Faculteit der Economische Wetenschappen en Econometrie

SERIE RESEARCH MEMORANDA

An adaptive agent model for analysing co-evolution of management and policies in a complex rangeland system

Marco A. Janssen
Brian H. Walker
Jenny Landgridge
Nick Abel

Research Memorandum 1999-53

November 1999

vrije Universiteit amsterdam

An adaptive agent model for analysing co-evolution of management and policies in a complex rangeland system

Marco A. Janssen

Department of Spatial Economics
Free University
De Boelelaan 1105
1081 HV, Amsterdam
The Netherlands
+31 20 44 46004 (fax)
+31 20 44 46092 (phone)
m.janssen@econ.vu.nl (email)

Brian H. Walker
Jenny Langridge
Nick Abel

CSIRO Wildlife and Ecology,
GPO Box 284,
Canberra ACT 2601
Australia
(Brian.Walker@dwe.csiro.au/
Jenny.Langridge@dwe.csiro.au/
Nick.Abel @dwe.csiro.au)

Abstract

This paper describes an adaptive agent model of rangelands based on concepts of complex adaptive systems. The behavioural and biological processes of pastoralists, regulators, livestock, grass and shrubs are modelled as well as the interactions between these components. The evolution of the rangeland system is studied under different policy and institutional regimes that affect the behaviour and learning of pastoralists, and hence the state of the ecological system. Adaptive agent models show that effective learning and effective ecosystem management do not necessarily coincide and can suggest potentially useful alternatives to the design of policies and institutions.

Keywords: Complex Adaptive Systems, Ecosystem Management, Rangelands, adaptive agents

1. Introduction

This paper explores the widespread problem of how to avoid a long term decline in productivity in savanna rangelands due to grazing, while still maintaining a livelihood in the short term (Walker 1979, Tothill and Mott 1985). We deal only with commercial systems, where changes in vegetation structure and soils are common causes of declines in productivity.

The problem arises out of the change from the pattern of vegetation use by wild animals on open range under which the ecosystem evolved, to the present patterns of use on commercial holdings. The former consisted of intermittent grazing by mobile herds, often of mixed grazers and browsers. Grazing pressure was usually lower than now, and fires relatively frequent. The system was adapted to rainfall that is highly variable in time and space. Under commercial management, the pattern has changed to one of constant, heavy grazing in fenced paddocks, often with permanent drinking water. This can lead to a reduced grass cover, little build up of fuel and infrequent fire. Browsing animals are uncommon, ranches being stocked mainly with sheep or cattle, both primarily grazers. Their feeding generally does not suppress shrubs. Common consequences are an increase in woody plants, and a decline in grass production per unit of rainfall (Stafford Smith and Pickup, 1992). These effects are recoverable to an extent, depending on the attributes of the landscape and the reduction of grazing pressure. However, de-stocking is expensive due to income foregone. Factors influencing range managers' decisions include the policy and institutional environment, and financial, forage and animal production considerations. In this paper we focus upon interactions between the policy and institutional environment and pastoralists' decisions. This is because of the potential for effecting widespread changes in range management through adaptive changes in policy and institutional settings (Abel, 1999).

The evolution of scientific understanding and policy advice for rangelands under grazing has progressed from a rather naive model based on linear, reversible succession (a too-literal interpretation of Clementsian theory), through recognition of hysteresis effects in recovery from loss of potential primary production, to the development of multiple stable state models, a pragmatic version of which is the state-and-transition model (Westoby et al., 1989).

An approach that gives useful insights on commercial systems is optimal control theory, in which it is assumed that the manager maximises some index of welfare (usually net income) over a specified time under a given discount rate (eg Per-rings and Walker, 1997). The critical assumption is that the manager is maximising a simple objective function, and is willing and able to adopt optimal patterns of stocking and burning.

An alternative approach, the subject of this paper, is to consider the rangeland, the pastoralists and the policy makers as a complex adaptive system (Holland, 1992; Abel, 1998). Complex adaptive systems can be studied by adaptive agent models that deal with a population of diverse and interacting agents (e.g. Janssen, 1998a; Carpenter et. al., 1999). Behavioural rules at the level of individual agents lead to emergent properties at the macro level. Instead of traditional deterministic equilibrium seeking models, adaptive agent models evolve, leading to irreversible structural changes. External and internal disturbances prevent the system reaching equilibrium.

A recent special issue of Science (April, 1999) gives an overview of disciplinary studies of complex (adaptive) systems. In this paper an interdisciplinary, or integrated model is discussed. Integrated models combine simplified versions of expert models of various disciplines (Janssen, 1998b). They combine social, economic and ecological sub-systems. One purpose of integrated models is to develop principles for managing and adapting to real complex systems.

Our rangeland model consists of ecological and socio-economic sub-systems. The ecological sub-system is a simplified version of more comprehensive models. Relations are empirically based. The socio-economic sub-system describes the “regulator” and the behaviour of pastoralists. The regulator comprises the policy and institutional environment within which pastoralists make management decisions. The socio-economic sub-system is based on theory and evidence from psychology (Abel et al., 1998; Jager et al., 1999), cultural anthropology (Thompson et al., 1990; Janssen and de Vries, 1998), economics (Ellis, 1988; Simon, 1947), and organisation and management (Roe et al., 1998; Sandford, 1983). Its political-economic background is in Abel, 1999.

Potential decision rules for pastoralists were developed in discussion with experts on rangeland management and simplified for the model. Both the decision-making environment and the pastoralists’ decision rules necessarily lack the complexities of real systems. We believe they retain sufficient complexity for the purposes of this paper, which are to:

- study patterns and emergent properties arising from interactions between the simple decision rules of policy makers and pastoralists and the dynamics of the rangeland;
- track and explain the evolution of simulated populations of pastoralists and the condition of the range under different regulatory regimes;
- contribute to the development of general principles about management and adaptation in ecosystems.

The paper has four parts: 1) a model of the ecological system, 2) an account of the social and economic system, 3) a description of the overall model and the results of a number of 'experiments' using the model, 4) a final section on the insights gained and the implications for further work.

2. The Ecological System

2.1 Model Description

Essential biophysical variables and their interactions, depicted in Fig 1, are sheep, grasses and woody plants. The model includes one hundred management units (pastoral properties, or ranches) which can be in one of two kinds of land system (Speight, 1988; Walker, 1991). Half the properties are in a land system with massive red earth soils prone to erosion and surface sealing and supporting grasses and mainly inedible or inaccessible woody plants. This is referred to as the '*mulga*' *(Acacia anew-a)* land system. The other half are in a drier, more calcareous land system with edible, chenopod dwarf shrubs and grasses. The biophysical model is based on Perrings and Walker (1997), Ludwig et al (1997) and Moore et al. (1997). It takes into account the growth of grass and woody plants in response to rainfall, and the effects of fire, grazing and browsing. The rates of grass and woody growth are modified by competition between themselves and each other. Smaller, younger woody plants have a greater inhibitive effect on grass growth per unit of woody plant biomass than do larger, older woody plants. To capture the essential dynamics of the system over time, including lag effects, a number of ecological processes are included. It is this set of interacting processes that gives each rangeland its characteristic behaviour, and it is what managers must manage. The processes are:

1. Reduction and recovery of potential primary production.

Change in the productive potential of the rangeland is reflected as a change in maximum possible grass production. Grass growth in response to a unit of rainfall is a function of the ecological state of the system, which is determined in this model by grass biomass itself. If, through heavy grazing, drought or a combination of the two, grass biomass remains below some minimum threshold level for more than one year, there is a decline in potential production (through reduced water infiltration and loss of perennial grasses). The process is represented by a progressive reduction in the maximum potential grass biomass (g_{max}) down to some minimum proportion of this value (O-l) depending on the kind of rangeland. Removing grazing pressure after potential primary production has been reduced allows the system to recover, and potential production to increase gradually. The extent and rate of reduced potential primary production as well as the recovery rate (with recovery being generally slower than reduction) are determined by the kind of land system. For the purposes of our model we equate the changes in the parameter 'q' with the loss and re-establishment of the spatial processes described in Tongway and Ludwig 1997. The actual spatial dynamics of run-off, run-on and soil nutrient status that underlie the net effect are much more complex than our model allows.

2. Changes in woody plant density and biomass.

Both the biomass and density (number per unit area) of woody plants are important in the dynamics of the rangeland. We need biomass to calculate browse and the densities of plants in various age classes in order to capture the time course of shrub encroachment and its effects on grass growth. Woody plants are determined initially in terms of density, calculated for four age classes - seedlings, establishing young plants within the grass layer, middle aged and old shrubs. For all but the seedling age class there is a mortality factor dependent on the amount of woody leaf browsed, rainfall and fire. Individuals move through these age classes with seedlings germinating when rainfall is above a threshold. Establishment of germinated seedlings also depends on the amount of competition from grass and existing woody plants. Leaf biomass is determined from a regression equation averaged for eight shrub species, relating shrub height to leaf biomass (Harrington, 1979). Seedling contribution to total woody leaf is negligible and ignored.

The intensity of the fire is dependent on the fuel load. The decision to bum is driven by the density of shrubs in the establishing age class and the fuel load at which a pastoralist is prepared to bum. Fuel load is the grass biomass remaining after grazing. It can accumulate to a maximum level, beyond which decomposition more than offsets the rate of accumulation. In the event of a fire the fuel load is removed, grass biomass reduced and shrubs are thinned differentially depending upon their age class and the intensity of the fire.

3. Livestock and wool dynamics.

The number of sheep changes through births, deaths, sales and purchases. We exclude additional grazing pressure from wild or feral animals (eg kangaroos, goats). Sales and purchases are dealt with in the next section. Mortality and natality are linear functions of the amount of grass and woody browse available for consumption. As forage increases above the amount required to maintain an animal, the growth rate increases to a maximum level. Likewise when forage falls below that required to maintain an animal, death occurs and increases to a maximum rate.

Forage consumption per head of sheep is a constant. We do not include mortalities due to factors other than forage.

Potential wool production declines linearly when green leaf biomass falls below a threshold of 75kg/ha (Freudenberger, 1999). For this model we assume, first, that the livestock produced or bought in the current year do not contribute to that year's wool yield and, second, that all leaf is green and includes (by definition) that available as woody browse. Note that only chenopod browse is available.

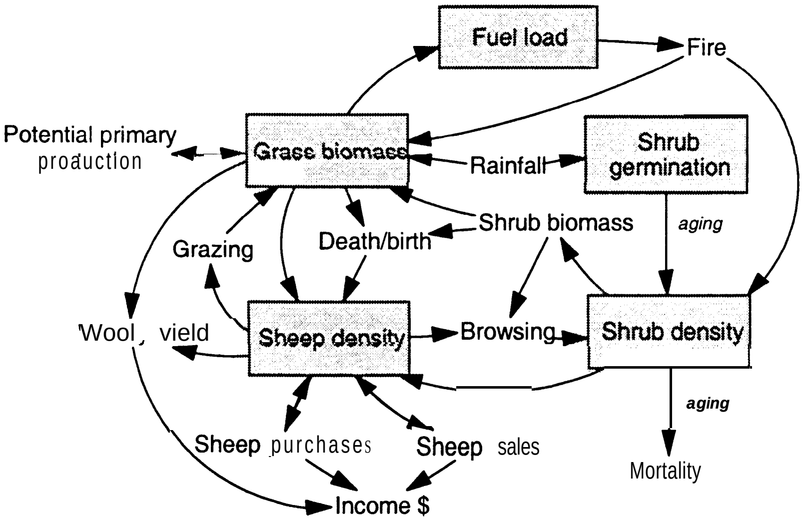

Figure 1. Relationships amongst the main variables in the ecological system.

2.2 Model equations

The equations for change in the four state variables, grass biomass (g), density of woody vegetation (*d*), leaf biomass of woody vegetation (w) and livestock (*x*) are as follows:

$$g_{it+1} - g_{it} = \beta \bullet Vi? \bullet git\,(I - c_{gg}\cdot g_{it}/(g_{maxi} - q(g_{it})) - c_{wgit}\cdot w_{it}/w_{maxi}) - \gamma(g_{it}, br_{it}) - b(g_{it})\cdot g_{it} \tag{1}$$

where:

g_{it} = grass biomass for property i at time t,

β = the rate of regeneration of grasses at time t,

v_{it}= rainfall modifier coefficient [min((rf_{it}-100) /500,1) rf_{it} = rainfall for property i at time t],

c_{gg} = intraspecific competition between grasses,

$g_{\max_i}$ = maximum potential grass biomass for property i,

$q(g_{it})$ = reduction in gmax $= ad_{it} \cdot (g_{\max_i} - p_i \cdot g_{\max_i})$

where:

ad_{it} = the accumulating reduction in potential maximum grass biomass can increase to a maximum of 1 or decline towards 0 depending upon: $ad_{I(t+1)} - ad_{it} = r_{redi} \cdot k_{it} - r_{reci} \cdot (1 - k_{it})$

and:

$r_{red\,i}$ = reduction rate for property i (constant)

k_{it} = 0 (normally) or 1, when grass biomass falls below a threshold value (gd) for two consecutive years for property i at time t,

$r_{rec\,i}$ = recovery rate for property i (constant),

p_i = proportion by which $g_{\max}$ can be reduced when potential primary production is at its minimum for property i,

$c_{wg_{it}}$ = competition coefficient for the effect of w on g for property i at time t

$$= (c_{wg_{\max}} - c_{wg_{\min}}) \cdot \sum_{h=2}^{3} d_{iht} / \sum_{h=2}^{4} d_{iht} + c_{wg_{\min}}$$

and:

$c_{wg_{\max}}$ = maximum w/g competition coefficient

$c_{wg_{\min}}$ = minimum w/g competition coefficient

d_{iht} = density of woody plants for property in height class h (for h = 2-4) at time t calculated as:

$$d_{ih(t+1)} - d_{iht} = d_{i(h-1)t} / a_{ih-1} - d_{iht} / a_{ih} \text{[illegible]} - m_{it} \cdot d_{iht} - f_h(g_{it}) \qquad (2)$$

where:

a_{ih} = average time of woody plants for property i in age class h.

m_{it} = mortality rate of woody plants as a function of browsing and rainfall for property i at time t $= 1 - (m_{max} \cdot \min(rf_{it}/rf_{drought}, 1)(1 - (br_{it}/w_{it}) + m_{max} - 1)$

and:

m_{max} = maximum mortality rate for woody plants

$rf_{drought}$ = rainfall below which mortality of woody plants will occur.

br_{it} = woody leaf biomass browsed on property i at time t =

$\min(x_{it} \cdot cf \cdot (\theta_i \cdot w_{it} / (g_{it}\ \theta_i \cdot w_{it})), \theta_i \cdot w_{it})$

and:

x_{it} = livestock density on property i at time t:

$$x_{it+1} - x_{it} = \alpha . x_{it}(1 - (\gamma(g_{it}, br_{it}) + br_{it})/(g_{it} + br_{it})) - k.x_{it} + u_{it} \tag{3}$$

where:

α = the maximum growth rate

$\gamma(g_{it}, br_{it})$ = grass biomass removed by grazing as a function of grass biomass and browsing $= x_{it}.cf - br_{it}$

and:

cf = grass/browse consumed per head of livestock,

k = maximum death rate of the herd,

u_{it} = herd offtake/addition for property i at time t determined from the socio-economic model,

θ_i = percentage of woody leaf available as browse for property i,

w_{it} = total woody leaf biomass for property i at time t calculated as:

$$w_{it} = \sum_{h=2}^{4} e^{-2.254 + 2.551 \ln(hgt_{ih})} d_{iht} \tag{4}$$

where:

hgt_{ih} = average height for property i, of woody age class h,

$f_h(g_{it})$= the rate of depletion of woody plants due to fire for property i in height class h at time t = $\min(0.5.\varpi_h.l_{it} / g_{\max}, \varpi_h).ld_{it}$

and:

ϖ_h = maximum proportion of woody density destroyed by fire in height class h,

l_{it} = fuel load for property i at time t where: $l_{it+1} - l_{it} = g_{it} - \gamma(g_{it}, br_{it}) - ld_{it} \bullet \; lit$

ld_{it} = fire decision for property i at time t determined from the socio-economic model

d_{i1t} = density of germinating woody plants for property i, for age/height class 1 at time t calculated as:

$$d_{i1t} = dg_{it}.v_{it}\left(1 - c_{ww} \cdot w_{it} / w_{\max_i} - c_{gw} \cdot g_{it}\right).d_{\max} \tag{5}$$

where:

dg_{it} = switch for germination for property i at time t, set to 1 when rainfall is above a threshold value (rg) otherwise 0 (no germination)

c_{ww}= intraspecific competition between shrubs

w_{maxi}· =maximum woody leaf biomass for pastoralist i,

c_{gw} = competition between grasses and shrubs

d_{max}= maximum number of seedlings

$b(g_{it})$ = rate of depletion of grasses due to fire at time t, $b(g_{it}) = \sigma.ld_{it}$

where:

σ = proportion of grass biomass destroyed by fire

Wool production is calculated as:

$$wp_{it} = (x_{it} - (1 - (\gamma(g_{it}, br_{it}) + br_{it})/(g_{it} + br_{it}))).wp_{\max}.wm(g_{it}, w_{it}) \quad (6)$$

where:

wp_{it} = wool production for property i at time t,.

wp_{max}= annual average greasy wool production per sheep.

$wm(g_{it},w_{it})$ = wool production modifier which is set to 1 when available forage $(g_{it}+\theta.w_{it})$ is greater than 75kg, otherwise = $0.0053.(g_{it} + \theta_i .w_{it}) + 0.6$

The initial and maximum values of the state values, and the parameter values in the example are presented in Table 1.

Table 1 Parameter values of the ecological model.

Mulga (i=1-50)	Chenopod (i= 51-100)	all pastoralists (i=l- 100)	
$g_{max} = 800$	$8_{max} = 600$	$x_{i0} = 0.1$	$d_{max} = 5000$
$w_{max} = 3000$	$w_{max} = 1000$	$g_{i0} = 400$	$\sigma = 0.2$
$r_{red} = 0.015$	$r_{red} = 0.01$	$d_{ih0} = 0,1000,1000,100$	$a_{ih} = 1,5,20,24$
$r_{rec} = 0.01$	$r_{rec,} = 0.01$	$ad_{i0} = 0$	$m_{max} = 02$,
$gd = 100$	$gd = 50$	$1_{i0} = 0$	$rf_{\iota\ drought} = 200$
$p = 0.2$	$p = 0.6$	$\beta = 3$	a = 0.3
$rg = 500$	$rg = 400$	$cgg = 1$	k=O.1
$hgt_2 = 1$	hgt_2 – -. 5	cgw = 0.8	$cf = 400$
$hgt_3 = 2$	hgt_3 – – 1	$cww = 1$	$\varpi_h = 0,0.9,0.8,0.6$
$hgt_4 = 3$	hgt_4 – – 15.	$cwg_{min} = .6$	$wp_{max} = 6$
$\theta = 0$	$\theta = 0.5$	$cwg_{max} = .8$	

Figures 2 and 3 present the results of 200 year simulations of the ecological model for the mulga and chenopod rangelands, under two extremes of management – a very light grazing pressure, and a heavy grazing pressure induced by maximum stocking rates.

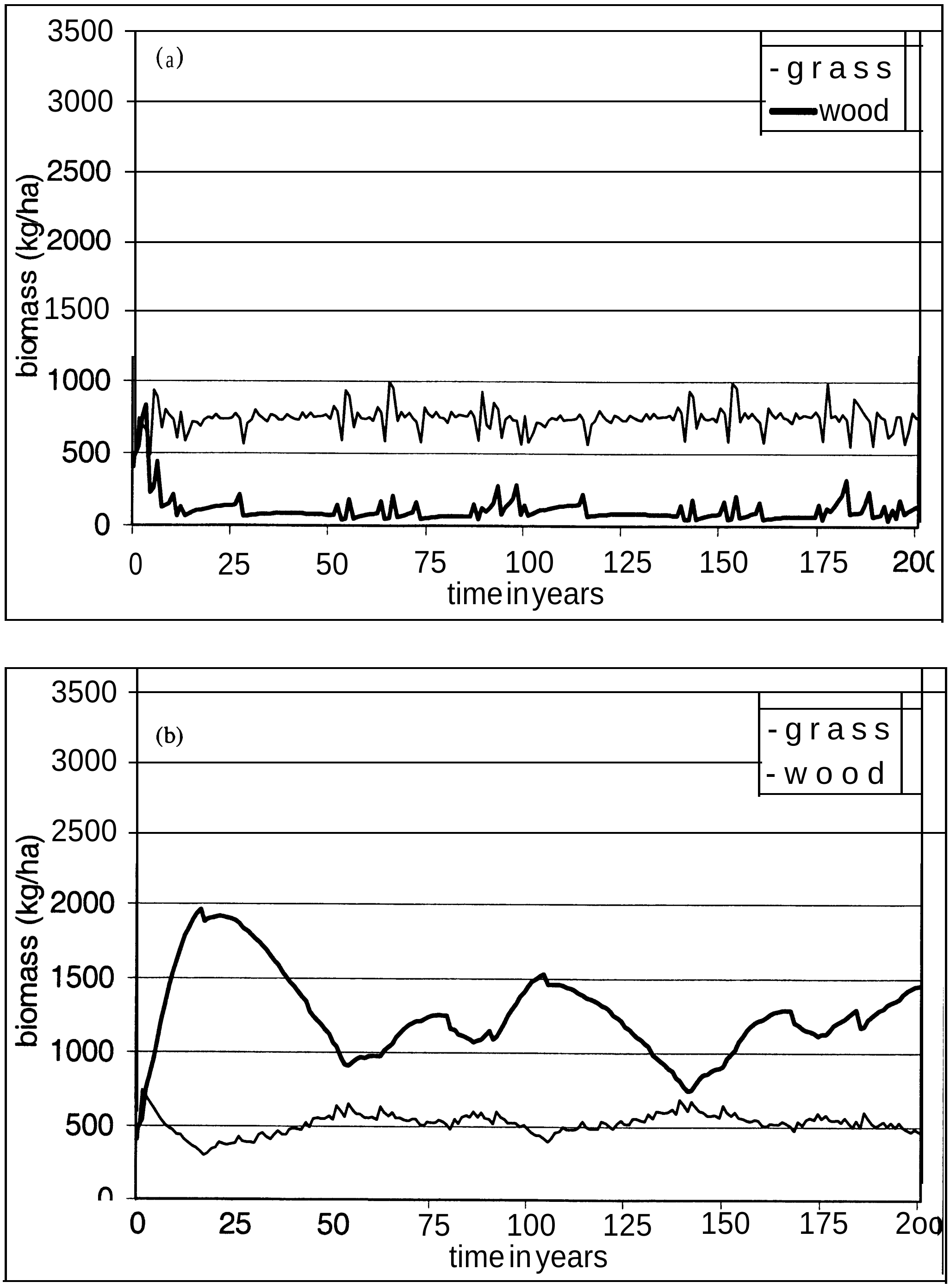

Fig 2. Grass and woody leaf biomass at a low stocking rate with (a) and without (b) fire.

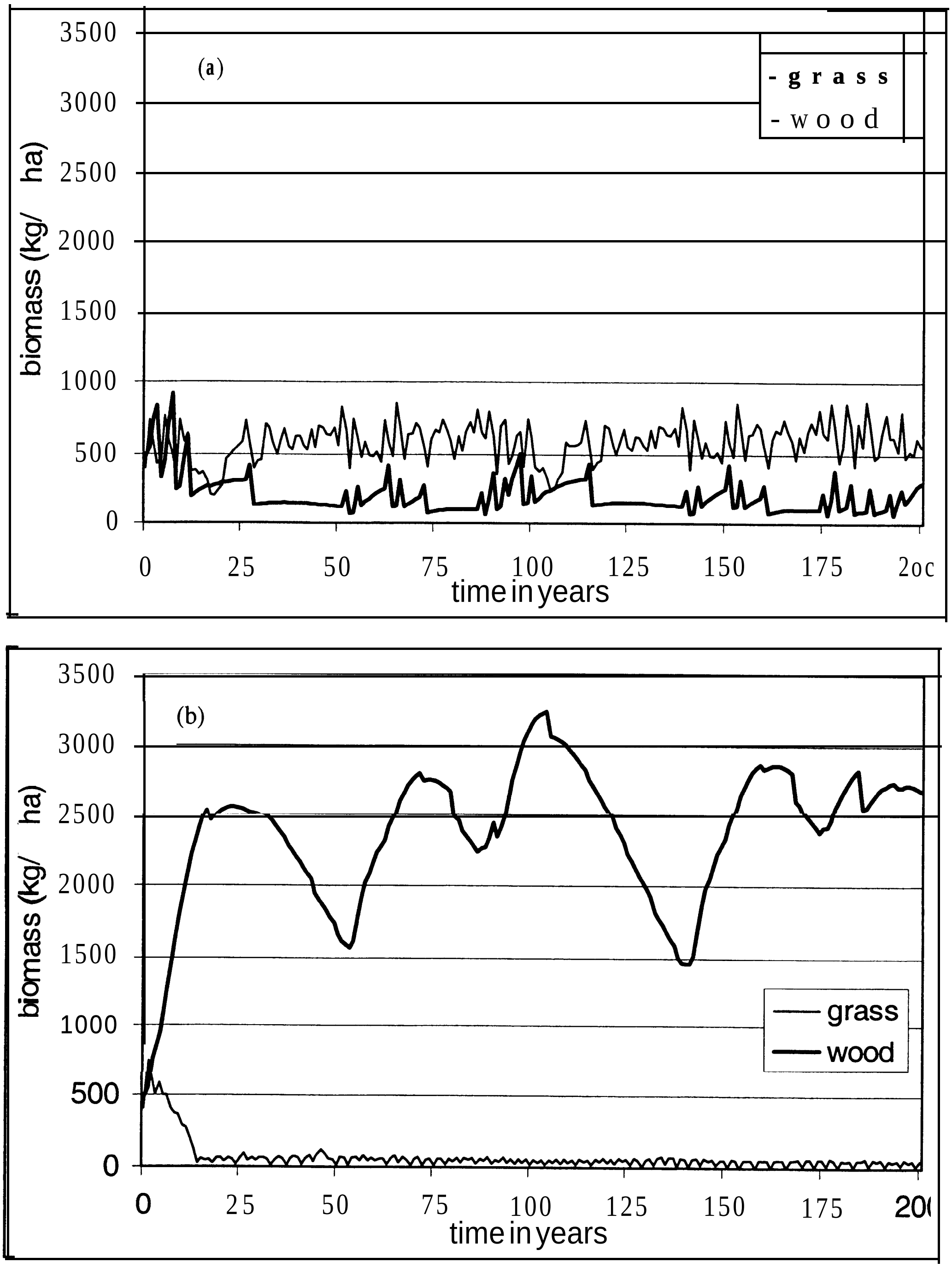

Fig 3. Grass and woody leaf biomass at a moderate to high stocking rate with (a) and without (b) fire.

3. The Socio-Economic System

3.1 Introduction

Social science theory dealing with decision making is divided by scale and discipline. Psychology addresses personal decisions, anthropology operates at cultural level, sociology is concerned with whole societies, while neo-classical economics deals with economies as if these are separated from society. Linkages between disciplines and scales are at best weak. Thus neo-classical economics uses utility-maximising models that are contradicted by empirical studies of decision making (Simon, 1957; Ormerod, 1994; Thaler, 1994; Loomes, 1998). In these circumstances we used elements of social science we thought important for our purposes, and which can be included in a formal model. Although formal models cannot include behaviour that approaches the sophistication or subtlety of decisions made by real people, they are clear in their assumptions and the resulting consequences.

Social scientists have used computers to simulate behavioural and social processes since the early 1950's. They are now exploring new ways of modelling human behaviour with techniques such as cellular automata, genetic algorithms and neural networks (Vallacher and Nowak 1994; Gilbert and Doran 1994; Gilbert and Conte 1995; Conte et al. 1997 and Liebrand et al. 1998). The general feature of this new work is the use of simulation models of interacting agents to study social processes in simple and complex environments.

3.2 Model desciption

Two levels of social behaviour are distinguished, at two different spatial scales: the pastoralists who manage their own land, and a regulator who attempts to influence the behaviour of all the pastoralists in the region.

The pastoralists

The behaviour of pastoralists is based on theories and modeling approaches from bounded rationality (Simon, 1957, 1996), social psychology (Jager et al. 1999), and mental models (Abel et al., 1998). Decision rules were drawn from empirical and modelling studies (Carman et al., 1998, Foran and Stafford Smith, 1991; Noble; 1997; Hodgkinson and Marsden, 1999; Buxton and Stafford Smith, 1996), and interviews with knowledgeable professionals from CSIRO Wildlife and Ecology.

The population of one hundred pastoralists differ in their financial and cognitive abilities, their perception of time, and in the utility they derive from consumption. Both commercial and life style pastoralists can have long or short time horizons. Those with long time horizons pay more attention to the quality of the rangeland compared to those with a short time horizon. One type of pastoralist is assumed to reach a given level of utility with a relatively low consumption level. They choose to live in the rangeland because they enjoy the lifestyle. The other type, the commercial pastoralist, is motivated purely by the financial returns from the land. We acknowledge that this is a great simplification, and that many of the factors that we know drive behaviour are omitted (family size, skill levels, school fees, external income and so on). The level of simplification is appropriate for our purposes.

To determine the level of consumption we take into account pastoralists' financial resources and utility functions, as related to life style. Financial resources in any year comprise net income for that year plus any surplus carried forward from the previous year. We assume that a pastoralist consumes a minimum amount that leads to a minimum level of utility U_{min}. When financial resources are above this minimum level, utility rises with consumption. Any financial resources above a certain level (R_{max}) ($/ha), are consumed and increase utility.

The utility function, U_i, of pastoralist i is therefore:

$$U_i=\ln(C_i^{\alpha i}) \qquad (7)$$

with

$$C_i=\max(\exp(U_{min})^{1/\alpha i}, c_{r,i} * inc_i, R_{i,t} - R_{max})$$

where consumption is denoted by C ($/ha/yr), and parameter α determines the degree of satisfaction per unit of consumption. R_i ($/ha) is the financial resources (cash held) of pastoralist i, in a particular year; $c_{r,i}$, consumption rate, is the percentage of the yearly income. An amount $1-c_{r,i}$, is carried forward to the next year to contribute to financial resources. The term inc_i ($/ha/yr) is yearly gross margin from sale of products. Depreciation and fixed costs are ignored.

Financial resources change due to revenue from wool, sheep purchases and sales, debt repayments and consumption. Due to uncertainties in rainfall, grass biomass, wool price, and growth of the sheep flock actual income may differ significantly from expected income. Pastoralists may have debt repayments, db_i, and this debt increases when financial resources are negative, in line with the interest rate, int. A pastoralist may decide to buy sheep for the price of

p_{sb} each if the actual stocking level x_i is not equal to the expected stocking level $E[x_i]_t$. The pastoralist may also sell surplus sheep at a price p_{ss} ($<p_{sb}$) (\$/sheep) each if the property or the sheep are in poor condition.

The net income, Inc_i, is defined as

$$Inc_i = x_{i,t}*wp_{max}*pw_t - (db_{i,t} - int*min(0,R_{i,t-1})) - max(0,x_{i,t}-E[x_i]_t)*p_{sb}+max(0, -E[x_i]_t+x_{i,t})*p_{ss} \quad (8)$$

Where: x is the stocking rate; wp_{max} the amount of wool yield per sheep (kg); and pw is the wool price (per kg) minus the variable costs of production, (per kg). Net income, savings brought forward and consumption constitute financial resources.

$$R_{i,t} = R_{i,i-1} + inc_i - C_i \quad (9)$$

The expected stocking level of sheep at the beginning of period t is the lesser of:

- the flock size resulting from natural increase
- the flock size that would consume the expected biomass of grass (g) at the specified consumption rate per head, cf.

$$E[x_i] = min((1+\alpha)* x_{i,t-1} ,E[g_i]/cf) \quad (10)$$

Debt repayment is assumed to be related to the interest rate, int, and the pay back period PBP (years), and only holds when financial resources, RI, are negative. Debt payments make it difficult for pastoralists to return to positive resources again. When negative resources fall below a tolerable debt level D_{max}, then the pastoralist is assumed to go bankrupt.

$$db_{i,t} = int/[1-(1+int)^{-PBP}] * max(O, -R_{i,t-1}) \quad (11)$$

We consider two cognitive processes affecting stocking decisions. If a pastoralist is satisfied (s)he is assumed to process information automatically and show habitual behaviour. We assume dissatisfaction when growth rate of stock is poor, or when grass biomass or financial resources fall below certain levels. Dissatisfaction stimulates the pastoralist to consider changing management. The pastoralist may still be seen as an economically rational agent who does not spend scarce time and cognitive abilities on complex problem solving when (s)he is already satisfied (Simon, 1957). From a psychological viewpoint, the hierarchical nature of personal constructs mean that individuals change their minds on major matters somewhat reluctantly (Kelly, 1955).

Decisions on stocking rate

So long as financial and ecological conditions are satisfactory, the pastoralist will continue to stock at a rate linearly related to expected grass biomass ($E(g_i)$) and consumption rate (cf). The sheep graze all the allowable proportion (ms) of the expected biomass. The number of sheep is that which fully consumes the maximum allowable proportion of grass biomass, and the pastoralists differ with respect to their perceptions of this proportion (ms). Equations are:

$$x_i = ms*E[g_i]/cf_i \tag{13}$$

$$E[g_i]_t = g_{i,t-1}(1+ gr_{i,t} *(E[rf]-gd)/rg) \tag{14}$$

The expected rainfall, E[rf] (mm/yr), is assumed to be a moving average over the last 5 years. A refinement of the model could be the introduction of different forecasting techniques. Some pastoralists use high tech information on weather forecasts, while other wait and see. The parameter gr is an expected growth rate of grass as defined below.

Mental model theory proposes that because humans necessarily abstract from complex information, mental models cannot be faithful mirrors of reality (Abel, 1998). Pastoralists' mental models were therefore constructed for our simulation so they had imperfect understanding. Theory also predicts that changes in mental models to accommodate contradictions between the mental model and incoming information are made somewhat reluctantly (Kelly, 1955). Therefore a pastoralist will only update his or her mental model as defined below if dissatisfaction with financial or ecological conditions exceeds a threshold. If dissatisfied by range condition, they will reduce stocking rate. We simulate destocking by assuming another parameterization of the linear relation, where ds c ms.

$$x_i = ds*E[g_i]/cf_i \tag{15}$$

If the pastoralist is dissatisfied because of negative financial resources, (s)he uses the ms-equation for the stocking rate. If both the financial and the ecological conditions are poor, the financial situation is assumed to take priority.

Fire management

On mulga rangelands, pastoralists burn when the amount of young woody weeds (yww) exceeds a certain threshold level yww (kg/ha), and when enough fuel (grass), is available. The threshold level yww is an individual characteristic of the pastoralist representing his or her understanding of fire management. Pastoralists who never use fire, because of its effect on short-term pasture availability, hence income, have high thresholds. Pastoralists who use fire intensively to reduce woody weeds have low thresholds.

Updating mental models

Pastoralists who are financially or ecologically dissatisfied seek new ways of increasing utility and are assumed to update their mental models. Values of parameters in the pastoralists' mental models of the rangeland system are modified accordingly. The parameter $gr_{i,t}$ denotes the expected growth rate of grass in relation to rainfall, assuming constant competition from shrubs. According to the mental model, the expected grass growth does not change through small changes in shrubs.

To determine the growth rate of grass in the mental model, we first assume that no burning occurs and that grazing is zero. Then we can write grass biomass g (kg/ha) as a function of the biomass of the previous period plus grass growth Δg

$$g_{i,t} = g_{i,t-1} + \Delta g_{i,t} \tag{16}$$

where grass growth is dependent on grass biomass, the actual rainfall, rf_{it} , and a number of parameters and variables related to shrub dynamics and potential primary production.

$$\Delta g = g_{i,t-1}\, \beta\, v_{i,t}\, (1-c_{gg}\, g_{max} - c_{wg}\, w_{max}) \tag{17}$$

We now can rewrite grass biomass as

$$g_{it} = g_{i,t-1}\, (1+v_{i,t}\, \beta\, (1-c_{gg}\, g_{max} - c_{wg}\, w_{max})) \tag{18}$$

we assume now that $gr= \beta\, (1-c_{gg}\, g_{max} - c_{wg}\, w_{max})$ which can be assumed to be constant in the mental model of the pastoralist, which is now:

$$g_{i,t} = g_{i,t-1} * (1 + gr * E[v_{it}]). \tag{19}$$

The expected rainfall modifier value depends on the expected rainfall, which is an average value of an historical record, say 5 years. Note that grass growth in reality follows equation 18, where the competition effect of woody weed on grass is variable as defined in the ecological model. The grass growth in the mental model is determined using expected rainfall instead of actual rainfall (eq. 19), and a constant value of the competition effect from the last update of the mental model.

"Renewal" of pastoralists

If the financial resources of a pastoralist drop below a certain threshold value D_{max} , the maximum tolerable debt level, we assume the pastoralist goes bankrupt and leaves the system. The land may be acquired by a pastoralist already in the system, or by a new pastoralist with a random set of cognitive characteristics. We assume that the higher the financial resources of a particular pastoralist, the higher the chance that the renewed agent has the same characteristics as the "fittest" pastoralist, otherwise a new pastoralist with random characteristics is chosen. This is implemented as in the following equation

IF $U[u_{min}, u_{max}] < LN(MAX(R_i))$ THEN characteristics of "fittest" existing pastoralist ELSE random new characteristics (20)

This says that when a random number drawn from a uniform distribution U[] is lower than the natural logarithm of the maximum of all resources, the characteristics of the fittest pastoralists, that is the pastoralist with the highest amount of resources, is copied to replace the pastoralist who went bankrupt. Otherwise the new pastoralist has parameters of the behavioural model that are drawn randomly. An increase of the highest amount of resource leads to an increase, at a decreasing rate, of the chance of copying, and a lower chance of introducing new behavioural patterns.

This algorithm has some similarities with genetic algorithms (Goldberg, 1989; Holland, 1992; Mitchell, 1996). Genetic algorithms simulate the adaptive processes of natural systems. They have a population of agents who produce offspring that are similar but not identical to their parents. The number of offspring that an agent produces is determined by a fitness function. In our model, the "fitness" of the pastoralists is related to their financial stock. If it becomes too low the pastoralist "dies". If other pastoralists are "fit" enough the fittest acquires the land, otherwise a random new pastoralist comes into the system which may bring in a new management style. This process will lead to an evolution of the characteristics of the pastoralists. Given the social and physical environmental conditions pastoralists with certain characteristics will come to dominate during the simulation. A key question in this regard is; which characteristics dominate under which types of social and physical environmental conditions? An important variable in the social environment of the pastoralists is the type of regulation policy.

The regulator

The regulator in our model is a very simple representation of government. In line with the notion of different cultural perspectives (Schwartz and Thompson, 1990; Thompson et al., 1990; Rayner, 1990), we distinguish three different types of regulator: conservation, stabilisation and free market. A change in "regulator" may in reality reflect a change in policy style, rather than an actual change in the administration.

A conservation policy aims to protect the ecosystem from negative influences of human activities. We assume that this policy causes pastoralists to destock their property when the grass biomass falls below a certain threshold (say 150 kg/ha).

The stabilization type of policy tries to maximize the long-term welfare of society by balancing range condition with income. If rainfall drops below 200 mm in a year, all pastoralists receive a grant of $\{(ms-ds)*E[gr]/cf\} * 15\$/ha$ provided they (partly) destock.

The free market policy does not intervene, leaving pastoralists responsible for managing land in good and bad times.

3.3 Change of regulation policy

Abel (1999) discussed regional, state and national influences on policies and institutions affecting these rangelands. These complexities are not included here. Instead we explored interactions among rangelands, pastoralists and regulators on the assumption that the conditions of rangelands and pastoralists were the sole determinants of policy style. Similar experiments have been performed for climate change (Janssen, 1998b; Janssen and de Vries, 1998) and lake eutrophication (Janssen and Carpenter, 1999). We define thresholds which, when exceeded, lead to a change in regulation. The first is related to opportunity cost expressed as the amount of Income per ha that could be earned at a stocking rate at which all grass is eaten. Wool price also determines this opportunity cost. The second threshold is related to ecological condition, the percentage of properties which have a grass biomass below a minimum amount of 200 kg/ha for mulga, and 150 kg/ha for chenopod.

For each type of regulation we defined conditions in which the regulator maintains or changes policy.

The conservation policy aims at maintaining the initial state of the environment which was "good". If the percentage of properties in good condition remains below 60%, the conservation policy continues. If the percentage of properties in good condition rises above 60% policies change. The free market policy is adopted when opportunity cost is more than 2$/ha. If this cost is less, a stability policy of policy is applied.

If the free market policy is already in effect, it continues a free market regulation when the so long as opportunity cost is more than 1$/ha. Otherwise one of the other policies is adopted. A conservation policy is adopted if the percentage of properties in good condition is below 60%, otherwise stability policies are employed.

If a stability policy is in force, it continues as long as no extreme circumstances occur. It changes to conservation when the percentage of properties in good condition drops below 50%, or to free market when the lost opportunities are above 2$/ha.

4. Results

4.1 Introduction

In this section we describe a number of experiments. First, we determine the optimal values of the behavioural rules for a one-property system. Then we analyse the social, economic and ecological consequences of applying each policy style during runs in which the style does not change in response to changing conditions. Next we run experiments in which the policy style changes according to the rules described above.

Historical yearly median rainfall and wool price data from 1986 to 1997 are used for each rangeland. Wool prices are in real terms. Our data cover only the last century. As the model runs are 200 years, rainfall and wool price data are repeated, but a price peak caused by the Korean War (1950s) was removed from the first 100 years (see Figure 4).

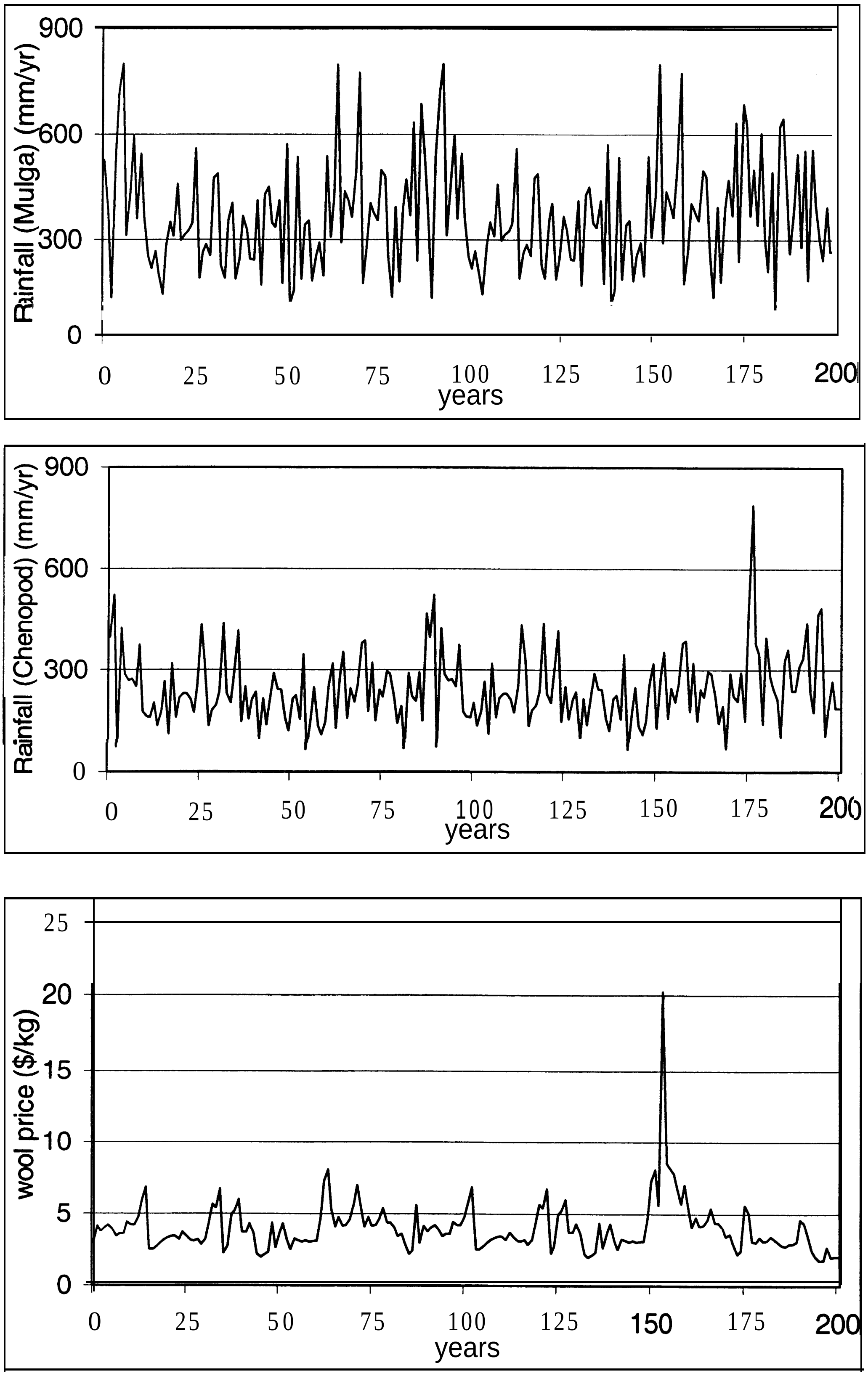

Figure 4. Rainfall and wool prices used for all simulations.

4.2 Optimal management strategies

Given that rainfall and wool prices are known for the 200-year period, what parameter values maximise the (discounted) net income stream? The non-linear optimisation problem is solved by the standard optimisation algorithm (Powell algorithm) in the Vensim software, the package in which this model has been implemented (Ventana, 1998). Because of complexity and non-linearity, we used a large number of starting points for the runs (200) for a single property in each of the mulga and chenopod rangelands, and the best solutions are given in Table 2.

In general, short periods of intensive stocking, followed by a period of recovery characterise the optimal solutions. This flip-flop behaviour of stocking is most extreme for the chenopod type of property, because mulga is more sensitive to intensive grazing, which leads to shrub increase and reduced potential primary production. The α values are low for mulga, which means pastoralists are mainly commercial (high minimum consumption level). The high savings rate, l-c,, and the frequent use of fire suggest a long time horizon during decision making. The chenopod rangeland case is different. The low α value combined with a low savings rate suggests a lifestyle pastoralist with a short time horizon.

The stocking rate, grass biomass and income from mulga rangeland are about twice those from the chenopod type. In the optimal case, the pastoralist burns about once a decade in the mulga type.

Figures 5 and 6 depict the yearly income, grass biomass and shrub biomass for the optimal case. The periodic flipping of high and low stocking leads to huge variation in yearly income and grass biomass. On mulga rangeland, burning limits woody growth. On chenopod rangeland, shrubs have natural patterns of growth and decline.

Table 2: Optimal parameter values of the behavioural rules, using 200 starting points. Ms is the share of expected available grass biomass to be consumed by the sheep when enough grass biomass is available, otherwise a lower share, ds, is used. Grass biomass_{min} is the threshold that marks the line between good and bad condition of rangeland. Natural growth,, is the threshold that marks the line between good and bad condition of livestock. The % consumption of income is denoted by c_r. The parameter of the utility function leading to a minimum level of consumption is a. Yww_{min} is the threshold of young woody weeds above which the pastoralist burns to control shrubs.

	Mulga	Chenopod
ms	0.801	1.000
ds	0.03	0.000
Grass biomass_{min}	475	104
Natural growth_{min}	0.194	0.13
c_r	0.172	0.69
a	2.64	9.60
yww_{min}	1193	X
Mean stocking rate	0.52	0.25
Mean grass biomass	511	180
Mean woody weed	205	203
Mean income	16.03	8.40
Mean reduction in ppp*	0.0	0.0002
Number of fires	22	X

* ppp = potential primary production

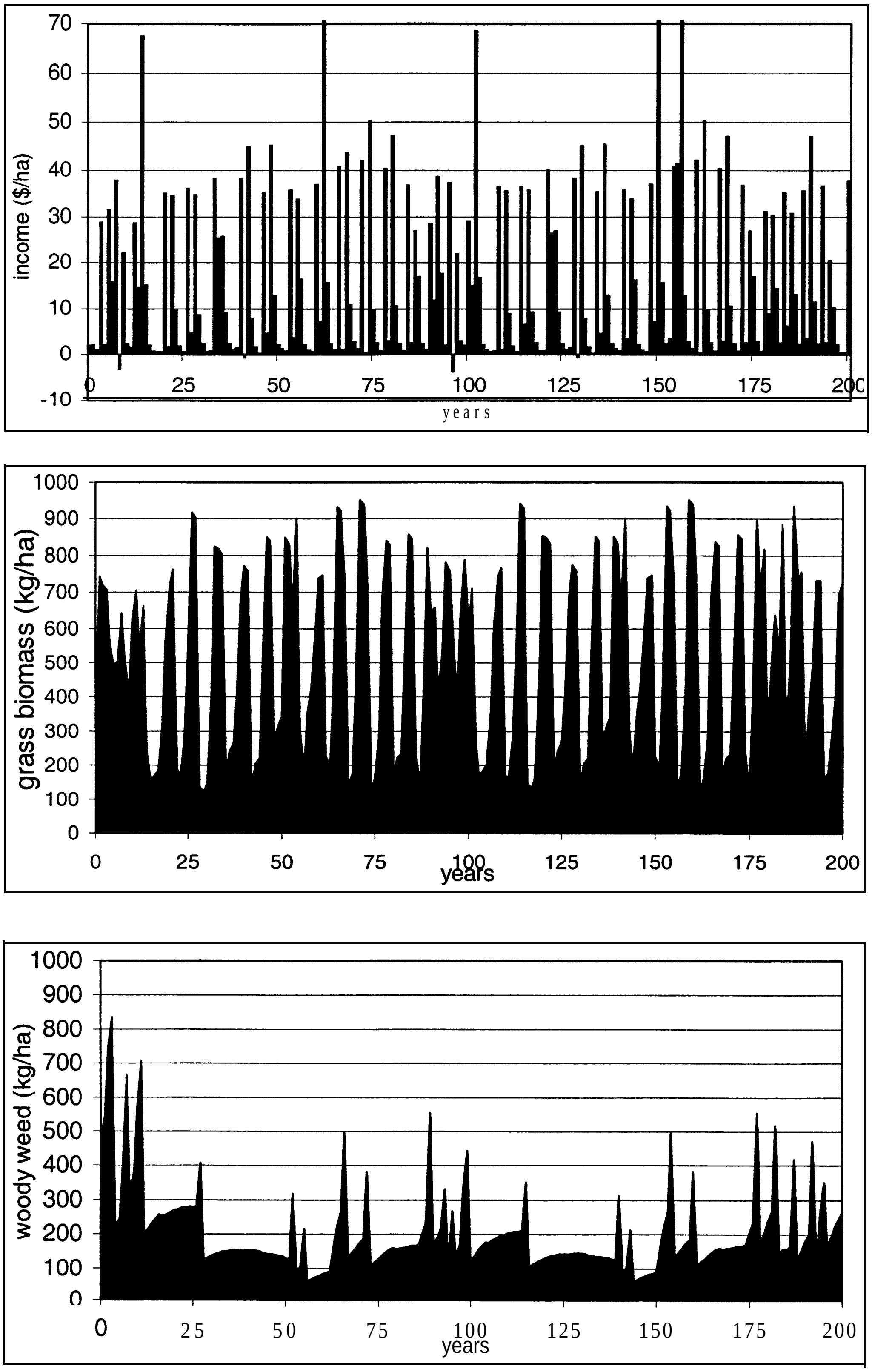

Figure 5: Income, grass biomass and woody weed developments for the mulga type rangeland.

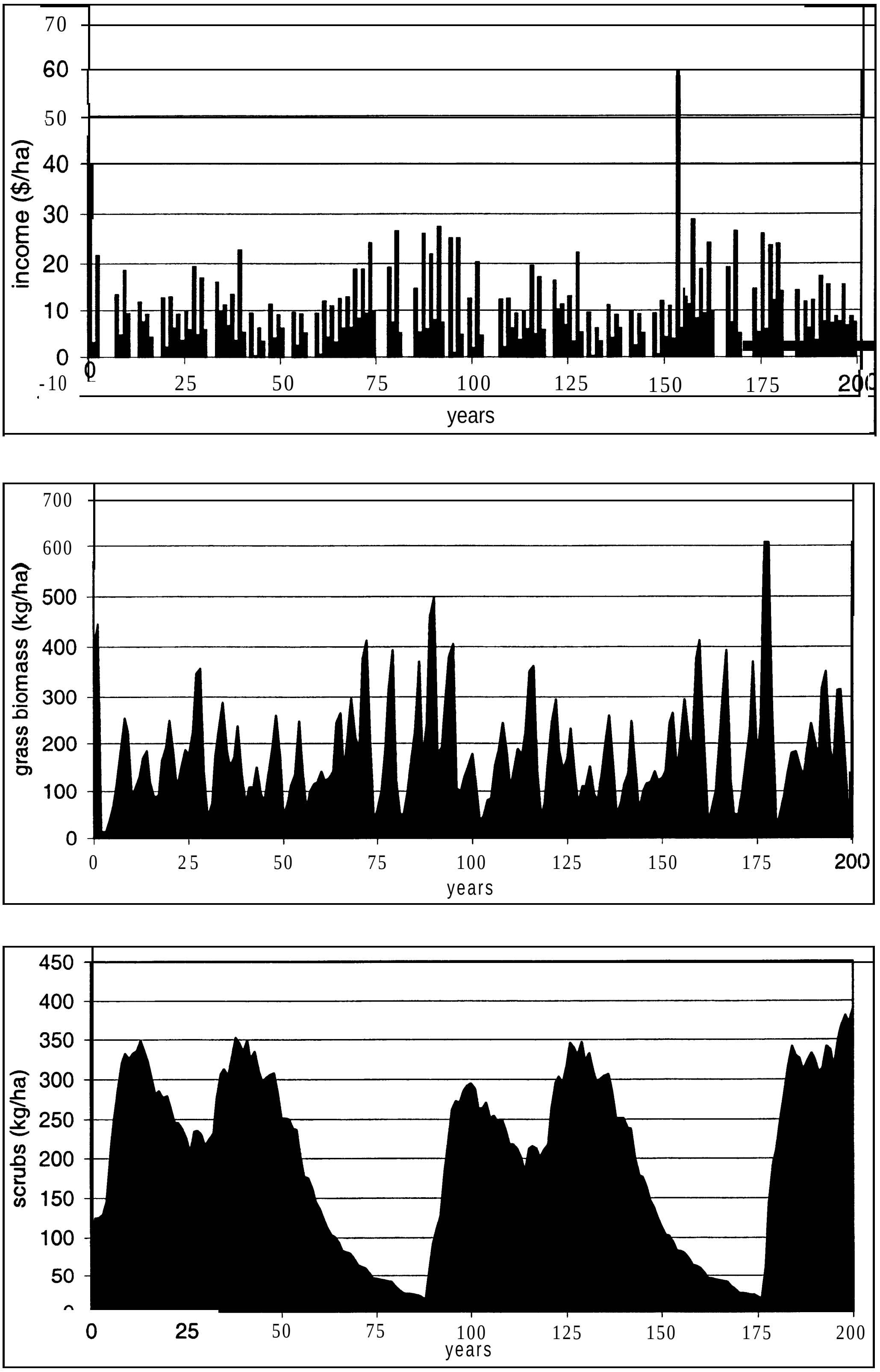

Figure 6: Net Income, grass biomass and shrub biomass, chenopod rangeland.

As an additional experiment, we repeated the previous optimisation runs, but used a discount rate of 5% on the yearly net income instead of the 0% discount rate of the previous exercise. The stocking rate is even more unstable, varying to an extreme between zero and a rate at which all grass is consumed. The threshold of grass biomass that determines the change from or to destocking is lower when returns are discounted, so destocking occurs at lower sheep densities. The threshold for fire management is higher so there is less burning. Pastoralists have lower-income levels but consume almost their whole income (high c_r values). The discounted income is only slightly lower for the chenopod case, but significantly lower for the mulga type of rangeland. In the case of mulga, the grass biomass is much lower, and the woody weed is much higher than the same indicators in Table 2. Moreover, potential primary production is reduced.

Table 3: Optimal settings behavioural rules when maximising income with a discount rate of 5%

	Mulga	Chenopod
ms	0.999	1.000
ds	0.000	0.000
Grass biomass_{min}	401	102
Natural growth,,	0.09	0.19
c_r	0.98	0.82
a	8.89	7.68
yww_{min}	1972	X
Mean stocking rate	0.51	0.24
Mean grass biomass	430	177
Mean woody weed	417	215
Mean income	11.46	8.36
Mean reduction in ppp	0.003	0.0002
Number of fires	18	X

4.3 System dynamics under different forms of regulation

In the optimisation experiments perfect foresight was assumed. In this section we use the adaptive rules. Initially, behavioural rules are distributed randomly among pastoralists. Unexpected changes in rainfall and wool prices cause some pastoralists to go bankrupt. They are replaced by new pastoralists as described earlier. After 200 years we derive a population of pastoralists who performed well in the face of uncertainty.

To explore the effects of regulation policy on rangeland and the evolution of pastoralists we ran 3 experiments, one for each policy type, each with 100 properties: 50 mulga, 50 chenopod. Each experiment was run 100 times with random new initial parameter values of the behavioural rules. A weighted average parameter value of the 100 runs was calculated for properties on each range type (Table 4). The level of the financial resources weights the parameter values of the pastoralists. The more successful a pastoralist, the more his/her parameter values are weighted. This weighting of properties is necessary to weight the success of different type of pastoralists under different policies. By weighting the parameter values of the behavioural model according to the resources of the pastoralists, an indication of the parameter values of a successful pastoralists can be derived.

Chenopod rangeland allows higher values of ms and ds, and switching to destocking at a lower level of grass biomass. The pastoralists all have a low minimum amount of consumption, and save about 60% of income when it exceeds the minimum consumption level. Because the survival of the pastoralists depends on their long-term financial resources, big spenders drop out quickly in bad years, leading to a rapid increase of the average α value during the first decades of the simulation.

The differences in parameter values between the different types of regulator seem modest. Under a conservation regime (obligatory destocking), the levels of ms and ds are somewhat higher for mulga compared to the other two regimes. Also, destocking starts at a lower level of grass biomass. If we view the state of the rangelands during the 200-year period, bigger differences occur (Table 5). For the mulga case, stocking rates and income levels are much higher under a conservation regime, compared to free market and stability policy styles. Woody weed and reduced levels of potential primary production are on average much lower. The conservation policy outperforms the other two types of regulation on these criteria. On chenopod rangeland a stability regime is preferred since it derived extra income from drought relief for destocking, although the system is robust enough to cope with drought years. The condition of the chenopod rangeland does not differ significantly between the different types of regulation.

Table 4: The parameter values of the behavioural rules that evolve after 200 years. The parameter values are the average value over 100 runs of the weighted average pastoralist for each run.

	initial	Mulga			Chenopod		
		Free Market	Stability	Conservation	Free Market	Stability	Conservation
ms	0.2-1.0	0.51	0.54	0.59	0.64	0.66	0.63
ds	0.0-0.2	0.11	0.11	0.13	0.15	0.15	0.15
Gb min	100-400	248	254	236	222	239	227
Ng_{min}	o-o.3	0.20	0.20	0.18	0.17	0.18	0.17
c_r	0.2-0.6	0.40	0.40	0.37	0.38	0.39	0.36
a	2.5-10	8.18	8.12	8.27	8.28	8.03	8.39
yww_{min}	100 - 4000	1676	1754	1597	x	x	x

Table 5: Statistics of the average condition of the rangeland over the 200-year period. The "death rate" is the average % of bankruptcy per year.

	Mulga			Chenopod		
	Free Market	Stability	Conservation	Free Market	Stability	Conservation
Mean stocking rate	0.21	0.21	0.32	0.21	0.21	0.20
Mean grass biomass	209	218	340	220	231	242
Mean woody weed	1625	1601	1065	180	178	176
Mean income	5.42	5.96	8.72	5.78	6.71	5.61
Mean drought relief	x	0.40	x	x	1.07	x
Mean reduction in PPP	0.335	0.308	0.018	0.003	0.002	0.001
Number of fires	4.9	49 .	6.6	x	x	x
"Death rate"	8%	7%	1%	0.5%	0.3%	0.7%

To measure the effectiveness of the learning process the parameter values of Table 4 are used as input for a 200 yr run of a one-property model under the three different types of regulation (Table 6). For mulga, the pastoralist who evolves under a free market regulation leads in general to the highest net income, and good range condition. Net income is somewhat less under a stability regime, where a significant part of income is from drought relief. Surprisingly, net income is much less under a conservation policy, and range condition is worse compared to the other two regimes, with less grass and more woody weed. This can be explained by the higher intensity of stocking which reduced the grass biomass. For chenopod rangeland, the stabilization type of regulation leads to the highest income levels, although the differences between policies are smaller than those for the mulga.

Why does the conservation policy favour the evolution of pastoralists who perform worse than those who evolved under free markets? This can be explained by the fact that obligatory destocking reduces the learning potential of the pastoralists. Pastoralists who follow a risky stocking strategy do not “survive” under a free market. They do survive under the conservation policy, whose obligatory destocking policy reduces the chance of destroying the property. However, the free market policy leads to better performing pastoralists, condition of the rangland is worse during the learning period compared to the conservation policy.

The stabilisation policy also reduced learning, but not as much as obligatory destocking. However, a drought relief policy does not improve the condition of the rangeland during the 200 years as compared to the free market regime.

These results lead to the question of what type of policy and institutional environment permits or stimulates learning while maintaining rangeland condition during the learning process. We explore this question in the next section where we let the style of policy change over time.

Table 6: Performance of the weighted average pastoralist who evolved after 200 years when subsequently entered in a one-property model for a simulation of 200 years.

Average net income Mulga		Regulator to test performance of evolved pastoralist		
		Free Market	Stability	Conservation
Regulator during initial 200 year experiment	Free Market	12.76	13.35 (0.59)	11.10
	Stability	10.71	11.25 (0.54)	11.23
	Conservation	5.70	6.16 (0.45)	8.34

Average net income Chenopod		Regulator to test performance of evolved pastoralist		
		Free Market	Stability	Conservation
Regulator during initial 200 year experiment	Free Market	6.06	6.90 (0.85)	5.74
	Stability	6.21	7.36 (1.14)	5.96
	Conservation	5.99	6.90 (0.90)	6.00

Average grass biomass (kg/ha) Mulga		Regulator to test performance of evolved pastoralist		
		Free Market	Stability	Conservation
Regulator during initial 200 year experiment	Free Market	445	445	456
	Stability	366	366	418
	Conservation	197	197	273

Average grass biomass (kg/ha) Chenopod		Regulator to test performance of evolved pastoralist		
		Free Market	Stability	Conservation
Regulator during initial 200 year experiment	Free Market	208	208	203
	Stability	218	218	217
	Conservation	214	214	216

Changing management styles

In simulations where the policy style of the regulators is allowed to change, each regulator is confronted with measures of system performance. This leads to changes in regulation styles. When the system starts under the stabilisation regulator, the high stocking rate rapidly decreases the amount of grass biomass to such a degree that the conservation regulator takes over for a brief period. The system recovers. Unexploited opportunities then allow the free market policy to dominate.

Because policy types change over time during these experiments, resulting parameter values lay between the values that evolved under fixed policies (Tables 4 and 7). The changing regime has less intensive stocking policies than the average pastoralist who evolved during the conservation policy, which indicates a more sustainable management style. Moreover, the state of the rangeland during the learning phase remains in a relative good condition (Table 8) compared to the average value of the fixed regulator policies (Table 4).

Table 7: The parameter values of the behaviour rules that evolve after 200 years under changing regulation policies. The parameter values are the average value over 100 runs of the weighted average pastoralist for each run.

	initial	Mulga	Chenopod
ms	0.2-1.0	0.55	0.64
ds	0.0-0.2	0.12	0.15
Gb_{min}	100-400	249	238
Ng_{min}	0-0.3	0.19	0.18
c_r	0.2-0.6	0.39	0.38
a	2.5-10	8.24	8.20
yww_{min}	100-4000	1658	x

Table 8: Statistics of the average condition of the rangeland over the 200 year period for changing regulation policies

	Mulga	Chenopod
Mean stocking rate	0.25	0.21
Mean grass biomass	261	234
Mean woody weed	1415	177
Mean income	6.91	6.13
Mean drought relief	0.21	0.48
Mean reduction in ppp	0.204	0.002
Number of fires	5.7	x
“Death rate	5‰	0.4%

Parameter values of Table 7 were used in a one-property analysis under different policy regimes, each lasting 200 years. Resulting net income and grass biomass levels are presented in Table 9. The pastoralist who evolves during changing styles of regulation leads to relatively good levels of income and grass biomass under all three types of regulation. This example shows that an adaptive pattern of policy style prevents extreme good and bad outcomes. On average the income levels of Table 6 and 9, both fixed and changing regulation, are similar.

Table 9: Performance of the weighted average pastoralist who evolved after 200 years when entered in a one-property model for a simulation of 200 years.

Changing regulation	Regulator to test performance of evolved pastoralist		
Mulga	Free Market	Stability	Conservation
Average Net Income	9.59	10.01 (0.42)	10.69
Average grass biomass	308	308	384

Changing regulation	Regulator to test performance of evolved pastoralist		
Chenopod	Free Market	Stability	Conservation
Average Net Income	6.08	7.16 (1.08)	5.71
Average grass biomass	220	220	207

5. Conclusions

The model describes the interactions between grass, trees/shrubs, sheep, pastoralists and the policy environment. We analysed the consequences of these interactions under different policy environments. We were particularly interested in the co-evolution of pastoralists' management styles and governmental policies.

The optimal control experiments show that under the assumptions of the model, including perfect information, a strongly fluctuating stocking density leads to the best financial and ecological consequences. It entails destocking for just long enough to let the grass grow again before re-stocking at a high rate. In mulga, frequently burning to reduce woody weeds contributes to the success of the strategy. The alternating style is a consequence of the lag effects in the ecological system.

Experiments with the adaptive agents version of the model show that each policy has different financial and ecological consequences. Regulation reduces the learning process but keeps the rangeland in relatively good condition while the limited learning occurs. This is especially true for mulga. The regulation process in the conservation regime keeps the system in reasonably good condition during the 200-year period but the pastoralist that evolved under the free market regime outperforms this 'conservation' pastoralist. The stability regime was not successful in keeping the rangeland in good condition, and reduced the learning rate of pastoralists. In general, the average pastoralist that evolves earns about 40% and 30% lower income in the mulga and chenopod rangeland compared to the respective optimal solutions. This is an estimate of the cost of managing under uncertainty and is in line with empirical case studies McKean et al. (1998) of differences in returns from ranges in high variable climate and stable climate conditions.

When the regulator is allowed to change there is an alternation between regulator styles as the system agents and policies adapt to changes in grass biomass and the loss of economic opportunities. The changes in regulation are triggered by surprises of high wool prices (the style changes to free market) and drought periods (change to conservation). Consumption levels are more stable in the adaptive than in the optimising model, and rangeland condition is maintained.

These results are preliminary. A program for developing the potential of this approach is likely to include:

- modification of policy regimes to include, for example, measures for distributing benefits and costs over time - incentives, taxation, insurance;
- changes in the economic environment that take account of other wool price regimes and also different interest levels;
- elaboration of management decisions to explore the influences of various levels of debt;
- modification of the biophysical sub-system to explore the effects of different rates of recovery of potential primary production, different sensitivities to grazing pressure, etc.

Such a developed model could become a significant tool for exploring interactions between human and ecological sub-systems for rangeland management policy. The exploratory experiments have shown the importance of different types of policies, and the consequences of changing the regime of policies.

The system can be confronted with many surprises, such as low wool prices, drought, changing sheep prices, changing interest rates, and so on. This may affect the behaviour of the pastoralists in such a way that the government has to change its regulatory procedures to allow the pastoralists to survive. These changes in regulation should be chosen with care since they may also reduce the ability of the pastoralists to learn, which is likely to reduce the resilience of the system as a whole. A simulation model as discussed in this paper, which is clearly only a caricature of the real complex system, might nevertheless be a tool that enables us to analyse the system characteristics of alternative management strategies. One of the big challenges of this type of model is to design institutional regimes that balance ability to learn, returns from the rangeland, and condition of the ecosystem.

Finally, this type of modelling may provide additional insights compared with the optimal control models from economics, and the detailed bottom up models from ecology. It integrates the important elements of managing real complex ecosystems. This type of modelling therefore provides an interesting approach to the science of integration, and to the development of promising management and policy strategies.

Acknowledgements

We are grateful to the Resilience Network, which is funded by the MacArthur Foundation, for funding the visits of the first author to CSIRO Wildlife and Ecology in March and June 1999; all the participants during seminars where previous versions of the model were presented; and especially the following people for giving their valuable time and drawing on their long experience: Mike Austin, Carl Binning, Barney Foran, Ken Hodgkinson, Mark Howden, Art Langston, Jim Noble, Mark Stafford Smith and Paul Walker.

References

Abel, N., 1999. Resilient rangeland regions. In Eldridge, D, and D. Freudenberger (Editors), People and Rangelands; Building the Future. Proceedings of the Vith International Rangeland Congress. pp. 21-30. (VI International Rangeland Congress, Inc.: Townsville).

Abel, N., Ross H. and Walker P., 1998. Mental Models in Rangeland Research, Communication and Management. Rangeland Journal. 20(1): 77-9 1.

Abel, T., 1998. Complex Adaptive Systems, Evolutionism, and Ecology with Anthropology: Interdisciplinary Research for Understanding Cultural and Ecological Dynamics. Georgia Journal of Ecological Anthropology. 2: 6-29.

Buxton, R. and Stafford Smith, M., 1996. Managing Drought in Australia's Rangelands: Four Weddings and a Funeral. Rangeland Journal. 18(2): 292-308.

Carman, K., Heywood, J. Pahl, L. and Marsden S., 1998. Graziers' Perceptions of total grazing pressure in the mulga lands of the Murray-Darling Basin: Part A, Project Report QO09003, Sheep and Wool Institute, Department of Primary Industries, Queensland, Australia

Carpenter, S.R., Brock, W.A. and Hanson, P.C., 1999. Complex Dynamics from Simple Interactions of People and Ecosystems. Conservation Ecology, in press.

Conte, R. Hegselmann, R. and Tema. P. (Editors), 1997. Simulating Social Phenomena, Lecture Notes in Economics and Mathematical Systems 456. Springer. Berlin.

Ellis, F., 1988. Peasant economics : farm households and agrarian development. Cambridge University Press. Cambridge.

Foran, B.D. and Stafford Smith, D.M., 1991. Risk, Biology and Drought Management Strategies for Cattle Stations in Central Australia. Journal of Environmental Management. 33: 17-33.

Freudenberger,D., Willson, A. and Palmer, R..1999. The effects of perennial grasses, stocking rate and rainfall on sheep production in a semiarid woodland of eastern Australia. Rangeland Journal 21(2) (in press)

Gilbert N. and Conte, R. (Editors), 1995. Artificial Societies: the Computer Simulation of Social Life. London: University of London College Press.

Gilbert, N. and Doran, J. (Editors) 1994. Simulating Societies: The Computer Simulation of Social Phenomena. London: UCL Press.

Goldberg, D., 1989. Genetic algorithms in search, optimization and machine learning. Reading (MA): Addison-Wesley.

Harrington, G., 1979. Estimation of above ground biomass of trees and shrubs in a Eucalyptus populnea F. Muell. woodland by regression of mass on trunk diameter and plant height. Aust. J. Bot. 27:135-143.

Hodgkinson, K.C., Marsden, S.G. and Hacker, R.B., 1999. Simulation modelling of two grazing strategies for Australian semi-arid wooded grassland. In D. Eldridge and D. Freudenberger (Editors), People and Rangelands Building the Future, Proceedings VI International Rangeland Congress. Vol. II. pp. 866-868. (VI International Rangeland Congress, Inc.: Townsville).

Holland, J.H., 1992. Complex Adaptive Systems. Daedalus. Vol. 121. 1: 17-30.

Jager, W., Janssen, M.A. and Vlek, C.A.J., 1999. Consumats in a consumat dilemma. Testing the behavioural rules of simulated consumers. COV report no. 99-01. Groningen: Centre for Environment and Traffic Psychology, University of Groningen. http://www.ppsw.rug.nl/cov/staff/jager/simpaper.pdf

Janssen, M.A., 1998a. Use of Complex Adaptive Systems for Modeling Global Change. Ecosystems. 1: 457-463.

Janssen, M.A., 1998b. Modelling Global Change: The Art of Integrated Assessment Modelling. Edward Elgar Publishers. Cheltenham UK/Northampton, MA, USA

Janssen, M.A. and Carpenter, S.R., 1999. Managing the Resilience of Lakes. Conservation Ecology. in press

Janssen, M.A. and de Vries, H.J.M., 1998. The Battle of Perspectives: a multi-agents model with adaptive responses to climate change Ecological Economics. 26(1): 43-65.

Kelly, G.A., 1955. The Psychology of Personal Constructs. Volumes I and II. W W Norton, New York.

Liebrand, W.B.G., Nowak, A. and Hegselmann, R. (Editors), 1998. Computer Modeling of Social Processes. SAGE Publications. London.

Loomes, G., 1998. Probabilities versus Money: a Test of some Fundamental Assumptions about Rational Decision-Making. Economic Journal. 108: 477-489.

Ludwig, D., Walker, B. and Holling, C.S., 1997. Sustainability, Stability, and Resilience. Conservation Ecology [online] 1(1):7. Available from the internet. URL: http://www.consecol.org/vol1/iss1/art7

McKeon, G.M., Hall, W.B., Crimp S.J. and Howden, S.M., 1998. Climate Change and Queensland's grazing lands: Approaches and Climatic Trends. Rangeland Journal 20: 151-176.

Mitchell, M., 1996. An introduction to genetic algorithms Cambridge: MIT Press.

Moore. J.L., Howden, S.M., McKeon, G.M., Carter, J.O. and Scanlan, J.C., 1997. A method to evaluate greenhouse gas emissions from sheep grazed rangelands in south west Queensland. McDonald, D.A. and McAleer, M.(Editors). Modsim '97 International Congress on Modelling and Simulation Proceedings, 8-11 December, University of Tasmania, Hobart. Modelling and Simulation Society of Australia, Canberra. pp 137-142

Noble, J., 1997. The Delicate and Noxious Scrub. CSIRO. Australia.

Ormerod, P., 1997. The Death of Economics. John Wiley & Sons

Perrings, C. and Walker, B., 1997. Biodiversity, resilience and the control of ecological-economic systems: the case of fire-driven rangelands. Ecological Economics. 22:73-83

Rayner, S. 1991. A Cultural Perspective on the Structure and Implementation of Global Environmental Agreements. Evaluation Review. 15(1): 75-102.

Roe, E, Huntsinger, L.and Labnow, K., 1998. High reliability pastoralism. Journal of Arid Environments 39: 39-55.

Sandford, S., 1983. Management of Pastoral Development in the Third World. Wiley. Chichester.

Schwartz, M. and Thompson, M., 1990. Divided we stand: redefining politics, technology, and social choice. New York. Harvester Wheatheaf.

Simon, H.A., 1947. Administrative Behaviour. New York. MacMillan

Simon, H.A., 1957. Models of Man, Social and Rational: Mathematical Essays on Rational Human Behaviour in a Social Setting. New York. Wiley.

Simon, H.A., 1996. The Sciences of the Artificial (Third edition). MIT Press. Cambridge. MA.

Speight, J.G, 1988. Land Classification. in R.H. Gunn, J.A. Beattie, R.E. Reid and R.H.M.van de Graaf (Editors), Australian Soil and Land Survey Handbook. Guidelines for Conducting Surveys. Inkata Press, Melbourne. pp 38-57

Stafford Smith, M. and Pickup, G. 1992. Understanding vegetation change and its implications for management in Australian rangelands. in Out of Africa. Looking in., l-30.

Thaler, R.H., 1994. The Winner's Curse: Paradoxes and Anomalies of Economic Life. Princeton University Press. Princeton NJ.

Thompson, M. Ellis, R.and Wildawsky, A., 1990. Cultural Theory. Westview Press. Boulder. Colorado.

Tothill, J.C and Mott, J.J. (Editors), 1985. Ecology and management of the world's savannas. Canberra: Australian Academy of Science. 1985

Vallacher, R.R. and Nowak, A. (Editors), 1994. Dynamical Systems in Social Psychology. Academic Press. Inc. San Diego.

Ventana 1998. Reference Manual Vensim 3.0. Ventana Systems. Inc. Harvard. MA.

Walker, B.H. (Editor), 1979. Management of semi-arid ecosystems. Elsevier Scientific Publishing Co.

Walker, P.J. 1991. Land Systems of Western New South Wales. Technical Report 25. Soil Conservation Service of New South Wales. Sydney.

Westoby, M., Walker, B. and Noy-Meir, I., 1989. Range management on the basis of a model which does not seek to establish equilibrium. Journal of Arid Environments. 17:235-239