

Grazing Management and Rehabilitation of Degraded Rangeland under Uncertainty

King-Min Wang*

Rangeland in the arid zone of Western Australia has been degraded by sheep overstocking since the turn of the century. 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.

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 5 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.

* Associate Research Fellow, Center for Energy and Environmental Studies, Chung-Hua Institution for Economic Research. The author gratefully acknowledges the helpful comments on the paper by the two referees.

本文文稿審查作業之執行由黃宗煌編輯負責。

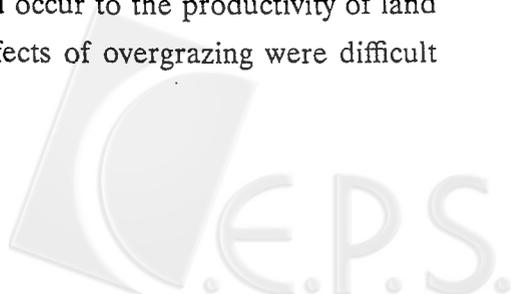


1. Introduction

Rangelands cover about three quarters of the Australia's land surface. The area is very sparsely populated. Apart from mining activities, the grazing of sheep is the predominant form of land use. The basic unit of the grazing industry in the area is a station which constitutes an area grazed by stock and is under the control of a manager. A station may be owned and managed by a family or it may be a unit in a company-owned chain. Sheep stations are usually completely fenced into a number of paddocks. The land has few permanent water holes and most stock water is pumped from bores or wells using windmills.

The principal objective of the station manager is to manage an extensive, low unit cost, grazing enterprise for profit. Since much of the rangelands is characterised by mean annual rainfall of less than 250mm, with insufficient rain for cropping in any season, the only strategy available is to manage grazing intensity astutely. However, due to the lack of knowledge about the range grazing ecosystem and the myopic approach adopted in range management which bases decisions on short-run profits, the traditional range grazing management has resulted in degradation of land resource through overgrazing. This degradation has been exacerbated during drought and the down turn of the wool market.

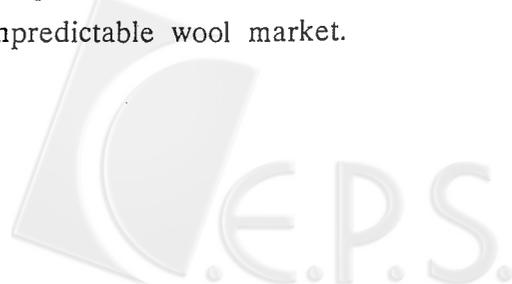
In a world of variable wool prices and increasing pressure associated with the cost/price squeeze, financial survival for woolgrowers has often depended on maximising short run profitability of their range resource. To achieve such an economic scale of production, woolgrowers had to increase sheep stocking rates to a level considerably in excess of the long-run sustainable carrying capacity. This myopic approach was also unduly enhanced by the fact that if effective rainfall occurred after a decision to increase stocking intensity was made, no long term loss would occur to the productivity of land resource. Furthermore, the detrimental effects of overgrazing were difficult



to be discerned in the short-run since the impacts on the range condition (i.e. range "health") could only be realised in the long term through the slow succession of the plant communities.

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, 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.

Degradation of rangeland resulting from sheep overstocking is widespread within the Australian arid and semi-arid zones. Within Western Australia about 23 per cent of the arid winter rainfall rangelands is considered to be in poor condition relative to its potential as a grazing resource. Typically the most degraded areas are those with the highest grazing potential so that the impact on pastoral productivity is considerably larger than the affected area would suggest (Harrington, et al., 1984). How to effectively utilise rangeland vegetation in terms of economic efficiency without causing significant degradation in the range condition is an important question in current range management. The major task of the manager is therefore to match stock numbers to the highly variable condition of the vegetation and wool markets. Mismatching means either economic loss in the long term due to deterioration in the carrying capacity of the vegetation through overgrazing, or the loss of current benefits due to under-utilisation of the range. Therefore, the purposes of this study are two-fold. First is the development of a stocking policy which achieves optimal utilisation under a stochastic climatic regime coupled with an unpredictable wool market.



Second is the evaluation of the long-term impact of the optimal policy in terms of both economic and ecological concepts.

Historically, most of the research done in studying rangeland grazing policy was through various experimental designs or through simulation modellings (e.g. Goodall, 1969; Van Dyne, 1970; Vickery and Hedges, 1972; Smith and Williams, 1973; Noble, 1975; Wight et al., 1984). The common feature of these studies was the analysis of various predetermined stocking rates by comparison their effects and related financial returns. The major limitation of these studies lay in their inability to identify the optimal decision rule efficiently: the proposed decision rules can be set in an infinite number of ways and the simulated or experimental results depend on the specific values of the environmental and other variables during the simulation or experiment.

By contrast, economic optimisation studies have applied various optimisation techniques in analysing grazing strategies. It ranged from deterministic to stochastic framework and/or from static to dynamic optimisation analyses. For example, Hooper and Heady (1970) used the static marginal analysis (the first-order rule in calculus) to derive the optimal stocking rate of grazing in a Californian grassland. Swartzman and Van Dyne (1972) combined linear programming (LP) and simulation to investigate the optimisation of grazing management in a system where two properties shared a common grazing area. Rodrigues and Roath (1987) applied dynamic programming to derive the optimal stocking rate policies. Burt (1972) explicitly specified a theoretical optimal control model which contained two control variables, i.e. change in stocking rate and a dichotomous renewal decisions. Huffaker and Wilen (1988) applied Pontryagin's maximum principle to analyse the optimal grazing decisions and the stability of the grazing system.

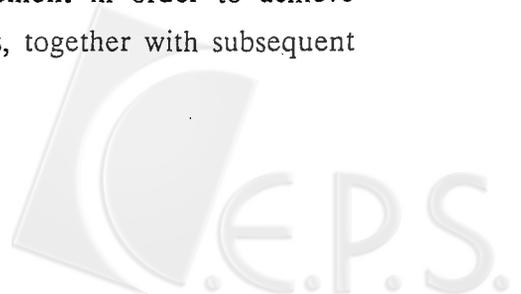
In the areas of stochastic optimal control, Fisher (1974) combined simulation and stochastic optimal control to derive the optimal decision of buying and selling sheep in the rangelands of Australia. Karp and Pope (1984)

developed a theoretical optimal control model for range management under uncertainty. Williams (1985) used stochastic dynamic programming to derive optimal grazing patterns for salt desert shrubs in the Great Basin of U.S.A.. Although many simplified assumptions were made about the transition probabilities, these studies demonstrated a promising applicability of the stochastic optimal control approach to the problem of range grazing strategies under uncertainty. It has been shown by Fisher (1974) and Williams (1985) that a detailed biological simulation model could be used to derive the transition probabilities for optimisation. This means that the realism can be retained, while the mathematical tractability of the problem is not lost. However, to the author's knowledge, no study has yet given the same attention to the problem considered here, i.e. the derivation of optimal grazing policies under a stochastic climatic regime coupled with an unpredictable wool market and, at the same time, analysing their long term economic and ecological impacts.

Rangeland ecology in essence is a dynamic system operating in a stochastic climatic and economic environment and involving very significant intertemporal effects through the succession of range plant communities. 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 under uncertainty can be described as below. 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 decision-making process described above can be formulated as a stochastic optimal control model. Mathematically, the formulation of the decision problem is to discover the optimal decision rule to maximize the expectation of the objective functional subject to the stochastic state transition equations. The constraints for the control and state variables are usually dealt with by the specification of the state and control space. The constraint, embodied in the set of state transition equations 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, the state in next period is a random variable, its conditional distribution depends on the current state and control as well as the distribution of random variables.

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

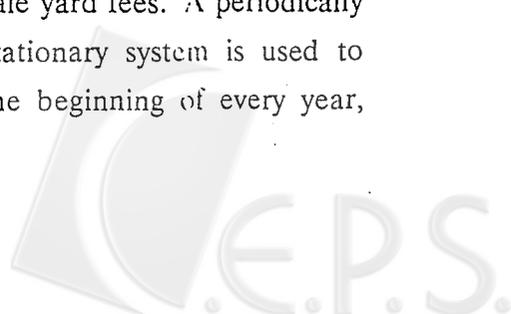
2.1 Objective Functional

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 as follows.



$$\begin{aligned}
 NPM = & \text{net value of wool} \pm \text{changing value of the flock} \\
 & - \text{stocking rate adjustment costs} - \text{average variable} \\
 & \text{costs} - \text{average fixed costs}
 \end{aligned}
 \tag{1}$$

For application to the sheep station in the pastoral zone of Western Australia, the annual net profit margin was calculated from the summation of three seasonal net profit margins over a four-month simulation period in each season (see below). Gross value of wool produced per sheep per season 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 beginning seasonal stocking rate and m_s is a seasonal sheep mortality rate which is an endogenous variable to be determined by the state, control and random variables of the grazing ecosystem during the season. 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 periodically steady state assumption for the periodically stationary system is used to calculate the change in the stocking rate at the beginning of every year,



i.e. $u_1 - u_0(1 - m_0) = u_1 - u_3(1 - m_3)$ where u_1 is the stocking rate at the beginning of every year, i.e. season 1. Although this assumption is valid for a deterministic case, I recognised that it may underestimate (or overestimate) the stocking rate at the beginning of the next year for the stochastic case if the state of grazing ecosystem at the beginning of next year is better (or worse) than that of the current year. This is because the state of the grazing ecosystem in the next year is stochastic and currently unknown to the range manager. 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 Π_t is thus specified as follows,

$$\begin{aligned} \Pi(x_t, c_t, w_t) = & \sum_{s=1}^3 \{ (PW)WC_s - SC \} u_s (1 - m_s) - PS_s (u_s - u_{s-1} \\ & (1 - m_{s-1})) - |u_s - u_{s-1} (1 - m_{s-1})| SAC_s - (AVC)u_s \quad (2) \end{aligned}$$

where

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

$$SAC_s = FC \quad \text{if } u_s > u_{s-1}(1 - m_{s-1})$$

and

s = seasonal index with three rainfall seasons (see below) of a year in the year t ;



- $\Pi(x_t, c_t, w_t)$ = annual net profit function which calculates net profit margin during year t from the value of state x_t , control c_t and random variables w_t , \$/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 the beginning of season s while $u_0 = u_3$ was assumed, 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).

2.2 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 annual expected average



return are used as a maximisation criterion. Mathematically, the objective functional $V(x_0)$ under this criterion can be specified as follows,

$$\text{Maximise } V(x_0) = \lim_{T \rightarrow \infty} (1/T) E \left\{ \sum_{t=0}^{T-1} \Pi(x_t, c_t, w_t) \right\} \quad (3)$$

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 to maximise the net present value. 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 current year to infinity. Thus

$$\text{Maximise } V(x_0) = E \left\{ \sum_{t=0}^{\infty} \alpha^t \Pi(x_t, c_t, w_t) \right\} \quad (4)$$

where the constant discount factor α 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. In the study, the average real annual interest rate of 6% and 5% are both adopted as a sensitivity analysis.

2.3 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.

2.4 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

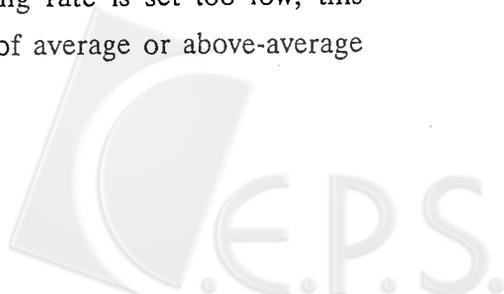


Table 1. Grazing Decisions Considered in the Model

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

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.

rainfall years. On the other hand, if the initial stocking rate is set too high, there is a potential for large profits in 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.

2.5 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.

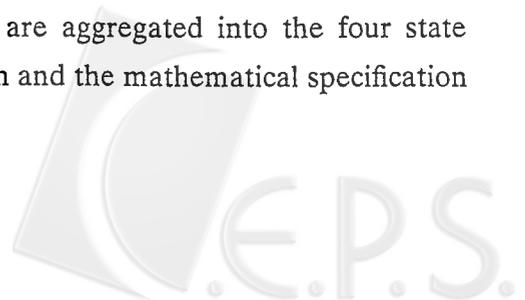


2.6 Transition probabilities

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



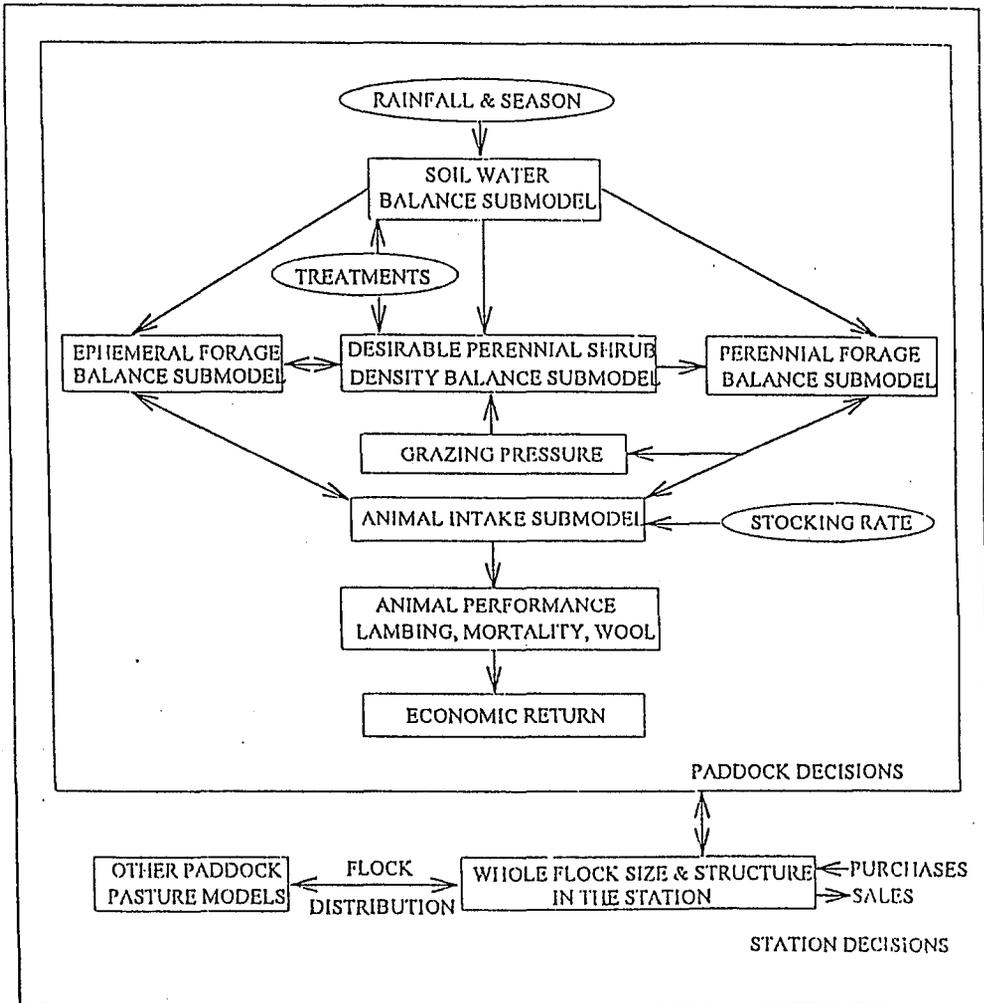


Figure 1. Conceptual model of a rangeland grazing system at the whole property level

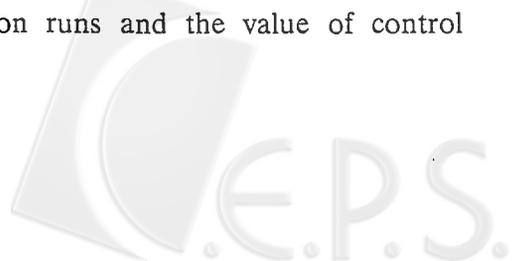


of the model was given in Hacker et. al. (1991).

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

An integrated approach for the simulation-optimisation-Markov chains analysis procedure is shown in the flow chart of Figure 2. This approach is best suitable for the quantitative analysis of renewable resource economics under uncertainty. It starts with the calculation of probability distributions of stochastic variables by using the statistical data. Then, the distributions combined with the initial values of the state variables, state grid intervals, model parameters, number of simulation runs and the value of control



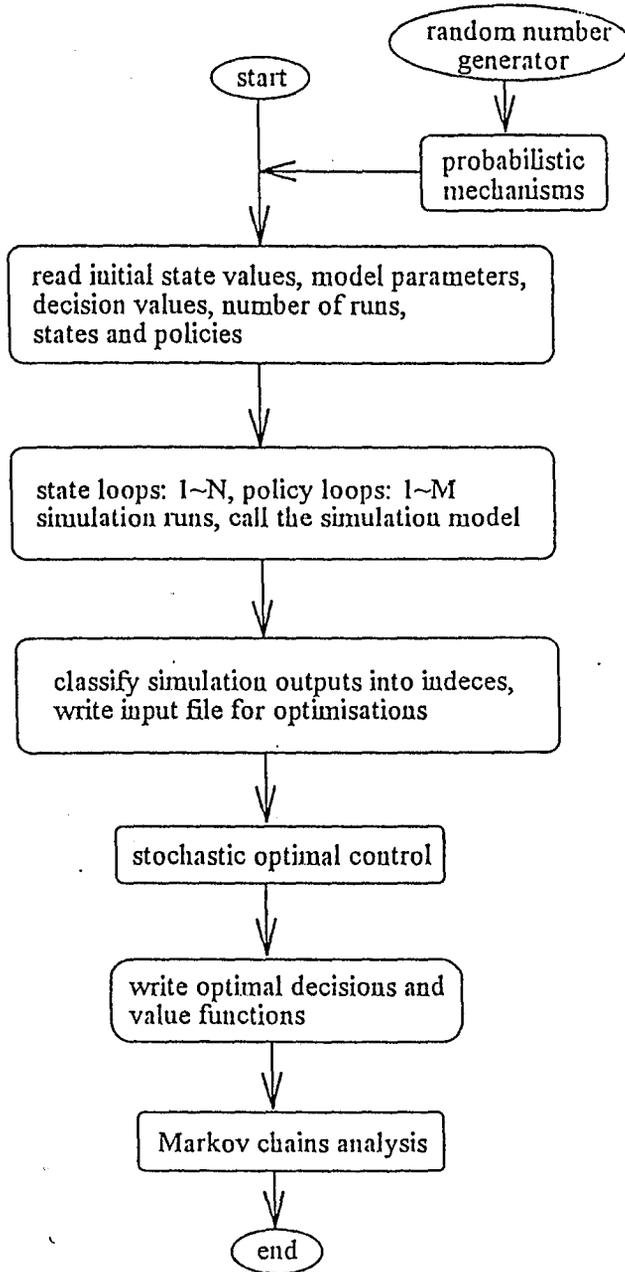


Figure 2: Operational Sequence for Combining Simulation, Optimisation and Markov Chains Analysis



variables are fitted into the simulation program for the calculation of transition probabilities. Simulation proceeds with the sequence of state loops, policy loops, simulation run loops. The bioeconomic simulation model IMAGES is then called in to calculate the relevant data for the optimisation. Simulations of IMAGES are run under the 33 grazing decisions, using initial values of the various combinations of the four state variables. The output data of the period-ending states from the simulations are classified into indices. At the end of simulation runs, the simulated outputs are organised into a data set with records consisting of number of distinct transitions, initial state index, decision index, average transition returns, frequency of transitions, and period-ending state index. The resulting data set is stored and subsequently used by a stochastic dynamic optimisation program (Bertsekas 1976) to determine optimal grazing policies. At the end of the optimisation algorithm, the optimal decision indices and value functions are recorded. The optimal policy in turn is used to extract the optimal transition probabilities from the input data file for further Markov chains analysis.

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 standard textbooks of Markov chains such as Freedman (1971) and Whittle (1986).

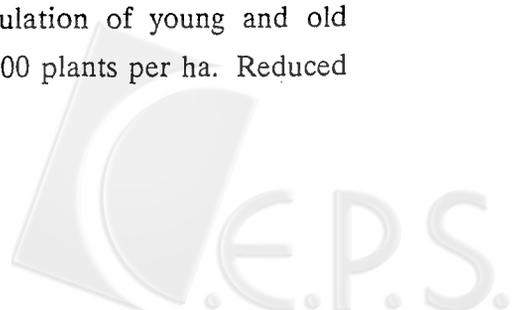


4. Results and Discussion

Under the average return criterion, 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

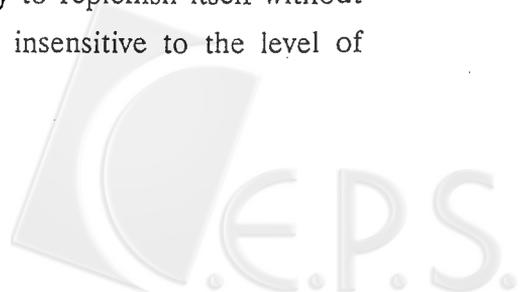


Table 3. Optimal value function under zero discounting criterion

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

Note: 1. Maximal expected 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 bsc.

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 range 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 (4001+, 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

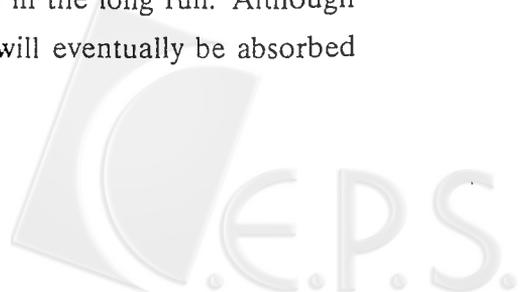


Table 4. Long run equilibrium and transient behaviour of the range ecosystem

under zero discounting criterion

| | | TOTAL FORAGE BIOMASS (KG/HA DRY MATTER) | | | | | | | | | | | | | | | | | | | |
|---|-------------|---|------|------|------|------|-----|---------|------|------|-----|-----|-----|-------------|-----|-----|-----|-----|--|-------------|--|
| | | 0 | 201 | 401 | 601 | 800 | 0 | 201 | 401 | 601 | 800 | 0 | 201 | 401 | 601 | 800 | | | | | |
| | | | | | | & | | | | | & | | | | | & | | | | | |
| | | 200 | | | | | | 400 | | | | | | 600 | | | | | | 800 & above | |
| A D U L T | 0-1000 | 372 | 372 | 372 | 372 | 372 | 368 | 368 | 368 | 368 | 368 | 362 | 362 | 362 | 362 | 362 | 362 | 362 | | | |
| | 1001-2000 | 372 | 372 | 372 | 372 | 372 | 368 | 368 | 368 | 368 | 368 | 362 | 362 | 362 | 362 | 362 | 362 | 362 | | | |
| P L A N T S | 2001-3000 | 369 | 369 | 369 | 369 | 369 | 360 | 360 | 360 | 360 | 360 | 353 | 353 | 353 | 353 | 353 | 353 | 353 | | | |
| | 4001+ | 356 | 356 | 356 | 356 | 356 | 250 | 250 | 250 | 250 | 250 | 152 | 152 | 152 | 152 | 152 | 152 | 152 | | | |
| Y O U N G | 0-600 | 355 | 355 | 355 | 355 | 355 | 249 | 249 | 249 | 249 | 249 | 151 | 151 | 151 | 151 | 151 | 151 | 151 | | | |
| | 601-1200 | 322 | 322 | 322 | 322 | 322 | 226 | 226 | 226 | 226 | 226 | 139 | 139 | 139 | 139 | 139 | 139 | 139 | | | |
| S E E D L I N G S | 1-600 | 35 | 35 | 35 | 35 | 35 | 25 | 25 | 25 | 25 | 25 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | | | |
| | 601-1200 | 34 | 34 | 34 | 34 | 34 | 24 | 24 | 24 | 24 | 24 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | | | |
| P L A N T S | 1200+ | 31 | 31 | 31 | 31 | 31 | 22 | 22 | 22 | 22 | 22 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | | | |
| | 0-300 | 0.04 | 0.11 | 0.1 | 0.01 | n/s | n/s | n/s | 0.01 | n/s | n/s | n/s | n/s | n/s | n/s | 1 | 1 | 1 | | | |
| P L A N T S | 3001-4000 | 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 | 1 | 1 | | | |
| | 4001+ | 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 | n/s | n/s | | | |
| P L A N T S | 0-300 | 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 | n/s | n/s | | | |
| | 301-600 | 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 | n/s | n/s | | | |
| P L A N T S | 600 & above | 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 | n/s | n/s | | | |
| | 600 & above | 600 & above | | | | | | | | | | | | | | | | | | | |
| PLANTS/HA | | 0-300 | | | | | | 301-600 | | | | | | 600 & above | | | | | | | |
| PLANTS/HA | | OLD SEEDLINGS (PLANTS/HA) | | | | | | | | | | | | PLANTS/HA | | | | | | | |

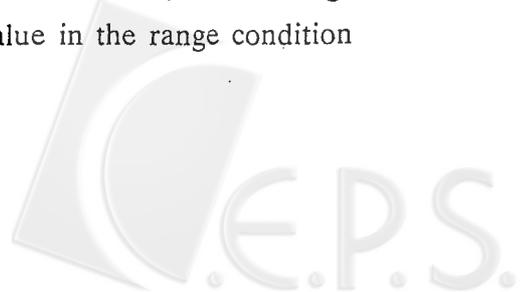
Note: 1. There is only one stochastic equilibrium indicated by shading with numbers indicating the long run probabilities and "n/s" referring to a probability value < 0.5%

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

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.

4.1 Sensitivity analysis

Similar to the average return case, the optimal decision calls only for set stocking and destocking policies under 6% and 5% discount rates. However, the optimal stocking rates are much higher with 6% discount rate than those under the average return case. When the discount rate drops one percent, the optimal stocking rates show a similar pattern and decrease slightly from those under 6%. This indicates that under the profit maximisation with 6% or 5% discount rate range manager will adopt a more exploitative strategy towards grazing. Although, as before, the expected net present value under both discount rates shows a positive correlation with the values of the four state variables, it is not sensitive to the level of both young seedlings and forage biomass. This implies that forage availability and young seedlings will not influence the long term profit significantly due to the exploitative nature of the grazing policy adopted. For both discount rates, old seedlings contribute a significant increase in the optimal value in the range condition



with less than 2000 plants per ha. 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 under both discount rates covering widely from good range condition with 4001 plants per ha to badly degraded condition with less than 1000 plants per ha. The mean absorption time decreases with an increasing discount rate and is very short ranging from one to several years only under both discount rates. This 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 under both discount rates. Although the covered area of the long run equilibrium is very large, there is very little chance that most states will occur. In fact, the range is very unlikely to exist in good condition (4001+ plants per ha) since the long run probabilities of all equilibrium states in good condition are insignificant with a value less than 0.005, although slightly higher value occurs in 5% discount rate. Therefore, under the profit maximisation criterion with a 6% or 5% 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.

The analyses suggest that pastoral management in this rangeland is not ecologically sustainable at a discount rate of 5 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

In both cases of maximisation of average return and net present value, 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 and the transient profit both increase 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.

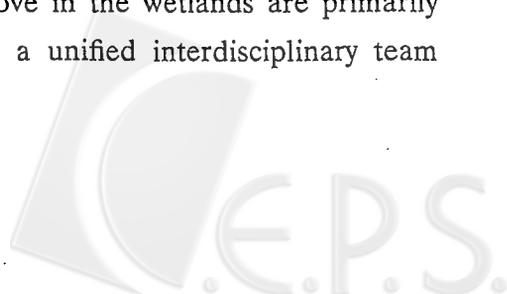
Markov chain analysis indicates that under the criterion of maximisation of the long run average return, for slightly degrade range with more than 2000 plants per ha, rehabilitation through grazing management alone is possible. For range which is moderately to severely degraded and is characterised by 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 5 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.

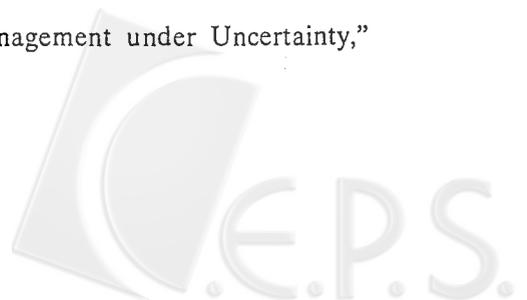
Finally, the usefulness of the approach adopted in this study is not limited to range resource only. Any resources with their dynamics involving very significant stochastic intertemporal effects can also fit well to this approach. These may include the management of flora, fauna, an ecosystem or, to the other extreme, a specific species. Particularly, in Taiwan, the study of sustainability and rehabilitation of endangered species such as certain species of fish, migratory birds, forest and mangrove in the wetlands are primarily concerned. This can be tackled through a unified interdisciplinary team



effort. First is to identify the key indicators (i.e. the state and control variables) in the relevant ecosystem and their relevant dynamics involved and then to work out the appropriate management decisions and their long run impacts accordingly by using the approach of this study.

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.
- Burt, O. R. (1972) "A Dynamic Economic Model of Pasture and Range Investments: Reply," American Journal of Agricultural Economics, 54, 131-132.
- Fisher, I. H. (1974) Resource Optimisation in Arid Grazing Systems, Ph. D. thesis, University of New South Wales, Sydney.
- Freedman, D. (1971) Markov Chains, Holden-Day Inc, London.
- Goodall, D. W. (1969) "Simulating the Grazing Situation," in Biomathematics 1: Concepts and Models of Biomathematics (ed: F. Heinmets), Marcel Dekker, New York.
- 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.
- Harrington, G. N., A. D. Wilson and M. D. Young (1984) Management of Australia's Rangelands, Division of Wildlife and Rangelands Research, CSIRO, Australia.
- Hooper, J. F. and Heady, H. F. (1970) "An Economic Analysis of Optimal Rates of Grazing in the California Annual-type Grassland," Journal of Range Management, 23, 307-311.
- Huffaker, R. G. and Wilen, J. E. (1988) "Stability of Bioeconomic Grazing Systems," Paper presented at the 1988 Amer. Agric. Econ. Asso. Conference.
- Karp, L. and C. A. Pope, III, (1984) "Range Management under Uncertainty,"



American Journal of Agricultural Economics, 66, 437-446.

Noble, I. R. (1975) Computer Simulations of Sheep Grazing in the Arid Zone, Ph. D. thesis, University of Adelaide, Adelaide.

Rodriguez, A. and L. R. Roath (1987) "A Dynamic Programming Approach for Short-run Grazing Management Decisions," Journal of Range Management, 40, 294-298.

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

Smith, R. C. G. and Williams, W. A. (1973) "Model Development for a Deferred-grazing System," Journal of Range Management, 26, 454-460.

Swartzman, G. L. and Van Dyne, G. M. (1972) "An Ecological Based Simulation-optimisation Approach to Natural Resource Planning," Annual Review of Ecological System, 3, 347-398.

Van Dyne, G. M. (1970) "A system approach to grasslands," in Proceedings 11th International Grassland Congress, University of Queensland Press, Brisbane.

Vickery, P. J. and Hedges, D. A. (1972) "A Productivity Model of Improved Pasture Grazed by Merino Sheep," Proceedings of Australian Society of Animal Production, 9, 16-22.

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

Wight, J. R., Hanson, C. L. and Springer, E. P. (1984) "SPUR: A Model for Simulation of Production and Utilisation of Rangelands," Working paper, 2nd International Rangeland Congress, Adelaide, Australia.

Williams, B. K. (1985) "Optimal Management Strategies in Variable Environments: Stochastic Optimal Control Methods," Journal of Environmental Management, 21, 95-115.



畜牧管理與劣化莽原之隨機復健研究

王京明

中華經濟研究院 能源環境研究中心

西澳洲乾燥地區的莽原長期以來因牧養過多的綿羊牲口而導致生態環境惡化，土地生產力也因而降低。補救這種生態惡化的方法很有限，本文利用隨機最適控制理論對各種不同惡化程度的莽原探討與其相對應之最適牲口數目的畜牧政策，並應用馬可夫鏈理論評估這些畜牧政策的長期經濟利益以及其對莽原生態所造成的衝擊效果。

研究結果顯示定畜或空畜政策是必要的，輪畜在目前的市場情況下不具經濟性。最適的綿羊牲口數目與莽原內週年生的成年植物樹木及其生質量呈正比，但與植物幼苗之數目呈反比。在追求長期平均淨收益最大的決策目標之下，輕微惡化的莽原經由最適畜牧政策，復健仍有可能；但中度至高度惡化的莽原復健則不太可能會成功。至於在追求長期淨收益現值最大的決策目標之下，若折現率為5%，一般而言，最適的畜牧政策雖能維持經濟的超額利潤，卻未能確保生態的永續性。因此惡化的莽原若仍然為維持私人利潤而使用的話，莽原的資源將逐漸失去其更新再生的能力。如果生態的永續發展是社會的一種規範，那麼惡化莽原的管理勢必不能只顧及經濟的理性，短期的利益必須放棄，同時也必須從事其它莽原更新的投資工作，以便維持莽原的長期生產力。

