Grazing Management and Rehabilitation of Degraded Rangeland in Western Australia

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ABSTRACT

Rangeland in the arid zone of Western Australia has been degraded by sheep overstocking since the turn of the centry. The strategies available for restoring the productivity of such degraded rangelands are limited. In this paper optimal economic policies with respect to the choice of stocking rates and grazing patterns were derived for various starting states under a stochastic optimal control framework. Evaluation of these optimal policies was carried out by comparing their long run economic and ecological impacts on grassland with ungrazed conditions.

All optimal policies call for a strategy of set stocking or destocking only. Rotational grazing is not economically viable at the specified cost levels. Optimal stocking rate increases with the level of forage biomass and adult plants, but decreases with the level of either young or old seedlings at the degraded range condition. The results indicate that under the criterion of maximisation of the long run average return, for slightly degraded range, rehabilitation through grazing management alone is possible. For range which is moderately to severely degraded, rehabilitation to fair or good condition is not technically practical. On the other hand, under the criterion of maximisation of the net present value at a discount rate of 6 percent, the consequence of the long run impact on the range resource following the optimal policy is ecologically unsustainable, though economically viable. These findings suggest that if degraded ranges continue to be exploited for private profit, the range resource may be driven beyond its capability to renew. If ecological sustainability is an Australian social norm, economic rationality should subside in the decision criterion, and range management will require some willingness to forego short term profits for the sake of long term rewards or investment in regeneration measures.

1. Introduction

Perceptions of the potential future and current role of Australia's rangelands have changed with time. Traditionally, exploitation and development for pastoral use was the sole objective. Future productivity was assumed, but practical measures to assure such an outcome were lacking. As a consequence, initially dominant shrub species, which are the basis for sustainable livestock production, were reduced from dense to scattered communities within the rangelands. The maintenance of high stocking rates has resulted in continual loss of valuable perennial pasture, which has been replaced, at best, by less desirable pasture plants. In many instances, where stock tended to be concentrated around specific areas, cover was completely destroyed and soil erosion occurred. This resulted in significant degradation of rangeland condition in many pastoral wool-growing areas of Australia, which in turn has reduced the future financial viability of woolgrowers. This decline in rangeland productivity and woolgrower's long-run financial viability is likely to continue in the future unless optimal management strategies are discovered which allow woolgrowers to rehabilitate their range, and thereby restore their financial returns.

In recent years, the view has developed that, due to their importance in animal production and the desirability of maintaining and improving the condition of the soil surface, rangelands should be managed as a renewable resource (Harrington *et al.* 1984). The purposes of this study are two-fold. First is the development of optimum rangeland grazing management strategies under assumptions of a stochastic climatic regime coupled with an unpredictable wool market. Grazing management strategies are simply concerned with determining the appropriate stocking rate for a specific paddock, dependent on the range condition, to conserve the resource base against future degradation and misuse and to enhance productivity of desirable plant species. Second is the evaluation of the long-term impact of the optimal policy in terms of both economic and ecological concepts.

Rangeland ecology in essence is a dynamic system operating in a stochastic climatic and economic environment and involving very significant intertemporal effects. Therefore, in formulating rangeland management as a long-term decision model, a stochastic optimal control approach was adopted in this study to derive optimal decisions which simultaneously determine stocking rate and grazing systems. The long-term impact of the optimal policy on the processes of rangeland degradation and rehabilitation was evaluated by applying Markov chains theory (Freedman 1971, Whittle 1986).

2. A Stochastic Optimal Control Model

The decision-making process for rangeland management in an uncertain climatic environment can be represented as follows. After assessing range condition and the wool market at the beginning of each decision period, the manager decides what utilisation and rehabilitation measures to implement in order to achieve the desired goals. These management decisions, together with subsequent climatic sequences, affect the evolution of the grazing ecosystem. As a result of this evolution, the state of the ecosystem may be transformed into a new state, so earning the manager extra returns from animal products at the end of the decision period. The new state in turn will affect future management decisions. Thus, the decision cycle is repeated.

The range management decision-making process described above can be formulated as a stochastic optimal control model. The formulation of such model involves the following components: an objective function; sets of state variables; stochastic and control (decision) variables; and a set of stochastic state transition equations. Mathematically, the formulation of the decision problem is to discover the optimal decision rule to maximize the expectation of the objective function subject to the transition probabilities which are derived from state transition equations. The constraints for the control and state variables are usually dealt with by the specification of the state and control space. In discrete time, the formulation can be specified as follows:

$$\text{Maximize } V(x_0) = E_0 \sum_{t=0}^{\infty} g(x_t, u_t, w_t) \tag{1}$$

Subject to

$$x_{t+1} = f(x_t, u_t, w_t) \tag{2}$$

$$x_0 \text{ is given} \tag{3}$$

where

$V(x_0)$ =the objective function conditional on the initial values of state variable x_0;

E_0 =the expectation held at initial period;

$g(x_t, u_t, w_t)$ =the return function at period t;

x_t, u_t, w_t =state, control, and random variables, respectively;

$f(x_t, u_t, w_t)$ =a set of transition equations which represent range dynamics.

The constraint, embodied in the set of state transition equations (2) can be replaced by the transition probabilities. This is possible because the evolution of the grazing ecosystem from a specific state into another is governed by transition probabilities which can be calculated from the state transition equations. For a system with discrete states, a transition probability $P_{ij}(k)$ is defined as the probability that the next period state of the grazing ecosystem will lie in the interval associated with the integer designation j if the current state observed lies in the interval associated with the integer index i and if a grazing decision k is applied. This can be specified mathematically by a conditional probability as follows:

$$P_{ij}(k) = P(x_{t-1}=j \mid x_t=i, u_t=k) \tag{4}$$

Therefore, state transition probabilities can be calculated from the transition equations (2) because the state in period t+1 is a random variable, its conditional distribution depends on the current state and control as well as the distribution of random variable w_t.

In the application of this decision model to range management, the components in the stochastic optimal control formulation have been defined as follows:

Objective Function

The range manager is assumed to be risk neutral, and so is assumed to seek to maximise expected returns. A profit function was used to calculate expected annual net profits for a given initial state and policy. These annual net profits, along with yearly transition probabilities, formed the data base for the optimization program. The profit function is based on the concept of net profit margin, NPM, which is defined as the gap between the price of one unit of output and its average total cost. For application to the sheep station in the pastoral zone of Western Australia, the net profit margin was calculated by the following rule:

NPM=net value of wool ±changing value of the flock - stocking rate adjustment costs
- average variable costs - average fixed costs (5)

Gross value of wool produced per sheep per season (see below) is calculated by multiplying average wool production per sheep WC_s and net average greasy price PW which is obtained by deducting wool marketing costs from greasy price. This value, which subtracts the costs of shearing and wool harvesting, is the net value of wool produced per sheep per season. The net value of wool is then converted to a per hectare basis by multiplying the stocking rate at the end of season $u_s(1-m_s)$, where u_s is the seasonal stocking rate and m_s is a seasonal sheep mortality rate. Changes in the value of flock per hectare are calculated by multiplying the market price of sheep PS_s by the change in the stocking rate. This value may be positive or negative. Value of death losses is imputed by multiplying the market price of sheep and the number of deaths. Stocking rate adjustment costs per hectare are calculated by multiplying the adjustment costs per sheep SAC_s and the change in the stocking rate. According to the direction of adjustment, this cost may or may not include selling costs SLC_s. If the direction of adjustment is to build up the flock, the adjustment costs include freight costs FC only. Otherwise, it consists of two components: selling costs and freight costs. Selling costs are 5 percent of sheep sale price as a commission charge and 22 cents per sheep for sale yard fees. A steady state assumption is used to calculate the change in the stocking rate at the beginning of every year, i.e. $u_0=u_3$. The average variable cost per sheep includes the cost of items such as direct labour which varies with sheep numbers, fuel and oil, and repair and maintenance of farm equipment. The average variable cost per season per hectare is calculated by multiplying the stocking rate and the average variable cost per sheep. Since the average fixed costs will not affect the optimal decision rule, these costs are omitted from the return function in the optimisation algorithm. Therefore, net profit margin in this study represents the returns to both the manager's expertise and the fixed factors such as land, family labour, and farm plant and equipment, etc. Mathematically, the annual return function is thus specified as follows:

$$g(x_t,u_t,w_t)= \sum_{s=1}^{3} \{(PW)WC_s-SC)u_s(1-m_s)-PS_s(u_s-u_{s-1}(1-m_{s-1}))$$
$$-|u_s-u_{s-1}(1-m_{s-1})|SAC_s-(AVC)u_s \qquad (6)$$

where

$SAC_s=FC+SLC_s$ if $u_s<u_{s-1}(1-m_{s-1})$
$SAC_s=FC$ if $u_s>u_{s-1}(1-m_{s-1})$

and

s = seasonal index with three rainfall seasons (see below) in a year;
$g(x_t,u_t,w_t)$ = annual net profit function which calculates net profit margin during year t by using the value of state, control and random variables, $/ha;
PW = annual average net greasy price, which is a random variable, $/kg wool;
WC_s = greasy wool production per sheep per season, which is a function of state, control, and random variables of the grazing ecosystem, kg/sheep;
SC = shearing and other wool harvesting costs on per sheep per season basis, $1.13/sheep;
u_s = stocking rate at beginning of season s, sheep/ha;
m_s = seasonal sheep mortality rate, which is a function of state, control and random variables of the grazing ecosystem;
PS_s = seasonal price of sheep which is a random variable, $/sheep;
SAC_s = stocking rate adjustment costs, $/sheep;
FC = freight costs for selling or buying sheep, $0.82/sheep;
SLC_s = seasonal sheep selling costs, $/sheep;
AVC = average variable cost per season per sheep, $1.26/sheep.

Note that wool production and changes in the flock size are nonlinear to the state and control variables, and adjustment costs are asymmetric. This is typical in the case of rangeland management. The derivation of the variables used in the annual net profit margin and the mathematical specification of the function in relation to other variables in the model are given by Hacker *et al.* (1991).

Decision criterion

In order for the decision problem to be completely specified, a decision criterion is needed for determining the ranger manager's preference among the outcomes of his decisions. In the study, the expected net present value and average return are used as two maximisation criteria. In the case of the maximisation of the net present value, the decision maker is assumed to maximise the cumulative sum of the discounted annual returns from curren year to infinity. Mathematically, the objective function under this criterion can be specified as follows:

$$\text{Maximise } V(x_0) = E\{\sum_{t=0}^{\infty} a^t g(x_t, u_t, w_t)\} \qquad (7)$$

The infinite decision horizon is used and the constant discount factor a is added to the annual return function. Assuming that the discount rate of utility is the same as the discount rate of profit, the discount factor equals 1/(1+r) where r is real interest rate. The average real annual interest rate used is 0.06. In average return criterion, maximisation of the average return can be viewed as a surrogate criterion for the special case of a zero discount rate for a risk neutral range manager. Under average return criterion, the objective function of (1) can be specified as follows:

$$\text{Maximise } V(x_0) = \lim_{T\to\infty}(1/T)E\{\sum_{t=0}^{T-1} g(x_t, u_t, w_t)\} \qquad (8)$$

State variables

The state space in the study is formulated as a multi-dimensional finite set. Each state variable represents a distinct dimension. In reality there are many such dimensions, but in the interests of mathematical tractability, only four state variables are used jointly to describe the state of the grazing ecological system. They are the levels of total forage biomass, which is a proxy for range carrying capacity in the short-run, desirable perennial adult plants, which is a proxy for potential range carrying capacity in the medium term, and desirable perennial young seedlings and desirable perennial old seedlings, which influence potential long-term range carrying capacity.

The forage biomass level is classified by five grid intervals: 0-200, 201-400, 401-600 , 601-800, 801+ (kg/ha dry matter), respectively. Young and old seedlings are divided into three categories to represent three possible levels: 0-600, 601-1200, 1201+ (plants/ha) for young seedlings and 0-300, 301-600, 601+ for old seedlings, respectively. The density of adult plants is classified by the five grid intervals: 0-1000, 1001-2000, 2001-3000, 3001-4000, 4001+ (plants/ha), respectively. These five levels for the adult plants are used to represent the classification of the range condition, and correspond to *severely degraded, moderately degraded, slightly degraded, fair, and good range condition*, respectively.

Using the above classification scheme, the state of the grazing ecosystem is thus described by a four-part descriptor (adult plants, total forage biomass, young seedlings, old seedlings) and there are 225 such states. For example, the state (0-1000, 0-200, 0-600, 0-300) represents a severely degraded area with 0-1000 adult plants, 0-200 kg/ha dry matter forage biomass, 0-600 young seedlings/ha, and 0-300 old seedlings.

Control variables

Grazing decisions are the only control variable in the study. Maximisation in (1) utilises 33 different grazing decisions, which reflect various prespecified stocking rates under three grazing systems: *total destocking, continuous grazing (set stocking) and rotational grazing (variable stocking rates).* Table 1 presents these 33 decisions. As indicated, Decision 1 involves total destocking, which is a "do nothing" policy and occasionally may be necessary to allow the establishment of seedlings to occur. Decisions 2 to 12 involve a pattern of continuous grazing in which the order of policy index increases with a rise in stocking rate. Decisions 12 to 33 involve various patterns of rotational grazing. A continuous grazing system sets the stocking rate at a certain level at the beginning of the year and subsequent adjustment is not required during the year. However, if the initial stocking rate is set too low, this strategy has a cost of income forgone in years of average or above-average rainfall years and large losses combined with land degradation in dry years. Rotational grazing in this study refers to a grazing policy which adjusts the stocking rate from season to season. This policy requires the sale of stock at the start of those periods when feed is likely to be short, and the repurchase or breeding up of stock when feed is likely to be abundant. Although breeding up is the more common practice for raising stocking rate in the rangelands because repurchase is limited by the shortage of stock after droughts and the high cost of transport from other regions, for analytical convenience it was assumed that the adjustment of stock can only be made through the market. The variable stocking rates are set at levels appropriate to expected rainfall in each of the three seasons: unreliable summer rainfall (January-April), reliable winter rainfall (May-August) and reliable summer drought (September-December). The level of stocking rates under the three grazing systems encompass the possible range of stocking rates current in the rangelands of Western Australia.

Stochastic variables

The stochastic variables include both climatic and economic factors. In the optimisation, the number of growth periods measured by the unit of 5 days, i.e. the number of wet pentads (NWP), is the only climatic stochastic variable used. The 50-year daily rainfall data for a hypothetical degraded site on Wooramel Station in Western Australia, and monthly average evaporation data are used in a water balance model (Hacker et al. 1991) to generate the distributions of the number of growth periods for the three rainfall seasons. The NWP distributions for the above three rainfall seasons are all positively skewed. The mean of the distribution increases when the range condition improves. This indicates a longer growth period is expected with better range condition. The stochastic economic variables are the prices of wool and sheep, and both are assumed to follow a uniform distribution. The expected annual net greasy price ranges from $2.49 to $4.2/kg, and the expected seasonal price of sheep ranges from $2.82 to $7.56 per sheep in season one, $4.61 to $12.45 in season two, and $1.05 to $7.95 in season three, respectively (Australian Wool Corporation 1992). In the simulations, these stochastic variables are assumed to be independent and a [0,1] random variable is used to generate values for these stochastic variables from their given distributions, respectively.

Transition probabilities

In order to derive the state transition probabilities a simulation model "IMAGES: an Integrated Model of an Arid Grazing Ecological System" constructed by Hacker et. al. (1991) is used. IMAGES integrates the evolution of an arid grazing ecosystem in the winter rainfall pastoral zone of Western Australia. The main functional components of the model describes the plant-animal-climate interface in a single paddock on a four-monthly time basis consistent with the abovementioned three rainfall seasons.

The essence of the model is depicted by Figure 1. A soil water balance submodel was used to derive the number of wet pentads over a four-monthly period for the aforementioned three rainfall seasons. Wet pentads together with the management decisions of stocking rate and cultural treatments such as reseeding and ploughing activities drive the vegetation dynamics through three related components: ephemeral forage biomass, perennial forage biomass, and desirable perennial plant density. The desirable perennial plant density consists of six four-monthly age-cohorts seedlings, i.e. 0-3, 4-7, ... 20-23 months and one adult class i.e. 24+ months. Seedlings are grouped into two classes: young seedlings with ages between 0-11 months and old seedlings with ages between 12-23 months. These three components in turn influence sheep performance in terms of wool production, mortality and lambing rate through sheep intake, which determines economic returns to the woolgrower.

The simulation model consists of nine difference equations for state transitions, one for each of the state variables: ephemeral and perennial forage biomass, and seven age-cohorts of desirable perennial plants. State transitions are functional on these state variables, management decisions and the number of wet pentads. For analytical convenience, a wether flock is assumed and the nine state variables are aggregated into the four state variables aforesaid. A detailed description and the mathematical specification of the model was given in Hacker et. al. (1991).

In the simulations, a uniform distribution is assumed to apply to the specific location within the four dimensional cell defining a state of the grazing ecosystem. Under this assumption, a transition probability of moving out of a state into another is calculated 100 simulation runs for different locations within the given cell and these values are averaged to get the overall unconditional probability, i.e., without regard to where within the originating cell the process actually rests. Three further fine grid points within the associated class intervals of the four state variables are used for simulation runs. In other words, each single state of the grazing ecosystem is represented by 81 different combinations of the fine grid points. The fine grid points used for a class interval of a state variable are 16.5%, 50% and 83.5% of that class interval, respectively. For example, for state (0-1000, 0-200, 0-600, 0-300), under a given policy, 100 simulation runs are implemented for each of the 81 possible combinations formed by the following fine grid values: adult plants, 166, 500, 834 (plants/ha); total forage biomass, 33, 100, 167 (kg/ha dry matter); young seedlings, 100, 300, 500 (plants/ha); old seedlings, 50, 150, 250 (plants/ha). Thus, a total of 8100 simulation runs are used to generate the transition probabilities for the above state under a given policy. The same procedure is used for every other 224 states and policies, respectively.

3. Operational sequence

Simulations of the arid grazing model IMAGES are run under the 33 grazing decisions, using initial values of the various combinations of the four state variables. The output from the simulations is organized into a data set with records consisting of number of distinct transitions, initial state index, policy index, average return, frequency of transitions and year-end state index. The resulting data set is subsequently used by optimisation algorithm to determine optimal grazing strategies. For the decision criterion of maximising expected net present value a dynamic optimisation formulation results in the following recursive equations (Bertsekas 1976):

$$V(i)= \text{Max}\ \{\bar{g}(i,k)+a\sum_{j=1}^{N} P_{ij}(k)V(j)\} \qquad i,j \quad [1,N];\ k \quad [1,M] \qquad (9)$$

and for the average return decision criterion

$$l+h(i)= \text{Max}\ \{\bar{g}(i,k)+\sum_{j=1}^{N} P_{ij}(k)h(j)\} \qquad i,j \quad [1,N];\ k \quad [1,M] \qquad (10)$$

where
i, j, k = initial and terminal state indices and k is a decision index;
$\bar{g}(i,k)$ = annual expected returns if initial state is i and decision k is adopted;
a = discount factor;
$P_{ij}(k)$ = the transition probability from state i to state j under a given decision k:
$V(i)$ = optimal value function given initial state is i;
N, M = the total number of states and decisions, respectively;
l = the optimal value of long run expected average return per annum;
$h(i)$ = the relative value function if initial state is i, this represents the transient profits earned before the dynamic system enters into the equilibrium state.

The recursive equations (9) and (10) are solved by using a successive approximation method based on backward dynamic programming with lower and upper bounds for the optimal values at each iteration to speed up the convergence of the value functions (Bertsekas 1976). Successive approximation starts with an arbitrary V(j) and computing V(i) by using (9), and substituting V(j) by V(i), then repeats these computations iteratively until V(i) and V(j) converge. At the end, it generates, in the limit, the optimal value function and optimal policy. A similar algorithm can be applied to equation (10) for h(j) and h(i) by setting one state as a reference state. In the limit, it generates optimal average return and optimal policy together with a set of N optimal relative values as transient profits specific to each state. The optimal policy in turn can be used to extract the optimal transition probability matrix for further Markov chains analysis. Finally, the long run equilibrium and transient behaviour of the optimally controlled grazing ecosystem were presented for discussions.

In Markov chains analysis, a long run stochastic equilibrium represents a range of the states that the system could fall in after an infinite number of transitions. The possibility distribution for these states is called the long run probability distribution. The absorption range of a stochastic equilibrium is the subset of the state space which may all approach to the equilibrium as time approaches to infinity. The states in the absorption range are transient states. These states represent the areas in which the stochastic system will temporarily remain for a certain period but once the system leaves these areas, it can never return. The possibility for a transient state to reach a stochastic equilibrium is the absorption probability and the expected time needed for this reaching is the mean absorption time. The methods to identify these characteristics can be found in most textbooks of Markov chains such as Freedman (1971) and Whittle (1986).

4. Results and Discussion

With zero discounting

As shown in Table 2, it is not economical to adopt rotational grazing for almost all range conditions. This indicates that stocking rate adjustments proposed are not economically feasible in the rangeland environment although rotational grazing can exploit better the opportunities of the fast growth of both ephemeral and perennial triggered by the winter rainfall. However, if the adjustment costs are lower or the sheep prices are not too high in the winter season rotational grazing may not be infeasible in the future. This is because the model assumes that the stocking rate can only be adjusted through sheep buying and selling activities and the market prices of sheep are usually against the need of the woolgrowers. Usually sheep prices are high in winter season and this prevents the increase of stocking rate (too expensive to buy) while low prices in season 1 and 3 prevents the reduction of stocking rate (difficult to sell).

Total destocking is most common when the forage biomass is at minimum level or when plant density is at the level of less than 3000 plants per hectare combined with medium to high level of seedlings. The adoption of total destocking at the minimal forage level is expected since a degraded pasture with little forage is the least resilient and destocking needs to allow the pasture to regrow. On the other hand, when the degraded range with medium to high level of seedlings has a higher possibility to be improved total destocking is needed to promote the establishment of both young and old seedlings.

More general, stocking rates positively correlate with the population of adult plants and the level of forage biomass. This is expected since the range with better condition and more forage available should be able to sustain higher stocking rates. Optimal stocking policy also shows a negative correlation between stocking rate and the population of young and old seedlings at the range condition with less than 4000 plants per ha. Reduced grazing pressure here is adopted to promote the establishment of both young and old seedlings when their populations increase from a minimal level. However, at the normal range condition with 4001+ plants per ha stocking rate is not sensitive to the density of either young or old seedlings. This is because at the normal range condition there are plentiful plants jointly with full potential of seed production and the plant community can thus replenish itself without extra redundant seedlings.

Since there is only one stochastic equilibrium of the system under the optimal grazing policy, as indicated below, the optimal expected long run average return per annum is independent of the initial ecosystem states. The optimal long run expected average return per annum is $4.26/ha from any ecosystem states. This has the implication that the range ecosystem will evolve into a single stochastic equilibrium in the long run and under the equilibrium the system has $4.26/ha as its returns to the fixed production factors employed. Apart from the average return, a set of state-specific relative cumulated returns are also computed using state (0-200, 0-600, 0-300, 0-1000) as a reference base. Table 3 shows these results. These values represent the profits the system can earn from a specific initial state before reaching the stochastic equilibrium. In other words, they are the profits associated with the transient behaviour of the system. Since each initial state may have a different approach path to the equilibrium the profits are state specific. In general, the relative value is positively correlated to the value of the four state variables. The impact of forage biomass on optimal relative values, other things being equal, seems insignificant, though it has a positive contribution. With regard to the impact of seedling population, the optimal transient value is not sensitive to the level of either young or old seedling populations in the range conditions with more than 3000 plants per ha. In this situation the plant community has the ability to replenish itself without the extra seedlings. Also, the optimal value is insensitive to the level of young seedlings in the range of 0-1200 seedlings per ha. When the level of young seedlings increases from 1200 seedlings per ha in the degraded range optimal transient profits increase significantly due to the greater possibility of range improvement. Therefore, the abundance of young seedlings is important in rangeland rehabilitation. With regard to old seedlings, the optimal value shows marked increases when the number of old seedlings increases except in the range with more than 3000 plants per ha. Thus, in degraded range conditions old seedlings play an important rehabilitation role. Regarding adult plants, the optimal transient profits increase significantly as plant densities increase for the degraded range conditions. This indicates the relatively more importance of adult plants in degraded ranges.

As indicated by Table 4, there is only one stochastic equilibrium indicated by shading in the optimal grazing ecosystem, which contains 79 states in the range conditions with more than 3000 plants per ha. Therefore, the equilibrium is globally stable and all transient states will finally be absorbed into it. The mean absorption time ranges from 1 to 372 years and the longest time occurs for states with the minimum level of adult plants and seedlings. In general, the mean absorption time decreases with increasing densities of adult plants and seedlings but it remains almost static for the whole level of forage biomass. This implies that for degraded ranges the length of rehabilitation process under the optimal policy is determined mainly by the number of adult plants and old seedlings. Young seedlings are occasionally important when they are abundant.

The most likely state of the system in the long run is good condition with 4001+ plants per ha. This is indicated by the global maximum of the long run probability distribution which occurs at state (4000+, 401-600, 0-600, 0-300) with a probability value of 0.15. Thus, on average, the system will recur to this state about every 6.7 (=1/0.15) years in the long run. Although only one stable equilibrium exists, and all states will eventually be absorbed into it under the optimal management, the absorption times are so long that for all practical purposes range with less than 2000 plants per ha would have to be considered in a stable degraded state. Continued grazing under such degraded conditions would not lead to complete degradation but regeneration could not be achieved within a practical time frame. Economical optimal management is compatible with land conservation if the land is originally in good condition with 3001+ plants per ha. For range in slightly degraded condition (2001-3000 plants per ha) restoration of range condition under optimal management may be possible within a reasonable time frame (say the life of a manager) but even this is debatable if few old seedlings are present. Therefore, grazing management alone could not be expected to restore range which is degraded below 2000 plants per ha within a reasonable time frame. Cultural intervention is necessary to restore degraded land.

Ungrazed conditions

Table 5 presents the long run equilibrium and transient behaviour of the grazing ecosystem under ungrazed conditions. The result is similar to that above except that absorption times are slightly shorter and the modal equilibrium states cover a higher biomass range, as might be expected. The long run probability distribution has a modal value of (4001+, 601-800, 0-600, 0-300) with a probability density of 0.23. The three adjacent states located in (4001+, 401+, 0-600, 0-300) account for more than 51% of the probability distribution. Thus, under ungrazed situation, the system will revisit these three states once about every two years in the long term. These states represent a range in good condition with 4001+ plants per ha combined with large amount of forage biomass and limited level of young and old seedlings. Since the long run probability distribution of the equilibrium states is relatively more concentrated on the range in good condition than that of the average return case the possibility for the system to remain in good condition with higher level of forage availability and seedlings increases. In other words, the system will recur to good condition more frequently in the long run under ungrazed conditions.

The mean absorption time ranges from 1 to 370 years with a similar pattern as above mentioned under the average return case but with a 1 to 2 years reduction. This confirms the view that cultural intervention will be necessary to restore degraded land in any reasonable time frame, destocking is not sufficient.

In both these analyses it is notable that the change from 1001-2000 plants per ha to 2001-3000 plants per ha produces a marked reduction in absorption times. 2000 plants per ha or thereabouts constitutes a threshold in this ecosystem which management should cross at its peril. This threshold marks a benchmark for the range where sustainability/unsustainability can be approximately known. The basic criterion for range sustainability is to manage the vegetation equal to or above this benchmark. For range in degraded condition below this benchmark, do nothing (ungrazing or destocking) policy is not likely to stabilise or reverse the land deterioration practically. Regeneration programs such as ploughing and waterponding which improve soil moisture retention, and associated with the re-introduction of suitable seed source should be adopted in unison with the optimal grazing management to rehabilitate the severely degraded range.

With 6% discount rate

As indicated in Table 6, the optimal decision calls for set stocking and destocking policies. Variable stocking rate policy is not optimal. This is consistent to the grazing strategy practised by most pastoralists in the rangelands of the region. High costs involved in the stock adjustments restrict the policy of variable stocking rates. Total destocking is again the most common when there is little forage available at the range condition with less than 3000 plants per ha. Therefore, under the criterion of the present value maximisation with 6% discount rate, pastoralists should spell the degraded range, once it is severely defoliated. Destocking is also optimal for many degraded range conditions where there are greater possibilities of range improvement. This is not unusual since destocking is the only effective option for rehabilitating degraded ranges when there are no cultural treatments involved.

Optimal stocking rates, in most cases, increase with the amount of forage biomass. Compared with the average return case, the optimal stocking rates are much higher with 6% discount rate and show more exploitative nature. With reference to the density of young seedlings, the optimal stocking rates are not sensitive to them although relatively lower stocking rates occasionally occur where the density of young seedlings increases from 1200 seedlings per ha at the range condition with less than 2000 plants per ha. The lower stocking rates are applied to take the advantage of higher possibility of range improvement through seedling establishment. With regard to the old seedlings, the optimal stocking rate shows a downward trend as the density of old seedlings increases in the range condition with less than 4000 plants per ha. The decline in optimal stocking rate is to allow more old seedlings to survive and whereby improve range condition. In the good range condition, the optimal stocking rate either displays a slightly increasing trend or is constant with respect to the density of old seedlings. This is similar to the previously observed in the average return case and is due to the redundancy of extra seedlings at this range condition.

Optimal stocking rate in most situations increases with a rise in the adult plant population except in the range condition with less than 1000 plants per ha where stocking rates are generally decreasing as the plant density increases. This imply that under the profit maximisation with 6% discount rate range manager will adopt a more exploitative strategy towards grazing at the badly degraded range. Compared to the average return case, the optimal policy indicates an evident increase in the stocking rate and a decrease in using total destocking to rehabilitate degraded ranges.

As shown in Table 7, the expected net present value of profits corresponding to the optimal policy increases with increasing values of the four state variables. The highest value of $87/ha occurs in state with the highest level of both plants and forage biomass. On the contrary, the lowest value of $12 occurs in state with the minimal level of plants and forage biomass. Thus, the opportunity cost of degradation could be as high as $75/ha for the severely degraded ranges if the highest potential of rangeland productivity is assumed. This cost can be reduced if there is a rise in the value of the four state variables. The optimal value is not sensitive to the level of both young seedlings and forage biomass, although a positive correlation exists. This indicates that, acting as a short run carrying capacity, forage availability will not influence the long term profit significantly. Young seedlings are also not important in determining the long term profits due to the exploitative nature of the grazing policy adopted.

With regard to old seedlings, a significant increase in the optimal value is observed as the density of old seedlings increases in the range condition with less than 2000 plants per ha where the optimal stocking rates show a decreasing trend. This is consistent since when the long term value of old seedlings increases a lighter stocking rate should be adopted currently to encourage their establishment, although the short run profits may be reduced due to the lower stocking rate adopted. With reference to the adult plants, the optimal value shows a decreasing trend at an increasing rate as the plant population decreases from its maximal level, i.e. 4001+ plants per ha. This implies that the cost of degradation will increase significantly once range condition becomes worse.

There is also only one stochastic equilibrium in the optimal grazing ecosystem represented by shading shown in Table 8. It extends from good range condition with

4001 plants per ha to badly degraded condition with less than 1000 plants per ha, and consists of more than half of the ecosystem states. Although the equilibrium states with 0-1000 plants per ha are visually separated from the other shaded area, in a four dimensional space they are actually connected with other equilibrium states and has possibilities to communicate with other equilibrium states. The mean absorption time ranges from 1 to 1.2 years. This indicates that, on average, the transient states will disappear within 1.2 years. The extremely short period for the absorption is due to the vast area covered by the equilibrium.

Moderately degraded condition (1001-2000 plants per ha) with little forage available is the most likely state for the system in the long run although there is a chance that land in this poor condition would be degraded totally and maintained in a totally degraded states (0-1000 plants per ha). Under the steady state the system is expected to revisit to the state in poor condition, i.e. the four-tuple (1001-2000, 0-200, 0-600, 0-300), every 2.5 years (1/0.4). Although the covered area of the long run equilibrium is very large, there is very little chance that most states will occur. The range is very unlikely to exist in good condition (4001+ plants per ha). Thus, if it starts in good condition it is very unlikely to remain in that condition and further degradation is highly possible. Optimal management of range under this discount rate is basically exploitative. Some period of non-optimal management would be required to maintain or improve range condition.

The most common stable states under this discount rate are those from which any return to good condition is not practically feasible under the average return case. In fact, the mean recurrence time of the grazing ecosystem in good condition will be intolerably long since the long run probabilities of all equilibrium states in good condition are insignificant with a value less than 0.005. Therefore, under the profit maximisation criterion with 6% discount rate, the optimal policy will eventually drive the system to more or less total degradation of the range. For range in good condition, further degradation is almost certain. Conversely, for range in degraded condition rehabilitation may be possible but the chance of success is slim. Compared to the average return case which is also a proxy for the special case of a zero discount rate, the results suggest that the long term equilibrium conditions of the grazing ecosystem are very sensitive to the assumed discount rate.

The analyses suggest that pastoral management in this rangeland is not ecologically sustainable at a discount rate of 6 per cent, though it is financially viable. If basic Australian societal requirements include that the rangeland be managed in ways that are ecologically sustainable, economic rationality should subside in the decision criterion. Maintenance or improvement of this resource will require some willingness to forego short term profits for the sake of long term rewards or investment in regeneration measures if the range is to be managed within its capability to renew.

5. Concluding Comments

This study uses stochastic optimal control framework to solve the range resource management problem with respect to decisions about stocking rate and grazing system. A bioeconomic simulation model IMAGES was adopted to represent the major components of the rangeland grazing system within the arid winter rainfall pastoral zone of Western Australia. Simulation runs for different management strategies and initial range conditions were conducted to derive the transition probabilities under the stochastic settings for both climate and market conditions. These transition probabilities were subsequently used for the stochastic optimal control.

Four variables, i.e. forage biomass, young seedlings, old seedlings, and adult plants, are used jointly to describe the state of the grazing ecosystem. The management strategies are specified by various decisions which incorporate stocking rates and grazing systems. The optimal policy was derived under two different decision criteria of the maximisation of the net present value and the long run average return, respectively. Evaluation of the optimal policy was carried out by analysing its long run economic and ecological impacts. The long run ecological impact was analysed by Markov chains theory which can determine the long run equilibrium and transient behaviour of a stochastic dynamic system. A natural rangeland system under ungrazed conditions was also studied to provide a benchmark to evaluate the long run ecological impact for sustainability.

In both decision criteria, the optimal policy calls for set stocking and destocking and it is not economical to adopt rotational grazing at the economic market conditions. Total destocking is found to be optimal when the range is almost totally defoliated or badly degraded coupled with high density of seedlings. In general, optimal stocking rate increases with the level of forage biomass and adult plants, but decreases with the level of either young or old seedlings at the degraded range conditions. The optimal expected net present value increases with increasing value of the four state variables. The opportunity cost of rangeland degradation is not sensitive to the availability of forage biomass but is very sensitive to the population of adult plants. The opportunity cost of degradation increases at an increasing rate as the population of adult plants decreases from 4001 plants per ha. Consequently, it is extremely important to prevent range degradation since the degradation cost will accelerate at an increasing rate once range degradation process begins.

Markov chain analysis indicates that under the criterion of maximisation of the long run average return, for slightly degrade range with more than 2000 plants per ha, rehabilitation through grazing management alone is possible. For range which is moderately to severely degraded and is characterised by less than 2000 plants per ha, rehabilitation to the fair or good condition is technically not practical. On the other hand, under the criterion of maximisation of the net present value at a discount rate of 6 per cent, the consequence of the long run impact on the range resource following the optimal policy is ecologically unsustainable, though economically viable. This implies that if degraded ranges continue to be exploited for private profit, the range resource may be severely depleted.

Since the optimal decision rule includes the whole possible set of range conditions, it can be used in each year for decision making. Following such an optimal decision rule, the range manager can first take note of the various dimensions of range condition and then select the optimal stocking rate and grazing system. Thus, the final suggestion is that range manager should monitor the changes in the state of his range condition, and thereby provide a basis for the application of the optimal grazing and rehabilitation or prevention strategies. The society, as a whole, also has a responsibility to provide objective benchmarks of range sustainability or unsustainability zone and a scientific measuring facility in order to ensure that rangeland resources are neither degraded nor destroyed (Schapper 1990). This can be done by setting up a national wide network of rangeland monitoring sites coupled with research tools such as the method used in this study.

With the help of IMAGES simulation model to identify those sites which may be in greatest need of attention, in terms of changed management practices, by predicting the composition of the state they may be heading for using Markov chain theory, range manager can know approximately whereabouts of current range condition in the sustainability or unsustainability zone. The proper management practices can therefore be designed and related to the condition of range resource. This is particularly important in practice as pastoralists need to set objectives in resource management and need to know what objectives are ecologically realistic for a degraded range.

References

Australian Wool Corporation (1992), Wool Market News, Monthly Perspective, Melbourne. (and previous issues).

Bertsekas, D.P. (1976), *Dynamic Programming and Stochastic Control.* Academic Press. New York.

Fox, B.L. and Landi, D.M. (1968), An algorithm for identifying the ergodic subchains and transient states of a stochastic matrix. *Communication of the Association for Computing Machinery* 11:619-621.

Freedman, D. (1971), *Markov Chains.* Holden-Day Inc, London.

Harrington, G.N., A.D. Wilson and M.D. Young (1984), *Management of Australia's Rangelands. Division of Wildlife and Rangelands Research.* CSIRO, Australia.

Hacker, R.B., Wand, K.M., G.S. Richmond and R.K. Lindner (1991), IMAGES: an integrated model of an arid grazing ecological system. *Agricultural Systems* 37:119-163.

Schapper, H.P. (1990). *Farm Land Care.* Seminar notes, School of Agriculture, The University of Western Australia. Perth.

Whittle, P. (1986), *System in Stochastic Equilibrium.* John Wiley and Sons, New York.

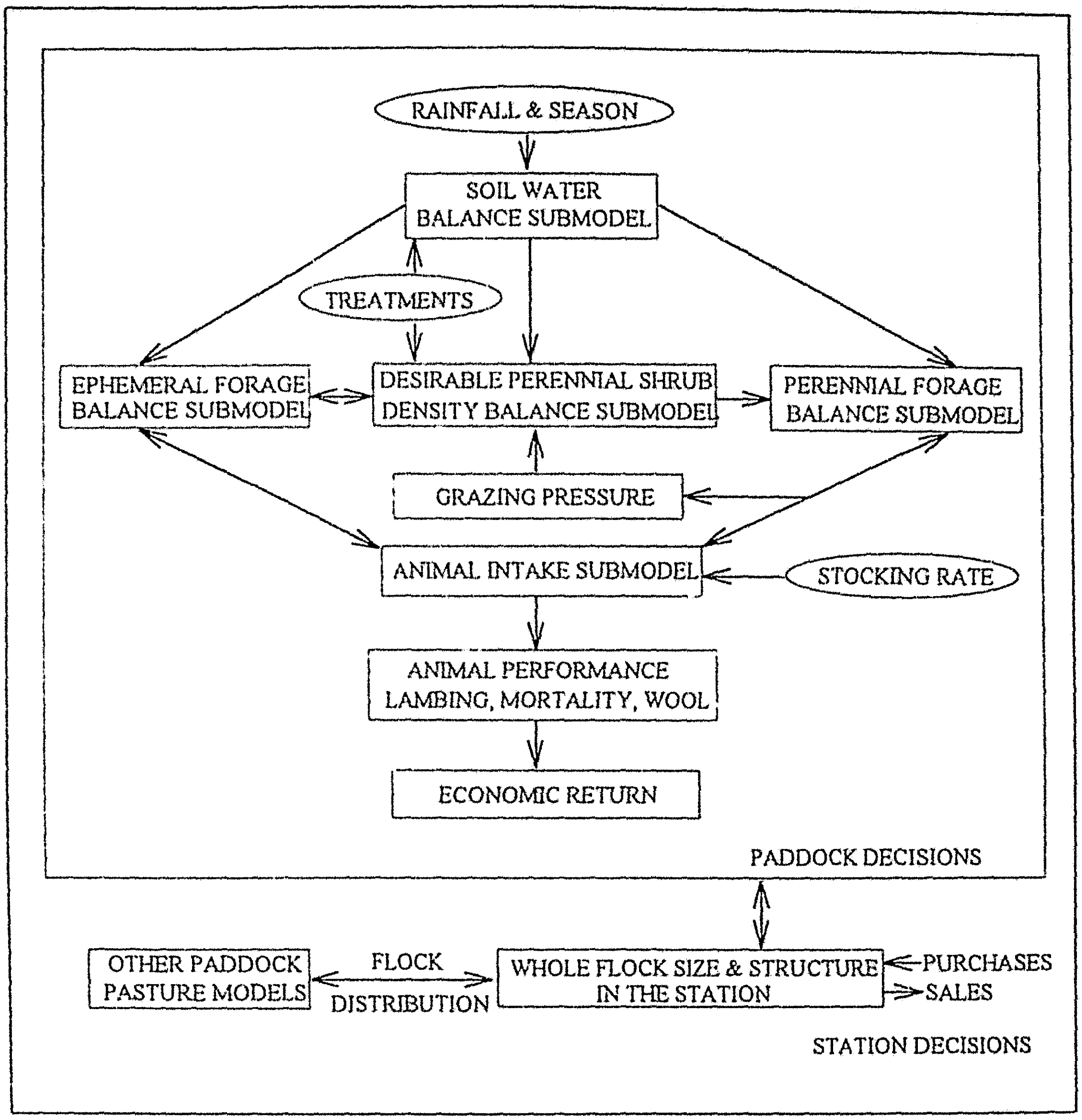

Figure 1. Conceptual model of a rangeland grazing system at the whole property level

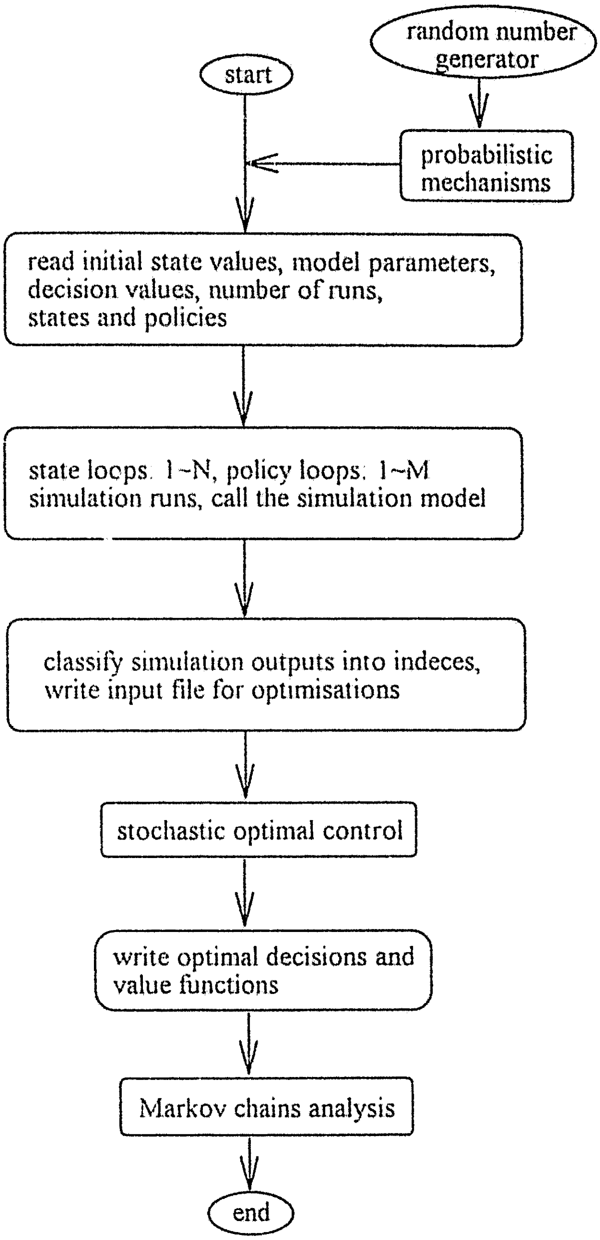

Figure 2: Operational Sequence for Combining Simulation, Optimisation and Markov Chains Analysis

Table 1. Grazing decisions considered in the model

Decision	stocking rate (hd/ha)		
index	season 1	season 2	season 3
1	0		
2	0.05		
3	0.07		
4	0.1		
5	0.15		
6	0.2		
7	0.3		
8	0.4		
9	0.5		
10	0.6		
11	0.8		
12	1		
13	0	0.2	0
14	0	0.4	0
15	0	0.7	0
16	0	1	0
17	0.05	0.4	0.05
18	0.05	0.7	0.05
19	0.05	1	0.05
20	0.05	1.5	0.05
21	0.1	0.4	0
22	0.1	0.4	0.1
23	0.1	0.7	0
24	0.1	0.7	0.1
25	0.1	1	0
26	0.1	1	0.1
27	0.25	0.4	0
28	0.25	0.4	0.1
29	0.4	0.7	0
30	0.4	0.7	0.4
31	0.4	1	0
32	0.4	1	0.4
33	0.5	1.5	0.5

Note: 1. Decision 1 is destocking throughout the year. Decisions 2 to 12 are set stocking policies ranging from 0.05 hd/ha to 1 hd/ha. Decisions 13 to 33 are various patterns of stocking rate adjustment during the year.

Table 2: Optimal grazing decisions under zero discounting criterion

		TOTAL FORAGE BIOMASS (KG/HA DRY MATTER)																
		0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above		
		decision indeces																
ADULT PLANTS	0-1000	1	1	11	12	12	1	6	7	8	10	1	1	1	1	3	0-600	YOUNG SEEDLINGS
		1	1	11	12	12	1	6	7	8	10	1	1	1	1	3	601-1200	
		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1200+	
	1001-2000	1	9	10	12	12	1	1	1	1	1	1	1	1	1	1	1-600	
		1	2	3	4	11	1	1	1	1	1	1	1	1	1	1	601-1200	
		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1200+	
	2001-3000	5	7	8	9	10	1	1	1	1	1	1	1	1	1	1	1-600	
		1	7	8	9	10	1	1	1	1	1	1	1	1	1	1	601-1200	
		1	1	13	4	10	1	1	1	1	1	1	1	1	1	1	1200+	
	3001-4000	4	9	10	11	11	1	6	8	9	11	1	1	9	10	12	1-600	
		4	9	10	11	11	1	6	8	9	11	1	1	9	10	12	601-1200	
		1	9	10	11	11	1	6	8	9	11	1	1	9	10	12	1200+	
	4001+	3	8	10	11	12	5	9	11	12	12	5	10	11	12	12	1-600	
		3	8	10	11	12	5	9	11	12	12	5	10	11	12	12	601-1200	
		3	8	10	11	12	5	9	11	12	12	5	10	11	12	12	1200+	
	PLANTS/HA	0-300					301-600					600 & above					PLANTS/HA	
		OLD SEEDLINGS (PLANTS/HA)																

Table 3. Optimal value function under zero discounting criterion

		TOTAL FORAGE BIOMASS (KG/HA DRY MATTER)														
ADULT PLANTS	YOUNG SEEDLINGS	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above
PLANTS/HA	PLANTS/HA	transient profits, $/ha														
0-1000	0-600	0	0	0	2	3	15	16	17	18	20	34	34	35	35	37
	601-1200	0	0	0	2	3	15	16	17	18	20	34	34	35	36	37
	1200+	10	10	10	10	10	37	37	37	37	38	61	61	61	62	63
1001-2000	1-600	57	59	61	62	64	347	348	349	349	350	613	614	614	614	615
	601-1200	60	61	62	62	64	349	350	351	351	352	615	616	616	616	617
	1200+	148	149	150	150	151	411	412	412	412	413	648	649	649	650	650
2001-3000	1-600	935	937	939	940	940	958	959	959	960	960	973	974	975	975	975
	601-1200	936	938	939	940	941	959	960	960	960	961	974	975	975	975	976
	1200+	944	945	945	945	946	966	966	967	967	967	978	979	979	979	979
3001-4000	1-600	1014	1017	1018	1019	1020	1019	1020	1022	1023	1024	1024	1026	1027	1028	1029
	601-1200	1014	1017	1018	1019	1020	1019	1021	1022	1023	1024	1024	1026	1027	1028	1029
	1200+	1015	1018	1019	1020	1021	1020	1022	1023	1024	1025	1025	1027	1028	1029	1030
4001 +	1-600	1039	1043	1044	1046	1047	1040	1043	1045	1046	1047	1040	1044	1045	1046	1047
	601-1200	1039	1043	1045	1046	1047	1040	1043	1045	1046	1047	1040	1044	1045	1046	1047
	1200+	1039	1043	1045	1046	1047	1040	1044	1045	1046	1048	1040	1044	1045	1047	1048
PLANTS/HA	PLANTS/HA	0-300					301-600					600 & above				
		OLD SEEDLINGS (PLANTS/HA)														

Note: 1.Maximal experted long run average return per annum =$4.26/ha for all states.

2.Transient profits are calculated by using state (0-1000, 0-200, 0-600, 0-300) as a reference base.

Table 4. Long run equilibrium and transient behaviour of the range ecosystem under zero discounting criterion

		TOTAL FORAGE BIOMASS (KG/HA DRY MATTER)																
		0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above		
ADULT PLANTS	0-1000	372	372	372	372	372	368	368	368	368	368	362	362	362	362	362	0-600	YOUNG SEEDLINGS
		372	372	372	372	372	368	368	368	368	368	362	362	362	362	362	601-1200	
		369	369	369	369	369	360	360	360	360	360	353	353	353	353	353	1200+	
	1001-2000	356	356	356	356	356	250	250	250	250	250	152	152	152	152	152	1-600	
		355	355	355	355	355	249	249	249	249	249	151	151	151	151	151	601-1200	
		322	322	322	322	322	226	226	226	226	226	139	139	139	139	139	1200+	
	2001-3000	35	35	35	35	35	25	25	25	25	25	18	18	18	18	18	1-600	
		34	34	34	34	34	24	24	24	24	24	18	18	18	18	18	601-1200	
		31	31	31	31	31	22	22	22	22	22	17	17	17	17	17	1200+	
	3001-4000	0.04	0.11	0.1	0.01	n/s	n/s	n/s	0.01	1	n/s	n/s	n/s	n/s	n/s	1	1-600	
		n/s	0.02	0.03	n/s	n/s	n/s	n/s	0.01	n/s	n/s	1	n/s	n/s	n/s	1	601-1200	
		n/s	0.03	0.09	0.04	0.01	1	n/s	0.02	0.01	n/s	1	n/s	n/s	n/s	n/s	1200+	
	4001+	0.02	0.05	0.15	0.08	0.03	n/s	n/s	0.01	0.01	n/s	1	n/s	n/s	n/s	n/s	1-600	
		n/s	0.01	0.02	0.02	n/s	1	n/s	n/s	n/s	n/s	1	n/s	n/s	n/s	n/s	601-1200	
		n/s	n/s	0.03	0.03	0.01	1	n/s	n/s	n/s	n/s	1	1	n/s	n/s	n/s	1200+	
	PLANTS/HA	0-300					301-600					600 & above					PLANTS/HA	
		OLD SEEDLINGS (PLANTS/HA)																

Note: 1. There is only one stochastic equilibrium indicated by shading with numbers indicating the long run probabilities and "n/s" referring to a probability value < 0.5%.

2. States without shading are transient with the numbers indicating mean absorption times in years.

Table 5. Long run equilibrium and transient behaviour of the range ecosystem under ungrazed conditions

		TOTAL FORAGE BIOMASS (KG/HA DRY MATTER)																
		0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above		
	OLD SEEDLINGS (PLANTS/HA)	0-300					301-600					600 & above						
ADULT PLANTS	PLANTS/HA																PLANTS/HA	YOUNG SEEDLINGS
	0-1000	370	370	370	370	370	366	366	366	366	366	361	361	361	361	361	0-600	
		370	370	370	370	370	366	366	366	366	366	361	361	361	361	361	601-1200	
		367	367	367	367	367	358	358	358	358	358	351	351	351	351	351	1200+	
	1001-2000	354	354	354	354	354	248	248	248	248	248	151	151	151	151	151	1-600	
		353	353	353	353	353	247	247	247	247	247	150	150	150	150	150	601-1200	
		321	321	321	321	321	225	225	225	225	225	138	138	138	138	138	1200+	
	2001-3000	33	33	33	33	33	24	24	24	24	24	17	17	17	17	17	1-600	
		32	32	32	32	32	23	23	23	23	23	17	17	17	17	17	601-1200	
		29	29	29	29	29	21	21	21	21	21	16	16	16	16	16	1200+	
	3001-4000	n/s	0.02	0.05	0.02	n/s	n/s	n/s	0.01	n/s	n/s	n/s	n/s	n/s	n/s	1	1-600	
		n/s	n/s	0.01	0.01	n/s	n/s	n/s	n/s	n/s	n/s	1	n/s	n/s	n/s	1	601-1200	
		n/s	n/s	0.01	0.03	0.02	1	n/s	n/s	0.01	0.01	1	n/s	n/s	n/s	n/s	1200+	
	4001 +	n/s	0.02	0.12	0.23	0.16	n/s	n/s	0.01	0.02	0.02	1	n/s	n/s	n/s	n/s	1-600	
		n/s	n/s	0.01	0.03	0.03	1	n/s	n/s	n/s	0.01	1	n/s	n/s	n/s	n/s	601-1200	
		n/s	n/s	n/s	0.03	0.08	1	n/s	n/s	n/s	0.01	1	1	n/s	n/s	n/s	1200+	

Note: 1. There is only one stochastic equilibrium indicated by shading with numbers indicating the long run probabilities and "n/s" referring to a probability value < 0.5%.

2. States without shading are transient with the numbers indicating mean absorption times in years.

Table 6. Optimal grazing decisions under 6% discounting criterion

ADULT PLANTS (PLANTS/HA)	YOUNG SEEDLINGS (PLANTS/HA)	TOTAL FORAGE BIOMASS (KG/HA DRY MATTER)														
OLD SEEDLINGS (PLANTS/HA)		0-300					301-600					600 & above				
		0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above
		decision indeces														
0-1000	0-600	1	9	11	12	12	1	6	8	10	12	1	3	4	5	7
	601-1200	1	9	11	12	12	1	6	8	10	12	1	3	4	5	7
	1200+	1	9	11	12	12	1	6	8	10	12	1	1	1	5	7
1001-2000	1-600	1	10	11	12	12	1	3	6	7	8	1	1	1	1	1
	601-1200	1	10	11	12	12	1	3	6	7	8	1	1	1	1	1
	1200+	1	1	10	12	12	1	1	5	6	7	1	1	1	1	1
2001-3000	1-600	1	10	11	11	12	1	7	9	10	12	1	1	10	11	12
	601-1200	1	10	11	11	12	1	1	9	10	12	1	1	10	11	12
	1200+	1	10	11	11	12	1	1	9	10	12	1	1	10	11	12
3001-4000	1-600	4	9	11	12	12	1	10	11	12	12	1	8	11	12	12
	601-1200	4	9	11	12	12	1	10	11	12	12	1	8	11	12	12
	1200+	4	9	11	12	12	1	10	11	12	12	1	8	11	12	12
4001+	1-600	5	9	11	12	12	5	10	12	12	12	5	10	12	12	12
	601-1200	5	9	11	12	12	5	10	12	12	12	5	10	12	12	12
	1200+	3	9	11	12	12	5	10	12	12	12	5	10	12	12	12

Table 7. Optimal value function for the range ecosystem under 6 % discounting criterion

ADULT PLANTS (PLANTS/HA)	YOUNG SEEDLINGS (PLANTS/HA)	OLD SEEDLINGS (PLANTS/HA) 0-300					301-600					600 & above				
		TOTAL FORAGE BIOMASS (KG/HA DRY MATTER)														
		0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above
		net present value, $/ha														
0-1000	0-600	12	13	15	17	19	15	16	17	18	22	18	18	19	21	23
	601-1200	12	13	15	17	19	15	16	17	18	22	18	18	19	21	23
	1200+	13	13	15	17	19	16	16	17	18	22	19	19	20	22	23
1001-2000	1-600	23	26	28	29	30	34	35	36	37	39	44	45	46	46	47
	601-1200	23	26	28	29	30	34	35	36	37	39	44	45	46	46	47
	1200+	26	27	28	29	31	36	37	38	39	40	46	47	47	47	48
2001-3000	1-600	57	61	63	63	65	62	63	65	66	67	65	66	67	68	70
	601-1200	58	61	63	64	65	62	63	65	66	67	65	66	67	68	70
	1200+	58	61	63	64	65	63	64	65	66	68	66	66	68	69	70
3001-4000	1-600	73	77	79	80	80	74	77	79	80	81	76	78	80	81	82
	601-1200	73	77	79	80	30	74	77	79	80	81	76	78	80	81	82
	1200+	73	77	79	80	81	74	78	79	80	81	76	78	80	81	83
4001+	1-600	79	83	85	86	87	79	83	85	86	87	79	84	86	86	87
	601-1200	79	83	85	86	87	79	83	85	86	87	79	84	86	86	87
	1200+	79	83	85	86	87	79	83	85	86	87	79	84	86	86	87

Table 8. Long run equilibrium and transient behaviour of the range ecosystem under 6 % discounting criterion

		TOTAL FORAGE BIOMASS (KG/HA DRY MATTER)																
		0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above	0-200	201-400	401-600	601-800	800 & above		
ADULT PLANTS	0-1000	0.02	n/s	1	1	1	1	1	1	1	1	1	1	1	1	1.2	0-600	YOUNG SEEDLINGS
		n/s	n/s	1	1	1	1	1	1	1	1	1	1	1	1	1.2	601-1200	
		1.1	1	1	1	1	1.1	1	1	1	1	1.1	1.1	1.1	1	1.2	1200+	
	1001-2000	0.4	0.2	n/s	1	1	n/s	n/s	n/s	1	1	1	1	1	1	1.1	1-600	
		0.02	0.04	n/s	1	1	n/s	n/s	n/s	1	1	1	1	1	1	1.1	601-1200	
		n/s	0.01	n/s	n/s	1	n/s	n/s	n/s	1	1	1	1	1	1	1.1	1200+	
	2001-3000	0.03	0.08	0.01	n/s	1	n/s	n/s	n/s	n/s	1	1	1	n/s	n/s	1	1-600	
		n/s	0.02	0.01	n/s	1	n/s	n/s	n/s	n/s	1	1	n/s	n/s	n/s	1	601-1200	
		n/s	0.03	0.01	n/s	n/s	n/s	n/s	n/s	n/s	n/s	1	1	n/s	1	1	1200+	
	3001-4000	0.01	0.02	0.02	n/s	n/s	n/s	n/s	n/s	n/s	1	1	1	n/s	n/s	1	1-600	
		n/s	n/s	0.01	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	1	601-1200	
		n/s	0.01	0.02	0.01	n/s	n/s	n/s	n/s	n/s	n/s	1	n/s	n/s	n/s	n/s	1200+	
	4001+	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	1	n/s	n/s	n/s	n/s	1-600	
		n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	601-1200	
		n/s	n/s	n/s	n/s	n/s	1	n/s	n/s	n/s	n/s	1	n/s	n/s	n/s	n/	1200+	
	PLANTS/HA	0-300					301-600					600 & above					PLANTS/HA	
		OLD SEEDLINGS (PLANTS/HA)																

Note: 1. There is only one stochastic equilibrium indicated by shading with numbers indicating the long run probabilities and "n/s" referring to a probability value < 0.5%.

2. States without shading are transient with the numbers indicating mean absorption times in years.