment retention) under differing climatic regimes (particularly climate change); and
2. configurations and extent – where do we locate the different vegetation types to maximise the desired set of ecohydrological functions?

2 METHOD

The model outlined within this paper is based upon the following interrelated stages:

- eliciting expert knowledge from farmers within the Western Catchments of the Brisbane River;
- generation of rule sets from farmers expert knowledge;

- parameterisation of a distributed parameter soil and water process model;
- development of a basic agent based model to utilise the output of the soil and water process model; and
- a loose coupling of the two models using the rule set to provide a constrained optimisation process related to testing the impacts of configurations of land covers on soil and water movements within the Western Catchments.

The general linkages between the soil and water process model and an agent based simulation, involve the development of GIS raster and vector data, parameterisation of the hydrological model, sharing of ascii files, and an autonomous object oriented programming platform for developing agents. The general architecture and procedures of these linkages are shown in Figure 1.

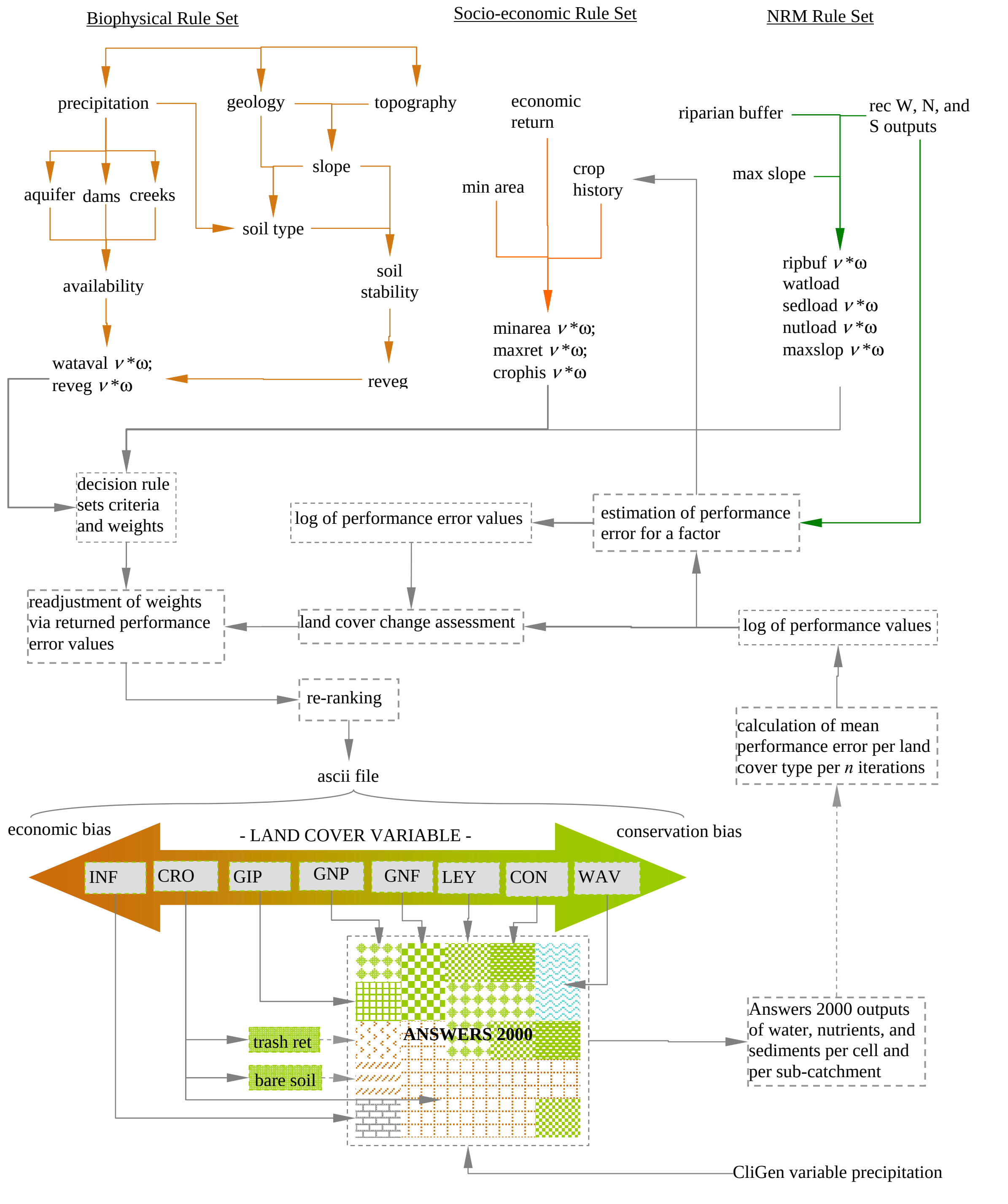

Figure 1. Schematic diagram of agent rule set and the flow of information between biophysical, socio-economic, and NRM variables, and Answers 2000. INF = infrastructure; CRO = crop; GIP = grazed improved pasture; GNP = grazed native pasture; GNF = grazed native forest; LEY = ley period; CON = conservation; WAV = water. (ν *ω = probability value x weighting)

2.1 Expert Knowledge and Rule Set Generation

Expert knowledge refers to an individual farmers preferences for a given set of land use practices based upon learning experiences and skills, markets, environmental stewardship, the legislative/policy arena, peer interactions, and opportunities for funding. These factors, over time, form a comprehensive and often overlooked source of information on the driving forces of change within production landscapes. The elicitation of expert knowledge has been achieved through a series of interviews and surveys comprised of farmers within the Western Catchments section of the Brisbane River Catchment, Southeast Queensland.

The capture of expert knowledge provides pertinent information on:

1. farmer decisions on which land cover to apply in what part of the landscape, and when it is likely to be applied in average years;
2. size of land use areas and frequency of management applications;
3. farmers response to changed climatic conditions, such as prolonged dry periods;
4. values attached to ecohydrological functions that support production and the natural resource base; and
5. importance, location, and size of risk areas associated with dysfunctional ecohydrology that a farmer may address in any one year.

The responses from a survey of 27 farmers provides the outline for a generalised set of rules for the agents. Rules are based upon probabilities derived from analyses of respondent choices using Bayesian belief networks. This procedure provides the probabilities that a location within the landscape being in state A (a given land cover) will proceed to state B (an alternate land cover) under some driver (or set of drivers), such as extreme climatic conditions or risk of experiencing ecohydrologically dysfunctional states (e.g. erosion, nutrient loss).

2.2 Biophysical Process Model

This procedure involves the application of ANSWERS-2000, a distributed parameter hydrological process model used to evaluate the effectiveness of agricultural 'best management practices' in reducing sediment and nutrient delivery to streams in surface runoff (Dillaha *et al.* 1998).

The setting up and running of ANSWERS-2000 is based upon a number of variables of differing spatial extent, resolution, and completeness, all of which can be applied within ArcView 3.2, and later extended with ArcInfo 9 modelling capabilities. Long-term stream fluviograph and water quality monitoring data, which are very sparse in most Queensland catchments, are not entirely necessary to run the model successfully.

ANSWERS-2000 will be run on the case study catchments at a resolution of 25 metres, and subsequent outputs of water, nutrients, and sediments will be written to an ascii file for each raster grid cell, as well as for the confluence of the sub-catchment. This ascii file is then exported to agent 'objects' using Python scripts in ArcInfo 9.

As climate is a core driver of most ecohydrological processes, the effects of variable climatic regimes on outputs of water, sediments, and nutrients must also be incorporated into agent decisions on land use type and configuration. ANSWERS-2000 uses the CliGen climate generator to partition average annual precipitation into differing climatic events per iteration (daily or monthly). This allows the effects of extreme dry and intense storms (typical in Queensland) on soil and water movements to be tested under differing land covers.

2.3 Agent Based System

The agents within this simulation are assigned both a global and local rule set. Global rules refer to those rules which apply to all agents at all times throughout the course of the simulation, while local rules may be modified throughout the simulation based upon an agents individual experiences after a number of iterations. These agent rule sets are outlined based around three basic principles as suggested by Holland (1995):

- performance system – the capabilities of the agent;
- credit assignment system – assigning weights to parts of the system which are either at fault or advantages the agent; and
- rule discovery – making changes to the agent's capabilities, based on prior performance of low credit parts.

2.3.1 Global Rule Set

The setup for the agents revolves around an object oriented approach. A Python based script from ArcInfo 9 can provide the necessary library of classes for creating, running, collecting, and displaying data from the agent based simulation and ANSWERS-2000. Using the topological relationships created by ArcInfo 9, each agent is partitioned a group of cells based upon areal extents of land cover types as typically applied within mixed cropping/grazing landscapes. This is relatively straight forward, as agent based systems can be complementary to raster GIS (Itami 1994; Wu and Webster 1998).

Agents manage a group of grid cells and interactions between other cells using a two-dimensional list of discrete topological attributes (Box 2002). Elements generated as output from ANSWERS-2000, are provided with unique identifiers that enables the exchange of information between ANSWERS-2000 and the simulated agents. The principle objective is to allow the environmental variable of land cover to be updated by the agents after each iteration of a monthly cycle within ANSWERS-2000.

As each agent is responsible for a discrete group of cells (elements in ANSWERS-2000), the outputs for any factor (Ψ) of water (W), nutrients (N), or sediments (S), is firstly related to each cell (c_{ij}), and secondly to the group of cells the agent manages ($\{c_{ij}$). Equation 1 provides the average output per cell for a given function under some land cover for the current iteration

$$Pf_{t1} = \frac{\sum \Psi . c_{ij}}{\sum \{ c_{ij}} \qquad (1)$$

where
Pf_{t1} = is the performance function
Ψ = a factor (W, N, or S)
c_{ij} = a cell at location i,j
$\{c_{ij}$ = an agents set of cells

An agent assesses the current performance (Pf_{t1}) of the land cover configuration for a given factor (Ψ) for their group of cells (c_{ij}), and compares this value to previous values (Pf_{t0}). As the growth of a woody plant (i.e. Eucalypts) will continually alter the ecohydrological functioning of a site anywhere between one and forty years (or more), these effects must be accounted for through a mean performance function (μPf). A run-time log of the Pf_{t0} values over the previous n iterations is used to provide the μPf, and thereby an estimate of the importance of changes in the structure and function of woody vegetation over time.

The outputs for a factor (Ψ) over n iterations is related to the current land cover configuration, and assessed against a pre-determined threshold or target value ($_{rec}Pf$). This value is also derived by expert knowledge from NRM officers and landscape ecologists. The difference between the two values is termed the performance error (Pf^e) as given by Equation 2

$$Pf^e = \frac{_{rec}Pf_{t_n}}{\mu Pf_{t_1 - t_n}} \qquad (2)$$

Agents may then evaluate changes by comparing the current Pf^e value with the $_{rec}Pf$ value (Equation 3), which operates similarly to a threshold within a neural network

$$change = \frac{\mu Pf}{_{\text{rec}} Pf} =< 1 \qquad (3)$$

$$same = \frac{\mu Pf}{_{\text{rec}} Pf} =\geq 1$$

2.3.2 Dynamics of Agent Weighting Schemas

The initial input land cover configuration within the simulation reflects the current landscape state of the Western Catchments. As such, all land covers within the simulation are applied within a discrete area based upon the probabilities derived through Bayesian analysis of farmer expert knowledge. As each subsequent iteration of ANSWERS-2000 progresses however, the land cover variable is concurrently altered by the agents based upon the Pf^e values supplied by ANSWERS-2000 output for a land cover, and a weighting schema for each land cover.

Weighting schemas apply a numerical bias on the rule set for each land cover. That is, the bias is calculated based upon the Pf^e and applied to a weighting that either promotes or demotes the future chances of a land cover being selected due to prior performance for one or more factors (Ψ). Where output values are low for a Ψ under a given land cover for example, selection of these land covers are further reinforced (positive bias), while increased output values result in reduced probability that the land cover will be applied again (negative bias).

2.3.3 Idiosyncrasies of Agent Decisions

While all agents share the same set of global rules based upon probabilities for a land cover to be applied and ability to update weighting schemas, there are certain idiosyncrasies that any agent may arbitrarily develop. These relate to the selection of one of three primary utility functions when the simulation begins:

1. maximising the productive capacity of the landscape;
2. maximising the conservation of ecohydrological functions within the landscape; or
3. finding the ‘middle ground’ between these two extremes.

The selection of a primary utility function by an agent subsequently affects how the bias on weighting schemas are updated according to the returned Pf^e. For example, if a production focussed utility function is selected by an agent and the simulated outputs are low for a Ψ, the bias toward a land cover that is more likely to be economically rewarding, such as a type of crop, is afforded a larger positive bias on its weighting scheme. This increases the likelihood of this crop being selected in future iterations.

The inverse also applies where a conservation utility function is selected and outputs for a Ψ are high under a given land cover, it is more likely that this land cover will be assigned a large negative bias in its weighting schema. In this instance, transitions must be toward land covers that are amenable to regulating outputs for a Ψ more effectively, such as grazed pastures or agroforestry (planted Eucalypts).

In using such weighting schemas, agent objectives reflect the range of variations found within farmers attitudes toward management opportunities and constraints, such as economic and conservation costs/benefits and practicality of implementation. Farmers however, also rely on the experiences of their neighbours when deciding what may be a desirable course of action to take in any one season.

This is also incorporated within the simulation by allowing an agent to learn from the weighting schemas as applied by other nearby agents (basically – 'to look over the fence'). Both the agents own experiences and that of their neighbours are therefore, incorporated into an updated weighting schema for a land cover type under across a range of locations throughout the landscape. This process allows for the effects of landscape position on the subsequent flows of water (*W*), sediments (*S*), and nutrients (*N*), to be incorporated within the simulation.

More specific criteria for agents to evaluate each iteration are considerations of:

- potential economic output per land cover type mediated by land resource potential and management practices;
- minimum contiguous area of similar land cover types for marginal economic return;
- minimum contiguous area of similar land cover types for marginal conservation benefit;
- adjacency to riparian vegetation;
- biophysical constraints (e.g. steep slopes); and
- adjacency to infrastructure.

2.3.4 Complexity of Feedbacks Between Agent Decisions and a Variable Climate

If transitions from one land cover state to another were based purely upon locations within the landscape, finding optimal configurations for any given land cover would be relatively straight forward. Other factors however, affect the response of a landscape to land cover changes. These include time-lag effects of prior land cover configurations (landscape 'memory'), the present landscape state (configuration and stage of growth of vegetation), as well as stochastic inputs from precipitation. The subsequent effects of the type and timing of a land cover change further complicates the landscapes likely response.

One measure to account for such inherent complexity within the simulation, is to allow asynchronous updating of some land covers. This provides an amount of time for a land cover to be tolerated due to the need to estimate the possible changes in landscape responses from vegetation growth stage and possible variations in precipitation inputs. In this instance, a global rule provides constraints on when land cover types may be updated at certain time intervals (iterations) within any complete runtime cycle (40 years). This process allows for the effects of changes in growth structure, humus accumulation, leaf area index, runoff, and nutrient regulation and storage, upon the hydrological response of a catchment within ANSWERS-2000.

Depending upon the response of ANSWERS-2000 outputs to the configuration of the land cover variable, and the stages of growth of the vegetation within them, each agent that is responsible for managing that group of cells with values higher than a prescribed rate, reconfigures the land cover types within those cells. All agents make their respective decisions and the cumulative land cover alterations are tallied and written to an ascii file. This file is then exported back into ANSWERS-2000 for the next iteration. As the simulation progresses, each successive iteration updates an agent's weighting schema as constrained by their chosen primary utility function.

It is anticipated that where consistent patterns form within agent rule sets, and therefore in land cover patterns within the simulation, these may present possible land cover configurations in which to test ecohydrological design principles within the Western Catchments. The possible effects of such a design when implemented, may then be monitored with strategically placed piezometers and in-field weather stations, and the resulting data reincorporated within the simulation. This is a procedure related to adaptive management, where learning is reincorporated into experimental design.

3 CONCLUSION AND RECODMMENDATIONS

The coupled simulation model outlined within this paper highlights the potential for providing possible guidelines for the spatial extent and configurations of native vegetation to address ecohydrological functions within production landscapes. The simulation model developed through the coupling of ANSWERS-2000 and an agent based system, is designed to allow numerous alternative land use scenarios to be tested over larger spatial scales, particularly cumulative effects of localised land use decisions, as well as 30 to 40 year temporal effects of land use. Where simulated outputs of water, sediment, and nutrient outputs are below some pre-determined values after numerous iterations of the model, these configurations may then be validated in real world settings.

There are many debates over the existence of thresholds, and the points at which they occur within various landscape systems. Identifying critical thresholds for the clearing/restoration of native vegetation below which landscapes begin to display dysfunctional ecohydrological systems, may also be tested within this simulation environment. The model therefore, may be useful to NRM groups where they wish to test various hypotheses regarding where and how much native vegetation should be maintained/restored for the maintenance of one or more ecohydrological functions across the landscape.

4 REFRENCES

Barrett, D. J., Bates, B., Cleugh, H., Colman, R., Coops, N., Dix, M., Finnigan, J., Gross, J., Hobday, A., Howden, M., Mitchell, C., Rayner, P., Raupach, M., Robertson, M. and Wang, Y. P. (2001). *Earth System Science: A report from the CSIRO/BMRC Panel*. Canberra, CSIRO.

Box, P. (2002). Spatial units as agents: making the landscape an equal player in agent-based simulations. *Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes*. H. R. Gimblett. Oxford, Oxford University Press.

Clayton, M. H. and Radcliffe, N. J. (1996). *Sustainability: a systems approach*. Boulder, Westview Press.

CSIRO (2004). *Water for a Healthy Country National Research Flagship*. CSIRO. http://www.cmis.csiro.au/healthycountry/research.htm.

Dillaha, T. A., Wolfe, M. L., Shirmohammadi, A. and Byne, F. W. (1998). *ANSWERS-2000*. International ASAE Meeting - Paper No 982199, Orlando.

Ernoult, A., Bureau, F. and Poudevigne, I. (2003). Patterns of organisation in changing landscapes: implications for the management of biodiversity. *Landscape Ecology* **18** (3): 239-251.

Itami, R. M. (1994). Simulating Spatial Dynamics - Cellular-Automata Theory. *Landscape and Urban Planning* **30** (1-2): 27-47.

Holland, J. H. (1995). *Hidden order: how adaptation builds complexity*. Reading, Addison-Wesley.

Le Page, C., Bousquet, F., Baron, C. and Trebui, G. (2004). *a multi-agent toolkit to model natural resources management based on dynamics at multiple scales*. FIRMA. http://firma.cfpm.org/course/modelling/modeltoolkitw.htm.

NLWRA (2001). *Australian Agriculture Assessment 2001*. Canberra, National Land and Water Resources Audit (NLWRA).

Parker, D. C., Manson, S. M., Janssen, M. A., Hoffmann, M. J. and Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers* **93** (2): 314-337.

Pickett, S. T. A. and Cadenasso, M. L. (2002). The ecosystem as a multidimensional concept: Meaning, model, and metaphor. *Ecosystems* **5** (1): 1-10.

Rapport, D. J., Gaudet, C., Karr, J. R., Baron, J. S., Bohlen, C., Jackson, W., Jones, B., Naiman, R. J., Norton, B. and Pollock, M. M. (1998). Evaluating landscape health: integrating societal goals and biophysical process. *Journal of Environmental Management* **53** (1): 1-15.

Reuter, D. J. (1998). Developing indicators for monitoring catchment health: the challenges. *Australian Journal of Experimental Agriculture* **38** (7): 637-648.

Torrens, P. M. (2004). *An introduction to geosimulation for modeling urban environments*. http://www.geosimulation.org/geosim/.

Veldkamp, A., Kok, K., De Koning, G. H. J., Schoorl, J. M., Sonneveld, M. P. W. and Verburg, P. H. (2001). Multi-scale system approaches in agronomic research at the landscape level. *Soil and Tillage Research* **58** (3-4): 129-140.

Williams, R. J. and Gascoigne, H. (2003). *Redesign of plant production systems for Australian landscapes*. Solutions for a better environment: Proceedings of the 11th Australian Agronomy Conference, Geelong, Victoria. Australian Society of Agronomy.

Wu, F. and Webster, C. J. (1998). Simulation of land development through the integration of cellular automata and multicriteria evaluation. *Environment and Planning B-Planning & Design* **25** (1): 103-126.