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REHABILITATION OF DEGRADED RANGELAND UNDER OPTIMAL MANAGEMENT DECISIONS*

K. Wang and R.K. Lindner

Agricultural Economics
Discussion Paper: 7/90

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ABSTRACT

Rangeland in the arid zone of Western Australia has been degraded by sheep overstocking. The strategies available for restoring the productivity of degraded rangelands are limited. In those situations where there is still reasonable residual soil and vegetation despite moderate erosion and depletion of palatable forage plants, rehabilitation through manipulation of grazing pressure is possible. In extreme situations where there has been severe depletion of palatable perennial plants coupled with advanced soil erosion, reclamation is unlikely to succeed without various forms of cultivation or earthworks, associated with the re-introduction of a suitable seed source. Optimal range rehabilitation policies need to be discovered to restore this resource base for future use.

In this paper optimal economic policies with respect to the choice of stocking rates and the timing of soil cultivation and reseeding were derived for various starting states under a stochastic optimal control framework. Evaluation of these optimal policies was carried out by analysing their long run economic and ecological impacts. All optimal policies call for a strategy of grazing management only. Even for severely degraded range, the reseeding policy is not economically viable at current cost levels. More generally, rehabilitation for moderately degraded ranges is possible if there are sufficient seedlings available, while for severely degraded ranges reclamation cannot be justified by future returns from woolgrowing, so further degradation is to be expected if this range continues to be exploited for private profit.

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 condition of their range, and thereby restore their financial fortunes.

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, the 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 management strategies. 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 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, grazing systems and whether or not to apply a reseeding treatment which involves both ploughing and reseeding. 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).

Formulation of Rangeland Regeneration as 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 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 the 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. Thus,

$$\text{Maximize } E_0\sum_{t=0}^{\infty} \alpha^t g(\mathbf{x}_t,\mathbf{u}_t,\mathbf{w}_t) \qquad (1)$$

Subject to

$$\mathbf{x}_{t+1}=f(\mathbf{x}_t,\mathbf{u}_t,\ \mathbf{w}_t) \qquad (2)$$

$$\mathbf{x}_0 \text{ is given} \qquad (3)$$

where

E_0 = the expectation held at initial period, t=0;

α = the discount factor, $\alpha=1/(1+r)$, r is real annual interest rate;

$g(\mathbf{x}_t,\mathbf{u}_t,\mathbf{w}_t)$= the annual net return function;

$\mathbf{x}_t,\mathbf{u}_t,\mathbf{w}_t$ = the vector of state, control and random variables, respectively;

$f(\mathbf{x}_t,\mathbf{u}_t,\mathbf{w}_t)$= 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 $P_{ij}(\mathbf{u}_k)$. A transition probability is defined as the probability that the next period state will be j given that the current state is i and control $u=u_k$ is applied. It can be specified as a conditional probability

$$P_{ij}(\mathbf{u}_k)=P(\mathbf{x}_{t+1}=j|\mathbf{x}_t=i,\mathbf{u}_t=\mathbf{u}_k) \qquad (4)$$

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**.

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

Objective Function

In this paper, the range manager is assumed to be risk neutral, and so to maximise expected net present value of annual 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 transitions 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 price of one unit output and its average total cost. In the application to the sheep station in the pastoral zone, the net profit margin can be calculated by the following rule:

NPM = net value of wool ± value of changes in the flock size -

stocking rate adjustment costs - average variable costs -
average fixed costs - treatment cost (5)

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 value and the derivation of the variables used in the annual net profit margin and the mathematical specification of the function are given by Wang *et al.* (1989).

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 partitions of these variables are as follows:

1. Total forage biomass, (kg/ha dry matter (d.m.)):
   grid points:0, 80, 160, 320, 800;
   grid intervals: 0-40, 40-120, 120-240, 240-560, 560+;
2. Young desirable perennial seedlings, seedlings/ha:
   grid points: 0, 1200, 2400;
   grid intervals: 0-600, 601-1800, 1800+;
3. Old desirable perennial seedlings, seedlings/ha:
   grid points: 0, 300, 600;
   grid intervals: 0-150, 151-450, 450+;
4. Adult desirable perennial plants, plants/ha:
   grid points: 0, 400, 800, 1600, 4000;
   grid intervals: 0-200, 201-600, 601-1200, 1201-2000, 2000+.

The forage biomass is classified by five grid points which represent 0, 5, 10, 20 and 50 per cent of the maximum environmental carrying capacity, respectively. Young and old seedlings are divided into three categories to represent three possible levels: zero, low, and high, respectively. The density of adult plants are classified by the five grid points 0, 5, 10, 20, and 50 per cent of the maximum environmental carrying capacity, 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, poor, and normal range condition*, respectively.

Using the above classification scheme, the total number of states in the state space is, therefore, 5x3x3x5=225. The state of the grazing ecosystem is thus described by a 4-tuple (total forage biomass, young seedlings, old seedlings, adult plants). Although it may not be possible to observe some of the combinations in the field, they are retained to facilitate the computer programming in the classification of simulated results. For example, the 4-tuple (800,0,0,0) represents a scalded area with no desirable perennial plants and seedlings but with abundant forage biomass. While this combination of states could not occur naturally, it can be viewed as representing a situation where 800 kg dry matter/ha are transferred (by the manager) into the paddock at the time of observation. Another justification for not excluding such combinations is the transient nature of such states. In other words, these artificial combinations will disappear in the long run and inclusion of them in the set of grazing ecosystem states will not produce errors in the determination of the long run distribution of range conditions.

Table 1 presents the one-to-one relationships between state index and the set of ordered quadruple (total forage biomass, young seedlings, old seedlings, adult plants). For example, state 1 corresponds to the 4-tuple (0,0,0,0) which represents a totally scalded area with zero forage biomass and zero plants. State 116 corresponding to (0,2400,300,800) represents the combination of zero forage biomass, 2400 young seedlings/ha, 300 old seedlings/ha, and 800/ha adult plants. State 225 corresponding to (800,2400,600,4000) represents the combination of 800 kg/ha dry matter of forage biomass, 2400 young seedlings/ha, 600 old seedlings/ha, and 4000 adult plants/ha.

The table can be subdivided into 5 sections according to the population of adult plants, i.e., section 1 =0/ha; section 2 =400/ha;

section 3 =800/ha; section 4 =1600/ha and section 5 =4000/ha. These 5 sections correspond to the five different range conditions respectively. Each section comprises 3 rows and 15 columns. Three rows correspond to the variation of three young seedling levels (i.e., row 1 =0/ha; row 2 =1200/ha; row 3 =2400 young seedlings/ha). The 15 columns are subdivided into three column groups according to the three old seedling levels (i.e., column 1-5 represents 0/ha; column 6-10 represents 300/ha; column 11-15 represents 600 old seedlings/ha, respectively. Within each column group, 5 forage biomass levels are represented (i.e., each column group is made up of column 1 =0/ha; column 2 =80/ha; column 3 =160/ha; column 4 =320/ha, column 5 =800 kg/ha d.m. forage biomass).

Control variables

To derive an optimal decision rule which simultaneously determines stocking rate, grazing system and timing of reseeding all possible grazing decisions alone and in combination with the reseeding treatment were specified. Hence, the control space consists of combinations of two variables: grazing strategy and reseeding policy. There are 30 partition points in the grazing strategy variable which reflect various prespecified stocking rates under three grazing systems: *total destocking, continuous grazing (set stocking) and rotational grazing.* Reseeding is defined to include ploughing combined with appropriate seeding techniques. Thus, seeding is a method of restoring depleted seed banks of desirable perennial species to degraded rangelands and of promoting successful germination and establishment. In the study, the effect of seeding is assumed to restore the seed stock to its maximum level in the year of reseeding, but to have no carry over effect into subsequent years because of germination and other causes of seed loss. Also, seeding is assumed to occur in the late summer, i.e. season 1. Ploughing as part of reseeding treatment affects range dynamics mainly through the water balance model by reducing the value of the rainfall runoff coefficient, thus improving the soil water storage. There will be a total of 30*2=60 decisions. However, since some of the grazing strategies are not reasonable to apply with the ploughing treatment policy, they are excluded from the control space. Thus, the control space is partitioned into 50 decisions instead of 60. Table 2 presents these 50 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 11 involve a pattern of continuous grazing in which the order of policy index increases with a rise in stocking rate. Decisions 12 to 30 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. 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.

Decisions 12 to 30 involve various patterns of rotational grazing, which in this study refer 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. Decisions 31 to 50 involve a subset of the policies described above in combination with reseeding.

Stochastic variable

The stochastic variable used is the number of growth periods (measured by the unit of 5 days). The 50 years daily rainfall data for a degraded site, and monthly average evaporation data are used by a water balance model (Richmond and Wang 1989) adapted from Fitzpatrick *et al.* (1967) to generate the distributions of the number of growth periods for the three rainfall seasons.

Transition probabilities

In order to derive the state transition probabilities a simulation model needs to be constructed. The model used in this study is that of Wang *et al.* (1988) which integrates the evolution of an arid grazing ecosystem in the winter rainfall pastoral zone of Western Australia. The main functional components within the plant-animal-climate interface in a single paddock on a four-monthly basis were simulated.

The essence of the model is illustrated by Figure 1. As indicated, a soil water balance submodel was used to derive the number of wet pentads i.e. 5-day growth periods, over a four-monthly season. Wet pentads together with the management decisions of stocking rate and treatment 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 6 four-monthly age-cohorts seedlings, i.e. 0-4, 4-8, ... , 20-24 months and one adult class i.e. 24+ 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, 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 by Wang *et al.* (1988).

Summary of operational sequence for the study

Simulations of the arid grazing model were run under the 50 management decisions, using initial values of the various combinations of the four state variables. The output from the simulations was 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 was subsequently used by optimisation algorithm to determine optimal strategies. The optimisation uses a successive approximation method based on backward dynamic programming (Bertsekas 1976). The optimal decision rule in turn was used to extract the optimal transition probabilities for further Markov chain analysis. Finally, the long run equilibrium and transient behaviour of the optimally controlled grazing ecosystem were presented.

Results and Discussion

Optimal decision rule

(a) Reseeding treatment

Optimal rehabilitation strategy is presented in Table 3. As shown, it is not economical to adopt reseeding treatment. This indicates that, at the current cost level of reseeding, a strategy of grazing management only is economically more efficient for the risk neutral manager under a stochastic climatic regime. This has three possible implications for the severely degraded rangelands. First, it may imply that both grazing and reseeding can rehabilitate badly degraded range but the former alone can do it cheaply. Second, it could imply that the badly degraded range cannot be rehabilitated by both policies. However, since grazing management is less capital intensive the cost under grazing is lower. Third, it could also imply that reseeding treatment can improve severely degraded range but the cost is too high to adopt. Thus, at current stage, rehabilitation can only rely upon the grazing management no matter whether it can improve the range or not. If the second or the third implication is true and the grazing management cannot rehabilitate the range, the total destocking policy shown in the Table represents abandon of badly degraded range completely. It can be viewed as a "do nothing" or "wait and see" policy which abandons the range temporarily until other cost effective treatment techniques can be found. The true implication cannot be known right now without detailed analysis of the optimal transition matrix. Therefore, it is postponed to the section of the Markov chains analysis.

(b) Grazing system

With regard to the optimal grazing strategy, total destocking is most common when the forage biomass is at zero level. In addition, it also is optimal for many degraded range conditions. This is to be expected when reseeding is not economical since destocking or lenient grazing is the only available option for rehabilitating degraded ranges. Continuous grazing tends to predominate in the higher levels of forage biomass (≥800 kg d.m./ha); while rotational grazing occurs more often when the forage biomass is relatively low (≤320 kg d.m./ha). This is because a range with abundant forage biomass tends to be resilient to grazing and thus not suitable for the rotational grazing system. Rotational grazing in a resilient range can only contribute limited increase to animal production but incurs an extra substantial expenditure in stock movement. Therefore, set stocking is economically more efficient. At relatively low forage biomass level due to the low growth rate of both ephemerals and perennials such a range is not resilient to grazing. Set stocking will put extra stress on the survival of plants and seedlings during dry periods. Therefore, continuous grazing is not suitable and rotational grazing which adjusts stocking rate at critical time is more appropriate. As can be seen, in most situations when the range condition is poor or degraded, the rotational grazing system involves destocking in the third season. This supports the conventional theory about the choice of stocking rate for range regeneration during the dry period at which time the resilience of the range species to grazing is at minimum.

There are exceptions to the above principle and these could be attributed to three possible reasons: the possibility of range improvement, strong resilience to grazing at relatively low forage biomass level, and the problem of coarse grids. When the range has a high possibility of improvement, the rotational grazing is better than set stocking. This can be reflected by those exceptions which have abundant seedlings such as states (800,2400,0,400), (800,2400,600,400), (800,2400,0,800), (800,2400,300,800) and (800,0,600,1600). For some states at a relatively low forage biomass level, resilience to grazing is still strong enough for set stocking. This can be reflected by those states with 320kg/ha d.m. at normal range conditions. When the above two reasons cannot apply the last possibility is due to the problem of coarse grid. In other words, if stocking rates and the state variables can be further partitioned into fine grids the occurrence of exceptions will be reduced. States (160,0,600,0), (160,0,600,400), (160,1200,600,400), (80,0,800,300) and (160,0,2400,0,400) can be included in this category.

(c) Optimal stocking rate

Optimal grazing policies, in most cases, vary with the amount of forage biomass. Stocking rates are positively correlated to the availability of forage biomass, though the grazing pattern may change. In most cases, total destocking is optimal for forage biomass at zero level in most cases. Therefore, under a stochastic case, risk neutral pastoralists should spare the range once it is totally defoliated. Figure 2 gives the impact of forage biomass on the optimal average stocking rate at different range conditions when there are neither young nor old seedlings. As illustrated, the optimal average stocking rate per year varies from 0 sheep/ha to 1 sheep/ha and shows an upward trend with respect to the level of forage biomass in all range conditions.

With regard to young seedlings, optimal grazing decisions do not vary at the section of high (4000/ha) adult plant density. They are also not sensitive to young seedlings at the range of 0-1200/ha. However, more changes in the stocking rates occur when the level of young seedlings increases from 1200/ha to 2400/ha. In poor or degraded range conditions, the optimal stocking rate often presents a downward trend when the level of young seedlings increase.

The above findings can be explained as follows: at poor and degraded range conditions the occurrence of abundant young seedlings has the higher possibility to improve range condition. Therefore, a lighter stocking rate should apply to promote seedlings establishment. However, when less young seedlings are available the chance of improvement in range condition is small. Thus, optimal stocking rates are not sensitive to the low level of young seedlings. At the normal range condition it is not important to have seedlings present since the range cannot not be improved any more.

There are exceptions to these tendencies. For example, at the section of 400 adult plants/ha with no old seedlings when the number of young seedlings increases from 1200/ha to 2400/ha some states display an increasing stocking rate. This is due to the problem of coarse grids which make the extra young seedlings redundant. For these states, the level of 1200 young seedlings/ha is sufficient to transit into a year-end state with 300 old seedlings/ha. Although with 2400 young seedlings/ha the chance of transition into a year-end state with 600 old seedlings/ha is high, the transition in the next year from a state with either 300 or 600 old seedlings/ha will all end with a state in a slightly degraded range condition (i.e. 800 adult plants/ha) rather than those states with 1600 adult plants/ha. Therefore, a higher stocking rate applies since extra 300 old seedlings are redundant in terms of transition into a state with 800 adult plants/ha. Accordingly, compared to the level of 1200 young seedlings/ha, 1200 young seedlings are redundant in those states with 2400 young seedlings/ha at the section aforesaid. A similar coarse grid problem also occurs in other areas in the table. For example, from states (320,1200,600,0) to (320,2400,600,0), (80,1200,600,1600) to (80,2400,600,1600). Figure 3 presents the effects of young seedlings on the optimal average stocking rate at different range conditions, holding forage biomass at 160 kg/ha d.m. and old seedlings at 0/ha level. Apart from the normal range condition, the downward trend in the stocking rate is evident.

Comparing the optimal policies with respect to old seedlings, the optimal stocking rates show a decreasing trend in the range of 0-300 old seedlings/ha at the section of 0-400 adult plants/ha, and in the range of 300-600 old seedlings/ha at the section 800-1600 adult plants/ha. The decreasing trend indicates that in order to improve the ranges more old seedlings should be currently preserved. Thus, for a range with more old seedlings the number of stocks should be lower so as to reduce grazing pressure and increase seedling establishment. At the normal range condition, the optimal stocking rate is not sensitive to the old seedlings, due to the same reason as given for the young seedlings. However, in the range of 300-600 old seedlings/ha at the section of 0-400 adult plants/ha, or in the range of 0-300 old seedlings/ha at the section of 800-1600 adult plants/ha, the optimal stocking rates display either an increasing trend or a constant pattern with respect to the level of old seedlings. This can be explained by the coarse grid problem in the discrete dynamic programming. For example, at the section of 0 adult plants/ha, both states with 300 and 600 old seedlings/ha will enter into an end state with the same level of 400 adult plants/ha. Although the state with 600 old seedlings has extra 300 old seedling, this will not contribute any advantage in terms of transitions for range improvement. This is because it requires more than 600 old seedlings for a state, e.g. (320,2400,600,0) to go into a state with 800 adult plants/ha. Therefore, compared to the level of 300 old seedlings/ha, the extra 300 old seedlings are redundant. Figure 4 presents the relationships between optimal average stocking rate and the old seedling population at different range conditions, holding forage biomass at 320 kg/ha d.m. and young seedlings at 0/ha level. As illustrated, the optimal stocking rate is constant at the normal range condition. In other situations, a downward trend in the optimal stocking rate is evident in the range of 0-300 old seedlings/ha at the range condition of 0-400 adult plants/ha, and in the range of 300-600 old seedlings/ha at the range condition of 800-1600 adult plants/ha. An upward trend can be seen in the range of 300-600 old seedlings/ha at the range condition of 0-400 adult plants/ha and this is due to coarse grid problem.

As to the adult plants, although the grazing system may change, the optimal stocking rates in most situations increase with a rise in adult population. However, in some cases, e.g from state (800,0,0,800) to (800,0,0,1600), (800,0,600,400) to (800,0,600,800), the stocking rates are reduced with an increasing adult population. Similar to the old seedlings, this is caused by the problem of coarse grid. The impacts of adult plants on the optimal average stocking rate at different forage availabilities are illustrated in Figure 5, holding both young and old seedlings at 1200/ha and 300/ha level, respectively. The optimal stocking rate presents an evident upward trend with respect to the level of adult plants at all forage availabilities except the level of 0 kg/ha d.m. where total destocking is optimal no matter what the range condition may be.

Optimal value function

Table 4 presents the expected net present value of profits corresponding to the optimal policy. As it can be seen from the Table, the optimal value increases with increasing value of the four state variables. The highest value $78/ha occurs at the states with the highest level in both adult plants (4000/ha) and forage biomass (800 kg/ha d.m.). The lowest value $0/ha occurs at state (0,0,0,0) and (80,0,0,0). Therefore, the opportunity costs of degradation could be as high as $78/ha for the severely degraded ranges.

With reference to forage biomass, the optimal value shows insensitive in most situations, although a positive correlation exists. This implies that the net present value of rangeland is not sensitive to the short-run fluctuations of the potential range carrying capacity. Figure 6 displays the shadow price (i.e. value of marginal product) of forage biomass at different range conditions, holding both the young and old seedlings at 0 level. As illustrated, a downward trend in the value of marginal product of forage biomass exists in the range condition of 800-4000 plants/ha. The high value being at the range of 0-80 kg/ha d.m. forage biomass level indicates the high cost of total defoliation. For the range condition of 0-400 plants/ha the shadow price has an increasing trend. This is because without both young and old seedlings these states cannot be rehabilitated and the optimal policy tends to utilise the forage as much as possible.

In most situation, the optimal values are not sensitive to young seedlings at the level ≤1200/ha. However, when the young seedling population increases from 1200 to 2400/ha in degraded range conditions, optimal values show marked increases with young seedlings. Therefore, the most important contribution of young seedlings occurs when the range is degraded and the presence of young seedlings is abundant. This can be explained by the same reason given for the optimal stocking rate. Figure 7 shows the shadow price of young seedlings at different range conditions, holding the forage biomass at 320 kg/ha d.m. and the old seedlings at 300/ha level, respectively. In all situations except the normal range condition, the shadow price increases with a rise in the seedling level. This is due to the high possibility of range improvement at high level of young seedlings. The insensitivity in the normal range condition is due to the problem of coarse grid.

With respect to old seedlings, the optimal value shows a significant increase at the same sections when the optimal stocking rates show a decreasing trend. This is consistent since, when the value of old seedlings increases, a lighter grazing pressure should be adopted to encourage their establishment. Figure 8 gives the shadow price of old seedlings at different range conditions, holding the forage biomass at 160 kg/ha d.m. and young seedlings at 0/ha level, respectively. As indicated, the shadow price is relatively high in the range of 300-600 old seedlings/ha at the range condition of 800-1600 plants/ha, and in the range of 0-300 old seedlings/ha at the range condition of 0-400 plants/ha. The low value of the shadow price is due to the problem of coarse grid.

Comparing the optimal values to adult plants and holding other state variables constant, an upward trend appears in all situations. Figure 9 shows the shadow price of adult plants at different forage availabilities, holding young and old seedlings at the 2400/ha and 600/ha level respectively. As it can be seen, the shadow price of adult plants shows a downward trend. Thus, adult plants are relatively important at degraded ranges. As to the forage biomass, the shadow price of adult plants is not sensitive to them in all range conditions.

Markov Chains Analysis of the Optimal Transition Matrix

Ergodic chains and their absorption range

The ergodic chain is the stochastic counterpart to the steady state of a deterministic dynamic system. It represents a range of the states that the system could fall in after an infinite number of transitions. The possibility distribution for these states, i.e ergodic chain, is called the long-run probability distribution. The absorption range of an ergodic chain is the subset of state space which will all approach to the ergodic chain, i.e. stochastic equilibrium, as time approaches to infinity. The states in the absorption range are called transient states. Thus, they 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 an ergodic chain is called absorption probability and the expected time needed for this reaching is the mean absorption time.

Table 5 shows the classification of the states of the optimal transition matrix and associated long run equilibrium and transient behaviour. Ergodic chains which represent stochastic equilibria are indicated in the table by shading. Numbers attached to the states within ergodic chains indicate the long run probability distribution of the ergodic chain and "ns" represents a probability value <0.005. States without shading are transient. The absorption ranges of different ergodic chains are distinguished by lines. Note that under stochastic equilibrium the absorption ranges of the steady states is not mutually exclusive; a temporary region is marked by a common area which is shared by different equilibria.

There are three ergodic chains distributed in the sections of 0/ha plants, 400/ha plants and 4000/ha plants respectively. The ergodic chain comprising states (0,0,0,0) and (80,0,0,0) represents a scalded range which has no economical value. The absorption range of this ergodic chain includes most states in the severely degraded range condition. Therefore, the optimal grazing policy may lead to further degradation for these states.

The second ergodic chain which comprises states (0,0,0,400), (80,0,0,400) and (160,0,0,400) represents a moderately degraded range. The absorption range of this chain includes most transient states within various degraded range conditions and it can be divided into two regions according to range conditions, i.e. severely degraded ranges (states with 0 adult plans/ha), moderately and slightly degraded ranges (states with 400 and 800 plants/ha, respectively). For those transient states within moderately and slightly degraded ranges, the optimal policy could cause further degradation in the long term. Contrarily, for those transient states within severely degraded ranges, the optimal policy could improve the range condition from badly degraded to moderately degraded.

The third ergodic chain consists of 35 states within the normal condition range. This chain is a desirable and ideal destination for the evolution of a grazing ecosystem. The absorption range of the chain includes all transient states within the poor and normal range conditions and those states with abundant young or old seedlings within the slightly and moderately degraded range conditions. Since all transient states within the normal and poor range conditions have absorption probabilities of value 1 these states will be absorbed by the ergodic chain with certainty. This implies that under optimal decision rule the range in normal range condition will not degenerate into poor or degraded conditions. For those transient states within the degraded ranges, the absorption probability and expected absorption time of this ergodic chain represent the possibility and the expected time for a degraded state to be rehabilitated to a normal range condition (see Appendix 1).

Long run probability distribution

The long run probability distribution of an ergodic chain represents the probability distribution of the states of the grazing ecosystem in the indefinite future if the system enters into the chain, i.e. in equilibrium. As indicated in Table 5, for initial states within the ergodic chain of 0 plants/ha, the most likely state in the long run is (0,0,0,0) with probability value 0.96. This state represents a scald with no vegetation present. For the chain of 400 plants/ha the most likely state is (80,0,0,400) with probability value 0.68. This state represents a combination of 80 kg/ha d.m., neither young nor old seedlings, and 400 adult plants/ha, while in the normal range condition the most likely state for the ergodic chain in the long run is (320,0,0,4000) with a probability value 0.21. This implies that, under normal range condition, about every 5 years state

(320,0,0,4000) will occur under the optimal decision rule. Apart from the global maximum in the ergodic chain of a normal range, some local maxima of the distribution such as states (320,0,300,400), (320,1200,0,4000), (320,1200,300,400), (320,2400,0,4000), etc. also exist. These states have a relatively higher probability to occur than other states.

Summary and Conclusion

This paper uses stochastic optimal control framework to solve the range regeneration management problem with respect to decisions about stocking rate, grazing system, and whether to adopt reseeding treatment or not. Four variables, i.e. forage biomass, young seedlings, old seedlings, and adult plants, are used jointly to describe the state of grazing ecosystem. The management strategies are specified by 50 decisions which incorporate stocking rates, grazing systems and reseeding treatment. The optimal policy was derived for a risk neutral manager under a stochastic climatic regime. 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.

The optimal policy calls for grazing management only and it is not economical to adopt reseeding treatment at current cost level. The optimal grazing system prefers set stocking when the range is resilient to grazing, or rotational grazing when not. A resilient grazing pasture is indicated by abundant forage biomass and a high level of desirable perennial adult plants. Total destocking is found to be optimal when the range is totally defoliated or badly degraded. 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, although there are some exceptions due to the coarse grid problem in the state classifications. The optimal expected net present value increases with increasing value of the four state variables. The value of marginal product for the four state variables was shown graphically. It was found that in general the value of adult plants and forage biomass are high when their levels are low. For young or old seedlings the value increases with their levels, though some exceptions exist.

Markov analysis indicates that rehabilitation for slightly and moderately degraded rangelands is possible if the number of seedlings is adequate, while for those severely degraded rangelands reclamation to the normal condition is impossible and further degradation may be expected.

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Table 1

One to One Relation between State Indices and the Values of the Four State Variables

		TOTAL FORAGE BIOMASS (kg d.m./ha)																
		0	80	160	320	800	0	80	160	320	800	0	80	160	320	800		
		------	------	------	------	------	state indices				------	------	------	------	------	------		
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	0	Y
A	0	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1200	O
D	0	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	2400	U
U	400	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	0	N
L	400	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	1200	G
T	400	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	2400	
	800	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	0	S
P	800	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	1200	E
L	800	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	2400	E
A	1600	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	0	D
N	1600	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	1200	L
T	1600	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	2400	I
S	4000	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	0	N
	4000	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	1200	G
	4000	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	2400	S
	plants/ha	0	0	0	0	0	300	300	300	300	300	600	600	600	600	600	plants/ha	
		OLD SEEDLINGS (plants/ha)																

Table 2
Decision Indices and the Corresponding Grazing and Treatment Decisions

Decision Indices	tocking Rate	Decision Descriptions
1	0	total destocking throughout the year
2	0.05	set stocking with initial stocking rate 0.05/ha sheep in summer
3	0.1	......0.1/ha sheep......
4	0.15	......0.15/ha sheep......
5	0.2	......0.2/ha sheep......
6	0.25	......0.25/ha sheep......
7	0.3	......0.3/ha sheep......
8	0.4	......0.4/ha sheep......
9	0.6	......0.6/ha sheep......
10	0.8	......0.8/ha sheep......
11	1	......1/ha sheep......
12	0/.1/0	rotational grazing with 0.1/ha sheep in season 2 but destocking in season 1 and 3
13	0/.4/0	......0.4/ha sheep......
14	0/.7/0	......0.7/ha sheep......
15	0/1/0	......1/ha sheep......
16	.05/.4/.05	rotational grazing with 0.05/ha, 0.4/ha and 0.05/ha sheep in season 1, 2 and 3 respectively
17	.05/.7/.05	......0.05/ha, 0.7/ha and 0.05/ha sheep......
18	.05/1/.05	......0.05/ha, 1/ha and 0.05/ha sheep......
19	.1/.4/0	......0.1/ha, 0.4/ha and 0/ha sheep......
20	.1/.4/.1	......0.1/ha, 0.4/ha and 0.1/ha sheep......
21	.1/.7/0	......0.1/ha, 0.7/ha and 0/ha sheep......
22	.1/.7/.1	......0.1/ha, 0.7/ha and 0.1/ha sheep......
23	.1/1/0	......0.1/ha, 1/ha and 0/ha sheep......
24	.1/1/.1	......0.1/ha, 1/ha and 0.1/ha sheep......
25	.25/.4/0	......0.25/ha, 0.4/ha and 0/ha sheep......
26	.25/.4/.1	......0.25/ha, 0.4/ha and 0.1/ha sheep......
27	.4/.7/0	......0.4/ha, 0.7/ha and 0/ha sheep......
28	.4/.7/.4	......0.4/ha, 0.7/ha and 0.4/ha sheep......
29	.4/1/.4	......0.4/ha, 0.1/ha and 0.4/ha sheep......
30	.5/2/.5	......0.5/ha, 2/ha and 0.5/ha sheep......

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Decision Indices	Stocking Rate	Decision Descriptions
31	0	reseeding combined with total destocking
32	0.05	reseeding combined with set stocking with initial stocking rate 0.05/ha sheep
33	0.1	........0.1/ha sheep.......
34	0.15	........0.15/ha sheep.......
35	0.2	........0.2/ha sheep.......
36	0.3	........0.3/ha sheep.......
37	0/.1/0	reseeding combined with rotational grazing with 0.1/ha sheep in season 2 but destocking in season 1 and 3
38	0/.4/0	........0.4/ha sheep.......
39	0/.7/0	........0.7/ha sheep.......
40	0/1/0	........1/ha sheep.......
41	.05/.4/.05	reseeding combined with rotational grazing with 0.05/ha, 0.4/ha and 0.05/ha sheep in season 1,2 and 3 respectively
42	.05/.7/.05	........0.05/ha, 0.7/ha and 0.05/ha sheep.......
43	.05/1/.05	........0.05/ha, 1/ha and 0.05/ha sheep.......
44	.1/.4/0	........0.1/ha, 0.4/ha and 0/ha sheep.......
45	.1/.4/.1	........0.1/ha, 0.4/ha and 0.1/ha sheep.......
46	.1/.7/0	........0.1/ha, 0.7/ha and 0/ha sheep.......
47	.1/.7/.1	........0.1/ha, 0.7/ha and 0.1/ha sheep.......
48	.1/1/0	........0.1/ha, 1/ha and 0/ha sheep.......
49	.1/1/.1	........0.1/ha, 1/ha and 0.1/ha sheep.......
50	.4/.7/0	........0.4/ha, 0.7/ha and 0/ha sheep.......

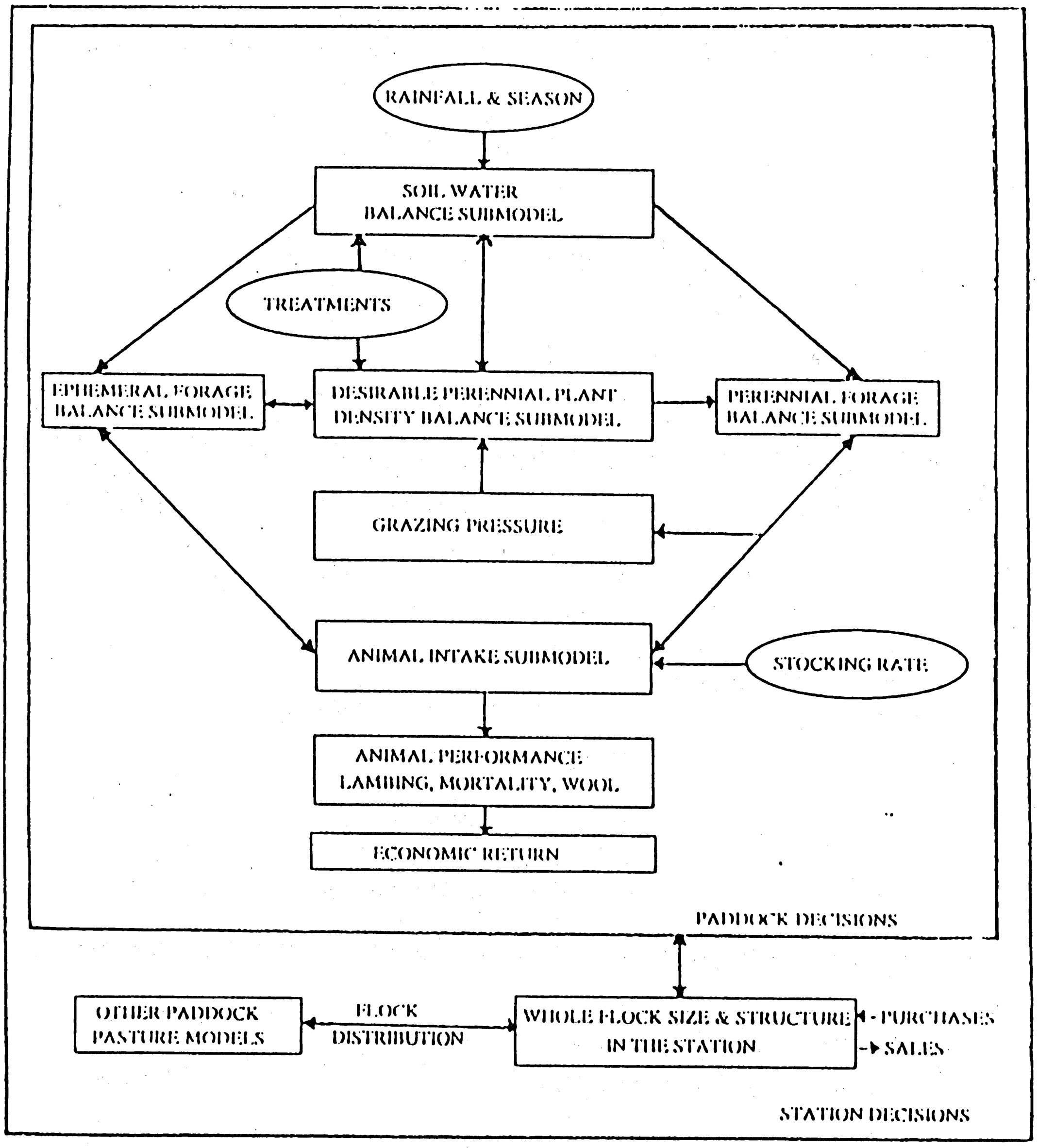


FIGURE 1. SIMULATION MODEL OF RANGELAND ECOSYSTEM

Table 3
Optimal Policy for Range Regeneration under a Stochastic Climatic Regime

		TOTAL FORAGE BIOMASS (kg d.m./ha)																
		0	80	160	320	800	0	80	160	320	800	0	80	160	320	800		
		optimal grazing decisions																
	0	0	0	.25/.4/0	.25/.4/0	1	0	0	0	0	1	0	0	.05	.25/.4/0	.8	0	Y
A	0	0	0	0	.25/.4/0	1	0	0	0	0	0	0	0	0	0	.05	1200	O
D	0	0	0	0	.25/.4/0	.6	0	0	0	0	0	0	0	0	.25/.4/0	.4	2400	U
U	400	0	0	.4/.7/0	.4/.7/0	1	0	0	0	0	.05	0	0	.15	.4/.7/0	.8	0	N
L	400	0	0	0	0	.05	0	0	0	0	.05	0	0	.15	.4/.7/0	.8	1200	G
T	400	0	0	.05	.25/.4/0	.4/.7/0	0	0	0	0	.05	0	0	0	0	.4/.7/0	2400	
	800	0	0/.1/0	.4/.7/0	.4/.7/0	1	0	.05	.4/.7/0	.4/.7/0	1	0	0	0	0	.1	0	S
P	800	0	0/.1/0	.4/.7/0	.4/.7/0	1	0	.05	.4/.7/0	.4/.7/0	1	0	0	0	0	.1	1200	E
L	800	0	0	0	.1/.4/0	.4/.7/0	0	0	0	.1/.4/0	.4/.7/0	0	0	0	0	.1	2400	E
A	1600	0	.25/.4/0	.4	.4/.7/0	.8	0	.1/.4/0	.25/.4/.1	.4/.7/0	1	0	0	0/.1/0	0/.1/0	0/.1/0	0	D
N	1600	0	.1/.4/0	.25/.4/.1	.4/.7/0	.8	0	.1/.4/0	.25/.4/.1	.4/.7/0	1	0	0	0/.1/0	0/.1/0	0/.1/0	1200	L
T	1600	0/.1/0	0/.1/0	0/.1/0	.1/1/0	.4/.7/0	0/.1/0	0/.1/0	0/.1/0	.1/1/0	.4/.7/0	0/.1/0	0/.1/0	0/.1/0	0/.1/0	0/.4/0	2400	I
S	4000	0	.25/.4/.1	.4/.7/0	.8	1	0	.25/.4/.1	.4/.7/0	.8	1	0	.25/.4/.1	.4/.7/0	.8	1	0	N
	4000	0	.25/.4/.1	.4/.7/0	.8	1	0	.25/.4/.1	.4/.7/0	.8	1	0	.25/.4/.1	.4/.7/0	.8	1	1200	G
	4000	0	.25/.4/.1	.4/.7/0	.8	1	0	.25/.4/.1	.4/.7/0	.8	1	0	.25/.4/.1	.4/.7/0	.8	1	2400	S
plants/ha		0	0	0	0	0	300	300	300	300	300	600	600	600	600	600	plants/ha	
		OLD SEEDLINGS (plants/ha)																

1. Treatment policy is not economically viable for all states; numbers indicate stocking rates, sheep/ha.
2. States with only one stocking rate indicate continuous grazing system with the stocking rate set in the beginning of the year.
3. States with three stocking rates indicate rotational grazing system with the three stocking rates set for the three rainfall seasons January-April/May-August/September-December, respectively.

Figure 2: Optimal Stocking Rate (OSR) vs Forage Availabilities (TFA) at different Range Conditions (RC)

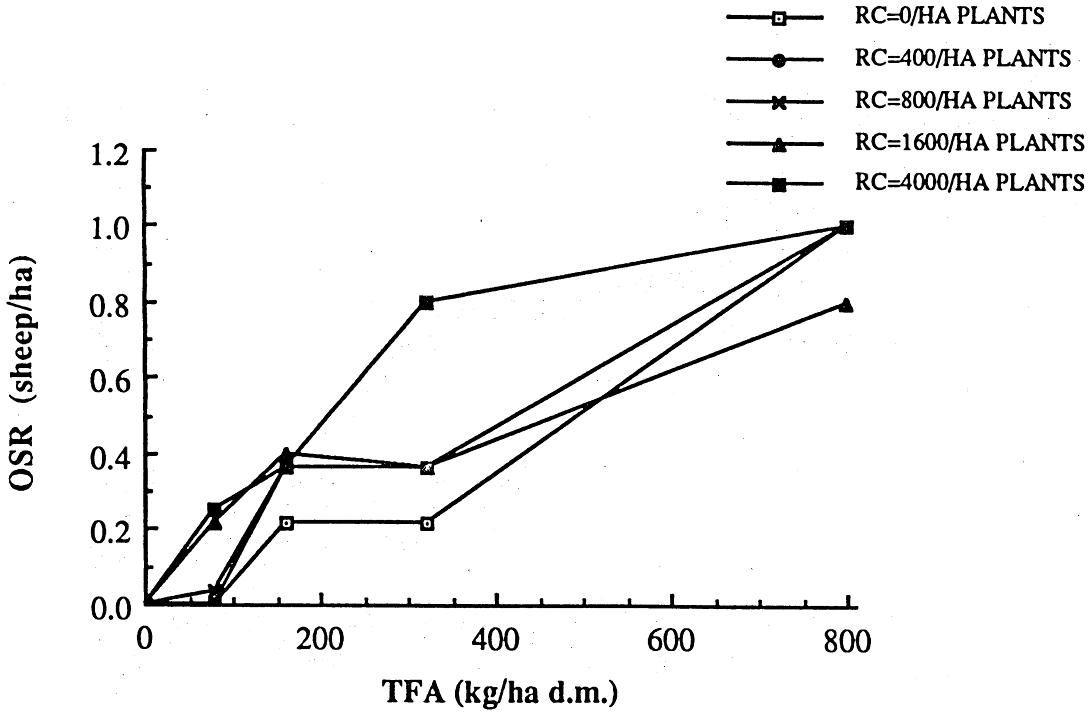


Figure 3: Optimal Stocking Rate (OSR) vs Young Seedling Population (YS) at different Range Conditions (RC)

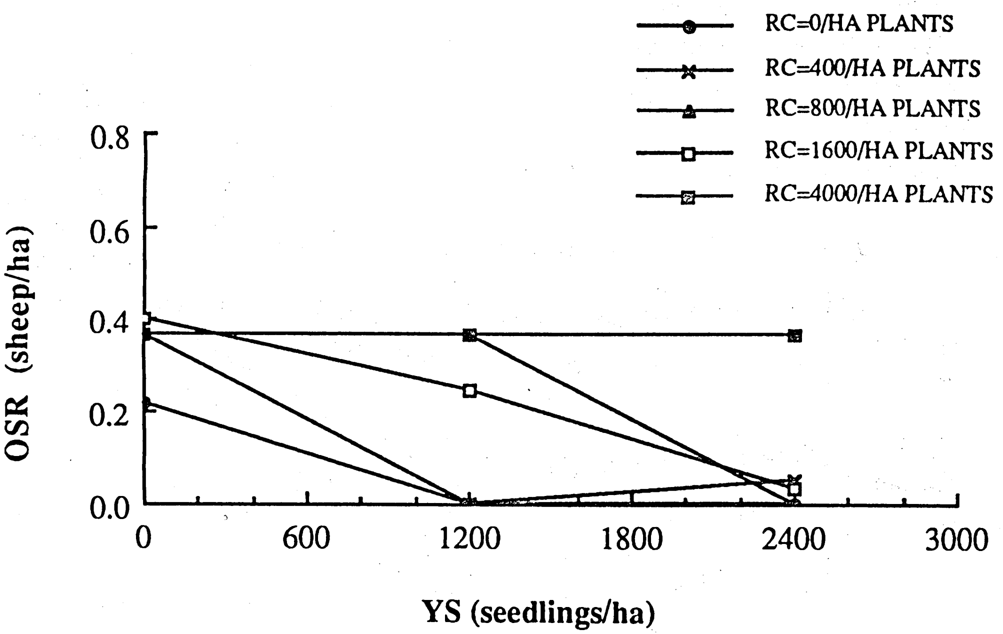


Figure 4: Optimal Stocking Rate (OSR) vs Old Seedling Population (OS) at different Range Conditions (RC)

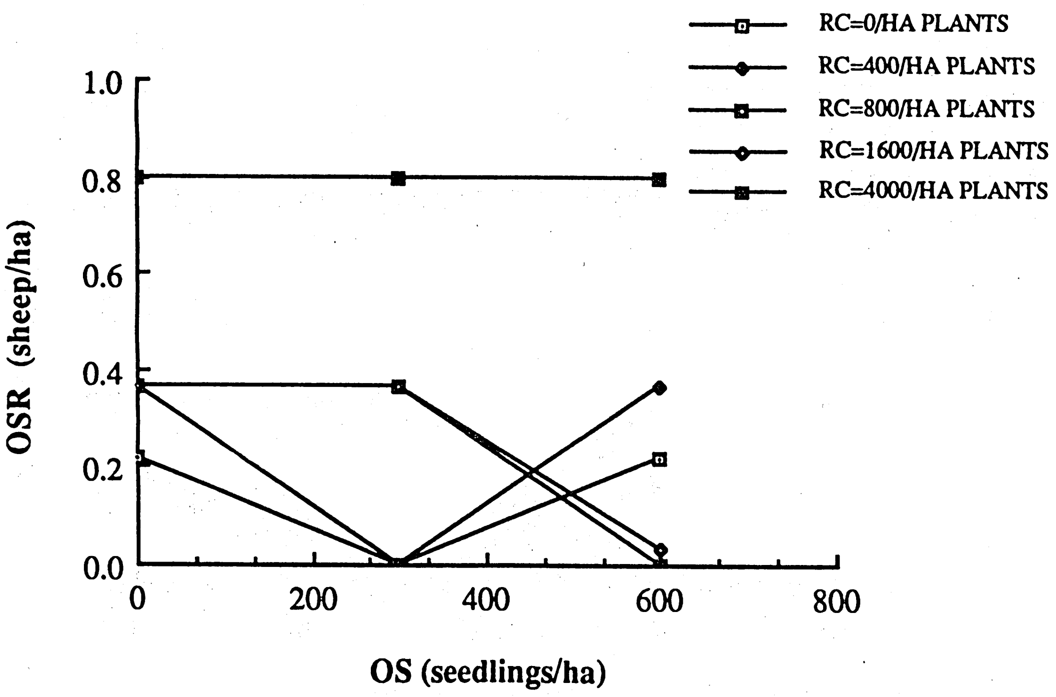


Figure 5: Optimal Stocking Rate (OSR) vs Desirable Mature Plants (SP7) at different Forage Availabilities (TFA)

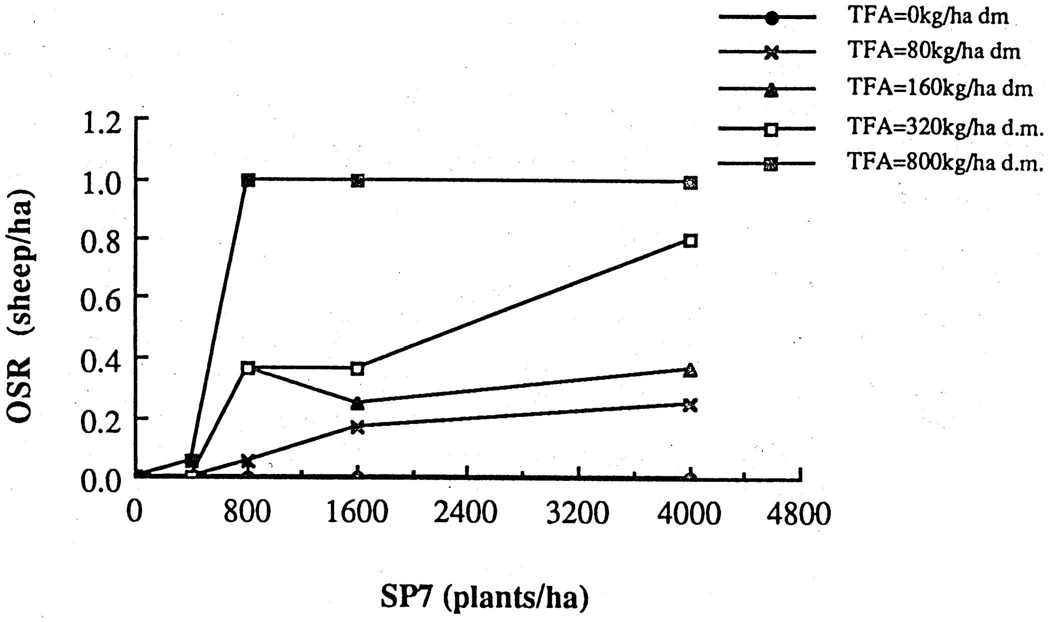


Table 4
Optimal Value Function corresponding to the Optimal Policy under a Stochastic Climatic Regime

		TOTAL FORAGE BIOMASS (kg d.m./ha)																
		0	80	160	320	800	0	80	160	320	800	0	80	160	320	800		
		net present value $/ha																
	0	0	0	0.2	1	5	2	2	2	2	5	2	2	3	4	7	0	Y
A	0	0.6	0.6	0.6	1	5	5	6	6	6	7	6	6	6	6	8	1200	O
D	0	2	2	2	3	6	13	13	14	14	15	13	14	15	15	17	2400	U
U	400	2	3	4	5	8	14	15	15	15	18	14	16	16	18	21	0	N
L	400	11	12	12	12	13	14	15	15	15	18	14	16	16	18	21	1200	G
T	400	14	15	15	16	18	41	43	43	43	44	43	44	44	45	46	2400	
	800	15	16	18	19	21	15	16	18	19	22	45	47	48	48	49	0	S
P	800	15	16	18	19	21	15	16	18	19	22	45	47	48	48	49	1200	E
L	800	43	44	45	45	47	43	44	45	45	47	63	65	65	65	66	2400	E
A	1600	46	49	50	52	54	47	49	51	52	55	66	69	69	70	70	0	D
N	1600	47	49	51	52	54	47	50	51	53	55	66	69	69	70	70	1200	L
T	1600	63	65	66	66	67	63	66	66	66	67	66	70	70	71	71	2400	I
S	4000	68	71	73	76	78	68	71	73	76	78	68	71	73	76	78	0	N
	4000	68	71	73	76	78	68	71	73	76	78	68	71	73	76	78	1200	G
	4000	68	71	73	76	78	68	71	73	76	78	68	71	73	76	78	2400	S
	plants/ha	0	0	0	0	0	300	300	300	300	300	600	600	600	600	600	plants/ha	
		OLD SEEDLINGS (plants/ha)																

Figure 6: The Shadow Price (VMP) of Forage Biomass (TFA) at different Range Conditions (RC)

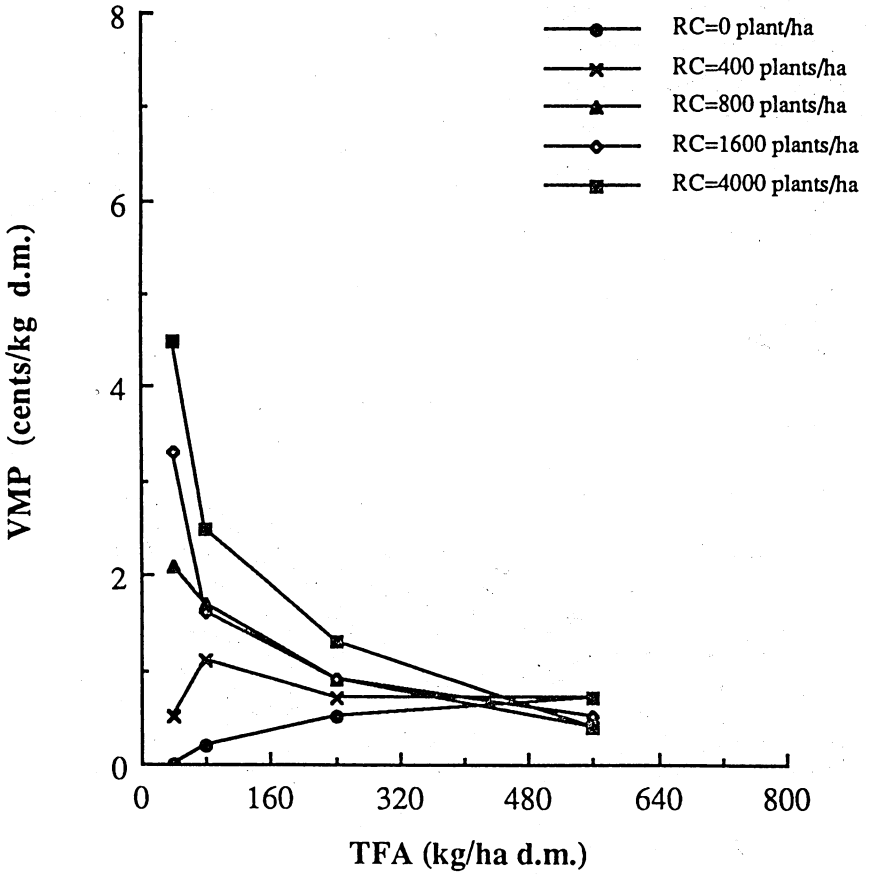


Figure 7: The Shadow Price (VMP) of Young Seedlings (YS) at different Range Conditions (RC)

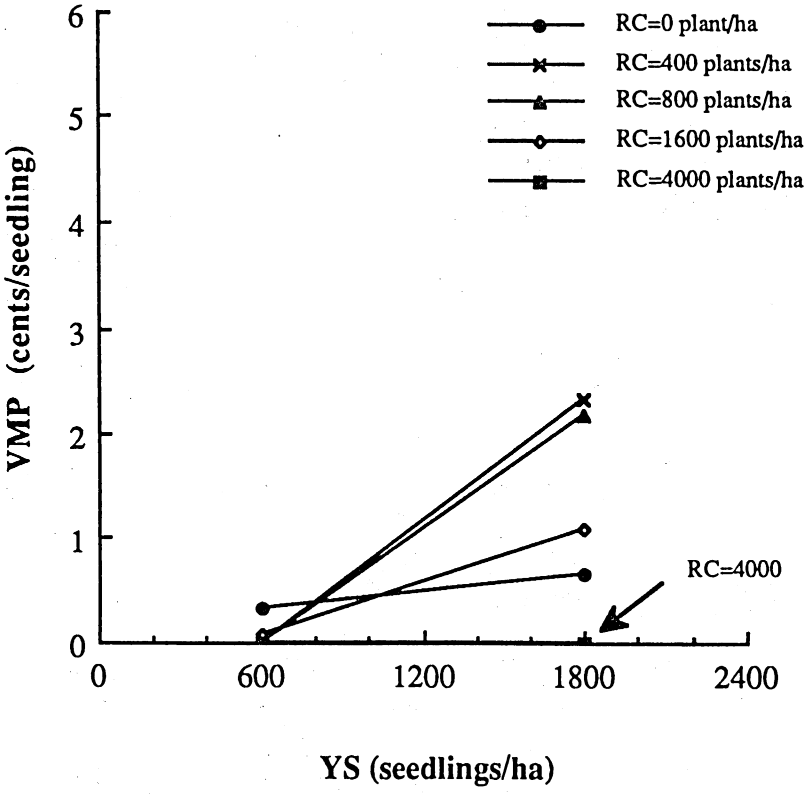


Figure 8: The Shadow Price (VMP) of Old Seedlings (OS) at different Range Conditions (RC)

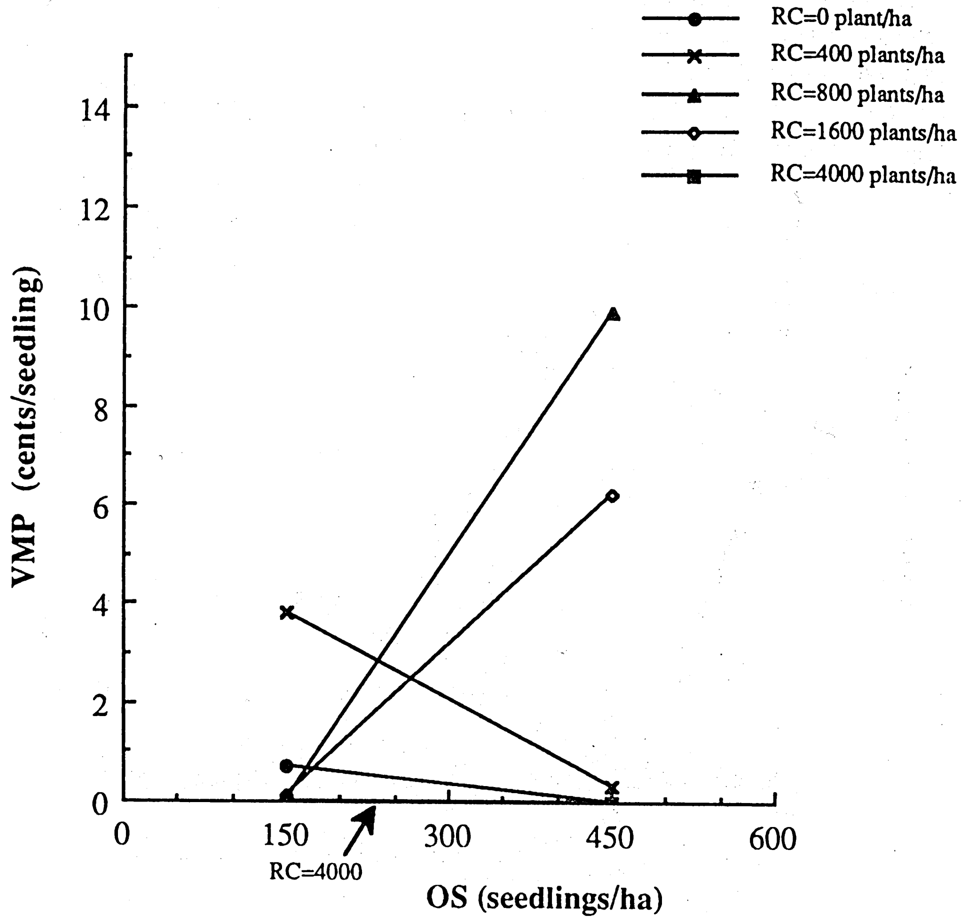


Figure 9: The Shadow Price (VMP) of Desirable Mature Plants (SP7) at different Forage Availabilities (TFA)

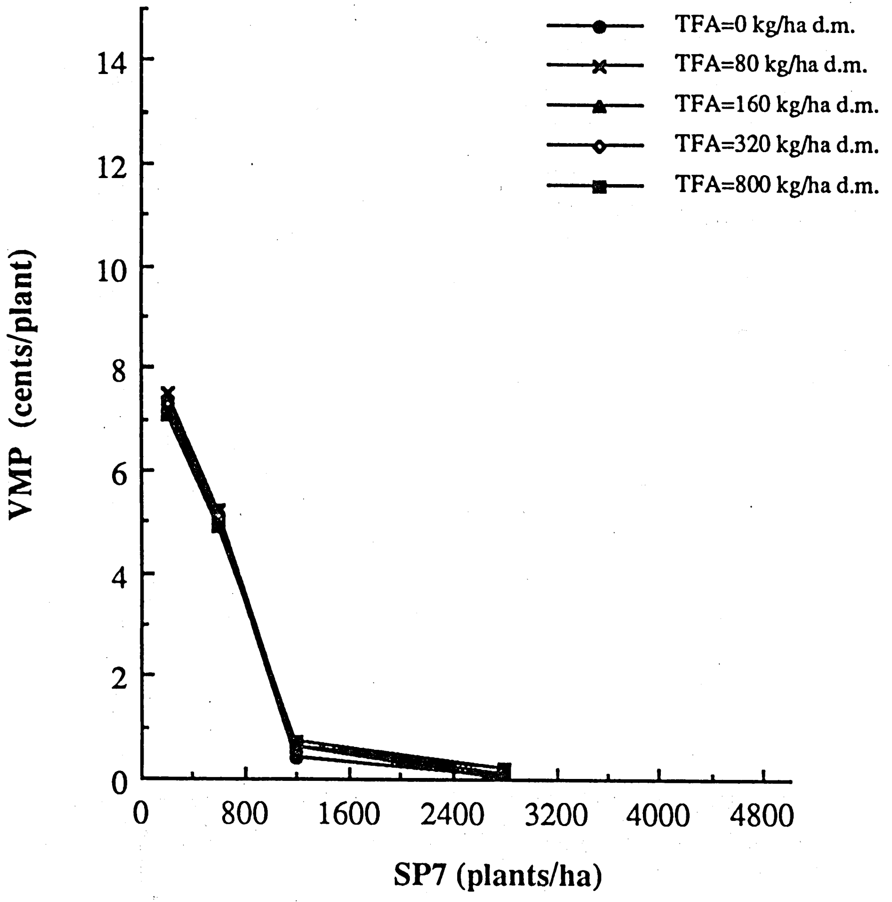
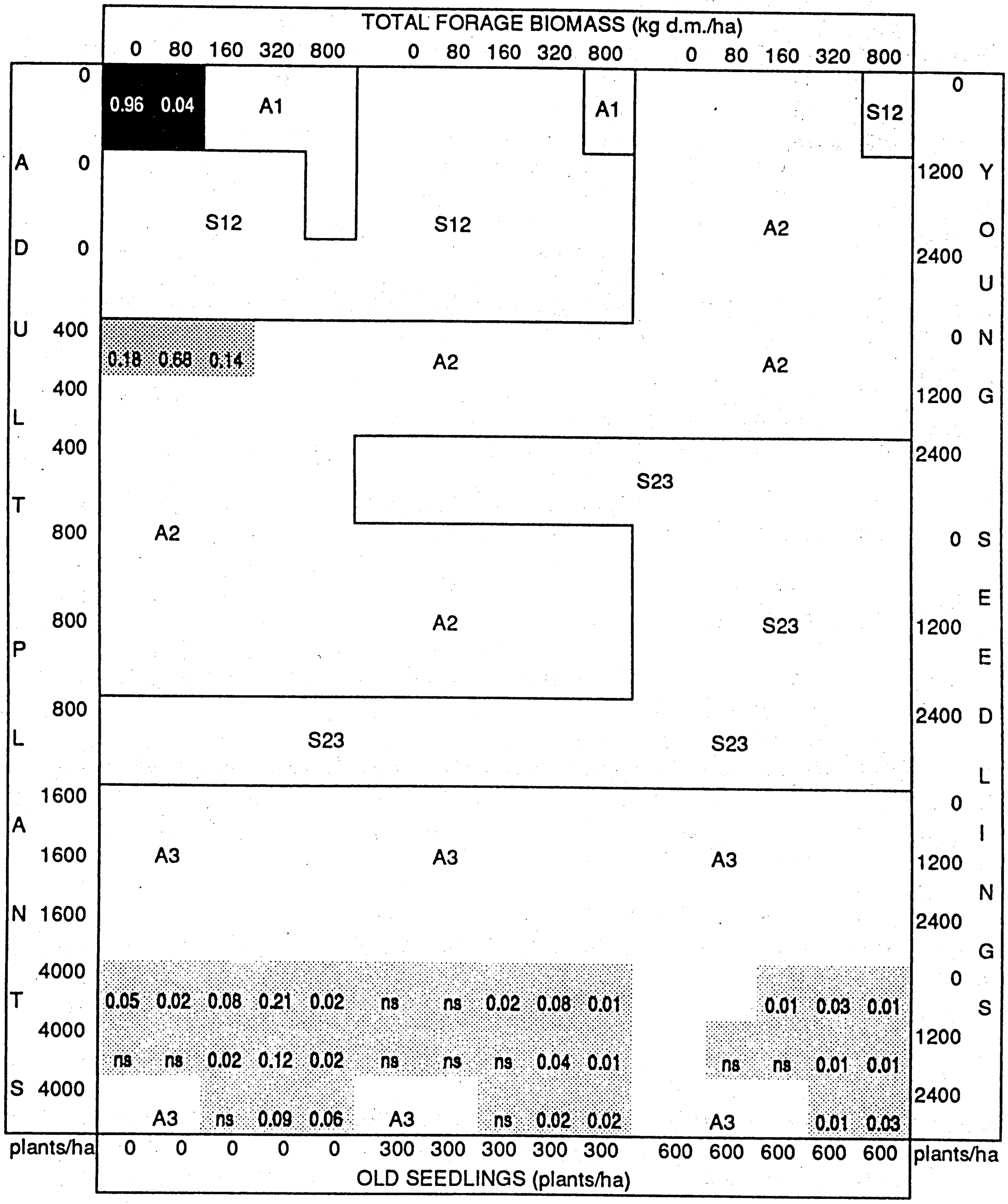


Table 5
State Classifications and Associated Long Run Equilibrium and Transient Behaviour



1. There are three aperiodic ergodic chains indicated by shading with numbers indicating the long run probabilities and "ns" referring to a probability value <0.5%. States without shading are transient.
2. S## stands for a common shared region and A# stands for the exclusive absorption range of an equilibrium. Numbers following the character A and S indicate the three equilibria which are represented by the ergodic chains in the section of 0/ha (1) and 400/ha (2) and 4000/ha plants (3), respectively.

Appendix 1

State Classifications and Associated Long Run Equilibrium and Transient Behaviour

ADULT PLANTS	TOTAL FORAGE BIOMASS (kg d.m./ha)															YOUNG SEEDLINGS
	0	80	160	320	800	0	80	160	320	800	0	80	160	320	800	
0	■	■	**1** *1*	**1** *1*	**1** *1*	**1** *0.08* *0.92*	**1** *0.08* *0.92*	**1** *0.08* *0.92*	**1** *0.08* *0.92*	**1** *1*	**1** *1*	**1** *1*	**1** *1*	**1** *1*	**1** *0.05* *0.95*	0
0	**1** *0.71* *0.29*	**1** *0.71* *0.29*	**1** *0.71* *0.29*	**1** *0.97* *0.03*	**1** *1*	**66** *0.08* *0.92*	**66** *0.08* *0.92*	**65** *0.08* *0.92*	**65** *0.08* *0.92*	**65** *0.08* *0.92*	**66** *1*	**66** *1*	**65** *1*	**65** *1*	**65** *1*	1200
0	**2** *0.01* *0.99*	**2** *0.01* *0.99*	**2** *0.01* *0.99*	**2** *0.06* *0.94*	**2** *0.15* *0.85*	**200** *0.01* *0.99*	**200** *0.01* *0.99*	**198** *0.01* *0.99*	**198** *0.01* *0.99*	**193** *0.01* *0.99*	**216** *1*	**216** *1*	**214** *1*	**206** *1*	**205** *1*	2400
400	▩	▩	▩	**1** *1*	**1** *1*	**203** *1*	**202** *1*	**201** *1*	**201** *1*	**201** *1*	**216** *1*	**214** *1*	**214** *1*	**208** *1*	**207** *1*	0
400	**169** *1*	**168** *1*	**168** *1*	**168** *1*	**162** *1*	**203** *1*	**202** *1*	**201** *1*	**201** *1*	**201** *1*	**216** *1*	**214** *1*	**214** *1*	**208** *1*	**207** *1*	1200
400	**216** *1*	**215** *1*	**215** *1*	**214** *1*	**211** *1*	**39** *0.07* *0.93*	**39** *0.07* *0.93*	**39** *0.07* *0.93*	**39** *0.07* *0.93*	**38** *0.07* *0.93*	**29** *0.02* *0.98*	**29** *0.02* *0.98*	**29** *0.02* *0.98*	**29** *0.02* *0.98*	**39** *0.07* *0.93*	2400
800	**216** *1*	**214** *1*	**212** *1*	**213** *1*	**207** *1*	**216** *1*	**214** *1*	**212** *1*	**213** *1*	**214** *1*	**27** *0.01* *0.99*	**27** *0.01* *0.99*	**27** *0.01* *0.99*	**27** *0.01* *0.99*	**28** *0.02* *0.98*	0
800	**216** *1*	**214** *1*	**212** *1*	**213** *1*	**207** *1*	**216** *1*	**214** *1*	**212** *1*	**213** *1*	**214** *1*	**26** *0.01* *0.99*	**26** *0.01* *0.99*	**26** *0.01* *0.99*	**26** *0.01* *0.99*	**28** *0.02* *0.98*	1200
800	**29** *0.02* *0.98*	**29** *0.02* *0.98*	**29** *0.02* *0.98*	**33** *0.04* *0.96*	**33** *0.04* *0.96*	**29** *0.02* *0.98*	**29** *0.02* *0.98*	**29** *0.02* *0.98*	**33** *0.04* *0.96*	**33** *0.04* *0.96*	**5** *0.01* *0.99*	**5** *0.01* *0.99*	**5** *0.01* *0.99*	**5** *0.01* *0.99*	**7** *0.02* *0.98*	2400
1600	**24** *1*	**24** *1*	**24** *1*	**24** *1*	**24** *1*	**23** *1*	**23** *1*	**23** *1*	**23** *1*	**23** *1*	**2** *1*	**2** *1*	**2** *1*	**2** *1*	**2** *1*	0
1600	**23** *1*	**23** *1*	**23** *1*	**23** *1*	**23** *1*	**22** *1*	**22** *1*	**23** *1*	**23** *1*	**23** *1*	**2** *1*	**2** *1*	**2** *1*	**2** *1*	**2** *1*	1200
1600	**4** *1*	**4** *1*	**4** *1*	**4** *1*	**6** *1*	**3** *1*	**3** *1*	**3** *1*	**4** *1*	**6** *1*	**2** *1*	**1** *1*	**1** *1*	**1** *1*	**1** *1*	2400
4000	░	░	░	░	░	░	░	░	░	░	**1** *1*	**1** *1*	░	░	░	0
4000	░	░	░	░	░	░	░	░	░	░	**1** *1*	░	░	░	░	1200
4000	**1** *1*	**1** *1*	░	░	░	**1** *1*	**1** *1*	░	░	░	**1** *1*	**1** *1*	**1** *1*	░	░	2400
plants/ha	0	0	0	0	0	300	300	300	300	300	600	600	600	600	600	plants/ha
	OLD SEEDLINGS (plants/ha)															

1. There are three aperiodic ergodic chains indicated by different shadings.
2. States without shading are transient with the italic numbers indicating absorption probabilities and the bold numbers indicating mean absorption times in years. For example, for state (0,0,600,800) it is expected to take 84 years with the chance of 31% for it to go to the ergodic chain in the section of 400/ha plants and the chance of 69% to enter into the ergodic chain in the section of 4000/ha plants.

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RANGELAND DEGRADATION AND REHABILITATION UNDER OPTIMAL MANAGEMENT DECISIONS[*]

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Abstract

Rangeland degradation within the arid zone of Western Australia has occurred as a consequence of sheep overstocking. The strategies available for restoring the productivity of degraded rangelands are limited. In those situations where there is still reasonable residual soil and vegetation despite moderate erosion and depletion of palatable forage plants, rehabilitation through manipulation of grazing pressure is possible. In extreme situations where there has been severe depletion of palatable perennial plants coupled with accelerated soil erosion, reclamation is unlikely to succeed without various forms of cultivation or earthworks, associated with the re-introduction of a suitable seed source. Optimal range rehabilitation policy needs to be discovered to maintain the resource base for future use. In this paper an economic optimum policy with respect to the choice of stocking rates and the timing of cultural treatment was derived under a stochastic optimal control framework. Empirical evaluation of the derived optimum policy was carried out by analysing its long run economic and ecological impacts. The derived optimal policy calls for grazing management strategy only. The treatment policy is not economically viable at current cost level. The range rehabilitation and degradation processes under the optimum policy were presented. Generally, rehabilitation for moderately degraded ranges is possible if there are sufficient seedlings observed, while for those severely degraded ranges reclamation is impossible and further degradation is expected.

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