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Two modelling approaches to determine the effect of sheep grazing on the sustainability of long lived native trees species in arid Australia

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Abstract: Populations of some native trees and shrubs have been declining in the arid rangelands of southern Australia due to grazing by herbivores, particularly sheep and rabbits. These reduced levels of regeneration are responsible for the gradual alteration of the composition and overall cover of vegetation. In the long term, this could result in a loss of palatable species considered valuable to the pastoral industry for animal production. Previous research has investigated the effect of sheep grazing on native arid land plant species in Australia, using Matrix Population Models (MPMs). The study was undertaken using a focus species, *Myoporum platycarpum*, which is a long lived tree species found in the chenopod shrublands of southern Australia. The results of the MPMs suggest that only with higher than average rainfall for extended periods will the *M. platycarpum* survive under grazing. In this paper, we describe the MPM model and its outcomes and also the alternative approach to the investigation of the effects of sheep grazing using a system dynamics approach. The motivation of the MPM study was based upon the need of arid rangeland graziers to assess alternative management practices in order to improve their ability to be both financially and environmentally sustainable. The system dynamics model again uses *M. platycarpum* as the focus species, it being assumed that the sustainability of the *M. platycarpum* population can be used as an indicator for the sustainability of the overall ecosystem. In the system dynamics model, existing and alternative land use practices are evaluated for three different scenarios in order to answer the following research questions: 1. 'What is the effect of alternative land use practices on the long term development of the ecosystems in the shrub land areas of southern Australia?' and 2. 'Which of these land use practices would be optimal to attain an ecologically and economically sustainable shrub land ecosystem in eastern South Australia?' The results of the system dynamics study show that the current land use practices are potentially unsustainable. It was found that three factors directly influence the population dynamics of the *M. platycarpum* population: presence of sheep, distance to water points, and rainfall. The system dynamics model was used to investigate three different grazing regimes: sheep enclosures, additional watering points, and a rotational grazing system, and found that rotationally grazing the sheep was by far the best alternative.

To investigate the effects of grazing, an MPM was developed to project the long term survival rate of a focus species, *M. platycarpum*, under grazing and non-grazing regimes. For simplicity, we assume that the sustainability of the *M. platycarpum* population can be used as an indicator for the sustainability of the overall ecosystem. The technique applied is an extension of the Leslie growth model (Leslie, 1948), where the vital rates are linked to random rainfall events and deterministic grazing. The effect of grazing is incorporated into the model based upon data primarily collected from the TGB Osborn Koonamore Vegetation Reserve, 400 km north of Adelaide in South Australia within and without a long established sheep exclosure. The results suggest that only with higher than average rainfall for extended periods will the species of interest, *M. platycarpum,* survive under grazing, without adopting alternative management practices. The second study proposes alternative management practices. The results of the system dynamics study also shows that existing land use practices are potentially unsustainable. The grazing process causes steep drops in the population of *M. platycarpum* and in some cases even leads to the extinction of the population. It was found that three factors directly influence the population dynamics of the *M. platycarpum* population: presence of sheep; distance to water points; and rainfall. Three alternative land use practices were investigated and the effect of each alternative land use practice is compared to the non-grazing scenario. This paper describes the results obtained from both studies.

Keywords: *herbivore grazing; Myoporum playtycarpum; matrix population models; system dynamics*

1. INTRODUCTION

1.1. Background

Approximately 85% of the land area of South Australia is covered by semi-arid and arid rangelands. For many decades, these rangelands provided the most important food source for native and introduced herbivores in the region. The grazing of the introduced species, such as sheep and rabbits, in particular contributed to the changed conditions of the natural resources in the area. The South Australian Rangelands Integrated Natural Resources Management Group (Rangelands INRM Group), based in Port Augusta, is responsible for the Natural Resource Management (NRM) of the South Australian rangelands. They have demonstrated that unmanaged grazing pressure is one of the major causes of degradation of the South Australian rangelands. Continuous grazing during prolonged periods of drought, in particular, is believed to be destructive, since the already weakened ecosystem must then endure more pressure, Rangelands (INRM, 2004). Although the precise consequences of grazing by sheep and other herbivores are yet unknown, it is believed that the continuation of the current grazing patterns of continuous grazing, will be unsustainable in the long term. This scenario would be incompatible with the vision of the Rangelands INRM Group proposed for the South Australian rangelands: “An environmentally, economically and culturally sustainable Rangelands Region that is recognised as supporting a diversity of land uses important to national prosperity and growth." (INRM, 2004).

The impact of grazing on the long term sustainability of arid zone trees and shrubs has been a topic of research for some time. Work by Crisp and Lange (1976), Crisp (1978), Graetz (1978), Harrington (1979), Lange and Willcocks, (1980), Silander (1983), Chesterfield and Parsons (1985), and more recently, Auld (1990, 1995) and Tiver and Andrew (1997), among others, has indicated that the long term survival of some species of native flora is at risk. In a study by McArthur et al. (2006) matrix population models (MPMs) were used to investigate the long term prospects for the species *M. platycarpum* under sheep grazing. A subsequent study by the authors used system dynamics models to propose sustainable grazing regimes.

M. platycarpum is found in the chenopod shrublands of southern Australia, mostly on pastoral land. Photographic and anecdotal evidence shows that individual plants live for up to 150 years, and that pre-European individuals still survive. The current populations are primarily dominated by geriatric individuals, with significant cohorts of younger individuals believed to have been generated from successive large rainfall events in the mid 1970s and again in the early 1990s. Chesterfield and Parsons (1985), discuss the phenomenon for the series of abnormally wet years in the 1950s and 1970s, (see McArthur et al. 2006).

The native vegetation in arid lands provides the sustenance for the livestock – mainly sheep – that comprise the local pastoral industry. The environmental sustainability of herbivore grazing on the chenopod shrub lands has been researched by Tiver and Kiermeier (2006), who showed that sheep, in particular, affect the regeneration of shrubs and trees in southern Australia. This is due to their close grazing habit. It is therefore anticipated that an alternative to the existing land use practices will be required in order to achieve environmental and economical sustainability in these areas.

1.2. Focus Species

The data for this study were collected by Tiver and Andrew (1997) from sites both within and outside the sheep exclosure at Koonamore Station and from several other sites throughout South Australia. Koonamore Station lies approximately 400 km north of Adelaide in South Australia. The Koonamore Reserve was established by T.G.B. Osborn in 1929 (Osborn et al., 1935) with the primary objective of studying the recovery of vegetation after overgrazing. The Reserve thus provides an ideal site for studying the regeneration of native flora in an environment ungrazed by livestock for 80 years.

2. MATRIX POPULATION MODEL

2.1. Method

Matrix Population Models (MPMs) (Caswell 2001) were developed to determine the effects of sheep grazing and rainfall on the long-lived tree species *M. platycarpum.* The details of this study can be found in McArthur et al. (2006). The general population model is given by equation (1) and the population after $t = k$ time steps is given by equation (2):

$$x(t+1) = Ax(t), \quad (1) \qquad\qquad x(k) = A^k x(0), \quad (2)$$

$$A = \begin{bmatrix} S_1 & F_2 & \cdots & F_{n-1} & F_n \\ P_1 & S_2 & \cdots & 0 & 0 \\ 0 & P_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & P_{n-1} & S_n \end{bmatrix} \quad (3)$$

where $x(0)$ is the initial $n \times 1$ population vector and $x(t)$ is the $n \times 1$ population vector at time t, consisting of the number of individuals in each of the n age classes.

The projection matrix A, given by equation (3), consists of entries which represent the fecundity and survival rates of individuals of different stages. At each iteration, each individual either remains in the same stage or proceeds to the next (Getz and Haight, 1989). The parameters F_i, S_i and P_i refer to the fertility of stage i, the probability of an individual in stage i surviving and staying in stage i, and surviving and progressing to stage $i+1$, respectively.

The matrix entries are collectively known as the vital rates and can take the following values:

$F_i > 0, 0 \leq S_i \leq 1 \text{ and } 0 \leq P_i \leq 1, \forall i = 1,2,\ldots,n$ where n is the number of stage classes. Figure 1 shows the life cycle graph for *M. platycarpum.*

The vital rates are expressed as functions of rainfall, (Mode and Root 1988) and are estimated using a combination of anecdotal evidence, experimental data, and historical and photographic documentation. The details are discussed at length in McArthur et al. (2006).

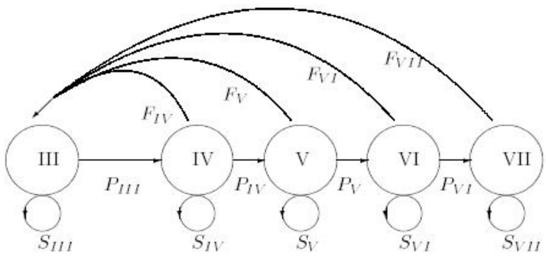

Figure 1. The life cycle graph for *M. platycarpum*. See Tables 1 and 2 for the definition of the notation.

Tiver and Andrew (1997) describe the stage distribution of over 50 species of native trees and shrubs using nine categories, specified in Table 1. The matrix projection model for *M. platycarpum* is constructed using five stages; stages described by Tiver and Andrew (1997) as III to VII inclusive. Stages I, II and III are non-reproductive so stage III in the model actually represents all three juvenile stages.

Table 1. Notation

Symbol	Definition
A	Projection matrix
x_i	Number of individuals in class *i*
t	Time step (year)
n	Number of classes
S_i	Probability of surviving and staying in class *i*
F_i	Fertility of class *i*
P_i	Probability of surviving and progressing to class *i*+1
λ	Dominant eigenvalue of *A*: indicates long term growth rate of the species
I_{regen} $I_{recruit}$	Regeneration and recruitment indices
r	Rainfall (generated by simulation of gamma distribution. Details in McArthur et al. 2006)

Table 2. The age classes defined in Tiver and Andrew (1997).

Class Number	Definition
I	Seedling
II	Bushy juvenile
III	Older juvenile
IV	Young mature (reproductive)
V	Mature
VI	Old mature
VII	Senescent
VIII	Standing dead
IX	Lying dead

2.2. Results

To improve the understanding of what the effects of grazing might be, the regeneration and recruitment indices, introduced by Tiver (1994) were also calculated. The regeneration index is defined as the ratio of the number of stage IV trees in the population to the number of stage IV-IX trees. The recruitment index is the ratio of all juvenile stages to all adult stages; that is, the number of stage I-III juveniles to the number in stages IV-IX. Thus, for x_i, the number of individuals in stage i, the regeneration and recruitment indices are given by:

$$I_{regen} = \frac{x_{IV}}{x_{IV} + x_V + x_{VI} + x_{VII} + x_{VIII} + x_{IX}} \qquad I_{recruit} = \frac{x_I + x_{II} + x_{III}}{x_{IV} + x_V + x_{VI} + x_{VII} + x_{VIII} + x_{IX}}, \quad (5)$$

and are calculated for both the grazed and ungrazed areas.

The results of the MPM investigation indicate that the probability of survival of juveniles is reduced under grazing by approximately 20-30%, Table 3, where I_{regen} = 0.21 and 0.62 for grazed and ungrazed paddocks respectively and $I_{recruit}$ = 0.19 and 1.55 for grazed and ungrazed paddocks respectively. The matrices of the vital rates were generated given randomly selected rainfall, r, for both the ungrazed and grazed regimes. The resulting growth rates, λ_{un} and λ_{gr}, for the ungrazed and grazed regimes respectively, were found to have a curvilinear relationship with rainfall, approximated here by a quadratic equation. The functional form of the growth rates, where r represents rainfall, can be expressed as

$$\lambda_{un} = 1.012 + 0.065r + 0.029r^2 \quad (R^2 = 99.80\%, P < 0.01) \qquad (6)$$

$$\lambda_{gr} = 0.97 + 0.005r + 0.002r^2 \quad (R^2 = 98.88\%, P < 0.01). \qquad (7)$$

It can be seen (Table 3) that the regeneration index for the ungrazed sites is approximately three times that of the grazed sites and the recruitment of ungrazed populations is 8 times that of the grazed. These numbers do not account for some other factors that might influence the survival of the individuals such as soil type, but nevertheless support the hypothesis that there is some grazing effect.

Table 3. The indices of the Regeneration (I_{regen}) and Recruitment ($I_{recruit}$) under no grazing and grazing conditions.

Regime	I_{regen}	$I_{recruit}$
No grazing	0.62	1.55
Grazing	0.21	0.19

The results also indicated that if the rainfall was greater than 2.70 standard deviations above the mean, then the effects of grazing on the long-term survival of *M. platycarpum* would be overcome. In other words, the current levels of stocking would eventually cause the die out of *M. platycarpum* unless uncharacteristically high levels of rainfall were received.

The sensitivity of the matrix A can be described as measuring the degree to which each entry affects the dominant eigenvalue, λ, which represents the long term growth rate. Sensitivity analysis, described in detail in McArthur et al. (2006), showed that S_V imposed the most influence on the long term survival; specifically the analysis indicated that the most crucial parameter is the duration of each stage; however, there is very little information available, apart from photographs and anecdotes, to estimate the duration of the later stages. The analysis does however, indicate that this is an important parameter and needs to be estimated carefully.

3. SYSTEM DYNAMICS MODEL

3.1. Method

Subsequent to the MPM model study, a system dynamics approach was employed based upon the findings of the MPM study. This method is based upon Jay Forrester's Industrial Dynamics system of stock and flow diagrams, (Forrester 1961). The stocks are the state variables, in this case *M. platycarpum*, and the flows are the rates of reproduction, death and progression between stages. The system is iterated over time and models the changes in the population over time. The model developed by the authors is used to analyse the effects of alternative land use practices on the environmental and economical sustainability of the shrub lands in eastern South Australia.

The effects of alternative land use practices on the shrub land ecosystems can be studied by focusing on the population dynamics of the species in the ecosystem, and we found that system dynamics modelling is an ideal method of investigating the effects of these land use practices on the system under study.

The study found that three factors directly influence the population dynamics of the *M. platycarpum* population:

- Presence of sheep
- Distance to water points
- Rainfall

Three alternative land use practices were proposed using the three factors that influence the development of the *M. platycarpum* population. The effect of each alternative land use practice was compared to the ungrazed site for three different grazed locations.

Firstly, since the sheep enclosure after periods of above-average rainfall showed an improvement in the *M. platycarpum* population, zero grazing was modelled to establish a reference scenario.

The second alternative is the construction of additional watering points. The investment costs of this alternative, however, are expected to be high and the option would require frequent maintenance of the watering points, which will likely decrease the support for this alternative.

The final alternative is the use of a rotational grazing system. Part of the grazing area will be excluded from grazing, with the duration to be maximized during the modelling process. The costs of the necessary fences will have to be considered. Figure 2 illustrates a component of the system dynamics model. (Full model details are available from the authors.)

The objective is to examine the long term population dynamics and this is achieved by describing the system using a set of differential equations and feedback loops. The sustainability of the *M. platycarpum* population under a specific land use practice is measured by comparing the development of the population under grazing to a reference scenario without grazing. Additional variance in the sustainability of the population is caused by the survival probability and the fertility of the populations. The sustainability of the *M. platycarpum* populations is influenced by a negative feedback loop between the fertility factor and the sustainability of the populations. This can be explained by the fact that the fertility of the populations decreases as the number of individuals in the population increases – primarily due to overcrowding. To model this, the ratio "actual population size/optimal population size" is included. As the ratio actual/optimal population decreases, the fertility of the population becomes very important. However, in the case where the ratio is greater than one, recruitment of the population decreases.

Rainfall and grazing intensity are the main factors that influence fertility and survivability. Grazing intensity can be managed; rainfall on the other hand, is far more difficult to manage and therefore considered to be an exogenous factor. Water management options could be analysed to improve the water supply, but the likeliness of lower costs and lesser complexity of alternative land use practices were the reasons for the demarcation of this research to the analysis of alternative land use practices only.

3.2. Results

The system dynamic model indicates that without grazing an improvement in the sustainability of the *M. platycarpum* population would be observed, but this option would not be viable due to economic non-sustainability, but was useful as a reference.

The second alternative examined was the construction of additional watering points. This resulted in population development that was by far the most sustainable of the three alternatives and approaches the non-grazing scenario in two cases. The investment costs of this alternative, however, are expected to be high and the option would require frequent maintenance of the watering points, which decreases the support for this alternative.

The final alternative is the use of a rotational grazing system where part of the grazing area would be closed to grazing for a period of approximately 10 years out of 40, so that the ecosystem can recover from the previous grazing events. This alternative results in a significant improvement of the sustainability of the *M. platycarpum* population and reaches an equilibrium value of mature *M. platycarpum* trees for all three research locations. The costs of the necessary fences are relatively low and support of the pastoral industry for this alternative is expected to be high, as the rotationally grazed system will provide the future food sources for their sheep. The rotationally grazed system is therefore considered to be the optimal land use alternative for the rangelands of eastern South Australia.

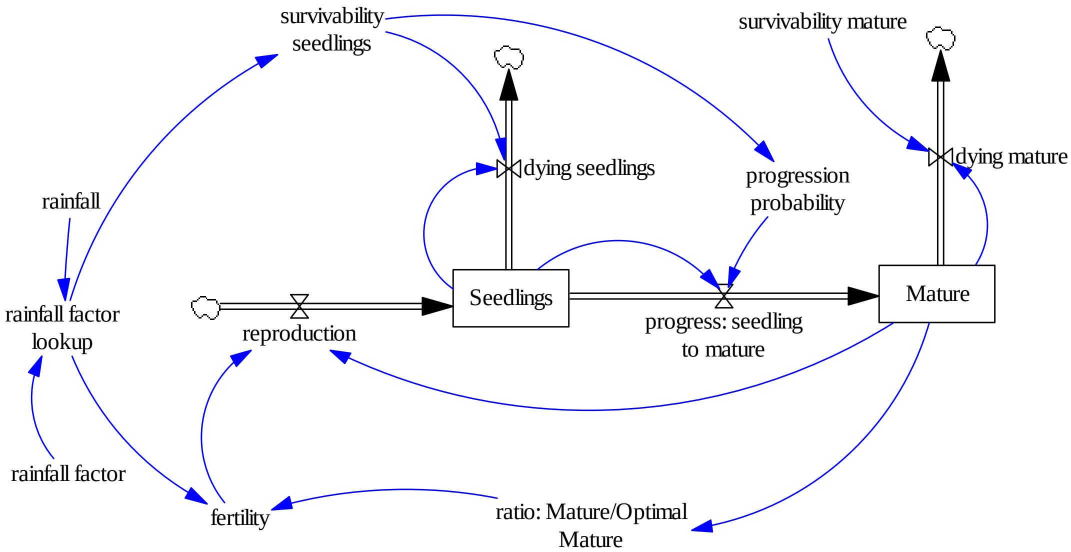

Figure 2. A component of the System Dynamics model for *Myoporum platycarpum.*

4. CONCLUSIONS

There is ample evidence that herbivore grazing can alter the composition and abundance of native flora, and the authors continue to endeavour to quantify this effect. The motivation is to produce an aid to managing pastoral lands to ensure better environmental and economic sustainability. These studies have shown that given a certain high level of rainfall, grazing can continue without necessarily causing a decline in recruitment or regeneration of *M. platycarpum.* Secondly, that a rotation system for grazing of a duration in the order of ten years out of each forty, would assist in providing adequate conditions for continued survival of the native flora.

Several limitations are evident in this study. There are underlying assumptions that may or may not be justified, such as the assumption of population equilibrium in the Koonamore Reserve. One of the major concerns is the lack of data for estimating the duration of each stage, since the long term growth rate is extremely sensitive to this parameter. The second major concern is that there is no data available at the time of the study on stocking rates. We make the, possibly unreasonable assumption, that one sheep would be sufficient to influence the regeneration and recruitment of *M. platycarpum.*

Also, the population of *M. platycarpum* is based on counts, with no measure of density attributed to the different sites. This is a major limitation, but we are comparing the total number of each stage within a given area, so the relative numbers are therefore used. At this stage we have only considered the long term (asymptotic) population dynamics and ignored the short term fluctuations (Yearsley, 2004). This will be considered in future studies. A model and tool, SHRUBPOP, has also been produced which is applicable to many different species in different regions, and used to support management decisions in arid rangelands, (Tiver et al. 2007).

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