ANALYSIS OF RANGELAND DEGRADATION USING STOCHASTIC DYNAMIC PROGRAMMING

The emerging problem of arid rangeland degradation is becoming increasingly topical in agricultural economics research. Globally, degradation of arid rangelands especially in regions such as the Sahel and China is a serious and pressing concern (Southgate *et al.* 1990). In Australia, Foran *et al.* (1990) argued that the arid rangelands do have non-trivial option and existence values. Indeed, the Australian Conservation Foundation recently released a report (Australian Conservation Foundation 1991) proposing radical plans to conserve the rangelands including complete destocking for up to five years and the reintroduction of dingoes to control kangaroos.

Although agricultural economists have been involved in efforts to conceptualise the issues and to identify possible causes of rangeland degradation (see, for instance, Kirby and Blyth (1987) in this Journal), they have paid less attention to quantifying those relationships. This is despite the considerable number of empirical studies examining crop land erosion problems (Stoneham 1991; McConnell 1983).

An empirical analysis of degradation in an important part of Australia's arid rangelands, namely the Queensland mulga rangelands, is reported. The characteristics of the Queensland mulga rangelands and the nature of its degradation are first described. The way such degradation relates to the concepts of sustainable resource use is then discussed along with the usefulness of stochastic dynamic programming in examining sustainable use of arid rangelands. A stochastic dynamic programming model is developed and used to explore the impact of variations in property size, wool prices, discount rates and risk attitudes on optimal rangeland decisions.

Degradation of the Queensland Mulga Rangelands

The south-west Queensland mulga rangelands (Figure 1), named after the dominant vegetation type, *Acacia aneura*, are a key part of the Queensland pastoral zone occupying some 19 million hectares or 17 per cent of the state's arid zone (Sullivan *et al.* 1986). To the west of Charleville and the Warrego river and stretching west to Quilpie lies the hard mulga distinguished by shallower, less fertile soils, a lower average rainfall and a more fragile ecosystem than the soft mulga to the east. Grazing properties range in size from under 10,000 hectares to over 200,000 hectares and stocking rates typically vary from 0.2 to 0.5 dry sheep equivalents (DSE)[1] per hectare.

[Figure 1 around here]

FIGURE 1 - Location of the Mulga Rangelands in Queensland's Arid Zone

Continued high stocking pressure since settlement has left vast tracts of the mulga rangelands in a degraded state (Mills 1989). The complex cycle of degradation in the mulga rangelands is influenced by drought, the extent of mulga feeding, stock management, grazing by native animals and fire (Figure 2). The cycle commences with reduced pasture biomass caused by drought or heavy grazing. Degradation may be avoided at this stage by reducing stocking rates or de-stocking to allow the pasture to recover. Researchers have shown that provided basal area (ground cover) does not fall below 2 per cent, no irreversible damage to vegetation and soils occurs (Beale 1985; Pressland and Lehane 1982). However continued heavy grazing of the depleted pasture inevitably leads to a loss of ground cover and a domination by less desirable species. The reduced cover leaves the soil vulnerable to sheet and gully erosion which occurs as a result of reduced plant water uptake and greater water run-off. Sheet erosion and the

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[1] Dry Sheep Equivalents are used to equate the fodder needs of various stock types and are based on the fodder requirements for a single dry ewe or wether. The estimates of DSEs for various stock types in this study were based on those reported in Queensland Department of Primary Industries (1982) with slight variations following suggestions from Queensland Department of Primary Industries officers.

corresponding lack of nutrients reduces the potential for bare areas to be regenerated, particularly if stocking pressure is maintained. A recent field survey by Mills *et al.* (1989) showed that woody weeds had reduced productivity on 44 per cent of the area in the western, hard mulga zone. Erosion was a serious problem in over 9 per cent of the area surveyed.

(Figure 2 around here)

FIGURE 2 - The Land Degradation Cycle

Sustainable Use of the Queensland Mulga Rangelands

Much of the debate about rangeland degradation has centred on the notion of sustainable resource use. In recent times, the notion of sustainability has become a topical issue in the economics of renewable resource use and conservation. Sustainable resource use embodies ethical issues such as the survival of life, provision of basic needs and the rights of future generations (O'Riordan 1988). It implies a balance between conservation and exploitation, satisfying the needs of the current generation while recognising the needs of future generations. Sustainability means preserving future opportunities without imposing hardship on current users of the resource. It links the concepts of economics, the environment and time, recognising an intertemporal, joint ownership of resources.

Critical to the development of a sustainable resource use policy is the recognition of a user cost, or shadow price, of current resource use (Fisher 1981). The user cost, or the net value of future rents foregone by the current use of an additional unit of resource, is a non-cash cost that is equivalent to an investment in conservation (Fisher 1981). The renewability of the resource and the social discount rate primarily determine the user costs. For instance, a high discount rate or a high renewability implies a low user cost. In the case of the rangelands, the renewability of the pasture resource will also be influenced by the non-renewable soil component of the rangeland system as shown in Figure 2.

In the traditional neo-classical framework, there exists a positive optimal rate of degradation that depends on the value of user costs (Quiggin, 1986; Kirby and Blyth 1987). This conventional interpretation of sustainability contrasts with that of Pearce *et al.* (1990) and that of ecologists. Pearce *et al.* state that in the case of land resources where no substitutes are available and degradation may be irreversible, a zero rate of degradation is preferred. Hence, resource use should be lower than the rate of renewal and each generation should benefit from the use of the same non-degraded resource base.

The excessive rate of degradation of the mulga rangelands appears to be inconsistent with both the neo-classical and ecological views of sustainable resource use. The irreversible loss of top-soil and ground cover clearly indicates that degradation is in excess of that desired for ecological sustainability. Moreover, the extent of the problem suggests that the rate of degradation may be greater than that preferred by society. This divergence between private and social optima is usually explained by market failure arguments such as imperfect information, externalities or the failure to recognise option and existence values. For example, positive option and existence values arise from environmental amenities and preservation of culture and history (Foran *et al.* 1990). However, there are other institutional and structural factors which are also responsible for the unsustainable exploitation of the mulga rangelands.

Indeed, numerous historical, physical and economic factors have encouraged the high stocking rates instrumental in the degradation of the mulga rangelands. Some of these factors include property size, financial constraints (interest and domestic costs), wool price variations, land tenure, lack of land market information and individual graziers' attitudes to risk. Other causes of degradation stem from the characteristics of the rangelands and production systems themselves. The competition from native and feral grazers, particularly kangaroos, imposes a unique common property problem on mulga rangeland resource use despite nominal private property rights. In addition, the ability to use mulga as top-feed enables stocking rates to be maintained during drought, reinforcing the degradation cycle. Another characteristic is the fine-wool effect whereby

graziers are encouraged by price premiums to induce fine, higher quality wool by adopting exploitive stocking strategies (Australian Conservation Foundation 1991).

Little empirical evidence of the impact of the above factors is available, although Passmore (1990) in a survey of mulga graziers, found some correlation between stocking rates and factors such as property size and interest costs. The issue of property size, stocking rate and land degradation has long been of contention. Land administrators recognised the importance of property size as early as the 1960s when they changed from a policy of subdivision to property build-up. The Warrego Graziers' Association (1988) suggested a regulated program of property build-up whereby graziers would be given first option to purchase neighbouring properties offered for sale. Mills *et al.* (1989), however, found that land condition did not differ significantly between the largest and smallest properties. Previously, McArthur and Dillon (1971) used a static utility model to show that increases in property size led to a fall in optimal stocking rates for the risk averse grazier. However, optimal stocking rates were not influenced by property size given a risk neutral attitude; that is, where maximisation of profits was the goal. The issue of property size and land condition is further investigated in the following sections, along with the other main factors influencing degradation in the Queensland mulga rangelands.

Sustainable Resource Use and Dynamic Programming

To date, much of the sustainability debate has involved qualitative analysis and discussion (see, for example, Kirby and Blyth 1987; and Wills 1987). Moreover, the scientific research from which rangeland policies have drawn has had little economic input and virtually no intertemporal analysis; focussing instead on the potential for rehabilitation and arresting of rangeland degradation through the use of ponding banks, grazing management and fire (Carter and Johnston 1986; McLeod 1990). The emphasis on the symptoms rather than the causes of degradation (Quiggin 1986) explains the persistence of land degradation problems despite an awareness of

these problems among graziers, scientists and land administrators alike. Disconcertingly, many policy measures, such as taxation concessions for conservation works, often provide a reward for those degrading the rangelands (Chisholm 1987).

Much of the quantitative analysis of degradation issues to date has relied on hedonic and econometric models. Various authors (Gardner and Barrows 1985; King and Sinden 1988; Palmquist and Danielson 1989) have used hedonic models to ascribe the effect of conservation measures on land prices. Passmore (1990) also used econometric methods to identify the various factors explaining stocking rates in the mulga rangelands. However, some difficulties were encountered by Passmore in separating the effects of regional diversity from the economic factors affecting stocking rates. Moreover, the analysis failed to incorporate the dynamic nature of the degradation process.

Despite generally being overlooked, dynamic optimisation methods are especially suitable in the formulation of policies for sustainable resource use. Dynamic optimisation techniques implicitly incorporate user costs in determining an intertemporal optimum resource allocation. Such techniques are most appropriate for analysis of sustainability issues, since they incorporate the concepts of economics, the state of the environment and time. Thus, important insights and information can be gleaned from these normative models; information of vital concern to policy makers and land administrators.

The dynamic optimisation problem is often formulated as an optimal control model and solved using dynamic programming or other forms of mathematical programming such as linear, non-linear and quadratic programming (Kennedy 1986). However, dynamic programming is more efficient for larger problems involving infinite stage and stochastic applications. For example, a linear programming approximation of a dynamic model in Miranowski (1984) required stages to be grouped in five year periods and entailed the use of a penalty function to approximate an infinite planning horizon. The inherent variability of the rangelands system, therefore, may be

best modelled using a stochastic dynamic programming model.[2]

After a lengthy gestation, dynamic optimisation methods have become accepted and useful tools for agricultural economists (Trapp 1989). Various authors, notably Kennedy (1986), have shown how dynamic programming is particularly useful in addressing the intertemporal nature of many resource management issues. With respect to land degradation and sustainable land use, however, most of the dynamic programming studies have focussed on crop land erosion problems (Burt 1981; Pope *et al.* 1983; McConnell 1983; and Stoneham 1991). Only a few dynamic programming studies have examined resource use and degradation of the rangelands (Karp and Pope 1984). The relative dearth of rangeland studies is especially pronounced in the Australian literature, with Wang and Lindner (1990) providing one of the few exceptions.

The focus on crop land degradation arises for several reasons. The degradation of prime quality crop land attracts considerable public concern and associated demands for policy responses to alleviate the problems. Conversely, the neglect of rangeland degradation in these studies may be attributable to a low social awareness of arid region problems. More importantly, however, much of the technical data needed to support dynamic programming analyses are more readily available in the case of crop land.

Furthermore, some analytical difficulties arise which complicate the examination of degradation on arid rangelands compared with that for crop lands. The latter analysis essentially involves a non-renewable resource problem as soil genesis occurs only on a geological time-scale and the costs of importing soil are largely prohibitive. However, the rangelands are a composite of both a non-renewable resource, soil, and a potentially renewable resource, pastures. In addition, most crop studies involve annual crops in which returns and costs are confined to a single production period. Only the soil resource carries over from one period to the next. Conversely, livestock are a capital input to the production system extending over more than one production period along

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[2] In some special cases, stochastic dynamic problems may be solved using a deterministic approach such as optimal control theory in association with a certainty equivalence theorem (Kennedy 1986). However, stochastic dynamic programming will often be the only suitable approach.

with the soil and pasture resources. Despite these added complexities, dynamic programming analysis of rangeland degradation is a worthwhile field of research endeavour. Accordingly, a stochastic dynamic programming model is developed in the following section as a basis for the empirical analysis in this paper.

The limitations of dynamic programming, however, must also be considered in analysing and - interpreting the results of such models. The data and computer memory constraints imposed by the so-called curse of dimensionality in dynamic programming models (Howitt 1982; Kennedy 1986) detract from their use as effective decision making tools by restricting the number of state and decision variables which describe the rangeland system.[3] The restricted number of variables can lead to a low sensitivity and lack of precision in outcomes. Although dynamic programming and related techniques serve as useful decision making aids in a number of areas (Trapp 1989), their use in guiding rangeland decisions is more contentious. Here, the variability of seasons, the frequency of drought and the fragility of the arid environment all call into question the usefulness of dynamic optimisation in the fine tuning of rangeland decisions. The simplicity of the decision making environment implicit in the stochastic dynamic programming model also restricts its use as a detailed rangeland management aid. However, the dimensionality and data problems may be less constraining from a policy analysis perspective.

The Model

At the beginning of each year, graziers are assumed to make decisions based on observations on the state of pasture and on their financial position. Expectations for price and climate will influence their decisions, along with their attitude to risk, planning horizon and management objectives. The decision chosen, along with the outcome of stochastic events such as rainfall,

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[3] For instance, Karp and Pope (1984) used only 12 stocking decisions to describe the range of options available to the user.

determine the state of the pasture and of their decision-making environment for the following year.

The decision process is formulated as a stochastic dynamic programming model with discrete time and an unbounded planning horizon. The model maximises the expected value of a stream of future stage returns subject to a state transformation equation and an initial level of the state variable, and is specified in the following manner:

$$(1) \quad \textit{Maximise} \quad E_0 \left[\sum_{t=1}^{\infty} a_t(x_t, u_t, k_t) i^t \right]$$

$$(2) \quad \textit{subject to:} \quad x_{t+1} = f(x_t, u_t, k_t) \qquad \textit{for all } t$$

$$(3) \qquad\qquad\qquad x_0 = X_0$$

where E_0 is the expectation operator at stage 0, t_0; and where $a_t(x_t, u_t, k_t)$ is the stage return function expressing annual returns as a function of the state variable, x_t, the decision variable, u_t, and the stochastic variable, k_t; i is the annual discount factor, $\{1/(1+r)\}$, with a real discount rate given by r; and $f(x_t, u_t, k_t)$ are the transformation equations which describe the determination of the state in the following period based on the current state, decision variables and stochastic variables; and X_0 represents the starting state at period t_0.

The state transformation equations were replaced by a transition probability matrix comprising probabilities of moving from state i in time $t-1$ to state j in time t given that decision u_i was chosen in period $t-1$. The matrix describes a Markov decision process with the outcome in period t dependent only on the state and decision chosen in the preceding period, $t-1$ and on the random variable k_t, and so does not require any knowledge of the system prior to the previous period.

The transition matrix and stage return functions remain the same for all decision stages, thus describing a stationary decision process.

The stochastic dynamic programming model generates optimal stocking rates and optimal net present values for each pasture biomass state. These net present values represent the discounted value of a future stream of rents or profits achieved by following optimal stocking rates for each pasture biomass state. The optimal net present values can then be used to derive shadow prices, or the marginal net present value of production realised from marginal increments in pasture biomass. Conversely, since they also measure the net present value of lost future returns from a marginal decline in biomass, the shadow prices are equivalent to user costs or scarcity rents (Fisher 1981). Mathematically, the shadow prices are the partial derivatives of the optimal net present value function with respect to the state variable. Among the other useful output of the stochastic dynamic programming model is the long-run or equilibrium probability distribution of pasture biomass states. This distribution provides insights into the potential for degradation by describing the pasture condition corresponding to the optimal set of stocking decisions.

The data requirements of the dynamic programming model[4] are by no means trivial, requiring time series data on a large number of not-readily-observable variables. Consider, for instance, the trial data needed to estimate the conditional probabilities of the transition matrix. In many cases, the information is not available in a primary form and has to be synthesised. In the following sections some of the data manipulations performed for some of the more important variables of the model are highlighted.

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[4]   The model was solved using Kennedy's *General Purpose Dynamic Programming* (GPDP) computer package (Kennedy 1989). The transition matrix and associated stage returns were calculated on a *SmartWare II* spreadsheet and written as a data file for analysis by GPDP. The analysis was conducted using an IBM compatible microcomputer with expanded memory. Solutions to most problems, once located into GPDP, were found in under 5 minutes. Full details of the model, along with the data needed to service the model, appear in Passmore and Brown (1991).

State and Decision variables

The dimensionality problems which plague dynamic programming studies (Burt 1981; Howitt 1982) imply that the selection of state and decision variables, along with the partitions for each variable, necessarily involves a trade-off between the requirement for an adequate description of the system and the need to make the problem tractable.[5] In the case of the mulga rangeland model, another major constraint to describing the system realistically is a lack of data on particular state and decision variables.

Pasture biomass was selected as the sole state variable as it provided the best indicator of rangeland condition. Basal area, or plant density, was also considered for inclusion as a state variable to indicate prolonged degradation, but was omitted due to the absence of data relating production to combinations of biomass and basal area. Pasture biomass was partitioned into 11 mutually exclusive intervals ranging from 0 to 2100 kg per hectare. The upper limit represented a maximum biomass level for destocked rangelands. To improve the sensitivity of the model to the more likely lower biomass ranges, the upper partitions were of unequal size.[6]

Stocking rate was chosen as the decision most likely to affect land condition in the mulga region. Data constraints restricted the number of partitions to seven, ranging from an average of 0.12 DSE per hectare to 0.76 DSE per hectare. Although the small number of partitions prevented the model from being used as a detailed decision making aid, it was sufficient for the purposes of this study, which was to examine the optimal responses of graziers to changes in economic and social parameters over time.

[5] Various techniques have been used to ease the dimensionality problems such as linear approximation between discrete values of the state and decision variables (Burt and Cummings 1977). In Kennedy's GPDP algorithm, linear interpolation is allowed for up to two state variables and two decision variables (Kennedy 1989).

[6] Specifically, pasture biomass between 0 and 899 kilograms per hectare was partitioned into 9 equal increments, with the remaining two partitions being from 900 to 1099 kg per hectare and from 1100 to 2100 kg per hectare. The notion of unequal partitioning of states is consistent with the approach adopted by Wang and Lindner (1990).

Transition matrix

Ideally, an historical series of observed states for given controls is required to generate the matrix of conditional probabilities. Due to the length of series required, the usual approach has been to use simulation models to generate the observations (Wang and Lindner 1990) or to use regression models applied to limited trial data (Van Kooten *et al.* 1990).

A hybrid of these two approaches was used in this study. It involved two stages. First, a series of observations on pasture biomass for each decision were derived from a simulation model developed by Meppem and Johnston (1990). The simulation model used technical trial data and 94 years of weather data from the mulga region and was adapted for use in this study. In the second stage, regressions of biomass on lagged biomass using a double-log functional form were then produced for each stocking rate decision, resulting in seven regression equations (Table 1). Probabilities for each combination of current state, previous state and decision were then derived from these regression equations using distribution theory. Specifically, in line with the approach of Van Kooten *et al.* (1990), each biomass state was first substituted into the regression equation to produce an estimate of the following state. Using these estimates, and the standard error of the estimate, the log-normal distribution[7] was integrated over each partition to produce a series of probabilities. The resulting matrix comprised 847 (11 current states x 11 previous states x 7 stocking rates) conditional probabilities. A more detailed description of the method along with the full transition matrix appear in Passmore and Brown (1991).

[Table 1 around here]

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[7] According to the simulation model of Meppem and Johnston (1990), the biomass states conformed to a log normal distribution.

Stage returns

The function used to derive stage returns, namely net property income after depreciation, rents, and an imputed value for family and operator labour, appears in Equation 4. Wool yield (or cut per head), price realised and stocking rate determine the gross value of production.

$$(4) \qquad R = (P \cdot Y \cdot S \cdot A) + O - VC - FC - SI$$

where R is the stage return ($); P is the wool price ($/kg clean); Y is the wool cut per head (kg clean/DSE); S is the stocking rate (DSE/ha); A is the area (hectares); O is other income ($); VC is total variable costs ($); FC is total fixed costs ($); and SI are stock adjustment and inventory costs ($).

Stage returns were estimated for each combination of pasture state and decision. Pasture biomass and stocking rate directly affect wool cut per head, and by influencing wool fibre diameter, determine the grazier's wool price received. The curvilinear relationships between wool productivity and the principal factors which affect feed available per DSE, namely stocking rate and pasture biomass, were modelled using a log linear regression equation (Table 1) based on data from a mulga stocking trial (Beale 1985). As expected, wool yields rose with increases in available biomass and fell as stocking rate was increased. The average wool cut per head over all combinations of pasture biomass and decisions was consistent with observed wool yields.

The combined influence of pasture biomass and stocking rate determines wool fibre diameter, the major indicator of wool quality. Feed deficiencies generally result in finer wool, the so called fine wool effect (Australian Conservation Foundation, 1991). As low fleece weights are also associated with feed deficiencies, fibre diameter is positively correlated to fleece weight. Thus, a combination of high pasture biomass and low stocking rate produces coarser wool. Trial data

from the mulga region (Beale 1985) revealed that fibre diameter increased by 2.1 microns for each one kilogram increase in clean fleece weight (Table 1). The estimated wool fibre diameter was then used to arrive at wool prices corresponding to each combination of pasture biomass and stocking rate. For each fibre diameter range, an average of historical wool prices was used in determining stage returns. The non-linear relationship between wool quality and price was incorporated using a double log regression of price on fibre diameter (Table 1).

An economic survey of 47 mulga rangeland graziers (Passmore 1990) provided most of the variable and fixed costs used in deriving the stage returns. Variable production costs consisted of the costs of shearing, hired labour and materials. Shearing costs remained at around $2.34 per DSE regardless of flock size. Hired labour costs per DSE were generally unchanged for flock sizes up to 12500 DSEs and increased thereafter. Conversely, material costs per DSE declined steadily as flock size increased. Operator and family labour costs were imputed from Queensland award rates, while depreciation was derived from taxation depreciation rates and estimated asset values provided by graziers in the survey.

Wool marketing charges were based on Gabry and Mercader's (1988) summary of charges, with some modifications for Queensland such as adjustments to freight and interlotting costs. At the time of the analysis (second half of 1990), a wool tax of 18 per cent applied. Various sensitivity tests were undertaken to examine the effect of alternative levels of wool price.

One challenging aspect of the data collection involved the estimation of the costs of stock losses and stock transfers which were expected to be related to stocking rate and pasture biomass. In the absence of trial data on stock mortalities, a surrogate procedure was required. In line with Australian Bureau of Statistics data, a base mortality rate of 4 per cent was imposed, reflecting the best outcome. To account for progressively worse seasonal conditions, stock losses were estimated on the basis of feed deficiency and on the cost of providing supplementary feed. For the mulga rangelands, this includes the labour and machinery costs of cutting mulga top-feed. The costs of stock adjustment between seasons were estimated as an average for each stocking rate using

simulation data. These costs recognise the freight costs and the losses associated with forced de-stocking. For higher stocking rates over time, these costs tended to be higher.

Results

Base model

The effects of property size, wool price, discount rate and risk attitudes on rangeland decisions and condition were analysed by assessing the divergence in optimal stocking rates and values, shadow prices and the likelihood of equilibrium pasture states from those observed in a base model. The base model used financial data for properties representative of the region, namely those properties which fell in a 35,000 hectare size group[*] (Passmore 1990). Wool prices were based on a historical average for the period 1974-75 to 1989-90 and were expressed in 1987-88 dollars. For the median 22 micron wool category, this represented a price of 829c/kg clean. A real discount rate of 5 per cent applied while profit maximisation was assumed.

Optimal stocking rates for the base model appear in Table 2. A positive correlation arises between optimal stocking rates and pasture biomass. The highest stocking rate (0.76 DSE/ha), however, does not occur in the optimal solution due to its severe impact on the regenerative ability of the pasture.

[Table 2 and Table 3 around here]

The optimal net present values from following the optimal stocking rates for the base model increase with higher levels of biomass, though at a declining rate (Table 3). For instance, the values range from $21/ha at 50kg/ha of biomass to more than $36/ha at 1600 kg/ha of biomass. Since land prices are equivalent to the present value of future after tax rents in the absence of land

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[*] The 35,000 ha size group encompassed properties ranging in size from 30,000 ha to 40,000 ha. Other property size groups used in the analysis were 15,000 ha (10,000ha to 20,000 ha), 25,000 ha (20,000 ha to 30,000 ha) and 45,000 ha (40,000 ha to 50,000 ha).

market imperfections (Barlowe 1978) and expections for real capital gains, the optimal net present values represent a set of maximum bid prices for the purchaser where wool price expectations and discount rates are in line with those assumed. Interestingly, the net present values listed in Column 2 of Table 3 are remarkably consistent with annual average land prices in the eastern mulga over the last decade which have ranged from $13/ha to $34/ha in 1987-88 dollars.

Related to the optimal net present values are the shadow prices (or user costs) which represent the marginal return (cost) from a unit increase (decrease) in biomass. These shadow prices, graphically depicted in Figure 3, declined from 4.23c/kg biomass at a biomass level of 50kg/ha to only 0.35c/kg at 1600 kg/ha. At low biomass levels, an additional unit of resource use incurs a higher user cost due to the greater probability that the pasture will suffer reduced regenerative ability and possibly irreversible damage. The estimated shadow prices in Figure 3 are broadly consistent with those of Wang and Lindner (1990) for the Western Australian mulga zone despite some differences in mode' structure, parameters and data.[9]

The long term distribution of equilibrium pasture condition corresponding to the optimal stocking strategy for the base model appears in Figure 4. The distribution is positively skewed with a modal pasture biomass state of 300-399kg/ha.

[Figure 3 and Figure 4 around here]

FIGURE 3 - Impact of Wool Prices and Discount Rates on the Shadow Price of Pasture Biomass[*]

[*] For a description of the base model and alternative specifications, see footnotes to Table 2.

FIGURE 4 - Impact of Wool Prices and Property Size on the Probability Distribution of Equilibrium Pasture States[*]

[*] For a description of the base model and alternative specifications, see footnotes to Table 2.

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[9] Specifically, Wang and Lindner's estimates of shadow prices ranged from 0 to 4.5c/kg of biomass.

Property size

Property size is a contentious issue both in research into causes of rangeland degradation and in the likely impact of various policies. To further investigate these issues, dynamic programming models involving a range of property sizes were compared with the base model to examine the effect of property size on the optimal decisions of graziers. The results of these comparisons appear in Table 2, Table 3 and Figure 4.[10]

Analysis of property size and optimal stocking rates revealed a trade-off between flock size economies and the long-term costs of land degradation. Optimal stocking rates tended to be lower on larger properties (Table 2), reflecting their greater capacity to take advantage of economies in flock size at lower average stocking rates. Conversely, it is optimal for smaller properties to adopt higher stocking rates, as the gains in cost economies compensate for foregone rents arising from land degradation. Hence, property size is an important factor in resource use decisions where profit maximisation is the goal. This observation contrasts with that of McArthur and Dillon (1971) who claimed that property size had no influence on optimal stocking rates under profit maximisation, with any such correlations being explained by risk aversion. The different observations primarily reflect the static nature of the McArthur and Dillon model and its inability to account for the key dynamic elements of the problem.

The optimal net present values reported in Table 3 emphasize the importance of property size in terms of long-run viability. Properties in the 15,000 hectare group realised negative net present values at most biomass levels despite their higher optimal stocking rates. The results suggest, *ceteris paribus*, that intending buyers should be willing to bid higher prices per hectare for the larger properties. Of course, exceptions arise for smaller properties purchased for property build-

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[10] Only results for an upper bound (45,000 ha) and lower bound (15,000 ha) for property size in the analysis are reported in the various tables and graphs. Other property sizes were examined to investigate the response surface, but generally were found to be consistent with the outcomes for the upper and lower bounds. Similar considerations apply to the sensitivity analysis for wool price, discount rate and the level of risk aversion.

up, more improved properties or those which feature a greater proportion of productive land types such as river frontage.

The countervailing effects of flock size economies and the costs of degradation resulted in only minor variations in shadow prices across property sizes. The expected lower shadow prices arising from the lower stocking rates on larger properties were inflated by the lower unit costs of production achieved through flock size economies. Conversely, higher production costs on smaller properties partly offset the effect of high stocking rates on the present value of foregone rents. Consequently, shadow prices for smaller holdings were only around 5 per cent to 8 per cent higher than those for larger holdings at most biomass levels.[11] Hence, shadow prices for various property sizes mimic those for the base model as reported in Figure 3.

The long-run probability distributions of Figure 4 reveal the benefits of larger property sizes in terms of pasture condition. Pasture condition for smaller holdings follows a more positively skewed distribution with a modal state in the 200-299 kg/ha range, compared to a modal range of 400-499 kg/ha for the largest holdings. Alternatively, the probability of realising a biomass under 300 kg/ha was 26.8 per cent for the smaller holding compared to only 11 per cent for the larger holding.

The results of the dynamic programming analysis vindicate the emphasis of recent policy initiatives on property build-up to reverse the effects of decades of sub-division. Despite widespread recognition of the degradation problem, the analysis reveals that it is in fact economically optimal for exploitive grazing strategies to be adopted on smaller properties. Short-term gains from flock size economies appear to offset pasture productivity losses caused by heavy grazing.

Various policy options to date have focussed on accelerating or removing impediments to the natural process of property build-up (Australian Conservation Foundation 1991; Mills *et al.*

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[11] For example, at a pasture biomass of 50kg/ha, shadow prices for the small and large properties ranged from 4.47c/kg to 4.19c/kg respectively.

1989). Suggestions have included streamlining of tenure arrangements, government acquisition of properties and supervision of property transfers. However, land reform also warrants further consideration of the pace of those changes relative to the ongoing process of degradation.

Wool prices and quality differentials

How robust are the results of the base model given they are based on average wool prices? The suspension of the reserve price scheme in 1991 triggered a dramatic fall in wool prices. Even under the reserve price scheme, wool prices were subject to marked fluctuations between seasons. An analysis of wool price variation on optimal rangeland decisions was made using wool prices 20 per cent above and 40 per cent below those used in the base model. For 22 micron wool this represented average gross prices of 1000c/kg clean and 500c/kg clean respectively.

Optimal stocking rates fell significantly with a relative decline in wool prices (Table 2). The lower stocking rates were accompanied by improved long term pasture conditions with a modal pasture biomass state of 500-599 kg/ha under the low price scenario compared to a modal state of only 300-399 kg/ha at the high price (Figure 4). For the profit maximising case, this outcome is primarily explained by the fine wool effect in which higher stocking rates are associated with finer, higher value wool and by the non-linear relationship which exists between wool quality and price.

The potential significance of the fine wool effect highlighted by the dynamic model warrants further attention, namely to ascertain the extent to which graziers recognise and plan for it in their management. According to the Australian Conservation Foundation (1991), although an economic incentive exists for using mulga top feed to support a heavy grazing strategy, the policy is not sustainable. Moreover, such a management approach raises animal welfare concerns. A more sustainable approach to fine wool production involves a combination of selective breeding and careful fodder management. These observations are supported by the results of an economic

survey of graziers (Passmore 1990) in which none of the respondents attributed their stocking policy to fine wool incentives. Overwhelmingly, graziers nominated property size and financial constraints as the reasons for high stocking strategies.

Optimal net present values are extremely sensitive to wool prices (Table 3). Even a slight change in buyers' expectations about wool prices may significantly affect the land price, *ceteris paribus*. For example, at real wool prices around 15 per cent higher than those used in the base model the present value of future rents almost doubles. For price expectations below 650c/kg clean for 22 micron wool (20 per cent below the prices used in the base model) the present value of future rents becomes negative at most pasture states. Similarly, shadow prices for pasture biomass responded markedly to a change in wool prices. At a biomass state of 50kg/ha, shadow prices ranged from almost 6c/kg at high wool prices to only 1.5c/kg at low prices (Figure 3).

Discount rate

The discount rate provides a means of weighting present or near-term cash flows relative to future long-term flows. As the discount rate rises, the present value of all future cash flows declines. With renewable resources, the rate of discount influences the rate of utilisation. Generally, a high discount rate implies a greater rate of immediate utilisation with the subsequent potential for land degradation. Myopia or selfishness on the part of current generations is often used to explain the apparent higher discount rate implicit in individual decisions compared with those of society (Kirby and Blyth 1987).

Although the divergence between social and private rates, albeit unquantified, may explain the process of degradation in general, it does not explain the different rates of degradation between individual properties. Here, the source of divergence in private discount rates between individual graziers is of concern. Such divergences may be attributable to debt and other financial pressures, risk, ownership intentions, stage of life and planning horizon.

The pressure of debt or domestic costs, such as education costs, forces many graziers to adopt a short term perspective which is revealed in a high discount rate. Alternatively, conservation minded graziers with a long term planning horizon may exhibit a discount rate close to zero. In this analysis, upper and lower bounds on real discount rates of 15 per cent and 0.1 per cent[12] respectively were used to explore the impact of discount rates on optimal rangeland decisions.

As expected, optimal stocking rates were positively related to the discount rate (Table 2). However, the effect was most noticeable for biomass levels below 500 kg/ha. The lower biomass pastures incur a greater risk of degradation, forcing lower stocking rates into the optimal decision set in order to maximise long-term profits. Conversely, at higher biomass levels, the greater regenerative capability of the pasture offsets the effect of the discount rate.

Optimal net present values varied markedly to different discount rates (Table 3). Not only were the net present values lower at the higher discount rate, but they also varied widely across pasture biomass levels. At a discount rate of 15 per cent, for example, the optimal net present values varied from $2.89/ha to $16.24/ha compared with $20.83/ha to $36.58/ha for a discount rate of 5 per cent. Generally, graziers with the lowest discount rate will be inclined to bid the most for land. Shadow prices, reflecting a type of intertemporal opportunity cost, also responded markedly to discount rate (Figure 3). A low or zero discount rate inflates the present value of foregone future benefits from an additional unit of current resource use. Shadow prices at a biomass state of 50kg/ha, for example, increased from 3.2c/kg at a 15 per cent discount rate to 5c/kg at 0.1 per cent discount rate.

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[12] The solution algorithm used in GPDP does not give a solution for a zero discount rate for the infinite-stage problem. Accordingly, a rate of 0.1 per cent was used to approximate the effects of a zero discount rate.

Risk attitudes

The results presented above were based on a profit maximising model assuming risk indifference. However, alternative attitudes to risk by graziers are likely to influence their stocking decisions (McArthur and Dillon 1971). For instance, income uncertainty due to climatic factors may force risk averse graziers to adopt lighter stocking rates so as to reduce the impact of drought, while wool price uncertainty may encourage the risk averse grazier to increase stocking rates to extenuate the impact of lower wool prices.

One way of examining the behaviour of optimal stocking rates in a utility maximising framework involved replacing the stage returns of the base model with utility values derived from a utility function.[13] A form of utility function commonly used in empirical analysis (Anderson and Griffiths 1982), including dynamic programming analysis of rangeland degradation (Karp and Pope 1984), is the negative exponential function, namely:

$$(5) \qquad U(x) = (-\frac{1}{a}) e^{-ax}$$

where x is the stage return; $U(x)$ is the utility associated with stage return x; and a is the coefficient of risk aversion. The negative exponential function has an infinite domain and produces utility values asymptotic to zero. Despite graziers operating in an inherently risky environment, it is commonly accepted that they are risk averse when facing significant financial choices (Bardsley and Harris 1987; Anderson *et al.* 1977). The initial risk aversion coefficient for the negative exponential function ($a = -0.00005$) was selected so that the maximum possible monetary

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[13] Kennedy (1986) notes that the discount rate for discounting utility is not necessarily the same as the rate for discounting monetary values. To consider this problem, an alternative approach involves converting the stage utility function to its monetary equivalent using the inverse of Equation (5) and discounting the monetary equivalents at the appropriate rate of discount. For this problem, however, use of the alternative approach did not alter the optimal stocking rates or the long term distribution of equilibrium pasture condition.

outcome coincided with a zero utility value. The effect of a reduced degree of risk aversion was examined by increasing the coefficient to -0.00003.

A comparison of optimal stocking rates for the typical 35,000 hectare property under different assumptions about the risk attitudes of graziers appears in Table 2. Optimal stocking rates fell markedly with increasing risk aversion. The effect was most pronounced at higher biomass levels, producing a much more uniform optimal decision set across biomass levels for the risk averse scenarios. The risk averse grazier seemingly maximises utility by consistent conservative stocking, thereby reducing the probability of low biomass states and negative returns in the long term. That is, the risk of sto k loss, climatic variability and degradation effectively forces the adoption of lower stocking rates to minimise disutility.

There are several useful extensions to the utility maximising model. One extension involves allowing for the variance of wool prices to be taken into account in determining stage utility. Another involves using the utility maximising model to analyse the effects of financial pressure and debt on optimal stocking rates. As mentioned previously, a greater degree of risk aversion seemingly results in lower optimal stocking rates (Table 2). Hence, graziers in financial difficulties may seek to maximise stocking rates and short-term profits at the possible expense of the long-term condition of the pasture and the income streams that can be generated from them. Conversely, the grazier without pressing financial commitments, *ceteris paribus*, may well adopt a more risk averse stance by conserving the pasture in the immediate term so as to avoid potentially disastrous outcomes at some future time. The effects just described are supported by the positive correlation between debt pressure and stocking rates observed by Passmore (1990). Further analysis using the utility maximising model may shed additional insights on the important and topical issue of financial pressures and stocking rates.

Concluding Remarks

Solutions to the complex issues of arid rangeland degradation lie in the broad context of improved information, more appropriate institutions and a change in individual and social attitudes. However, dynamic programming can contribute to this process by providing some useful insights into the incentives or constraints which may lead graziers to high stocking strategies and to subsequent degradation of the rangelands. A more thorough understanding of these underlying incentives may lead to more sustainable solutions to the degradation problem. Most importantly, rangeland resource policies should target these underlying causes rather than the symptoms of the problem.

The dominant concern in the mulga rangelands is the constraint on management imposed by small property sizes, a problem also identified in other studies (Warrego Grazier's Association 1988; Mills 1989; Passmore 1990; Australian Conservation Foundation 1991). Policies to encourage property build-up should not only focus on more active government intervention and control, but also confront impediments to the natural process of adjustment. For example, previous policies of direct assistance, concessional finance and taxation incentives have prolonged the survival of smaller properties and promoted unsustainable resource use practices. Improved information on carrying capacity and living area standards is however, a prerequisite for the formulation of an effective property build-up policy.

While property size emerges as the main target for policy, other factors such as wool prices, discount rates and risk attitudes cannot be overlooked. Depending on the individual grazier's management philosophy, these factors may intervene to diminish the benefits from a policy of property restructuring. Moreover, the short-term pay-off from the fine wool effect may induce opportunistic graziers to adopt higher stocking rates. The complication of these and other incentives makes it essential that policy-makers recognise the heterogeneity of grazing properties, their land types, economic circumstances and management.

While dynamic programming can provide useful insights into the intertemporal nature of the rangeland system, its use as a decision making model may be more limited. Although computational limits are a key constraint, part of the problem lies in the lack of technical data needed to service these models. As greater research effort is now being devoted to uncovering more information about rangelands and rangeland degradation, it is important that the appropriate types of technical and economic information be sought. Dynamic programming analysis can aid those efforts by highlighting the relevant information required to make more informed decisions.

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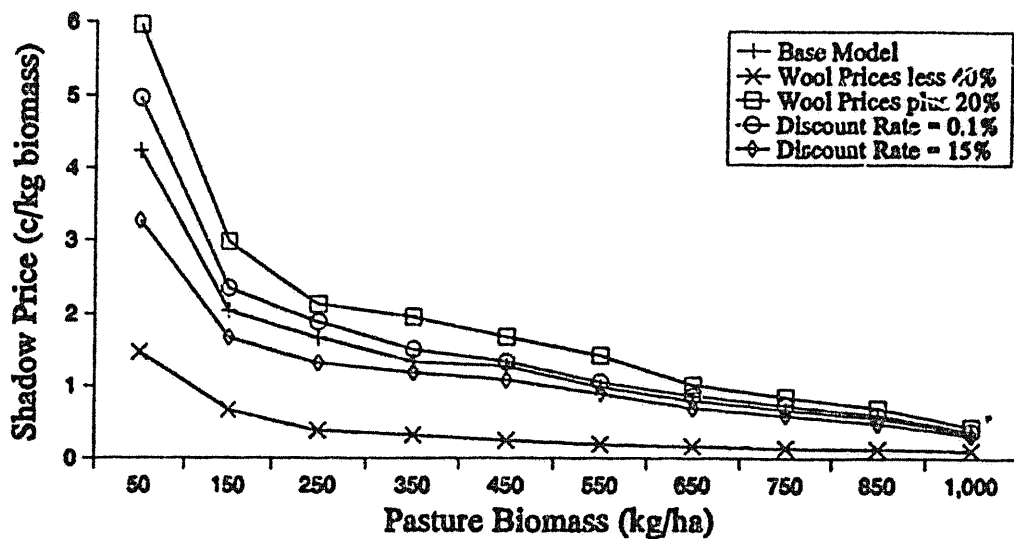
FIGURE 3 - Impact of Wool Prices and Discount Rates on the Shadow Price* of Pasture Biomass.

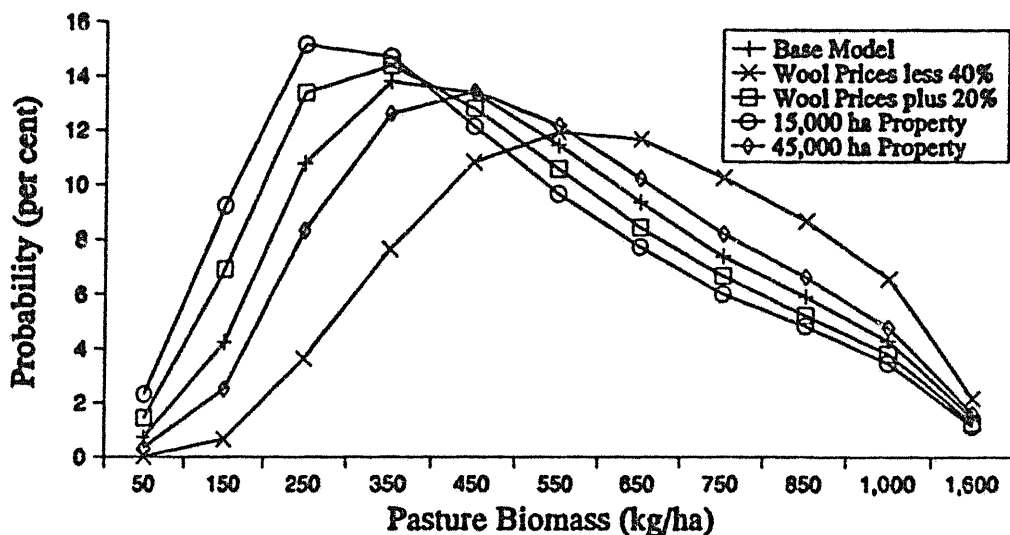* For a description of the base model and alternative specifications, see footnotes to Table 2.

FIGURE 4 - Impact of Wool Prices and Property Size on the Probability Distribution of Equilibrium Pasture States*

* For a description of the base model and alternative specifications, see footnotes to Table 2.

TABLE 2

The Impact of Property Size, Wool Price Variations, Discount Rates and Risk Aversion on Optimal Stocking Rates (DSE/ha)

Pasture biomass (kg/ha)	Base Model[a]	Property size (ha)		Wool prices[b]		Discount rate		Risk aversion[c]	
		15,000	45,000	-40%	+20%	0.1%	15%	-.00003	-.00005
50	.18	.12	.18	.12	.18	.12	.18	.18	.18
150	.24	.18	.18	.12	.24	.12	.24	.24	.24
250	.24	.48	.18	.12	.36	.12	.36	.36	.36
350	.24	.48	.18	.18	.36	.18	.36	.36	.36
450	.48	.56	.36	.18	.48	.18	.48	.36	.36
550	.48	.56	.36	.24	.48	.48	.48	.48	.36
650	.56	.56	.48	.24	.56	.56	.56	.48	.36
750	.56	.56	.48	.24	.56	.56	.56	.48	.36
850	.56	.56	.56	.24	.56	.56	.56	.48	.36
1000	.56	.56	.56	.36	.56	.56	.56	.48	.36
1600	.56	.56	.56	.56	.56	.56	.76	.48	.36

[a] Base model describes a 35,000 hectare property and assumes clean wool prices in cents per kilogram of 698, 741, 782, 829, 883, 964 and 1088 for wools with fibre diameter of 25 through 19 microns. A real discount rate of 5% was used.
[b] Wool prices are 40% below and 20% above those stated in footnote (a).
[c] The degree of risk aversion is indicated by the a-coefficients from a negative exponential utility function (equation 6).

TABLE 3

The Impact of Property Size, Wool Price Variations and Discount Rates on Optimal Net Present Values ($/hectare)

Pasture biomass (kg/ha)	Base Model[a]	Property size (ha)		Wool prices[b]		Discount rate[c]
		15,000	45,000	-40%	+20%	15%
50	20.83	-13.46	31.39	-28.2	51.63	2.89
150	25.07	-9.00	35.58	-26.7	57.53	6.17
250	27.10	-6.68	37.59	-26.1	60.57	7.84
350	28.77	-4.97	39.29	-25.7	62.68	9.15
450	29.93	-3.70	40.43	-25.3	64.63	10.33
550	31.20	-2.31	41.58	-25.1	66.31	11.41
650	32.19	-1.36	42.70	-24.9	67.73	12.31
750	32.98	-0.52	43.48	-24.7	68.74	13.00
850	33.66	0.20	44.22	-24.6	69.59	13.60
1000	34.49	1.14	45.12	-24.4	70.67	14.32
1600	36.58	3.31	47.18	-23.8	73.21	16.24

[a] See footnote [a] to Table 2.
[b] See footnote [b] to Table 2.
[c] Since optimal net present values approach infinity as the discount rate nears zero, optimal net present values at a discount rate 0.1% are omitted from the table.

TABLE 1

Regressions Used in Determining the Transition Matrix and for Estimating Stage Returns[a]

Transition matrix regressions:

-: SR = 0.12 DSE/ha:

$\ln (Bt) =$ | 1.5397 | + 0.7932 ln (Bt-1) | Adjusted R^2 = 0.67
 | (2.06*) | (6.54*) | SEE = 0.406

-: SR = 0.18 DSE/ha:

$\ln (Bt) =$ | 1.99 | + 0.711 ln (Bt-1) | Adjusted R^2 = 0.61
 | (3.80*) | (8.79*) | SEE = 0.410

-: SR = 0.24 DSE/ha

$\ln (Bt) =$ | 1.5746 | + 0.7654 ln (Bt-1) | Adjusted R^2 = 0.60
 | (3.57*) | (11.75*) | SEE = 0.397

-: SR = 0.36 DSE/ha

$\ln (Bt) =$ | 1.5402 | + 0.7641 ln (Bt-1) | Adjusted R^2 = 0.59
 | (3.18*) | (11.72*) | SEE = 0.450

-: SR = 0.48 DSE/ha

$\ln (Bt) =$ | 1.5103 | + 0.7618 ln (Bt-1) | Adjusted R^2 = 0.59
 | (3.59*) | (11.63*) | SEE = 0.416

-: SR = 0.56 DSE/ha

$\ln (Bt) =$ | 1.5633 | + 0.7488 ln (Rt-1) | Adjusted R^2 = 0.57
 | (3.70*) | (11.20*) | SEE = 0.519

-: SR = 0.76 DSE/ha

$\ln (Bt) =$ | 2.1845 | + 0.6274 ln (Bt-1) | Adjusted R^2 = 0.40
 | (4.66*) | (7.97*) | SEE = 0.661

Wool cut per head (CPH)[b]

CPHt = -1.0824 | + 0.4262 ln (Bt) | - 1.2073 ln (SRt) | Adjusted R^2 = 0.81
 (-1.12) | (10.39*) | (9.68*) | SEE = 0.731

Fibre diameter (M)

Mt = 15.6517 | + 2.1277 CPHt | Adjusted R^2 = 0.78
 (20.49*) | (8.06*) | SEE = 0.67

Wool price (P)

$\ln (Pt) =$ 11.5378 | - 1.554 ln (Mt) | Adjusted R^2 = 0.98
 (45.02*) | (-18.72*) | SEE = 0.0201

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[a] Variables used in the equations are stocking rate (SR); pasture biomass (B); wool cut per head (CPH); wool fibre diameter (M); and wool price (P). The subscript t denotes the current year and t-1 the previous year. SEE is an acronym for standard error of the estimate. All t-statistics are given in parentheses below each coefficient, and significance at the 5% level is identified by the asterisk, *.

[b] Wool cut per head was estimated using a full-time autoregressive and cross-sectionally heteroscedastic model (Kmenta 1971).
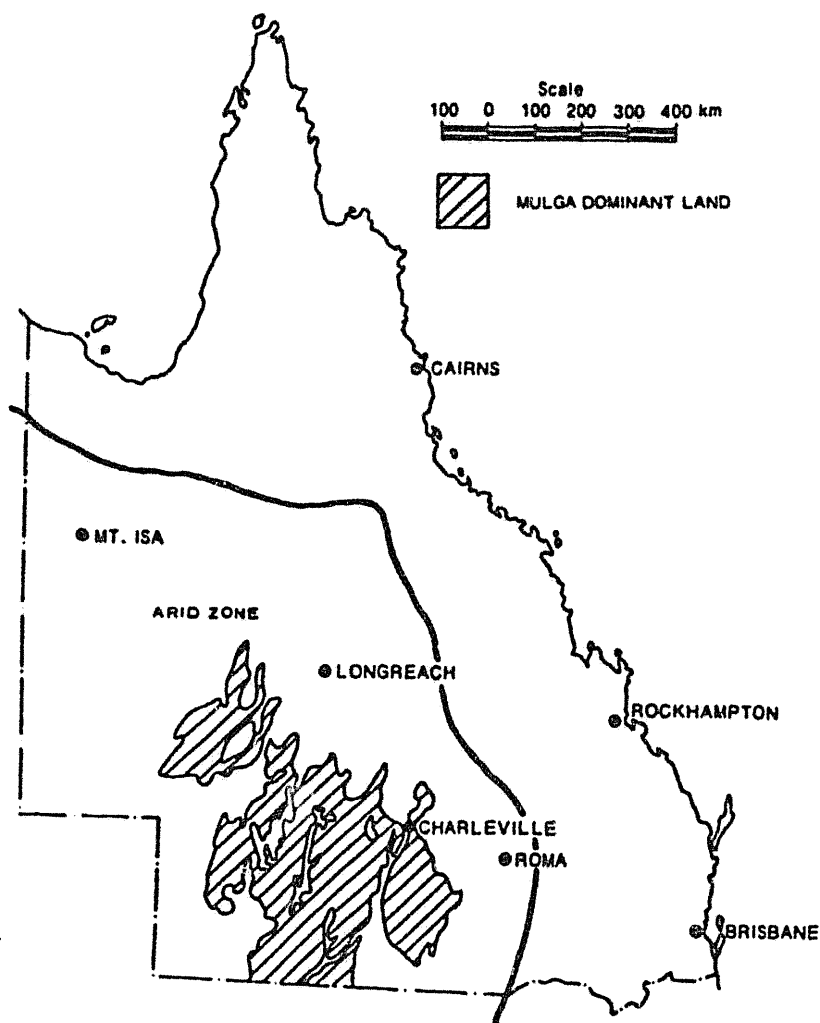
FIGURE 1 - Location of the Mulga Rangelands in Queensland's Arid Zone.
Source: Mills, 1989
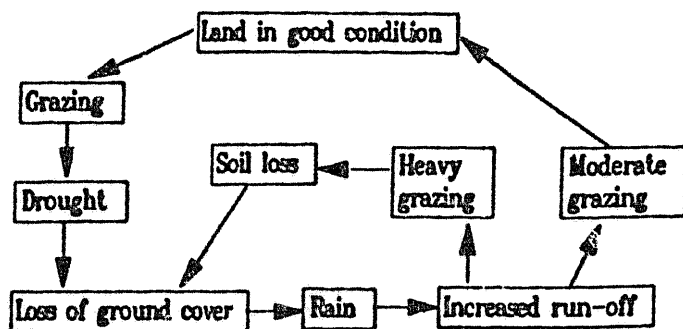
FIGURE 2. The Land Degradation Cycle.
Source: Mills, 1989