Chapter 1. Introduction

1.1 Background

Agriculture is an important part of the Australian economy, it accounts for $28.2 billion per year, or 22%, of Australia's total exports. The Australian sheep industries currently generate $3.6 billion annually in export earnings and represent 13% of total agricultural exports (Curtis and Dolling, 2006).

One of the largest problems faced by Australian sheep producers is that over the 25 years up to 2001-2002, the annual change in producer terms of trade has averaged -2.1% while gains in total factor productivity have only averaged 0.9% (ABARE, 2004b). This has led to a general decline in sheep producers' farm incomes.

Increasing and maintaining higher levels of productivity from the utilisation of the pasture resource in the most profitable way is, and will continue to be, one of the highest priorities of producers involved in extensive large animal production in Australia (Wheeler, 1981). Declining terms of trade, degradation of pasture resources, and a greater realisation of environmental responsibilities over the past two decades have led to increased emphasis on the development of more sustainable grazing systems (Gramshaw *et al.*, 1989; Humphreys, 1997; Hutchinson, 1992; Kemp and Dowling, 2000; Wilson and Simpson, 1994).

A critical component of grazing systems that are capable of sustaining high levels of productivity as well as meeting environmental objectives, is the use of more productive deep-rooted introduced perennial and leguminous species (Humphreys, 1997). The degradation of the productive capacity of the pasture resource since large areas of introduced species were established during the 1960s and 1970s, has largely been attributed to the loss of desirable species, both perennial grasses and legumes (Archer *et al.*, 1993; Kemp and Dowling, 2000).

Although the sowing and fertilising of introduced species has been identified as one of the major reasons for increased productivity in grazing industries since the mid 20th century (Crofts, 1997; Menz, 1984), the risk of pasture establishment failure and reduced persistence of the introduced species (Reeve *et al.*, 2000), appears to have made grazing industries in Australia view this investment as un-economic in all but high rainfall-highly fertile soil regions (Vere *et al.*, 1993; Vere *et al.*, 2001; Vere and Muir, 1986). However, with increasing environmental pressure and the need to continually improve the productive capacity of the pasture resource, producers still believe sown perennial grass species that persist are important to their pasture systems (Brown *et al.*, 1997; Reeve *et al.*, 2000).

1.2 The Research Problem

Making decisions regarding the development and management of a farm's pasture resource is an important and complex bioeconomic problem. It involves the consideration of interactions between pasture ecology, the use of technology to improve and manage the resource, environmental externalities, utilisation of the resource by grazing animals, and the profitability of the farming system.

Within any grazing system, decisions need to be made by managers on how to best manage the existing mosaic of pasture resources. This involves making decisions about how to utilise the existing resource through the adjustment of stocking rates and grazing management. It also involves making decisions about the use of inputs and existing technologies such as fertiliser, the sowing of introduced species and subdivision of paddocks for the improved management of grazing to ultimately improve pasture productivity, quality and persistence. These represent a series of tactical and strategic decisions that need to be made in a climate of uncertainty about their degree of success in improving production and profits (Kingwell *et al.*, 1993).

Tactical decisions represent decisions made by producers to adjust their farming strategies in response to changes in seasonal and market conditions (Antle, 1983). Strategic decisions represent decisions made for the development of the business which involve inter-temporal benefits and costs (Rae, 1994).

The pasture resource is dynamic in its response to utilisation and climate, and the impacts of decisions made at different points in time significantly influence profitability over the long term. This is a sequential decision problem where producers manage the grazing system by making both tactical and strategic decisions at intervening states of the system as uncertainty unfolds (Trebeck and Hardaker, 1972). Climate risk, which influences the future profitability of the grazing system and the state of the pasture resource, introduces embedded risk in the decision making sequence (Hardaker *et al.*, 1991).

The complexity of the grazing system, and the need for it to be integrated within the farming system in a profitable and sustainable way, limits the usefulness of relying solely on field experimentation to obtain answers. Modelling and simulation of complex farming systems provides the most efficient method of undertaking management and systems research to improve decision making (Bywater and Cacho, 1994). Therefore there is a need to develop bioeconomic models that take into account the biophysical system and integrate dynamic pasture resources with livestock production and economic analysis.

1.3 Research Objectives

The objective of this research is to develop a method that adequately models the dynamic nature of pasture resources and integrates the sequential nature of the decision making problem faced by sheep producers under climatic uncertainty. The method developed must be capable of identifying the optimal decisions, in regard to the development and management of the pasture resource, that maximise the long-term profitability of the grazing system.

The specific objectives of the research are to:

1. review the background to the pasture resource management problem and define the structure of the problem;
2. review previously applied methods to solving the problem and identify opportunities for improving the way the problem is solved;
3. develop a bioeconomic framework capable of solving the sequential decision problem under climatic uncertainty;
4. solve the sequential decision problem to identify the optimal tactical and strategic decisions for the case study region.

It is hypothesized that accounting for a stochastic climate and dynamic relations in pasture composition will improve our estimation of the benefits and costs associated with pasture development technologies. The integration of a dynamic pasture resource simulation model and an economic optimisation model will allow optimal tactical and strategic decisions to be identified that improve the information available for the management and development of the pasture resource in grazing systems.

1.4 Thesis Design

The first part of this thesis, which includes Chapters 2 and 3, provides the background to the research and reviews studies relevant to the research area. Chapter 2 begins with a review of the history of pasture resource development in south-eastern Australia and the dynamics of the pasture resource. The effects of developmental technologies are reviewed and discussed in relation to the pasture resource development problem. Chapter 3 reviews both the biophysical and economic approaches previously applied to the pasture resource problem. It begins with a review of the theoretical frameworks for the description of dynamic pasture systems. The biophysical models used to simulate the productivity and composition of pastures are discussed. The previous economic approaches applied to solving the pasture resource problem are then reviewed with the chapter concluding with a discussion of the opportunities to improve decision making.

The second part of the thesis involves four chapters which describe the bioeconomic model, its development and application to solving the pasture resource problem. Chapter 4 begins with a definition of the problem structure and then proceeds to present the conceptual outline of the bioeconomic framework. Components of the framework are discussed and the sources of data for the calibration of the model introduced. Chapter 5 provides a detailed description of the dynamic pasture resource development (DPRD) model constructed to simulate and optimise the grazing system through the application of alternative pasture development technologies.

Chapter 6 describes the parameterisation of the dynamic pasture model and its validation through simulation in a Monte Carlo framework. The chapter begins with a description of the sources of experimental data used to calibrate a complex biophysical simulation model, from which data is extracted for the parameterisation of the DPRD model. The chapter concludes with the application of the DPRD model to the case study region within a Monte Carlo simulation framework. The results of the experimental simulations are used to investigate the production, profitability and risks associated with pasture improvement technologies and stocking rate policies. The simulation results are also used to demonstrate the benefits and costs from modelling the dynamic aspects of pasture composition and stochastic climatic conditions.

Chapter 7 describes the solution of the pasture resource problem through the integration of the DPRD simulation model into a seasonal stochastic dynamic programming (SDP) model. The SDP is used to find optimal tactical and strategic decision rules, in terms of stocking rates and pasture re-sowing as functions of pasture mass and composition. Multiple SDP runs are used to investigate the effects of different sheep production systems, pasture sowing costs, and discount rates on optimal pasture resource development decision rules.

The final chapter of this thesis provides an overview of the findings and discusses these in relation to the literature reviewed. It also provides a discussion of the limitations of this research and the implications of the research findings to industry. The chapter then ends with a discussion of opportunities for further research.

Chapter 2. An overview of pasture resource development

2.1 Introduction

Agriculture, based on the utilisation of grasslands by ruminants, occupies around 20% of the world's land surface (Hodgson and Illius, 1996). Australia maintains approximately 60% of its surface area as native or sown grasslands supporting the majority of the nation's livestock industries (Kemp and Michalk, 1994).

The productivity of these grasslands is affected by a range of environmental and human influences. Environmental conditions drive the ultimate productivity of the individual species existing in grasslands through soil or landscape resources and the variable provision of precipitation and temperature (Wheeler and Freer, 1986). Human activity, in its attempt to generate food and materials from grassland resources, interacts with the variable environment in the utilisation of this resource to result in a pasture resource that, over time, is dynamic in nature (Jones *et al.*, 1995).

The development, maintenance and utilisation of the pasture resource have varied throughout history in response to changing climatic and socio-economic conditions. Since the beginning of agriculture in Australia, cyclical prices for commodities, stochastic climatic conditions and the continual decline in terms of trade have been instrumental in shaping the utilisation, development and degradation of soil and pasture resources (Crofts, 1997; Peel, 1986; Vere and Muir, 1986).

This chapter provides an overview of pasture resource development in the high rainfall temperate pasture zone of Australia. The dynamics of pasture resources and the impact technologies have on their productivity, quality and persistence are also reviewed. A summary of the pasture resource development and management problem is provided in the final section of this chapter.

2.1.1 Pasture resource development in temperate Australia

The temperate climate zone of Australia (Figure 2-1), as defined by the modified Koeppen classification system (Stern *et al.*, 2005), indicates the distribution and expanse of the temperate woodlands and pasture zone of south eastern Australia.

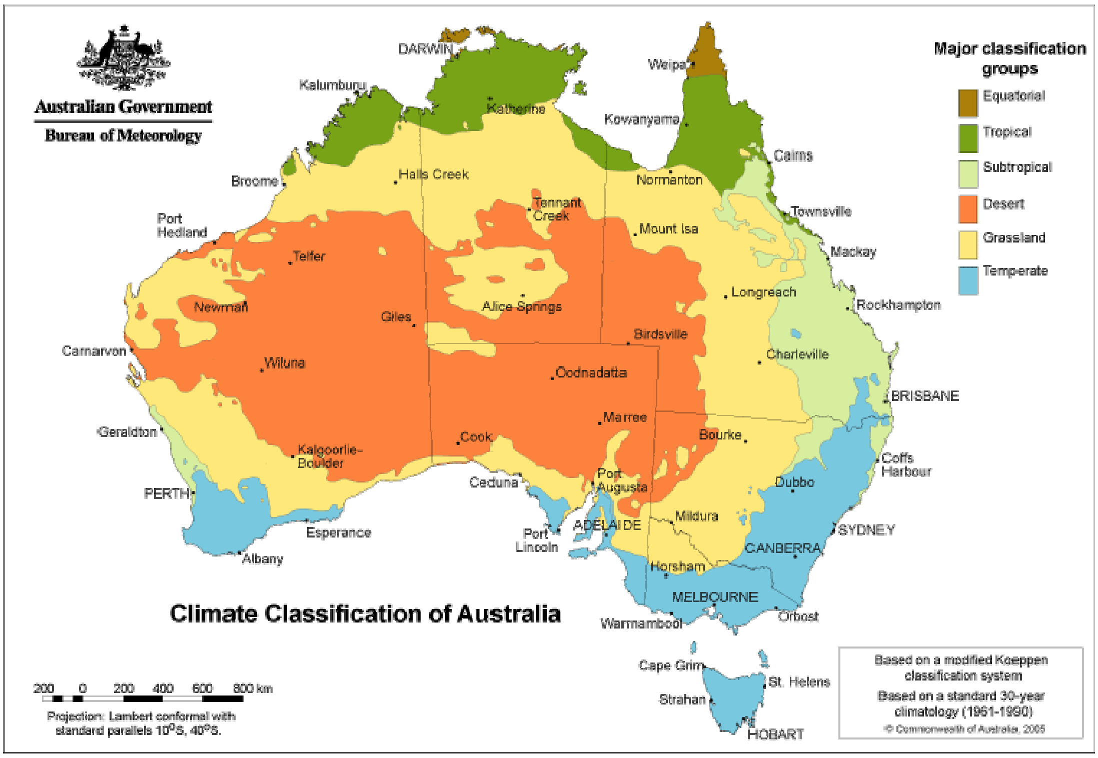

Figure 2-1: Climatic regions of Australia (BOM, 2005)

The successional path, resulting from grazing by introduced herbivores on the open temperate *Eucalyptus* woodlands of south eastern Australia, was originally described by Moore and Biddiscombe (1964). This was reviewed and modified further by Moore (1975), Wolfe and Dear (2001) and Garden and Bolger (2001). Prior to higher grazing pressures, above those of native herbivores such as kangaroos and wallabies, the grassland landscapes were dominated by tall warm season perennial grasses, such as *Themeda australis* (kangaroo grass) and other tall grasses such as *Poa caespitosa* (poa tussock) and *Stipa aristiglumis* (plains grass). These, predominantly summer growing species, were theorised to have utilised mineralised nutrients during the summer, preventing the ingress of other species and subsequently stabilising the community and limiting succession.

With the introduction of increased grazing pressure and clearing of timber, the landscape progressed towards grasslands dominated by a myriad of grazing-tolerant mixtures of short, cool season perennials, such as *Austrodanthonia* spp. (wallaby grass) and *Stipa* spp. (spear grass), and short, warm season perennials, such as *Aristida* spp. (three-awned spear grass), *Bothriochloa* spp. (red grass) and *Chloris* spp. (windmill grass in the more sub-tropical woodlands) (Figure 2-2). Following this period, the grasslands of south eastern Australia were transformed towards the current array of sown species, short, cool and warm season perennials and annuals. This transformation resulted from the naturalisation of cool and warm season annuals, nitrophilous annuals and biennials, and the broad scale application of phosphorus fertiliser with the introduction of exotic species.

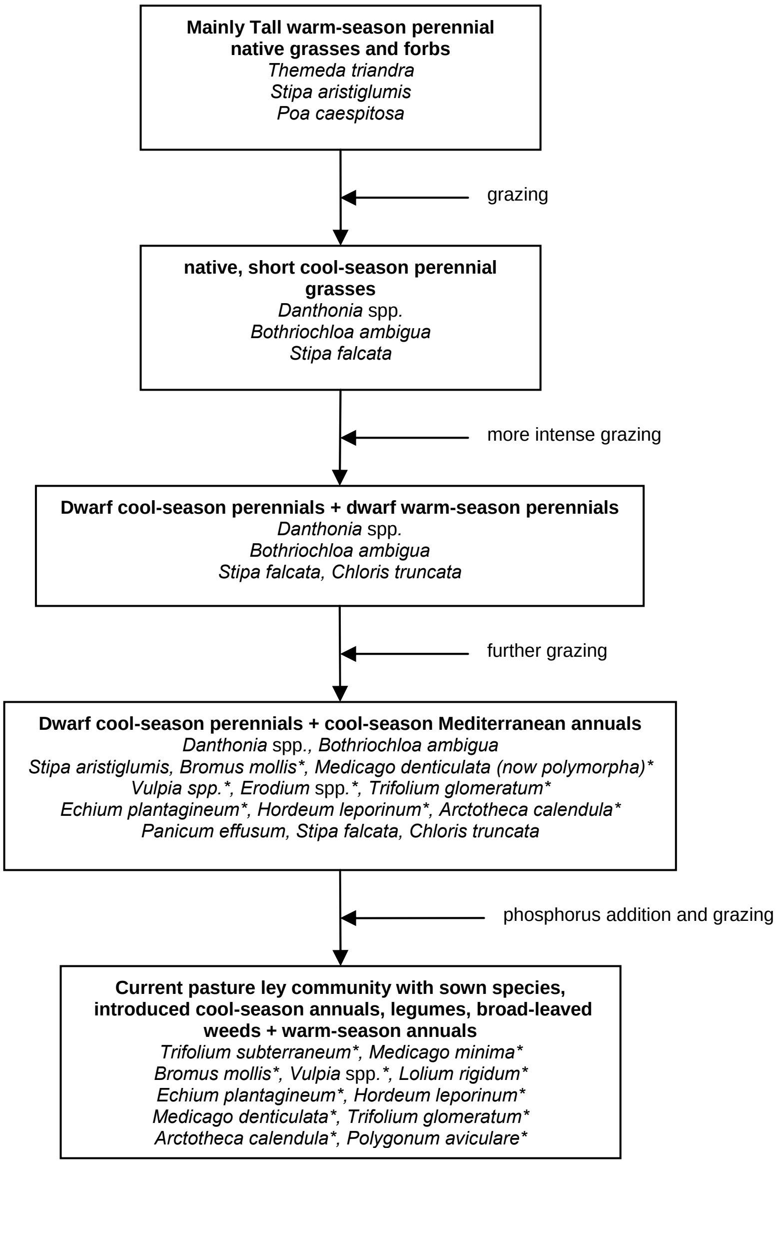

Figure 2-2: Change in botanical composition of temperate native grasslands of open Eucalyptus woodlands in south-eastern Australia, adapted from Wolfe and Dear (2001) and Garden and Bolger (2001). Asterisks denote introduced and naturalised species.

Pasture development, based on the introduction of exotic species into the Australian high rainfall temperate zone, where 80% of Australia's sown pastures have been established, peaked during the 1960s and 1970s. The 6% of grasslands that have been improved through the sowing of introduced species and the application of fertiliser carry 41% of Australia's domestic livestock (Hutchinson, 1992). By the start of the 1970s, the significant production benefit of introduced species over native species had led to the establishment of around 30 million hectares of sown pastures and grasses (Crofts, 1997; Donald, 1975). These introduced species responded better to nutrients and hence water and radiation (Humphreys, 1997).

The sown pastures were predominantly introduced legume species, such as subterranean clover (*Trifolium subterranean*), barrel medic (*Medicago truncatula*), lucerne (*Medicago sativa*) and white clover (*Trifolium repens*). The predominant perennial grasses included phalaris (*Phalaris* spp.), ryegrass (*Lolium perenne*), cocksfoot (*Dactylis glomerata*), and tall fescue (*Festuca arundinacea*) (Hutchinson, 1992).

Approximately two-thirds of this development of the pasture resource occurred during periods of high commodity prices with further pasture improvement activities coinciding with positive changes to farmers' terms of trade (Crofts, 1997). The sowing of so-called 'improved' pasture species with fertilisation had the greatest influence on returns to livestock production during the post-war periods of the 1950s and 1960s in high rainfall regions where it was considered economically feasible (Gruen, 1956; Menz, 1984; Vere and Muir, 1986). Net farm incomes were estimated to have doubled as a result of this development.

The High Rainfall Temperate Pasture Zone (HRTPZ, generally receiving greater than 600mm average annual rainfall) of south eastern Australia, with growing seasons of more than 5-6 months, provided environmental conditions most applicable to the broad adoption of these pasture improvement technologies. In the Monaro, Central and Southern Tablelands of NSW around 80% of land had been cleared of timber with half of that area being previously sown to introduced species (Garden *et al.*, 2000a). Three quarters of the sheep and cattle in Australia are now maintained in the HRTPZ (Wheeler and Freer, 1986) with the central and southern HRTPZ of New South Wales maintaining approximately 23 million sheep and 3.5 million cattle on around 5 million hectares of grasslands (Vere *et al.*, 2002).

A steep decline in farmers' terms of trade and the increasing costs of establishing and maintaining pastures resulted in reduced pasture improvement activity towards the end of the 1950s (Crofts, 1997; Vere and Muir, 1986). More recently, the estimated proportion of grazing areas being re-sown to introduced species is less than 1% in the central and southern tablelands of NSW (Kemp and Dowling, 2000) and around 2-4% per annum in Victoria, with the majority of previously sown pastures expected to have regressed to a naturalised state (Ward and Quigley, 1992; Wilson and Simpson, 1994).

Since the removal of the superphosphate bounty in 1974, the area of pasture receiving fertiliser applications has been significantly lower than those areas where introduced species have been sown (Crofts, 1997). This divergence, associated with a reduction in soil fertility on sown areas, has been suggested as one of the key reasons for the decline in productivity of legumes in pastures (Vere, 1998). In turn, this has influenced livestock production and the productivity and persistence of sown and fertility-responsive grass species (Kemp and King, 2001).

2.1.2 Degradation of the pasture resource

Declining inputs and several major drought events during the 1960s and 1970s led to ongoing changes in the pasture resource. In the HRTPZ, where most of the pasture improvement activity has occurred, the majority of sown pastures have degraded to a mixed native or naturalised state (Hutchinson and King, 1980; Lodge, 1994; Wilson and Simpson, 1994).

In the most recent survey of the NSW HRTPZ, 66% of paddocks that contained sown pastures, maintained an average of 27% sown perennial grass species with only 9.9% of paddocks maintaining greater than 50% of sown perennial grasses (Dellow *et al.*, 2002). This is supported by earlier surveys that provided evidence of the deterioration of sown perennial grass content even under conservative stocking rates and normal district management in the Central Tablelands of NSW (Kemp and Dowling, 1991). During the early 1990s previously sown areas in the Monaro, Central and Southern Tablelands received 80% more fertiliser than areas dominated by native pastures (Garden *et al.*, 2000a).

The estimated national average stocking rate of the Australian pasture resource and the divergence between the area used for sown pastures and the area of pasture receiving fertiliser is presented in Figure 2-3. It indicates a period of declining phosphate application to sown pastures, coinciding with a period of higher utilisation of the pasture resource. This would be expected to exacerbate degradation of the sown pasture resource leading to a shift towards native and naturalised states.

This correlates with the observed degradation of previously sown pastures throughout the high rainfall zone of south eastern Australia (Archer *et al.*, 1993; Wilson and Simpson, 1994). This is also supported by a review of the issues influencing the persistence of forage legumes in Australia by Gramshaw *et al.* (1989).

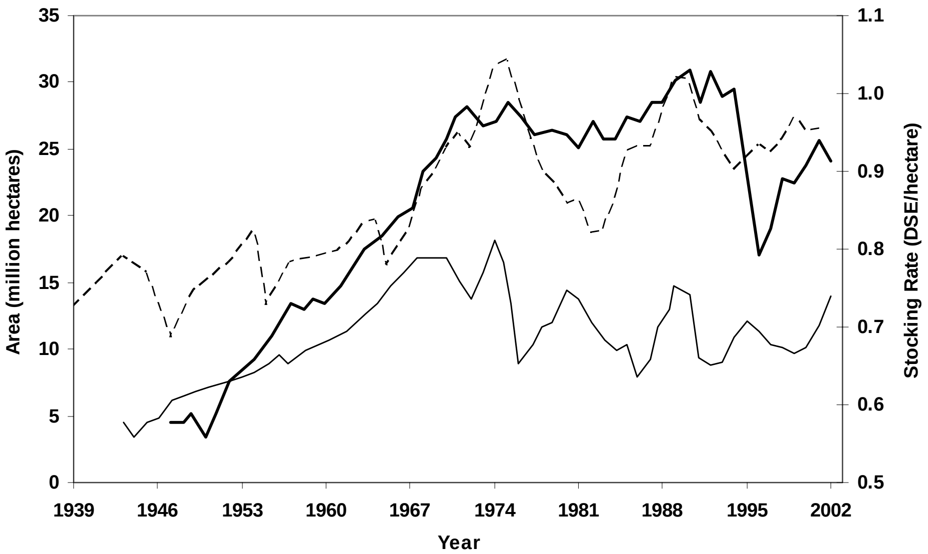

Figure 2-3: National average stocking rate (– –), area used for sown pastures (━) and the area of pasture fertilised (—) in Australia (ABS, 2001; Crofts, 1997). National average stocking rate (DSE/ha) calculated from national cattle and sheep numbers over the area used for grazing enterprises (ABARE, 2004a; ABS, 2002).

Degradation of the productive capacity of the pasture resource has largely been attributed to the loss of desirable species, both perennial grasses and legumes (Archer *et al.*, 1993). Wheeler (1986) notes that the carrying capacity in non-crop areas of NSW had fallen by 47% during the period from 1970 to 1984. This is also supported by Kemp and Dowling (2000) who estimated that over the period between 1950 and 1990, both native and previously sown country had maintained a stocking rate at least 25% below their potential.

The loss of desirable introduced pasture species reported in much of the literature, is associated with the ingress of annual species (Hutchinson, 1992), such as annual grasses and broadleaf species, or perennial weed species, such as woody weeds or tussocks (e.g. serrated tussock). These species are categorised as less desirable due to their lower and more seasonal pasture growth and quality, which in turn have a cumulative effect on livestock production.

Since European settlement, many forms of land degradation in Australia have been linked to human influences and their subsequent impacts on vegetation. In particular, many forms of land degradation under grazing systems are associated with the loss of deep-rooting perennial species, which are capable of maintaining ground cover and utilising rainfall year round.

The production equivalent of land degradation in Australia has been estimated to be in the vicinity of 5-6 per cent of agricultural production per annum, or a national cost of around $1.15 billion (in 1994–95 values) per annum (Gretton and Salma, 1996). In one grazing study in the Lachlan valley of NSW, the production equivalent or the decline in net agricultural income resulting from sheet and rill erosion and soil loss was found to be $3.95/ha or $15 million per annum (Mallawaarachchi *et al.*, 1994).

Globally, poor management and over-utilisation of the pasture or rangeland resource has resulted in extensive degradation of natural grasslands throughout Asia, South America and Africa. Degradation of the productive capacity and environmental stability of pasture and rangeland resources is a significant social, environmental and economic issue.

2.1.3 Managing and developing dynamic pasture resources

Increasing and maintaining levels of productivity and utilisation of the pasture resource in the most profitable way is, and will continue to be, one of the highest priorities of producers involved in extensive large animal production (Wheeler, 1981). However, continuing pressures from drought, commodity price fluctuations and high debt to equity ratios, are forcing farmers to put the highest priorities on dollar returns, even though the management of the pasture resource needs to concurrently maintain a biologically and economically resilient system (Hutchinson, 1992).

The importance of improving the management of newly sown and previously modified native/naturalised pastures is critical to the persistence, sustainability and economic performance of any investment. The potential of increased climate variability indicated by climate change studies (Clark, 2004) and the reassessment of technologies and management strategies for pasture resource development is expected to become more important with increased variability and reduced rainfall (John *et al.*, 2005).

The more recent approach to managing pasture resources is the continuation of a paradigm shift which occurred during the late 1980s and 1990s. There has been an acknowledgement that there was a need for pastures and grasslands to be managed as continually changing ecological systems (Harris, 2000) with options or technologies available to change the influence of management and utilisation on the pastures state under stochastic climatic conditions.

Kemp and Michalk (1994) defined pasture management as the process of actively intervening in the production of plants and their utilisation by grazing animals to maintain or improve production while sustaining the resource. Given the economic pressures experienced by farmers and the ability to replace deteriorated pastures in most environments at a cost, the definition of pasture management could perhaps be modified to include the need to find a balance among pasture productivity and persistence, environmental constraints, livestock production and whole farm profit.

The use of conventional production economics to support decision making regarding shorter term production and profit objectives of livestock grazing systems is unlikely to be viewed as acceptable to modern community values, where the focus is increasingly on improving environmental outcomes. The challenge lies in identifying profitable and ecologically sustainable livestock production systems from dynamic pasture resources (MacLeod and McIvor, 2006).

A greater realisation of environmental responsibilities over the past two decades has led to an increased emphasis on the development of sustainable grazing systems (Gramshaw *et al.*, 1989; Humphreys, 1997; Hutchinson, 1992; Kemp and Dowling, 2000; Wilson and Simpson, 1994). A critical component of sustainable grazing systems that are capable of sustaining high levels of productivity as well as meeting environmental objectives, is the use of more productive deep-rooted introduced perennial and leguminous species (Humphreys, 1997).

Currently only around 11% of NSW is sown to introduced pastures, with 37% being naturalised and native pastures (ABS, 2001). The importance of native species has been recognised through their contribution to grazing systems and given the limitations to the adoption of sown pastures (Lodge, 1994). Nevertheless, there are still significant opportunities to increase pasture resource productivity through the sowing of exotic species. The area sown to introduced species is estimated to be only 15-20% of the area which potentially could be sown to pastures. Only 25 million hectares of a potential 172 million hectares suitable for pasture development have actually been sown to improved species (Wheeler and Freer, 1986).

In a recent survey, 45% of farmers in the sheep-wheat and high rainfall zone indicated that the use of deep-rooting perennial pastures species was a key management strategy being adopted to address land degradation (Nelson *et al.*, 2004). The sowing of introduced perennial species also has the potential to contribute to the sustainability of the grazing system. In a review of grasslands contribution to global warming and carbon sequestration, Humphreys (1997) supported the importance of establishing and maintaining adequately fertilised 'elite' deep-rooted grass species and legumes in improving net primary production, the quality of feed available to ruminants to reduce methane emissions, and in increasing the level of carbon sequestration under grasslands.

Given the complexity of pasture dynamics, the following section will focus on outlining the key interactions involved in determining the dynamics of temperate pastures. The scope of this section will include the interactions that drive differences in competition between species, production and botanical composition over a time frame of 20-30 years. These interactions, in turn, determine potential levels of livestock production attainable from the pasture resource.

2.2 Pasture Dynamics

The integration of pasture dynamics, livestock production and economics is necessary to improve decision making regarding pasture resource development and management. Within a sward, the relative competitive ability of different species and the way management interacts with the environment both play a significant role in determining the competition between species, future states of the pasture sward, ecological impact of the sward and its potential for livestock production (Kemp and King, 2001). When making decisions about pasture development and management, there are six key themes that describe the ecology of pastures:

1. biodiversity,
2. competition between species,
3. resilience and persistence,
4. growth and production,
5. livestock interactions, and
6. cyclical changes in botanical composition.

These are described in greater detail below with the role of pasture resource development and management in the greater environment and society also being introduced. This broader role of farm-level management is becoming an increasingly important component of grassland development and management (MacLeod and McIvor, 2006).

2.2.1 Biodiversity

In a survey of the HRTPZ of New South Wales, a total of 176 different taxa were identified with the average pasture containing 17.6 different species (Dellow *et al.*, 2002). This is similar to what has been found in long-established swards, whereas, up to 100 different species may be found in naturalised grasslands containing mixtures of introduced, volunteer and native species (Kemp and King, 2001; Kemp *et al.*, 2003). Sown pastures tend to become naturalised with a mix of native, introduced and invasive species over time, due to the existence of a seed bank and the ingress of surrounding species. This results in a mosaic of pastures ranging from original native swards to sown swards not yet degraded (Kemp and King, 2001).

The interaction between the heterogeneity of resources, microclimate, differences between species in their ability to utilise resources, and competitive strategies of plants ensures diversity in the majority of grasslands. This diversity is in a continuous state of change with unoccupied micro-environmental niches varying in availability over time, providing the opportunity for existing species or new species to colonise and spread in grasslands (Kemp and King, 2001). Diversity in grasslands is also influenced through the seasonal availability of nutrients in response to climatic variation and the nutrient-extraction capability of different species (Humphreys, 1997; Tainton *et al.*, 1996).

Species diversity in grasslands contributes to variable quantities and qualities of forage produced for grazing livestock (Tainton *et al.*, 1996). The seasonality and spatial distribution of forage and its quality will influence selective grazing as well as livestock productivity and potential profitability from the pasture resource in its current state. However, increased biodiversity or species richness in pastures does not necessarily relate to increased grassland productivity or stability of production (Humphreys, 1997; Kemp *et al.*, 2003). Increased diversity in the grassland may also lead to marginal increases in the metabolic cost of selective grazing through increased grazing time and reduced daily intakes (Rutter, 2006).

2.2.2 Competition

There is competition between individual plants for water, nutrients, light, and space within a sward. Concurrent competition for resources occurs even though different species require different amounts of resources to grow and regenerate. With resource availability varying over time, species vary in their growth and interactions with other species within the sward (Kemp and King, 2001).

The intensity and form of competition between species for different resources varies with resource levels in different environments (Bullock, 1996). In nutrient and water rich environments, light and space become the limiting resource. However, in much of the HRTPZ, nutrients and water are limiting and hence competition for these two resources has a large influence on the success of competing species.

The degree of competitive interference between species is dependent on the morphology and biochemistry of interacting species (Kemp and King, 2001). Differences in the way individual plant species utilise space through growth habit, stem and leaf design influence competitive interference between species for light and space resources in a mixed sward. The photosynthetic pathway of different species influences their seasonality of growth and subsequent resource demands and use. Allelopathic effects between species and the influence of litter on diurnal temperature variations may also limit the regeneration of annual species (Wolfe and Dear, 2001). In contrast, the fixation of atmospheric nitrogen by legumes has direct positive effects on the quality of herbage available to the grazing animal and can have positive effects on the productivity and competitive interference of companion grass species.

Competition between species is also influenced by grazing, through both the selectivity of plants and their components, and their temporal variation in availability and desirability. This includes their ability for grazing tolerance and avoidance (Bullock, 1996).

In Australian pastures, survey evidence has suggested inverse relationships between perennial and annual species (of both grasses and legumes) where they coexisted, suggesting that neither species group maintains a greater competitive ability than the other and that they occupy different niches within a pasture as well as complement each other through, for example, nitrogen dynamics. The broad array of botanical compositions of pastures in the HRTPZ are a function of climatic, environment and management interactions (Kemp and Dowling, 1991).

2.2.3 Resilience and persistence

The concept of resilience is associated with the Competition-Stress-Disturbance model theories described in section 3.2.2. Ecological systems vary in their ability to withstand disturbances and stressors and maintain a stable state. The ability to withstand disturbances and stressors, determines a plant's ability to persist. The persistence of a species is largely influenced by rooting depth, growth habit, tolerance and avoidance of grazing (Blair, 2005; Cullen *et al.*, 2006).

Long-term grazing trials in Australia have described how the persistence of different species interacts with management and climate to determine the resilience of a pasture system. Studies by Hutchinson *et al.* (1998) showed that increasing stocking rate under set stocked conditions reduced the stability and resilience of the grazing system. Figure 2-4 illustrates the relationship between *Phalaris* spp. (phalaris) resilience, stocking rate and climatic events. With each major climatic stress event, such as a drought, the proportions of more productive perennials declined and were replaced by less productive shorter lived annuals and C4 grasses (Hutchinson, 1992; Hutchinson *et al.*, 1995).

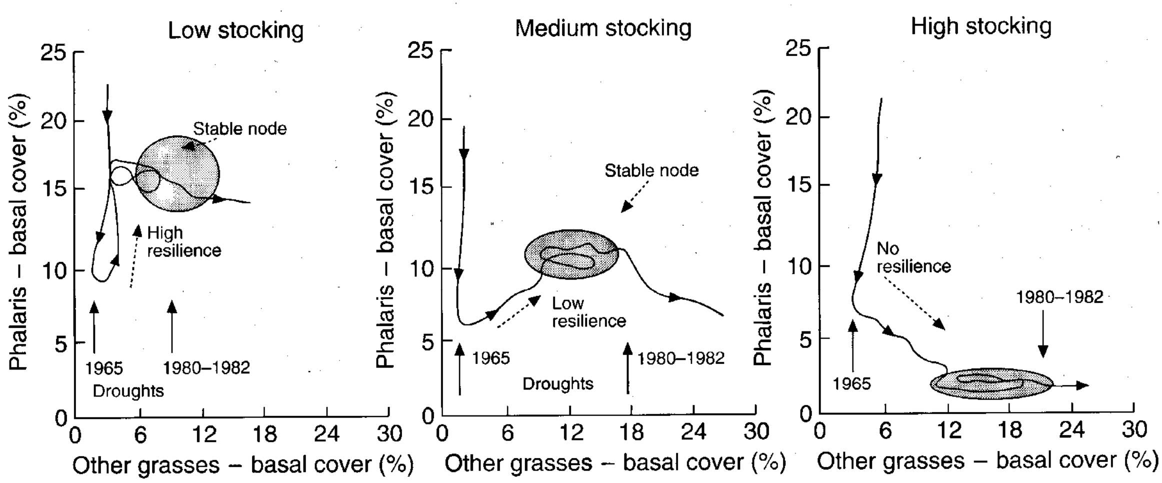

Figure 2-4: The stability and resilience of phalaris pastures from 1964 to 1991 on the Northern Tablelands of NSW (Wolfe and Dear (2001) after Hutchinson (1992)).

Similarly, the persistence of white clover in well-fertilised pastures in the New England region of NSW was found to be governed by interactions between seasonal moisture stress, stocking rate, inter-specific plant competition, and seed pool dynamics (Hutchinson *et al.*, 1995).

Numerous studies and surveys support this concept of both subtle and significant shifts in botanical composition in response to management and climate interactions (Culvenor, 2000; Dowling *et al.*, 2005; Kemp and Dowling, 1991; Reeve *et al.*, 2000). Most large changes in plant populations are episodic and coincide with either favourable growing conditions or periods of stress, with drought and overgrazing during such periods critical. The sensitive balance between the stochastic nature of pasture growth and grazing on pasture persistence was shown by Boschma and Scott (2000) who found that plant mortality was higher under moderate drought than under severe drought, whilst the severity of the defoliation significantly reduced green leaf material and energy reserves for survival. As such, changes in plant energy reserves and basal cover interact closely with persistence, regrowth and potential for soil erosion in grazing systems (Scott *et al.*, 1997).

2.2.4 Growth and production potential

Changes in the growth and production potential of pasture resources occur in response to changes in the soil or water resources available, or due to shifts in the botanical composition. The impact of botanical composition shifts on growth and production potential will depend on the nutritive value and yield potential of the invasive species against those of the resident species.

In the northern parts of the temperate region of south eastern Australia, where more summer rainfall occurs, summer growing species, such as *Bothriochloa macra* (red grass) have been shown to invade sown pastures and lead to reduced seasonal pasture production and feed quality for grazing livestock (Archer and Robinson, 1988; Cook *et al.*, 1978b; Hutchinson, 1992). In the more southern parts of this region, pastures based on sown introduced species are commonly replaced by annual grasses, broadleaf weeds and less erect short perennial native grasses (Wilson and Simpson, 1994).

The progressive loss of sown perennial pastures and legumes in the HRTPZ has led to a decline in pasture productivity, more variable production within seasons and between years, and a reduction in the ability of pastures to counteract soil erosion, acidification and dryland salinity (Dowling *et al.*, 2006).

2.2.5 Cyclical changes in botanical composition

Within a pasture, annual cycles in botanical composition occur as a continually dynamic seasonal process and, over the long term may reflect the dominance of a particular functional group of species (Kemp and King, 2001). The cyclical changes within swards to a particular group of species or plant type will depend on environmental conditions, soil factors and fertility, and interactions with grazing management (Harris, 1978; Pearson and Ison, 1997).

In the New England region, the growth rhythm of different species, in this case *Bothriochloa macra* (red grass) and *Lolium perenne* (perennial ryegrass), had significant effects on the quality and quantity of pasture available for grazing livestock (Cook *et al.*, 1978b). Over time, the cyclical degeneration of sown pastures to summer rain-responsive pastures reduced digestibility and productivity of the pasture (Cook *et al.*, 1978a).

2.2.6 Livestock interactions

Within a pasture sward, different species respond in different ways to grazing pressure through changing growth, quality and persistence (Harris, 2000). Grazing by herbivores is accepted as one of the contributors to heterogeneity in pastures, through patch or selective grazing with the pattern of utilisation being an important contributor to pasture degradation (Parsons *et al.*, 2001; Tainton *et al.*, 1996). The species or mix of species of herbivores utilising the pasture is also accepted as a contributing factor in the selective grazing of plants within a sward (Tainton *et al.*, 1996). The grazing behaviour of different ruminants both spatially, and in their ability to select plant components, interacts with the availability of plants, their components and stage of growth (Harris, 1978; Rutter, 2006).

The grazing behaviour and intake of animals interact with the balance between the amount of pasture on offer and its demand from grazing animals, botanical composition of the pasture and grazing management (Chapman *et al.*, 2007). The most important factors determining selective grazing and the intake of pastures are changes in pasture and species availability as well as pasture quality, particularly its digestibility, which vary both spatially and temporally (Chapman *et al.*, 2007; Rutter, 2006; Watkin and Clements, 1978). The interaction of variations in grazing preference and plant availability during a growing season, even under continuous stocking, provides the opportunity for different species to remain resilient and for legumes to contribute to soil mineral nitrogen (Chen *et al.*, 2002). The distribution of excreta from grazing animals and the impact of trampling may also influence the distribution, competition and growth of different species within a sward (Kemp and King, 2001; Watkin and Clements, 1978).

In Australia, it has been estimated that 60% of sown pastures are grazed by sheep (Menz, 1984). Quigley and Ford (2002) found that the type of sheep production system influences botanical composition. The changes in pasture composition were associated with different grazing pressures at different times of the year and not with different selective grazing patterns. In this study, increased grazing pressure during the autumn tended to lead to the more desirable perennial ryegrass being replaced with annual grasses and broadleaf weeds.

The interaction between the seasonality of pasture utilisation, changes in plant availability and quality, and the cumulative stress or opportunity, including climate and resource availability, placed on individuals within a sward will drive changes in botanical composition (Harris, 1978). In turn, this impacts on livestock production over the short and long term.

2.2.7 Pasture dynamics and sustainability

There are many definitions of sustainability with concepts of intergenerational fairness, efficiency of resource use, weak and strong sustainability in regards to the maintenance of and substitutability between capital stocks (Howarth, 1997; Pearce and Turner, 1990; Stoneham *et al.*, 2003). Sustainability is essentially a social construct (Lambert *et al.*, 1996) and a broad set of concepts (Graham-Tomasi, 1991) which varies in regards to the timeframe over which it is being considered (Scott *et al.*, 2000b). Sustainability does not represent a set of technologies (Graham-Tomasi, 1991), rather a continually evolving goal that involves environmental stability, intergenerational equity and economic efficiency (Pannell and Schilizzi, 1999).

In single paddock or multi-paddock farming systems it is difficult to define whether a system is more or less sustainable than another, although there have been attempts through the use of sustainability indexes (Lambert *et al.*, 1996; Scott *et al.*, 2000b). The externalities of different management and technologies are difficult to define given their interactions at the regional and national scale. Jones and Dowling (2004) suggested that, although tactical grazing rests and increased soil fertility increase the perennial grass composition of pastures, it was not possible to describe the resulting system as sustainable. Without consideration or knowledge of the impact of increased perennials, reduced deep drainage, and erosion on the broader catchment and their implications on the public benefit of increasing the proportion of perennials, the system could not be described as sustainable. Although it could be described as more sustainable than a degraded annual species based pasture.

The following section provides an overview of the impact of technology on pasture production, quality and resource dynamics. The specific technologies reviewed are the use of fertiliser, sown introduced species and grazing management. Other technologies that may be applied to manipulate pasture productivity and composition, such as the use of herbicides and physical alterations to the pasture (for example burning, slashing or chipping), although important in some situations, will not be considered in this thesis.

2.3 Technology and the pasture resource

Throughout the history of pasture and grassland development in Australia, a range of technologies have been adopted that increase the productivity of the pasture resource. Technology such as the introduction of single superphosphate fertiliser and annual legumes, such as *Trifolium subterraneum* (subterranean clover) and *Medicago* spp. (annual medics), dramatically improved the productivity of grazing lands during the first half of the 20th century and led to much broader adoption of sown pastures (Crofts, 1997; Menz, 1984). Apart from basic subdivision fencing to control the broad-scale movement of livestock, the use of this technology to improve grazing management, and subsequently the productivity and sustainability of pasture resources, has only seen broad scale adoption since the 1970s. The use of fertiliser, sown pastures and grazing management have had an impact on pasture dynamics and productivity.

The basic composition of pastures in the HRTPZ has changed in response to:

- the application of fertiliser which promotes soil-fertility responsive species,
- the sowing and introduction of legumes and grasses, and
- overgrazing of pastures during catastrophic events such as droughts, and increased grazing pressure which encourages an increase in grazing-tolerant and resilient species.

If production and profit is the primary focus for a paddock, area of the farm, or the whole farm then the decision to adopt grazing management or other pasture improvement innovations needs to be based on how effectively these tools can be used to develop and sustain a more desirable species mix. Based on the above pressures, the most desirable species mix can be defined as one that optimises long term livestock production, business profit and the sustainability of the grazing system.

The most desirable species mix will vary depending on the livestock production system and the landscape within which the producer operates (Kemp and Michalk, 1994; Wilson and Simpson, 1994). Wilson and Simpson (1994) suggested that the ideal mix of species in high rainfall areas would include legumes or forbs for nitrogen fixation and feed quality, annual species for winter growth, perennial species for extending the growing season and grasses for forage persistence over the dry season. The emphasis required on each of these attributes would determine optimal pasture composition for each region.

Archer *et al.* (1993) hypothesised that it should be possible to combine moderate to high livestock production levels and profit with sustainable pastures given the correct application of technology. In this instance the appropriate grazing management, fertiliser and liming strategy. It has also been substantiated that soil fertility, climate and type of sheep production system are critical in determining the economic benefit of implementing pasture improvement technology (Vere *et al.*, 1993).

Up until the mid-1980s the grazing management of sown, native and improved pastures was thought to have little influence on the productivity of pasture-livestock systems, although it was known to have an influence on botanical composition (Morley, 1968b). The reason for this may have been the frequent sowings of introduced species during the good years of the 1950s, 60s and 70s, which may have masked the problems that have become more apparent since the cessation of the fertiliser bounty in 1974 (Crofts, 1997).

Since the mid-1980s the recognition of pasture degradation has led to grazing management being considered as a complementary tool to sowing pastures and improving soil fertility (Kemp *et al.*, 2000). Given the progression of thought on developing profitable and sustainable pasture systems, there is a need to consider the adoption of technologies, such as sowing pastures, grazing management and improving soil fertility, and how they interact with each other through the botanical composition of pastures. These interactions will also influence the relative economic outcomes resulting from adoption of one or more of these technologies.

2.3.1 Fertiliser application

There exists a large amount of literature showing the benefits to the productivity of the pasture resource from the strategic application of fertiliser (Chapman *et al.*, 2003; Curll, 1977; Gourley *et al.*, 2007; Lewis and Sale, 1994; Robinson and Lazenby, 1976). Historically, the application of phosphate-based fertiliser increased pasture production by up to 10 fold and livestock production by at least 3 fold in the HRTPZ of Australia (Crofts, 1997).

These increases in productivity from the application of fertiliser have occurred due to both increases in the growth rate of newly established introduced, naturalised and native pastures, and improvements in the quality of the feed on offer for ruminant production (Sale and Blair, 1997; Saul *et al.*, 1999). The improved quality of feed on offer is a result of both a change in botanical composition and improvements in the dry matter digestibility and crude protein content of the grasses and legumes found within the sward, as well as the pastures response to utilisation (Saul *et al.*, 1999). The continued application of fertiliser has been shown to be necessary for the persistence and productivity of introduced and desirable species and to slow the ingress of less desirable species (Cook *et al.*, 1978a; Garden and Bolger, 2001).

2.3.2 Sowing introduced species

Historically, the strategic application of fertiliser with the sowing of introduced species has been capable of increasing stocking rates by 5 to 10 times over the carrying capacity of the indigenous native pasture (Pearson and Ison, 1997). In the Northern Tablelands of NSW, pastures sown with introduced species increased their carrying capacity to 20 ewes/ha, whereas formerly 2.5 sheep/ha was the limit on the native un-improved pastures (Wheeler and Freer, 1986). In the Central and Southern Tablelands of NSW, sown pastures are expected to be capable of supporting 10-15 DSE/ha with favourable soil fertility and rainfall, compared to less than 5 DSE/ha on native pastures (Garden *et al.*, 2000a).

The introduction of introduced perennial species, which tend to maintain longer growing seasons, has enhanced seasonal growth rates to increase the pasture feed supply for grazing animals (McPhee *et al.*, 1997; Wilson and Simpson, 1994). In the HRTPZ the introduced species have also replaced predominantly summer-growing native pastures of *Bothriochloa macra* (red grass) and *Aristida ramosa* (wire grass) which maintained significantly lower mean digestibility than the temperate sown species (Blair, 2005; Wheeler and Freer, 1986).

2.3.3 Grazing management

In the simplest of terms, grazing management involves the movement of animals to vary the timing, period, frequency and intensity of grazing and in a broader sense must take into account the interactions between livestock enterprise type and management (Beattie, 1994; Lodge, 1995). Earlier thoughts regarding subdivision and its role in grazing systems was that subdivision or controlled grazing was only critical when it had an impact on livestock production through changes in botanical composition with particular reference to lucerne persistence and minimising weed invasion (Moore *et al.*, 1954; Morley, 1968b). In the past, grazing management research tended to focus on the part of a system that was largely insensitive to the gradual changes in the resource base, that is, livestock production. Many early studies did not take into consideration changes in botanical composition and the degradation of both pasture and soil resources from continuous grazing systems, and as such suggested there was little benefit to be gained from rotational grazing (Lodge *et al.*, 1998).

More palatable species, without the interference of management to control grazing, become selectively grazed by livestock and tend not to persist in pasture systems (Blair, 2005). Grazing management has the potential to significantly increase sown pasture persistence, its productivity and economic performance (Chapman *et al.*, 2003; Lodge *et al.*, 1998).

Through the tactical adjustment of stocking rates and the application of tactical grazing rests producers have the potential to manipulate the persistence and proportion of desirable and introduced perennial grasses in the pasture. This is especially the case when these rests occur during periods of higher vegetative growth, or more importantly during their reproductive and recruitment phases under high soil fertility (Dowling *et al.*, 2005; Dowling *et al.*, 1996; Garden *et al.*, 2000b; Kemp *et al.*, 2000; Waller *et al.*, 2001). In some species, such as phalaris, the impact of tactical grazing rests are critical to their build up of regenerative ability in summer rainfall environments (Culvenor, 2000; Lodge and Orchard, 2000), and their regeneration and tillering in summer-dry environments (Virgona *et al.*, 2000).

The technology of more precise grazing management has large impacts on the utilisation of the pasture resource and its botanical composition. Chapman *et al.* (2003) proposed that producers can use set stocking and rotational grazing methods in temporal and spatial combinations to manipulate pasture mass and composition. The botanical composition of a pasture could be maintained within broad target ranges and achieve both high livestock production and the persistence of desirable species. The application of only set stocking or rotational grazing will put limitations on both pasture and livestock performance (Chapman *et al.*, 2003).

The following section summarises the preceding overview and defines the pasture resource development and management problem for sheep producers in the HRTPZ of south eastern Australia.

2.4 Summary

Historically, the development of the pasture resource in the HRTPZ of south eastern Australia has had major impacts on the productivity and profitability of extensive grazing systems. The technologies of fertiliser application with the concurrent sowing of introduced species have dramatically improved the carrying capacity of pastures in the HRTPZ.

More recently, declining terms of trade and reduced fertiliser inputs have led to both a reduction in the areas being sown with introduced species and the degradation of previously sown pastures. This has led to more emphasis being placed on the use of grazing management to manipulate the productivity and botanical composition of pastures. The continual development and management of the pasture resource is necessary to achieve the objectives of sustainable and profitable grazing systems.

The technologies of fertiliser application, sowing introduced species, and grazing management interact within a dynamic pasture resource. This interaction influences the productivity of the pasture within, and between years. The persistence of desirable species is critical to the levels of productivity that may be generated from the pasture resource.

The decision maker's problem, in developing and managing a pasture resource, is the identification of the optimal combination and application of the technologies available. The issues faced in making these decisions are:

- the strategic and tactical nature of the decisions to apply these technologies,
- the production and economic returns and the risks associated with the decision, and
- the impact of the decision made on the future state of the pasture resource.

Incorporation of these interactions into tactical and strategic decision making, allow many of the economic and sustainability issues surrounding grazing systems, as well as the development of pasture resources, to be considered.

The aim of the following chapter is to provide a review of the different approaches to modelling the pasture resource development problem. Chapter 3 begins by presenting a review of the biophysical models of dynamic pasture resources and discusses the most appropriate pasture models for decision making given the issues faced by the decision makers in the development and management of the pasture resource. The chapter then goes on to review the methods previously applied to the economic evaluation of pasture resource development and concludes with a discussion of the criteria for modelling and finding solutions to the pasture resource problem.

Chapter 3. Review of pasture resource models

3.1 Introduction

Chapter 2 discussed the development of the pasture resource in the HRTPZ of south eastern Australia and the major impacts this development has had on the productivity and profitability of extensive grazing systems. The declining state of the pasture resource, as well as reduced input/output margins for fertiliser and pasture sowing, have led to more emphasis being placed on the use of grazing management to manipulate pasture productivity and botanical composition. These technologies have been shown to interact within a dynamic pasture resource. This interaction influences the productivity of the pasture within, and between years, and the persistence of introduced and desirable species is critical to the levels of productivity that may be generated from the pasture resource.

The decision maker's problem, in developing and managing a pasture resource, is the identification of the optimal combination and application of the technologies available. Pasture resource development is a complex economic and biophysical issue that over the years has been modelled using a range of techniques. This chapter will review some of the different approaches used to model the pasture resource development problem.

In the first section, biophysical models of dynamic pasture resources are reviewed, beginning with an overview of theoretical frameworks for modelling the botanical composition of pastures and rangelands. This is followed by an overview of pasture and livestock systems models and their application in modelling pasture growth under grazing and botanical composition change. A discussion of the most appropriate pasture models for decision making, given the issues faced by the decision maker, in the development and management of the pasture resource follows. In the final section the methods previously applied to the economic evaluation of pasture resource development are reviewed. The chapter concludes with a discussion of the criteria for modelling solutions to the pasture resource problem.

3.2 Biophysical models of dynamic pasture resources

To make decisions regarding the development and management of pastures, there is a need for the outcomes of management and plant competition, on both the current production and future states of the pasture resource, to be predicted. The theoretical frameworks, as well as the models of pasture growth and grazing systems that have been developed are reviewed in the first part of this section. This is followed by a discussion of the applicability of the reviewed frameworks and models to the pasture resource development problem.

3.2.1 Theoretical frameworks for botanical composition change

Theoretical frameworks used to describe and predict changes in the composition of grasslands and rangelands have been evolving since the early 20th century (Harris, 2000). These conceptual models have attempted to describe the ecology of grasslands and rangelands through the use of principal factors that drive the biology of different species and competition between them (Kemp and King, 2001). There are four broadly applicable frameworks that have been described in the literature: the Clements theory of succession, the competition-stress-disturbance model, state and transition models, and the concept of equilibrium and non-equilibrium paradigms. These will now be discussed further.

3.2.1.1 Clementsian model of climax and succession

One of the earliest and most influential models of dynamic pasture resources was proposed by F.E. Clements in 1916 (cited by Humphreys, 1997). It presumes that grasslands (and rangelands) follow a natural successional path to reach a single vegetative climax in equilibrium, specific to each climatic region (Westoby *et al.*, 1989; Whalley and Bellotti, 1997). At this vegetative climax, the resource is in a state of equilibrium and any disturbance, such as grazing, fire or drought, moves the resource to a lower or degraded successional state by going against the natural successional tendency of the grassland (Westoby *et al.*, 1989; Whalley and Bellotti, 1997). Likewise, above-average rainfall or a reduction in grazing pressure accelerates the natural successional tendency of the grassland towards a vegetative climax (Humphreys, 1997).

If increased grazing or drought pressure is applied, equivalent to the rate of successional tendency, the grassland may be maintained in equilibrium at a lower successional state or disclimax. A sustainable stocking rate or yield of livestock product may be achieved at such levels of equilibria as long as the combined pressure or disturbance of drought and grazing is equivalent to the successional tendency (Westoby *et al.*, 1989).

Although widely adopted and accepted in rangeland management in the 1950s and 1960s, significant inadequacies of the model have become apparent (Humphreys, 1997). The most significant is the presumption that the condition of the rangeland or grassland is capable of being continually modified or reversed through the adjustment of stocking rate (Westoby *et al.*, 1989). This has been widely challenged through empirical evidence of the resilience in pastures and ecological systems, and the concepts of ecological thresholds from which recovery is not possible without technological intervention (Harris, 2000; Humphreys, 1997; Westoby *et al.*, 1989).

Another limitation of the successional model of grasslands is the difficulty of defining a single vegetative climax under erratic climates (Humphreys, 1997; Whalley and Bellotti, 1997). There are also potentials for many alternative persistent states due to differences in plant competition in response to initial conditions, positive feedback from fire events in rangelands, and changes in a grassland's vegetative state that lead to permanent changes in soil conditions through soil erosion, structure or chemistry (Westoby *et al.*, 1989).

3.2.1.2 Competition-stress-disturbance (CSD) model

The competition-stress-disturbance or competition-stress-ruderal model proposed by Grime (1977) provides a framework that classifies the adaptive features of plants according to their strategies for ecological success. Three types of plants based on the strategies adopted are: competitive plants (low stress-low disturbance), stress-tolerant plants (high stress-low disturbance) and ruderal plants (low stress-high disturbance). Stress and disturbance are defined as the two primary external factors limiting plant biomass in a habitat. Stress represents any condition that limits production, such as solar radiation, water, temperature, and soil fertility. Disturbance represents the partial or total destruction of plant biomass due to grazing animals, human interference (herbicides, mowing or cultivation), pathogens, wind damage, frosts, desiccation, soil erosion or fire (Grime, 1977).

Competitive plants that exploit conditions of low stress and disturbance utilise common resources between different species, but exclude any potential allelopathic effects that may exist (Humphreys, 1997). Plants exhibiting this strategy tend to maintain the potential for high growth rates with low amounts of resources being invested in reproduction. These plants predominate in undisturbed and productive situations such as lightly grazed pastures (Wolfe and Dear, 2001).

Stress-tolerant plants tend to maintain low growth rates with low amounts of resources being used for reproduction. These plants tend to dominate less disturbed and less productive sites. In contrast, ruderal species tend to maintain short life cycles, put a large amount of resources into flowering and seed production (including hard seededness), and quickly colonise disturbed sites such as heavily grazed pastures or productive cropping land (Humphreys, 1997; Wolfe and Dear, 2001).

In Australian grasslands, pasture species tend to maintain varying degrees of all three strategies, with the range of species maintaining different balances of Competition-Stress-Disturbance strategies and varying both spatially and temporally within any pasture sward (McIvor (1993) cited by Wolfe and Dear (2001)).

3.2.1.3 State and transition model

Westoby *et al.,*(1989) proposed an alternative model known as the state and transition model. This model is now more widely accepted than the successional model and is based on grasslands that are not in equilibrium with their environment (Humphreys, 1997). The model describes the process of change in grasslands between different vegetative states as transitions or sometimes transient states. Transitions are triggered by either natural events, such as drought, floods and fire, or human intervention, such as sowing pastures, fertilisation or changes to grazing management and pressure.

The role of management becomes one of avoiding hazards that move grasslands towards a less desirable state and making the most of opportunities that move the resource towards more desirable states (Westoby *et al.*, 1989; Whalley and Bellotti, 1997).

In order to apply this model to grassland or rangeland management, it is necessary to identify multiple stable states, the transitions that occur between these states, the reasons why they occur, and to quantify the thresholds for change (Humphreys, 1997). It has been suggested that the state and transition model adequately represents Australian grasslands because of the progressive and episodic events that have produced the current mosaic of pasture states (Wolfe and Dear, 2001).

3.2.1.4 Equilibrium and non-equilibrium paradigms

Models such as the Clements successional model and various derivatives are based on the premise of pastures being in equilibrium, either at their previous state or at a new disclimax. Alternatively, evidence suggests that many pasture systems are not capable of reaching a steady state and follow non-equilibrium dynamics (Tainton *et al.*, 1996).

Tainton *et al.*(1996) suggests equilibrium models, such as the successional model, are more applicable to regions with consistent high rainfall. Here, grazing management is suggested as the dominant force in determining changes in competition between species, temporal variability in pasture production, and spatial variability in botanical composition. Non-equilibrium models, such as the state and transition model, are suggested to be most appropriate in semi-arid and arid regions. Here climatic variability is suggested as the driving force behind forage availability and community dynamics with management having only a minor influence on outcomes.

This distinction between equilibrium and non-equilibrium models of grassland systems is likely to be an oversimplification of pasture ecosystems in practice, as evidenced by historical changes in pasture persistence and resilience in the temperate pasture zone. Even in humid environments with generally consistent and predictable climates, such as much of Europe, there is evidence of degradation through the invasion of ageing swards with volunteer grasses such as *Poa* spp., *Agrostis* spp. (bent grass) and *Holcus lanatus* (Yorkshire fog), as well as other broad-leaved species (Sheldrick, 2000).

Evidence suggests that the concept of maintaining pastures in a state of equilibrium can rarely be achieved, and not without further management or technology inputs. Rather it is more applicable to consider pasture or rangeland resources as a dynamic ecosystem that will respond to temporal and spatial management of grazing pressure, and climate (Harris, 2000). Whilst the stability or resilience of a pasture ecosystem may be greater in more predictable climates, both management and climate interact to evolve pasture ecosystems to either a more or less desirable state.

3.2.2 Pasture and livestock system models

Models used to simulate pasture and livestock interactions may be defined as either mechanistic or empirical. The development of mechanistic models is described as component research (Bywater and Cacho, 1994) and tend to describe what is known scientifically about the system of growth within organs and individual plants or animals (Thornley and France, 2007). Empirical models aim to predict the responses of a system using mathematical or statistical equations, with no regard for the processes by which output is obtained from a level of inputs (Cacho, 1997).

Given the nature of the pasture resource, two components exist in modelling the pasture system. These are the modelling of pasture/livestock interactions and the modelling of botanical composition change.

3.2.2.1 Pasture growth under grazing livestock

Numerous pasture growth models exist that incorporate grazing livestock, but the degree of complexity amongst them varies significantly. Models of pasture growth vary from complex mechanistic simulation models (Herrero *et al.*, 2000; Johnson and Parsons, 1985; Moore *et al.*, 1997; Schwinning and Parsons, 1999) to empirical models representing single equations that were fitted to yield data (Cacho, 1993; Harris, 1978). The requirement for different levels of models for pasture growth is dependent on the intended end-use (Cacho, 1993).

GrassGro is a mechanistic simulator of pasture growth that takes into account soil moisture and the interaction of grazing livestock on the selective grazing of sward components. The general structure of GrassGro recognises four functional groups of plants; annual and perennial species, and grasses and forbs (Moore *et al.*, 1997). It models both the components of the sward and the phenological developments of different species. The livestock model within the GrazPlan suite represents the equations described by Freer *et al.* (2007) and is a mechanistic animal biology module (Freer *et al.*, 1997) that predicts livestock growth from inputs describing the herbage quantity and quality.

The model described by Johnson and Parsons (1985) incorporates the physiological features of grass growth as well as herbage removal by grazing livestock. The pasture model takes into consideration the photosynthetic activity of individual leaves and the removal of individual plant components through grazing. This model has also been extended to study the role of spatial models in simulating the heterogeneous effect of grazing livestock on grass growth (Schwinning and Parsons, 1999).

The model of Herrero *et al.* (2000), described as a tropical pasture simulator, is a simple mechanistic model. It incorporates photosynthetic ability, age structures of plant components, uptake and cycling of nitrogen and mineralisation of soil organic nitrogen. In comparison to GrassGro's animal models, those described by both Herrero *et al.* (2000) and Johnson and Parsons (1985) are relatively rudimentary.

The single function equation described by Cacho (1993), uses a sigmoid equation based on three parameters which may be estimated either statistically from experimental data, or from more complex physiological models (Alford, 2004). It is a simple function that may easily be incorporated into grazing models and may be linked to models of sward dynamics under grazing.

3.2.2.2 Compositional change

Mechanistic models of plant competition reduce the growth of competing plants by restricting access to resources, such as water and radiation, on plants within a plant's zone of influence for growth and survival, as well as its relative size in maintaining a higher competitive advantage (Kemp and King, 2001). Thornley and France (2007) suggest that developing detailed mechanistic ecophysiological models for each species within a multi-species sward and putting them together is straightforward in principle, but difficult in practice, with detailed mechanistic models for more than 2 species.

However, several models exist that aim to simulate multi-species pastures. Corson *et al*. (2007) described the use of a 3-species pasture model within a whole-farm simulation model. In the model competition between species is based on competitive interference through the influence of rooting depth on water and nitrogen availability. The results indicated that the predicted net herbage accumulation within a season for 2 to 3 species was ±18% of observed values, and over a 12 month period botanical composition remained within ±15% of observed values.

The GrassGro model (Moore *et al.*, 1997) uses interference competition to adjust dominance between species within a sward. However, this only occurs at two points in the model: light interception by established plants and the withdrawal of moisture from the soil profile (Salmon *et al.*, 2003). Limitations have been identified in the study of pasture management on sward composition through the GrassGro model, even though it has been validated as a capable mechanistic model of plant growth and grazing livestock production (Clark *et al.*, 2000). The inability to simulate sparse clumpy pastures with bare ground was also reported as a limitation of GrassGro (Clark *et al.*, 2000).

The SGS pasture model (Johnson *et al.*, 2003) is a mechanistic biophysical simulation model developed in conjunction with the aggregated data of the Sustainable Grazing Systems Program (Mason and Kay, 2000). It incorporates modules for water dynamics, herbage accumulation and utilisation, nutrient dynamics and animal production. Competition between species within the model is influenced by their relative light interception and root distributions for soil moisture access, and their demand for water and nutrients, which is determined by their growth characteristics. Similar to GrassGro, no formal interspecies competition model or botanical composition model is incorporated.

The GRAZE model, as described by Loewer (1998), represents a selective grazing mechanistic model with multiple species. The approach taken in this model to reflect competition and botanical composition change is the use of 'partial' paddocks which represent the area occupied by each species within the sward. The grazing animal selectively grazes, based on dry matter availability and pasture quality, from all partial paddocks within a paddock, as no physical barriers exist between partial paddocks. The growth of an individual pasture species is simulated daily with the amount of forage available from each species weighted by the area of the paddock it occupies. A key assumption within the GRAZE model is that all species are uniformly distributed and that the proportion of the whole paddock they occupy remains constant, even though the relative quantities of dry matter available change (Loewer, 1998). Competition in the model is assumed to be encapsulated in the net growth figures due to pasture water use within a partial paddock.

3.2.3 Modelling dynamic pastures for decision making

The difficulty with the application of any of the models reviewed above to decision making regarding pasture resource development and management at the farm level is the dynamic nature of pasture ecosystems. The complexity of interactions between species and the variable Australian environment limit the ability of any particular model to explain the dynamics of pastures (Torssell and Nicholls, 1978; Wolfe and Dear, 2001).

However, modification of the state and transition model would enable the incorporation of both strategic and tactical decision making within and between multiple pasture swards commonly found within a farming system. This would be achieved through the definition of thresholds for rates of change in response to different levels of biotic and abiotic disturbance (Kemp *et al.*, 2000). This would provide the model with an infinite number of stable states, or a continuum of different pasture states, from which either negative or positive transitions may occur.

The modelling of functional groups of plants defined in terms of their seasonality of growth, responses to drought and grazing, capacity for livestock production and environmental value (Humphreys, 1997; Kemp and King, 2001) would enhance the applicability of the state and transition model to pasture resource and management decision making systems in broadly different environments. Considering the need for decision making within a complex farming system, modelling of functional groups would adequately differentiate the biophysical and economic outcomes of different management and technology options. Modelling of the intricate biophysical interactions taking place among large numbers of species over time is not justified or possible with any degree of accuracy given our current state of knowledge about how plants interact (Kemp and King, 2001; Thornley and France, 2007). However, adaptation of techniques, as described by Loewer (1998), has the potential to provide significant opportunities for the modelling of multi-species swards.

The concept of modelling different functional groups is also supported by agronomic principles and previous work where ordination of pasture survey data showed similar group interactions (Kemp and King, 2001). The measurement of relative changes between species groups, using the ratio of each species group biomass, has been successfully used to define the variable states of pastures, and transitions between states, in response to both management and climate (Kemp and King, 2001; Westoby *et al.*, 1989). The method of modelling functional groups also provides an opportunity to incorporate desirable native or naturalised species that fit into sown/perennial species functional groups, as some native species in Australian grasslands make significant contributions to pasture productivity, sustainability and profitability (Lodge, 1994).

The complexity of the biological model used to investigate the pasture resource development problem will depend on the identified economic framework that is to be applied. Given the nature of the pasture resource problem, the biological model should be dynamic and capable of simulating pasture production, its response to the grazing of livestock and the application of technologies, as well as adequately reflect the long term changes in botanical composition. However, as the complexity of the biological model increases it becomes more difficult to incorporate it into higher level economic models, that involve optimisation procedures (Cacho, 1998). Simpler models that provide dynamic descriptions of the key variables used in predicting changes in production may be adequate for making management decisions (Woodward, 1998).

3.3 Economic evaluation of pasture resource development

Models used to evaluate the economics of pasture resource development and management can be described according to the form of their biological equations (empirical or mechanistic), whether they make time-dependent predictions (dynamic) and if they include risk (stochastic or deterministic) (France and Thornley, 1984). Economic models may also be categorised based on how they deal with risk (embedded or non-embedded) (Hardaker *et al.*, 2002), and whether they are descriptive (positive) or optimising (normative) in analysing alternative decisions (Cacho, 1997). Various economic models and methods have been used to evaluate the production and benefit from the technologies of fertiliser application, sowing introduced species and the use of grazing management, in combinations or as components (Table 3-1).

A large range of economic tools have been applied to pasture resource development planning problems. In this field of management research the analyses have been predominated by the use of inter-temporal techniques (Rae, 1994), such as discounted cash flows and the optimisation of present values using more sophisticated simulation and mathematical programming techniques. Some studies have used annual gross margins to compare management options, but these have predominantly addressed issues constrained within a production year.

3.3.1 Deterministic and stochastic

In many of the earlier studies, researchers found it appropriate to apply economic tools deterministically through the use of median values for coefficients that determined production responses and economic returns (McIvor and Monypenny, 1995; White and Morley, 1977). Such coefficients included those that determined pasture or livestock production, output prices and botanical composition. Sensitivity testing was used in these analyses to study the impacts of pasture growth and price coefficients. However, given that many of the benefits and costs of applying pasture development technologies occur infrequently, such as the sowing of pastures or the use of tactical grazing rests for pasture persistence, a deterministic approach may lead to biased predictions of the performance of technologies and strategies.

Some of the more recent studies have incorporated the stochastic nature of the production system and commodity markets into analysis of technologies (Cacho *et al.*, 1999; Thornton, 1989). These studies provide superior results to deterministic approaches, as they systematically account for all possible consequences of the strategy being tested (Hardaker *et al.*, 2002). The impact of risk on defining the profitability of dynamic bioeconomic systems has been shown by Cacho *et al.* (1999) in the study of production risk in a grazing systems model. This was empirically supported by Kingwell *et al.* (1993) in a whole-farm planning model.

3.3.2 Descriptive and optimising models

A number of the studies into pasture resource development technologies have dealt with the uncertainty of potential outcomes or the risk surrounding decision making. The approaches that have been applied include non-optimising solution techniques such as stochastic Monte Carlo simulation (Cacho *et al.*, 1999) as well as optimising procedures such as stochastic non-linear programming (Lambert and Harris, 1990), discrete stochastic programming (Kingwell and Schilizzi, 1994) and numerical optimisation search techniques (genetic algorithms) (Barioni *et al.*, 1999).

Non-optimising simulation techniques have been a popular method for modelling pasture resource development and the application of technologies. Simulation models are particularly appropriate when components of models are highly non-linear and exposed to stochastic conditions (Pandey and Hardaker, 1995). In pasture resource development management research, these techniques have been used to evaluate series of experiments or 'what if' scenarios and, on occasions, the results have been assessed for risk efficiency (Cacho *et al.*, 1999). With sufficient numbers of experiments and the use of systematic search procedures it may be possible to locate near-optimal solutions (Pandey and Hardaker, 1995).

Mathematical programming optimisation techniques allow a model, with defined constraints and objective function, to find optimal solutions. In earlier applications of mathematical programming to pasture resource development, the uncertainty was confined to the objective function coefficients (Burt, 1971; Gruen, 1959; Throsby, 1964). More recently there has been an increasing trend to develop embedded risk models, where both constraint coefficients and the objective function are stochastic (Kingwell and Schilizzi, 1994; Pandey and Hardaker, 1995). The problem with programming methods is the 'curse of dimensionality' where the dimension of the decision problem increases with the number of stages or decision points in the sequence, the number of options at each decision point and the number of possible outcomes of each state (Kennedy, 1986). However, this constraint may be addressed through several methods described by Kennedy (1986) and with increased computing capacity (Hardaker *et al.*, 2002).

Alternative search procedures, as used by Barioni *et al.* (1999), are relatively new to the field of agriculture and are becoming more practical, especially with advances in computing capacity, as they require fewer restrictions on the model (Alford *et al.*, 2006). However, Alford *et al.* (2006) found little difference in the optimal solutions between numerical search procedures, such as genetic algorithms and evolutionary algorithms, and grid-search techniques, in a bioeconomic application to net feed efficiency in grazing cattle.

3.3.3 Dealing with Risk

The nature of the risk that affects the decision problem may be categorised as either non-embedded or embedded risk (Hardaker *et al.*, 1991). Non-embedded risk will influence the final outcome but does not influence the plan as it moves towards this outcome. The assumption of this method is that it is realistic to model the system as if all decisions are made initially and that the uncertainty of the decision unfolds over time and determines the outcome. In a system model with embedded risk there are decisions that are made initially and those that are made at a later stage after some of the uncertainty has unfolded. The later stage decisions are influenced by both the initial decisions and revealed uncertain outcomes. Under both non-embedded and embedded risk the final outcomes of all decisions are still regarded as uncertain (Hardaker *et al.*, 1991).

Many of the optimisation models that have been applied to pasture resource development have ignored risk, or not treated it as embedded risk. This is largely due to the complexity of embedding risk into mathematical programming models (Hardaker *et al.*, 1991). Embedding risk into the decision making process enables tactical and strategic responses to uncertainty to evolve over time. Accounting for tactical adjustments to risk has been found to be more important than accounting for a decision makers attitude to risk (Marshall *et al.*, 1997) as, regardless of a producer's attitude towards risk, they still tactically adjust their strategies in response to changing seasonal conditions and prices (Antle, 1983). The exclusion of seasonal variability and tactical responses embedded in a sequential decision making process has been shown to provide incorrect estimates of the economic benefits of a technology involved in complex biological and dynamic systems (Jones *et al.*, 2006a).

3.3.4 Biological models

The majority of models used in assessing technologies for pasture resource development have tended to utilise empirical functions in their biological models to define production responses. This has been due to the often high cost of developing and calibrating the more complex mechanistic models, as well as the data requirements (Pandey and Hardaker, 1995). However, the empirical models applied vary greatly in their sophistication. For example, the dynamic empirical models, which provide time-dependent predictions, are more sophisticated in describing biological processes.

In the context of pasture resource development, some of the previously applied methods have several limitations. The majority of studies that investigated the sowing of species maintained very basic empirical models of carrying capacity and static botanical composition models (Vere *et al.*, 2001). Although, as discussed in Chapter 2, it has been widely acknowledged that the persistence of sown species is highly variable and related to its utilisation under stochastic climatic conditions.

More recently, especially in rangeland studies, the dynamic nature of the pasture resource has been taken into account and has been shown to be significant in its impact on ecological and financial sustainability (Ludwig *et al.*, 2001; Stafford Smith *et al.*, 1995). In contrast, Torell *et al.* (1991) suggest there is little benefit from considering dynamic pasture resources in formulating optimal stocking rate decisions. Their study method predicted changes in the state of the rangeland resource based on the previous year's grazing pressure. The equation of motion used for botanical composition is rudimentary and estimations of grazing pressure and livestock performance were linear in response to changes in feed availability. In addition, some of the data presented by Torell *et al.* (1991) excluded two drought years from the equation of motion which may have changed the relationship, as it has been shown that the majority of shifts in botanical composition occur during periods of climatic and livestock grazing induced stress (Hutchinson, 1992).

Table 3-1: A chronological sample of published studies in the area of pasture resource development and management

Author (s)	**Objectives**	**Decision Variables**	**Biological model**	**Risk framework**	**Analysis technique (s)**
Gruen (1959)	Maximise NPV of annual cash flow over *n* years (life of investment) for pasture improvement plan (FL)	Area, labour, capital	Empirical production Static botanical composition	deterministic	Optimisation: Linear programming
Throsby (1964)	Maximise PV over *n* stages (FL)	Area of pasture improvement	Empirical production Static botanical composition	deterministic	Optimisation: Dynamic Programming
Burt (1971)	Maximise PV of pasture renewal over a planning horizon of *n* years (PL)	Length of current cycle	Empirical production Empirical botanical composition: with age	deterministic	Optimisation: Dynamic programming
White and Morley (1977)	Report annual cash flow and financial position for *n* years (PL)	Stocking rate	Empirical production Static botanical composition	deterministic	Descriptive cash flow Simulation with sensitivity analysis
Godden and Helyar (1980)	Maximise Discounted Net returns for *N* years (PL)	Fertiliser rate	Empirical production response Static botanical composition	deterministic	Optimisation: Heuristic algorithm
Pope and McBryde (1984)	Report NPV for a planning horizon of *T* years (PL)	Stocking rate	Empirical production Empirical botanical composition: with stocking rate	deterministic	Descriptive simulation
Thornton (1989)	Report expected cumulative net revenue over *n* years (FL)	Area of improved pasture, livestock enterprise type	Dynamic empirical production Static botanical composition: restricted persistence	Stochastic climate and price, non-embedded risk	Descriptive simulation
Lambert and Harris (1990)	Maximise PV of expected net worth over 10 years (FL)	Area of pasture sowing, herd size	Empirical production, distribution functions for forage production, Static botanical composition	Stochastic prices and climate, non-embedded risk	Optimisation: stochastic non-linear programming, second degree stochastic dominance
Torell *et al.*(1991)	Maximise NPV over a planning horizon of *n* years (PL)	Annual stocking rate	Dynamic empirical production Dynamic empirical botanical composition	deterministic	Optimisation: non-linear programming (optimal control)
Kingwell and Schilizzi (1994)	Maximise NPV - value of pasture for *n* years (FL)	Crop & single year pasture ley rotation, stocking rate	Empirical production Static botanical composition	Stochastic, embedded risk	Optimisation: Discrete Stochastic programming
Cacho *et al.*(1995; 1999) Finlayson *et al.* (1995)	Report expected annual gross margin (FL)	Stocking rate, forage conservation, management schedule	Dynamic empirical pasture & mechanistic livestock model Static botanical composition	Stochastic, non-embedded	Descriptive simulation; risk efficiency analysis to identify optimal sets of strategies

Table 3-1 continued

Author (s)	**Objectives**	**Decision Variables**	**Biological model**	**Risk framework**	**Analysis technique (s)**
Stafford Smith *et al.* (1995)	Report expected 5th year taxable income (FL)	Stocking rate	Dynamic empirical production Dynamic empirical botanical composition	Stochastic production, prices, & interest, non-embedded risk	Descriptive simulation
Woodward (1996)	Maximise NPV for *n* years (FL)	Multi-paddock fertiliser application	Dynamic mechanistic soil P model Empirical production Static botanical composition	Deterministic	Optimisation: optimal control
Moore *et al.* (1997)	Report gross margins & probability distributions for *n* years (PL)	Multiple combinations of livestock enterprise type & management	Dynamic mechanistic pasture, livestock and interference based botanical composition models	Stochastic climate, non-embedded risk	Descriptive simulation
MacLeod and McIvor (1998)	Report accumulated net cash flow for *n* years (FL)	Pasture development systems	Empirical production Static botanical composition	Deterministic	Descriptive simulation
McCall and Clark (1999) McCall *et al*. (1999)	Maximise annual gross margin (FL)	Grazing management, feed inputs, stocking rate calving date, lactation length	Dynamic empirical production Static botanical composition	Deterministic	Optimisation: Linear programming
Barioni *et al.* (1999)	Maximise expected annual gross margin (multi-PL)	Monthly herbage allowance, nitrogen application, lamb drafting weight, winter supplementation	Dynamic empirical production Static botanical composition	Stochastic pasture growth Embedded risk	Optimisation: genetic algorithm
Scott and Cacho (2000)	Report net worth for *n* years (FL)	Discretionary & non-discretionary fertiliser	Dynamic empirical production Static botanical composition	Deterministic	Descriptive simulation
Scott *et al.* (2000a)	Report pasture sowing NPV, IRR, BCA over *n* years (PL)	Stocking rate post-sowing	Empirical production Static botanical composition	Deterministic	Descriptive simulation
Vere *et al.* (2001)	Maximise DCF/BCA for a period of 10 years (PL)	Different pasture systems and stocking rates	Empirical production Static botanical composition	Deterministic	Optimisation of stocking rate (Linear programming); descriptive simulation
Kaine and Tozer (2004)	Report expected cash flow, biological resilience over 10 years (multi-PL)	Stocking rates, rotation period	Dynamic empirical production Dynamic botanical composition	Stochastic pasture growth, non-embedded risk	Descriptive simulation
Jones *et al.* (2006b)	Maximise NPV for planning horizon of *T* years (PL)	Tactical rests, stocking rate, pasture sowing, fertiliser	Dynamic empirical production Dynamic botanical composition	Deterministic	Optimisation: Dynamic programming

Definitions: NPV = Net Present Value; PV = Present Value; IRR = Internal Rate of Return; BCA = Benefit Cost Analysis; DCF = Discounted Cash Flow; FL = Farm Level; PL = Paddock Level

Several mechanistic simulation models have been developed and applied to various pasture resource development studies. Although these models have been developed for the study of complex plant and livestock interactions in grazing systems, their complexity has largely restricted these models to descriptive simulations. Examples of this include the use of Stockpol (Marshall *et al.*, 1991) to study pasture improvement (Webby and Sheath, 2000), GrassGro (Moore *et al.*, 1997) to study optimal stocking rates (Alcock, 2006), and BREW (White *et al.*, 1983) to study changing pasture seasonal growth characteristics on the profitability of a sheep grazing system (White, 1988).

Historically, a significant component of management systems research into pasture development has been the attempt to derive a method that defines the optimal stocking rate for an environment, farm, or paddock. Earlier studies focused on responses in animal production as the primary indicator of optimal utilisation of pasture resources. Some notable empirical analyses debated the relationship between livestock production per head, per hectare and stocking rate (Chisholm, 1965; Jones and Sandland, 1974). Morley (1968a) and White and Morley (1977) used deterministic simulation to identify optimal stocking rates based on identifying the maximum return on investment or that which generates the largest cash flow.

More recently, Rickert (1996) suggested that the maximum sustainable stocking rate occurs at the point prior to any pasture degradation. This level of stocking rate is proposed to be higher than the economic optimum stocking rate, which is the point when the maximum gross margin occurs, after taking into account curvilinear variable costs and changes in per head production (Jones and Sandland, 1974). Defining an optimum stocking rate in a pasture system is difficult when stocking rate decisions are made well in advance of the uncertain outcomes of pasture growth. In addition, if a biophysically optimum stocking rate was known in advance, it would need to be adjusted for not only the input and output price ratios, but also based on other criteria consistent with the manager’s preferences (Seligman *et al.*, 1989).

3.3.5 Bioeconomic models for pasture resource development

Bioeconomic modelling has been described as a particular form of management research or as a component within a whole farming systems research framework (Cacho, 1997). Bioeconomic models blend mathematical models that define biological processes within a production system with economic models used to define the benefits and costs of the system.

Pastures are complex and dynamic biological systems. They respond to applications of technologies such as fertiliser, sowing of introduced species and grazing management. The benefits from the applications of these technologies vary depending on the current state of the pasture resource, interactions between the technologies, and risk. The benefits are expressed through the consumption of the pasture resource by grazing livestock to produce meat and wool.

A bioeconomic model that can address the pasture resource development and management problem must adequately reflect the interactions between the dynamic components of the system under stochastic environmental conditions and the effect of technologies. The model describing the biophysical system must be dynamic and include pasture growth, botanical composition and livestock grazing and production. From this review, several models have met these criteria. However, the substantial limitation in the majority of these models is their inability to adequately model botanical composition change over time (Clark *et al.*, 2000; Kemp and King, 2001).

Given that technologies are applied at different frequencies in time, the economic framework that is required needs to take into account the sequential nature of the decision-making process for managing the pasture resource. There are inter-temporal trade-offs due to the effect of the changing condition of the pasture resource which will affect current and future production and income. There is also the potential for capital investment to re-sow a degraded pasture resource, or invest in supplementary feeding to substitute for the consumption of pasture.

Experimental simulation using a bioeconomic model with the desired criteria would allow thorough investigation of the interactions between the technologies and the dynamic nature of the pasture resource under stochastic and deterministic conditions. The application of systematic search techniques may also locate near-optimal solutions (Pandey and Hardaker, 1995).

3.4 Summary

This chapter has reviewed the different approaches to modelling the pasture resource development problem. The state and transition model (Westoby *et al.*, 1989) appears to be the most applicable theoretical framework for the modelling of dynamic pasture resources. The applicability of such a model would be enhanced through the use of different functional groups within the sward. The scope for biological modelling of these multi-species functional groups with complex biophysical models is, however, limited. The method described by Loewer (1998) may provide some opportunities for robust and dynamic pasture composition modelling in the HRTPZ.

The nature of pasture resource development requires a bioeconomic framework to address the problem. The framework needs to represent the dynamic interactions between the state of the pasture resource, the application of different technologies, and a stochastic climate. To improve the efficiency of the grazing business and improve the information for decision making in a risky environment requires the consideration of the dynamic nature of the pasture resource.

In many previous studies, trade offs have existed between model accuracy and detail in terms of botanical composition, and its incorporation within economic frameworks. Incorporating a bioeconomic simulation model into a mathematical programming or numerical search technique would enable optimal solutions to be found. Embedding of the risks associated with the application of pasture development technologies into the decision making process would also enable the optimisation of both tactical and strategic decisions.

The following chapter details the bioeconomic framework proposed for this study. Conceptually, the framework is capable of addressing the limitations of previous studies. It will also provide further insight into the interaction between dynamic pasture resources and the technologies available to producers for enhancing the sustainability, productivity and profitability of their grazing systems.

Chapter 4. Bioeconomic framework

4.1 Introduction

The previous chapter provided a review of the different approaches to modelling the pasture resource development problem. The review suggested that the most appropriate theoretical framework for modelling of dynamic pasture resources was based on the state and transition model (Westoby *et al.*, 1989). Its applicability would be enhanced through the use of modelling of different functional groups within the sward. This is because the scope for biological modelling of multi-species swards with complex mechanistic models is limited.

The development required to improve the information available for decision making includes a bioeconomic framework that adequately represents the dynamic interactions between the state of the pasture resource, the application of different technologies, and a stochastic climate. This requires the integration of a bioeconomic simulation model into either a mathematical programming or numerical search technique model to find optimal solutions to the pasture resource development problem. To further enhance the optimisation of both tactical and strategic decisions, the risks associated with the application of pasture development technologies should be embedded into the decision making process.

This chapter presents an outline of the bioeconomic framework proposed to solve the pasture resource development problem. It begins by defining the structure of the pasture development problem. This is followed by a conceptual outline of the bioeconomic framework applied in this study. The sources of data for the case study application of the bioeconomic model are also presented.

4.2 Defining the structure of the pasture resource problem

The decisions for developing and managing the pasture, through the use of alternative technologies, occur at different stages over the planning horizon. The sowing of introduced species is a strategic decision, whereas the application of fertiliser tends to operate at a more tactical level between production years in most grazing systems. Grazing management, which includes both the variables of stocking rate and time livestock spend on a paddock (and the corresponding rest periods from grazing), operates at a tactical level over periods of a year in set stocking systems to days in intensive rotational grazing systems.

In evaluating the benefits of each technology, consideration must be given to the interactions between the technologies and the sources of exogenous risk to the grazing system. These interactions are expressed in the short term through the production of pasture, and in the longer term through the botanical composition of the pasture. As such, there are inter-temporal trade-offs between the productivity of a grazing system and the persistence of desirable species comprising the pastures.

The process represents a complex and dynamic decision problem, in that it involves multiple and conflicting objectives of pasture resource production, persistence, livestock productivity and profit. The decision problem involves a dynamic and risky environment, with investments in sowing pastures, soil fertility build-up (and depletion) and grazing management being made in response to uncertain climatic conditions and the state of the pasture resource. This represents a sequential decision problem (Figure 4-1), where producers manage the grazing system by making both tactical and strategic decisions at intervening states of the system as uncertainty unfolds (Trebeck and Hardaker, 1972). Climate risk, which influences the state of the grazing system and the pasture resource, represents embedded risk (Hardaker *et al.*, 1991).

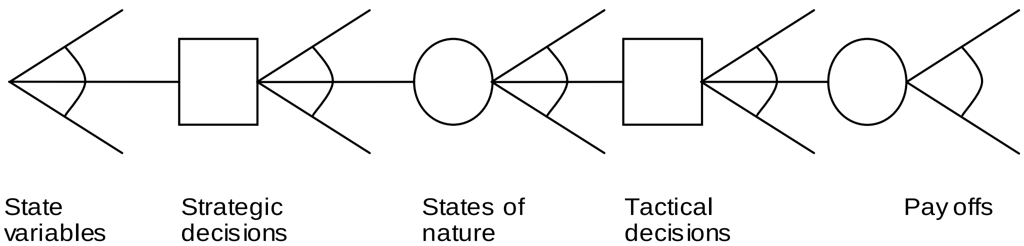

Figure 4-1: Sequential decision making. Adapted from Trebeck and Hardaker (1972).

The initial state variables of the system are represented by the state of the pasture resource in terms of both its herbage mass and botanical composition, as well as the fertility of the soil. In a multi-paddock grazing system, a mosaic of pasture states and soil fertility conditions would exist. The strategic decisions available to the producer at this stage include the re-sowing of a pasture with desirable species.

Multiple states of nature and tactical decisions that respond to the current condition of the system may occur between the strategic decision and the final pay-off from the grazing system. The tactical decisions include the application of fertiliser and grazing management. The economic returns from each strategic decision/state of nature/tactical decision sequence are stochastic and affected by the variability of climate during the period between tactical decision periods.

Within each stage of the sequence, the optimal decision will be based on the current state of the pasture resource and the expected returns from all future stages, which are influenced by a stochastic climate. As such, all possible stages of the sequential stochastic decision problem must be solved in order to solve the first stage decision (Trebeck and Hardaker, 1972).

The identification of optimal development paths in the pasture resource problem will require the consideration of embedded risk. That is, the development plan will need to be adjusted over time depending on uncertain events/states that influence economic returns and occur as the farm plan develops (Hardaker *et al.*, 2002). The sequence of decisions with embedded risk may be solved using stochastic programming methods (Hardaker *et al.*, 1991). Basic risk programming, which deals with non-embedded risk, such as linear programming, does not adequately define the reality within the pasture resource system and problem.

The working hypotheses for the development of the bio-economic framework that forms the basis of the present study are:

1. accounting for a stochastic climate and dynamic relations in pasture composition will improve our estimation of the benefits and costs associated with pasture development technologies; and
2. the integration of a dynamic pasture resource simulation model and a stochastic dynamic programming model, used for determining optimal tactical and strategic decisions will improve the management and development of the case-study grazing system.

In the following section, a conceptual framework is detailed that aims to solve the pasture resource development problem and investigate the working hypotheses.

4.3 Conceptual framework

A bioeconomic framework has been designed to improve farm decision making under risk where there are interacting technologies in a dynamic environment. The framework combines both simulation and mathematical programming techniques to study the benefits and costs of the three technologies described for the development of the pasture resource in sheep meat and wool production systems (Figure 4-2).

The framework is unique in that it takes into account the impact of embedded climate risk, technology application and management on the botanical composition of the pasture resource over time which, in turn, impacts on the optimal development strategies. This has been achieved through the development of a dynamic pasture resource development (DPRD) simulation model which is integrated into a seasonal stochastic dynamic programming (SDP) framework.

The DPRD simulation model operates at the paddock level on a daily time step and contains 5 sub-models accounting for soil fertility, pasture growth, botanical composition, sheep meat and wool production, and financial performance. A detailed description of the mathematical model and its components are presented in Chapter 5.

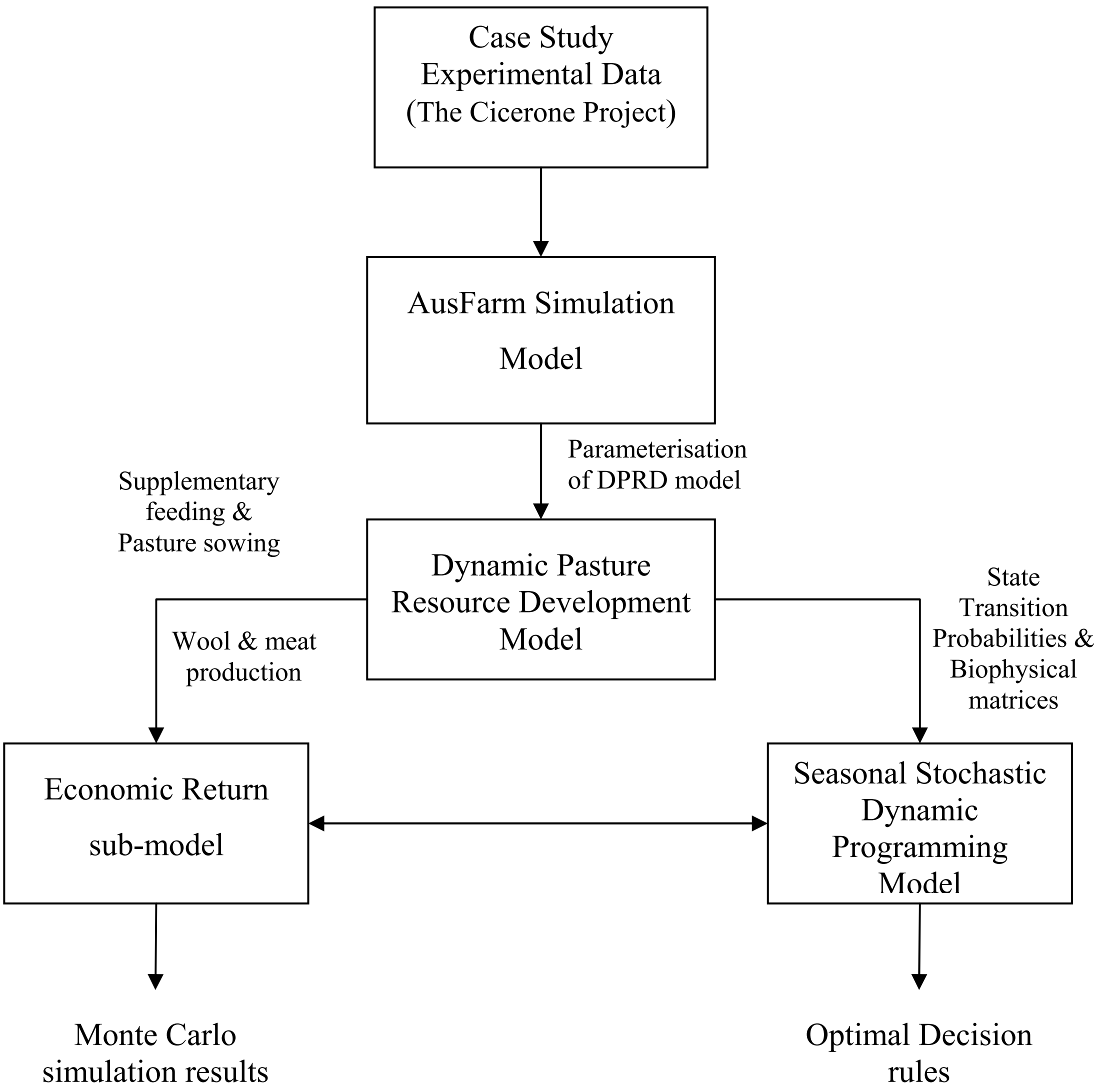

Figure 4-2: Bioeconomic modelling framework

Monte Carlo simulation procedures, detailed in Chapter 6, are used to demonstrate and evaluate the DPRD simulation model. This descriptive simulation framework is used to investigate the expected production outcomes, economic performance and risks associated with pasture improvement technologies and stocking rate policies over a 10 year planning horizon. The outputs from the Monte Carlo simulation experiments are also used to investigate the benefits and costs of incorporating a stochastic climate and dynamic botanical composition model into the pasture resource problem.

To solve the tactical and strategic decision sequence the DPRD model is then embedded into a seasonal SDP framework, as detailed in Chapter 7. The DPRD model, through Monte Carlo simulation procedures is used to generate state transition probability matrices and biophysical output matrices. These matrices are used in multiple SDP runs to investigate the effects of different outputs of sheep production systems (wool/meat), pasture sowing costs and discount rates on optimal pasture resource development decision rules.

The DPRD model is parameterised using experimental simulation output from a highly complex mechanistic grazing systems model, *AusFarm* (CSIRO, 2007). Highly complex biophysical models, such as *AusFarm*, that attempt to model biological systems as closely as possible, are not well suited to become part of an economic optimisation model (Cacho, 1998), because of the time required to solve each simulation run. Hence there is a need to achieve a balance between complexity in the biophysical model and adequacy of information for improved decision making. Achieving this compromise was the driving factor behind the design of the DPRD model and its parameterisation with *AusFarm*.

The *AusFarm* program was calibrated to field experimental data accessed from the Cicerone Project’s farming systems experiment. This experiment was set up as whole farmlet management systems to study the long term profitability of three different input and grazing systems near Armidale NSW, and operated over the period of 2000 to 2006 (Gaden *et al.*, 2004). Further details of the calibration process are described in Chapter 6. The initial state of pasture and soil resources reported at the start of the Cicerone Project experiment form the basis for the case study application of the bioeconomic framework in the HRTPZ.

4.3.1 Bioeconomic modelling process

Although the pasture growth and grazing model operates at a daily time step, the critical decision points in the DPRD and SDP models, operate at a seasonal time-step with respect to tactical and strategic decision making. Parameters for net pasture production, quality and botanical composition are varied between seasons but remain constant within a season. Four seasonal phases during a production year were identified arbitrarily based on a combination of the phenology of the dominant species, their expected variations in pasture growth and quality, and the reported critical points for grazing rest that have been identified through field research (Chapter 2: sections 2.2 and 2.3).

The seasonal decision stages were a compromise that enabled the integration of the DPRD model into the SDP model. Grazing management can operate over periods ranging from days under intensive rotational grazing systems to a whole year under set stocked systems. Therefore it would be desirable to have short decision intervals, where stock can be moved in and out of paddocks (Cacho *et al.*, 1995), but allowing for shorter decision intervals would make the SDP model too complex to be solved. The four seasonal stages are still able to replicate the tactical decisions of stocking rate or complete grazing rests. This compromise maintains the broad assumption that the seasonal adjustment of stocking rate represents tactical adjustments to grazing management.

The optimisation of the pasture resource problem at the paddock level and with four seasonal stages under flexible stocking rate conditions, required flock structure to be flexible. A representative merino wether enterprise was modelled as the base case to represent the impact of different technologies and management on the production of sheep grazing systems. The purpose was to replicate the harvesting of pasture for the production of wool and sheep meat. This structure assumed no changes in capital value between the start and end of the season, with the economic return being the net gross margin return calculated using net weight gain or loss and the quantity and quality of wool produced within that season.

This process allowed complete flexibility with respect to stocking rate and pasture utilisation which is unconstrained by flock structure. To indicate the impact of different sheep production systems on the optimal pasture development and management strategies, a method of adjusting the relative value of wool and meat produced by the base wether enterprise (which has an emphasis on wool production) was developed and applied in the SDP model. This enabled the representation of flock structures that produce mainly meat or wool/meat in near equal proportions.

4.3.2 *Incorporation of risk*

All producers of agricultural products are exposed to exogenous variables that influence their profitability. The natural phenomenon of climate variability exposes producers to production risk, and market fluctuations expose producers to economic risk (Antle, 1983). In the HRTPZ, commodity price fluctuations and variable climatic conditions have also been identified as the two main sources of risk faced by sheep production businesses (Counsell and Vizard, 1997).

Much of the literature regarding the choice between risky alternatives in agricultural production is oriented towards 'expected utility theory' (Hardaker *et al.*, 2002; Rae, 1994). This assumes that producers will aim to maximise their personal satisfaction or 'expected utility' based on their personal utility function, which depends on their level of risk aversion. Antle (1983) suggests that, because risk affects the economic efficiency of all producers, regardless of their level of risk aversion, dynamic risk-neutral models are more useful than static risk-averse models for understanding the role of production risk in decision making.

A method which does not require assumptions of risk aversion levels to be made, is applied to the 10-year Monte Carlo simulations of the DPRD model (Chapter 7). This is done through the derivation of a risk-efficient frontier (Cacho *et al.*, 1999). Different combinations of technologies and management strategies are evaluated based on expected returns and risk, to identify optimal sets of risk-efficient strategies. In this case, the risk is non-embedded as the results of the simulations describe the risky consequences of the decisions applied before any risky states occur.

As discussed in the previous chapter, embedding risk into the decision-making process enables tactical and strategic responses to uncertainty to evolve over time. Exclusion of seasonal variability and tactical responses embedded in a sequential decision making process has been shown to provide incorrect estimates of the economic benefits of a technology involved in complex biological and dynamic systems (Jones *et al.*, 2006a).

In the analysis presented in Chapter 6, price risk is not included as the main focus is on demonstrating and validating the DPRD model. However, price risk was considered and evaluated using Monte Carlo simulation techniques in a preliminary investigation into the role of sown pastures in pasture resource development (Behrendt *et al.*, 2006).

In this study, uncertainty surrounding commodity price fluctuations is assessed through a sensitivity analysis approach. This is represented by the value adjustment factors used in Chapter 7 for the investigation of the impacts of different sheep production systems on optimal pasture resource development decisions.

4.3.3 Modelling botanical composition of the pasture resource

In mechanistic pasture or crop models, botanical composition is generally modelled on the assumption of competitive interference for resources such as water, light and occasionally nutrients. The limitation of this method applied to pasture resource development is that it does not cope well with simulating more than two competing species. Furthermore, there is the underlying assumption in some models that species persist indefinitely and homogenously occupy space within the sward. Rather than modelling explicitly how plants interact, the response of plants to changes in their environment can be represented by the net ability of a group of plants to capture resources and compete (Kemp and King, 2001). For decision making, the modelled changes in botanical composition need to respond over the long term and represent the changes in the basal area of competing species, especially in response to sporadic events such as droughts (Jones *et al.*, 1995).

The empirical pasture composition sub model within the DPRD model adapts the method proposed by Loewer (1998) on the use of 'partial' paddocks. In Loewer's GRAZE model it is assumed that each species is uniformly distributed throughout a paddock and that the initial area they occupy remains fixed. However, the dry matter availability of each species is varied through selective grazing and independent species growth. In the DPRD model the space occupied by species is assumed to be variable and respond to climate, management and inputs. This enables the cycle of pasture degradation to very low populations of desirable species, followed by re-sowing, to be modelled adequately. It also enables the potentially positive response of the pasture resource to tactical grazing management and fertiliser inputs to be modelled.

This empirical modelling approach is analogous with in-field measures of basal areas of pasture species and is also similar to the methods of basal area adjustments applied in some rangeland models (Stafford Smith *et al.*, 1995). Separation of pasture yield and basal area of different species groups is also justified as basal area provides a more meaningful and stable indicator of ecological or botanical composition change than pasture yield (Cook *et al.*, 1978b).

The population of desirable species in the sward is modelled by using differential equations describing population growth and the impact of harvesting. These represent the pasture resource as an exploitable renewable resource as described by Clark (1990). In the DPRD pasture composition sub-model, a logistic growth model is used, as described in Chapter 5. This empirical method encapsulates the concept of state and transition models of rangelands (Westoby *et al.*, 1989), with the benefit of an indefinite number of pasture states and responses to climate, grazing and input factors. The modified partial paddock approach developed also allows the desirable components within the sward to increase their basal area over time, even when no re-sowing occurs. This assumption is supported by field evidence, where degraded sown pastures increase their basal areas under conditions of high soil fertility and in response to grazing rests, with a consequent increase in the proportion of the sward that is occupied by desirable native or introduced species (Cook *et al.*, 1978a; Garden *et al.*, 2000b).

In the DPRD model, two pasture populations are defined. They represent desirable and undesirable species groups. The two groups have different growth potentials and seasonal patterns, different responses to improvements in soil fertility and different dry matter digestibilities. All of these factors combine to influence the potential carrying capacity and livestock production. Data from individual species measured in the Cicerone farmlet experiment were classified and clustered into species type and growth pattern to identify representative species for modelling in the more complex *AusFarm* model. This process is supported by Kelly and Basford (2000) who described the process of grouping species on a functional basis so that the difference between species within groups is less than between groups. This process also allows the definition of changes in the quality of the pasture resource through changes in the total amount of herbage available to grazing livestock.

4.3.4 Modelling pasture growth

There are a number of mechanistic pasture growth models available (Thornley and France, 2007) as well as single function models which account for net pasture production (Woodward, 1998). Previous studies and reviews have shown that simple models of pasture growth may adequately represent the changes in net pasture production (Alford, 2004; Cacho, 1993). These simpler models may be adequate for making management decisions when they provide dynamic descriptions of the key variables used in predicting changes in production (Woodward, 1998).

The sigmoidal pasture growth curve (Cacho, 1993) is applied in the DPRD model as its parameters can be determined using complex biophysical models such as *GrassGro* (Alford, 2004). An equation that relates pasture growth to pasture mass, LAI or height, coupled with descriptions of seasonal changes in pasture quality is all that is required in this study as the animal-plant interactions are the main concern in the DPRD simulation model.

To enable incorporation into the SDP framework, the strategic decision of re-sowing a pasture has been applied as a decision option at each seasonal step. The re-sow decision option is structured to ensure that stocking rates remain at zero head per hectare in the season of establishment. However, as the sown pasture enters its second season, the optimisation process determines future stocking rates.

4.3.5 Modelling grazing livestock

To adequately represent the production of wool and meat, the livestock sub-model needs to be capable of responding to changes in the available pasture mass and changes in botanical composition with its inherent effect on feed quality. A more mechanistic approach was taken in developing the DPRD livestock sub model, with much of it based on the equations used in the *GrazPlan* suite of models (Donnelly *et al.*, 1997; Freer *et al.*, 2007). This was required to ensure there were adequate feedback mechanisms between the selective grazing by livestock and changes in botanical composition.

In this sub model, grazing sheep are capable of selectively grazing between the desirable and undesirable partial paddocks and between the digestibility pools of dry matter available to them within each partial paddock. This selective grazing is based on the assumption that grazing sheep will aim to maximise their intake based on the dry matter digestibility of plants. Such models, that base diet selection between species or species groups on the digestibility of the dry matter, have been validated by research into the influence of pasture degradation on diet selection and livestock production (Chen *et al.*, 2002).

Supplementary feeding is also available as a means of substituting for the consumption of pasture dry matter. The supplementation rules applied are minimalist in approach as the key area of study is the use of tactical grazing and strategic pasture improvement on the pasture resource.

The issue of flock structure was also separated from the optimal management of pasture resources as this would require the modelling of a complex multi-paddock system with constraints imposed on the application of tactical grazing management. In principle, there is no difference in selective grazing habits between different classes of sheep (Quigley and Ford, 2002). However, the seasonal consumption of different quantities of pasture varies with sheep class and enterprise systems and has been found to influence botanical composition (Quigley and Ford, 2002). Hence emphasis on the value of different products, wool or meat, is expected to influence optimal pasture development and management. This is investigated in the SDP framework described in Chapter 7.

4.4 Sources of data and application of the bioeconomic framework

To derive models of botanical composition in pastures, long term grazing trials are required due to the dynamic and often slow changes in botanical composition (Dowling *et al.*, 2005; Jones *et al.*, 1995). However, data from short term grazing trials may be used to derive trends to answer 'what if' questions as long as the model adjusts composition in response to sporadic events, such as the effect of droughts on soil moisture (Jones *et al.*, 1995).

The Cicerone Project's farmlet experiment was set up to investigate the sustainability and profitability of three farm management systems in the New England region of New South Wales (Gaden *et al.*, 2004; Scott, 2002). The experiment consisted of three farmlets of approximately 50 hectares each and ran over the period October 2000 to December 2006. Farmlet A represented a high input flexible grazing system; Farmlet B represented a moderate input system with flexible grazing (described as typical district practice); and Farmlet C represented an intensive rotational grazing system with the same moderate inputs as the typical practice farmlet (Farmlet B) (Appendix A and section 6.2).

Results from the experiment indicated that botanical composition in all of the farmlets changed in response to the level of system inputs and the imposed management (Scott *et al.*, 2005). Over the period of the experiment, there was a general decline in the proportion of introduced species in the sward with a corresponding increasing proportion of native species. The data available from the Cicerone Project farmlets, which includes biophysical, managerial and economic data, provide a sound basis for the calibration and demonstration of the *AusFarm* and DPRD models.

4.5 Summary

The pasture resource development problem may be structured as a dynamic sequential decision problem. The producer is exposed to both production and marketing risks. These risks impact on all stages of the decision sequence and influence the expected future states of the pasture resource and the economic returns from both strategic decisions on the sowing of pastures and fertiliser applications, and tactical decisions on grazing management.

A bioeconomic framework has been developed that involves the construction of a dynamic pasture resource development model and its integration into a seasonal stochastic dynamic programming model. The seasonal biophysical simulation model operates at the paddock level on a daily time-step. The model simulates the dynamic nature of the pasture resource with two partial paddocks containing the desirable and undesirable species groups. These partial paddocks represent the areas of the sward occupied by either species group. Each species group represents sub-groups of species allocated based on their functional characteristics. The groups are grown separately in their respective partial paddocks but are offered collectively to grazing livestock which graze selectively according to the relative herbage mass and quality available in either partial paddock at any point of time.

The seasonal stochastic dynamic programming framework is used to solve the sequential decision problem and identify optimal decision rules and paths arising from different initial states of the pasture resource. The programming model embeds the production risk caused by variable climatic conditions into the decision making process between tactical and strategic decision points.

The dynamic pasture resource development model is parameterised using a complex mechanistic biophysical model, *AusFarm*, and calibrated using data from the Cicerone Project's experimental farmlets.

The next chapter will provide a detailed description of the dynamic pasture resource development model. Chapter 6 will discuss how the DPRD model is parameterised and validated through the use of a Monte Carlo simulation framework. The integration of the DPRD model into a stochastic dynamic programming model to solve and identify optimal tactical and strategic decision rules will be presented in Chapter 7.

Chapter 5. A dynamic pasture resource development framework for sheep production systems

5.1 Introduction

This chapter describes a dynamic pasture resource development model which simulates pasture resource development and management at the level of a single paddock. The components of the model are derived from a range of previous studies into pasture and population dynamics, including competition within the sward structure and growth, sheep production and economics. The calibration and validation of the model is presented in detail in Chapter 6. In Chapters 6 and 7 the model is applied to a case study region in the high rainfall temperate perennial pasture zone of south eastern Australia. The described framework has broad applicability to improve tactical and strategic decision making with respect to investing in pasture improvement technologies and the utilisation of the pasture resource.

5.2 The Dynamic Pasture Resource Development model

The objective of the Dynamic Pasture Resource Development (DPRD) model is to provide a framework that is capable of simulating a dynamic pasture resource under stochastic climatic conditions. The methods applied and developed for the DPRD model simulate changes in botanical composition in response to stochastic pasture growth and its utilisation by grazing livestock. Within a Monte Carlo simulation framework this enables the investigation of the economics and risks associated with pasture improvement technologies, supplementary feeding and stocking rate policies, as described in Chapter 6. Embedding the DPRD model in a stochastic dynamic programming framework allows the optimisation of a dynamic and stochastic resource problem, as detailed in Chapter 7.

The method applied in the DPRD model incorporates two stages to modelling the change in pasture biomass in a season and between seasons, as described in Chapter 4. Figure 5-1 illustrates a conceptual outline of the DPRD model at the paddock level and Table 5-1 presents the major components of each of the sub-models.

In a single production year four representative seasons have been identified that relate to tactical and strategic decision points within a grazing system, the biophysical characteristics of plant growth, and botanical composition change within pastures. In each season pasture growth and consumption by grazing livestock operate on a daily time step. Between seasons the relative areas occupied by desirable and undesirable species groups within the whole sward are modelled using exploited population growth modelling (Clark, 1990).

Table 5-2 gives the estimated and reported values of parameters and constants introduced in each of the sub-models detailed.

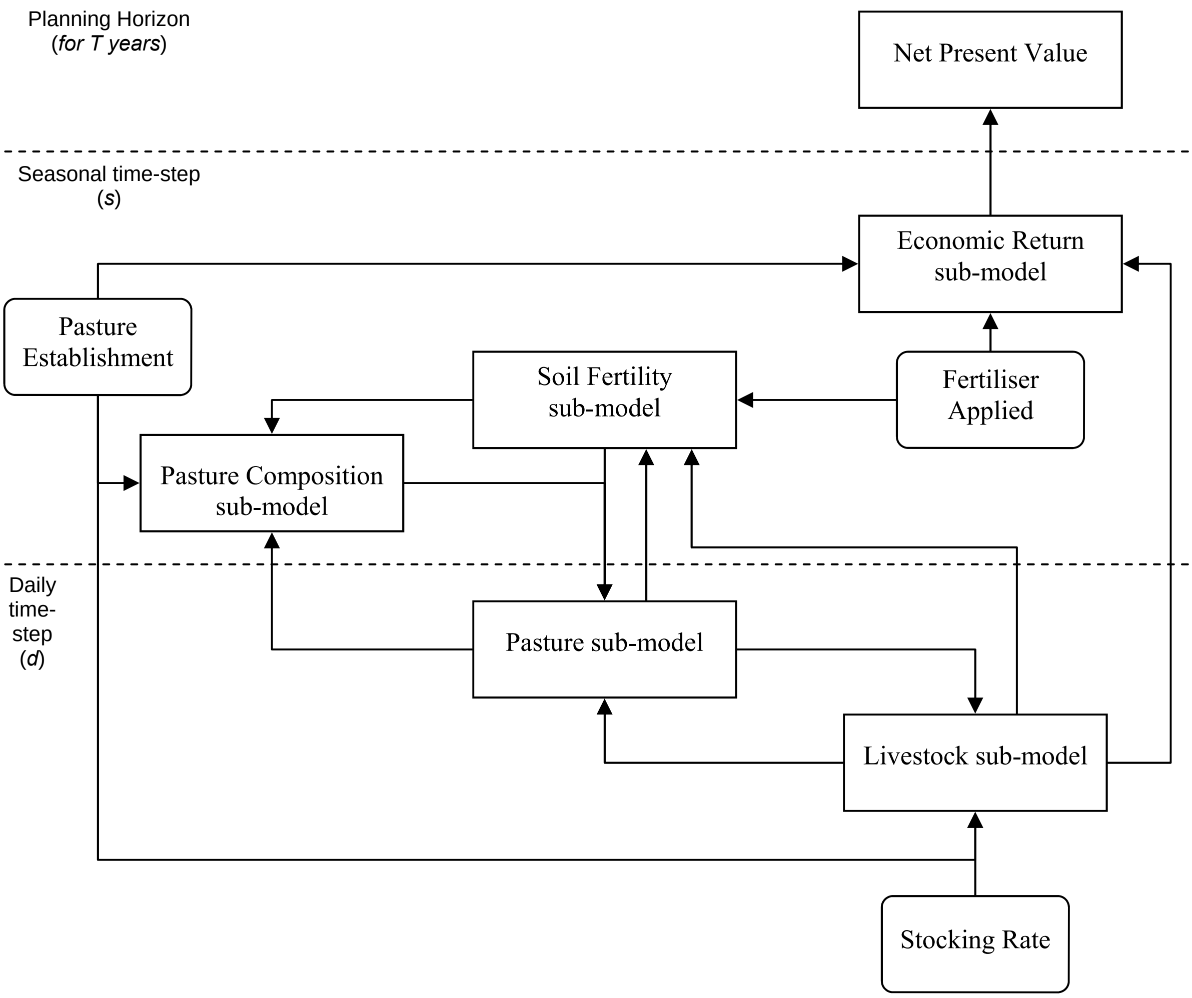

Figure 5-1: A diagrammatic outline of the Dynamic Pasture Resource Development simulation model at the paddock level.

Table 5-1: Major components of the sub-models

Sub-Model	Major Components
Soil Fertility	Soil P, Fertility gain through fertiliser application, fertility lost through consumption and fixation
Pasture	Pasture mass, growth, quality and consumption
Pasture Composition	Pasture composition, intrinsic rate of population growth, impact of harvesting by livestock, and pasture establishment
Livestock	Selective grazing of sward between species groups, pasture and supplementary feed consumption, wool growth and quality, net balance of liveweight gain or loss
Economic	Seasonal value of production, seasonal costs of production including supplementary feeding and pasture sowing costs

Table 5-2: DPRD model parameters and constants

Parameter	Units	Value	Description
ρ		0.0494	Real Discount Rate calculated from inflation & nominal interest rate data plus margin (1.5%), over 1976 to 2006 (ABARE, 2006)
β_{DP}		0.45	Sheep carcass:liveweight ratio
P_{SF}	\$/wet tonne	208.60	Cost of Supplements, mean feed wheat price 1997 to 2007 (ABARE, 2007)
θ_{SF}	\$/kg	0.254	Cost per kg fertiliser (single superphosphate) spread (ABARE, 2006)
SCOST	\$/ha	250	Pasture sowing costs (Scott, 2006)
VC	\$/hd/annum	15.68	Variable costs (Scott, 2006)
PCOST	\$/ha/annum	20	Pasture & paddock maintenance costs
α_E	MJ/kg	13.2	ME of empty body gain in sheep (Freer *et al.*, 2007)
α_{ME}	MJ Kg^{-2}	0.02	ME for grazing in sheep (Freer *et al.*, 2007)
β_{ME}	Hd/ha	40.0	Threshold stocking density for sheep (Freer *et al.*, 2007)
δ_{Udp}; δ_{Ddp}		variable	Relative distribution of sward dry matter in digestibility pools (*AusFarm* simulations)
α_{PI}	Kg kg^{-1}	0.04	(Freer *et al.*, 2007)
α_{RE}		1.12	Relative rate of eating (Freer *et al.*, 2007)
β_{RE}		1.12	Relative time eating (Freer *et al.*, 2007)
α_S		0.9	Dry matter:Wet weight ratio for supplement (Alcock and Bell, 2007)
δ_S		0.89	DMD for grain supplement (Alcock and Bell, 2007)
η_S	MJ ME/kg DM	13.0	MD for grain supplement (Alcock and Bell, 2007)

Table 5-2 continued

Parameter	Units	Value	Description
α_W	gm greasy wool/d	6	Basal rate of wool growth (Freer *et al.*, 2007)
β_W		0.03	Seasonal wool growth constant for merinos (Freer *et al.*, 2007)
γ_W		0.7	Yield - Clean:Greasy wool ratio
ε_W	MJ gram^{-1} greasy	0.13	Energy content of greasy wool (Freer *et al.*, 2007)
μ_{DP}		0.2	Undegradable dietary protein (McDonald *et al.*, 1988)
SRW	Kg Liveweight	50	Standard Reference Weight
SFW	Kg greasy fleece	5.0	Standard Fleece Weight
MFD	Microns	19.0	Mean Fibre Diameter at *SFW* for bloodline
$\sigma_D;\ \sigma_U$		variable	Mean daily pasture biomass survival net of decay for desirable and undesirable pastures (*AusFarm* simulation)
ρ_C		variable	Intrinsic rate of desirable population growth (*AusFarm* simulation, Hutchinson (*pers. comm.*) Scott (*pers. comm.*))
κ_C		0.95	Maximum population size of desirable species (proportion of paddock occupied)
λ_{SC}		variable	Seasonal livestock grazing impact co-efficient on desirable population (Cicerone Project & *AusFarm* simulation, Boschma and Scott (2000))
μ_C		2.5	Maximum utilisation constraint (*AusFarm* simulation, Scott (*pers. comm.*), Scott *et al.* (2000b))
α_F		-0.09508	Derived from Gourley *et al.* (2007)
PBI		76	Average PBI for all Farmlets (Cicerone Database)
β_F		0.089	Proportion of phosphorus in single superphosphate (Glendinning, 2000)
ζ_F	mg/kg colwell shift per kg P applied/ha	0.4313	Derived from Burkitt *et al.* (2001)
ι_F	Mg/kg Colwell	3.0	Minimum slow release phosphorous from non-expendable pools (Jones *et al.*, 2006b; McCaskill and Cayley, 2000)
ω_F	Kg P/kg clean wool	0.00026	Phosphorous content of wool (Glendinning, 2000)
μ_F	Kg P/kg liveweight	0.006	Phosphorous content of liveweight (Glendinning, 2000)
θ_F	Kg P/kg dung	0.007	Phosphorous content of dung (Helyar and Price, 1999)
υ_F	Kg P in urine/kg total P excreted	0.01	Proportion of phosphorous in urine (Helyar and Price, 1999)
o_F	Kg P	0.00685	Phosphorous lost in DM production (Helyar and Price, 1999)
ρ_F	g/mm	1.5	Phosphorous content of rainfall (Helyar and Price, 1999)
AR	mm/year	850	Average annual rainfall (Armidale NSW)
ε_F		0.83	Proportion of phosphorous in colwell extract (Colwell, 1963)
σ_F	g/cm^3	1.5	Soil Bulk Density (top 10cm)
σ_S	kg DM/kg liveweight	0.0115	Derived from Freer *et al.* (2007)

5.2.1 Economic return sub-model

In the DPRD simulation model, the economic sub-model assumes that a producer operating a wether enterprise aims to maximise the present value (*PV*) of the flow of seasonal gross margins over the planning horizon.

$$PV = \sum_{t=0}^{T} \left(A \sum_{s=1}^{S} GM_s \right) \delta^t \qquad 5\text{-}1$$

where *PV* is the discounted present value of annual gross margins, *T* is the planning horizon in years, *t* is an index for year, *A* is the size of the paddock in hectares, *S* is the number of seasons in a year, *s* is an index for season, GM_s is the paddock's seasonal gross margin per hectare, and δ is the discount factor;

$$\delta = \frac{1}{(1+\rho)} \qquad 5\text{-}2$$

where ρ is the real discount rate.

5.2.1.1 Seasonal returns

In calculating seasonal gross margins per hectare for a single paddock the complexity of modelling flock structure and dynamics cannot be adequately incorporated due to the process of enterprise operation and livestock movements not being representative of a closed system within the paddock. Thus a simplified gross margin approach is used to define the seasonal value of production and its cost.

This approach assumes animals that enter the paddock operate in a steady state with no changes in their capital value from the start to the end of the season. However the method applied does allow for negative values of net liveweight change over a season. The simplified gross margin approach allows the DPRD simulation model to be incorporated into the stochastic dynamic programming framework described in Chapter 7. As discussed in Chapter 4, this enables the complex issue of flock structure and the particular types of animals that are used to harvest the pasture to be separated from the issue of optimising the quantities of pasture to be harvested. The effect of different sheep production systems on the optimal management of the pasture resource is addressed in Chapter 7.

A single paddock's seasonal gross margin per hectare, GM_s is calculated at the end of each season (*s*) as follows:

$$GM_s = SR(W_{INC} + M_{INC} - VC) - PCOST - SF_s P_{SF} - FCOST - SCOST \qquad 5\text{-}3$$

where *s* is the index for season comprising a variable number of days, *SR* is the stocking rate decision variable (hd/ha), W_{INC} is the total value of wool produced in the season, M_{INC} is the total value of sheep meat grown in the season. The variable costs associated with each season are represented by *VC* and *PCOST* which are the pro-rated variable costs and pasture costs dependent upon the length of the season (VC_t or $PCOST_t \cdot D_s/365$), the total quantity of supplements fed SF_s, and the cost of supplementary feed P_{SF}, the cost of any fertiliser applied *FCOST*, and any costs of sowing a new pasture in a season *SCOST* ($/ha).

The total value of wool grown in any season, W_{INC}, is a function of the quantity of wool grown and its market value.

$$W_{INC} = P_{wool} \sum_{d=1}^{D_s} DW_d \qquad 5\text{-}4$$

where P_{wool} is the market value or price of the wool produced ($/kg clean) which is a function of mean weighted fibre diameter, FD_s, of the wool produced in that season, and DW_d which is the amount of wool grown in each day (*d*) over the length of the season in days (D_s). For notational convenience the subscript *s* has been left off references to the length of a season, *D*, in the remainder of this chapter. The function for the price of wool grown has been based on the median reported prices for 15 to 32 micron categories over the period July 1997 to July 2007 (AWEX, 2007; Woods, *pers. comm.*). A bivariate fit of median prices by micron was undertaken using *JMP IN* statistical software (SAS, 2004) to derive the wool price function, P_{wool}, with an R^2 of 0.9918.

$$P_{wool} = 1794 - 47FD_s + 2.2(FD_s - 22.2)^2 - 0.9(FD_s - 22.2)^3 + 0.3(FD_s - 22.2)^4 - 0.02(FD_S - 22.2)^5 \qquad 5\text{-}5$$

The total value of liveweight gain in any season, M_{INC}, is calculated from the net balance of liveweight gain over the season and its market value.

$$M_{INC} = P_{meat} \beta_{DP} WT_s \qquad 5\text{-}6$$

where P_{meat} is the price of the sheep meat produced ($/kg carcass weight), WT_s is the net balance of liveweight gain or loss over a season (kg/hd), and β_{DP} is the dressing percentage for sheep.

The total quantity of supplements fed in a season (kg/ha) is the conversion of the sum of daily amounts fed in dry matter to wet tonnes.

$$SF_s = \frac{SR\sum_{d=1}^{D} SDM_d}{\alpha_S} \qquad 5\text{-}7$$

where SDM_d is the daily amount of supplement dry matter offered to grazing animals (kg DM/hd/d), *SR* is the stocking rate, and α_S is the dry matter to wet weight ratio for the supplement.

The cost of fertiliser applied per season is calculated from the amount of fertiliser applied. The impact of any fertiliser applied, on raising soil fertility and promoting additional pasture growth, is assumed to occur in the season of application before accounting for maintenance phosphorus requirements.

$$FCOST_s = FERT_s \theta_{SF} \qquad 5\text{-}8$$

where $FERT_s$ is the amount of fertiliser applied in a season (kg of single superphosphate/ha), and θ_{SF} is the cost per kilogram of fertiliser.

5.2.2 Livestock sub-model

Livestock production in the paddock-level DPRD model over a season of grazing is a function of net balance of liveweight gain or loss and the quantity and quality of wool produced. The conceptual outline of the livestock sub-model is illustrated in Figure 5-2.

The livestock sub-model unless otherwise stated, is based on many of the equations described by Freer *et al.* (2007). This publication represents a revised version of the original report by SCA (1990) and fundamentally describes the functions used in the *GrazPlan* suite of decision support tools (Donnelly *et al.*, 1997; Freer *et al.*, 1997; Moore *et al.*, 1997), which have been broadly applied and shown to adequately predict livestock performance (Clark *et al.*, 2000; Salmon *et al.*, 2004).

As a mature wether enterprise is assumed to be operating in this model, many equations have been simplified. In addition livestock production has been estimated from the combined characteristics of two separately growing partial swards, namely the areas of the paddock occupied by the 'undesirable' and 'desirable' species groups. This has required the manipulation of partial sward data at steps in the process of predicting livestock production and pasture intake.

There are two stages involved in predicting the production of livestock in the sub-model:

1. The quantity of energy consumed is predicted by taking into account the potential intake of individual animals and their ability to maximise energy intake from the quantity and quality of the pasture or supplement on offer through selective grazing.

2. Estimation of energy partitioning to meet maintenance energy requirements, wool production and net liveweight gain or loss is undertaken

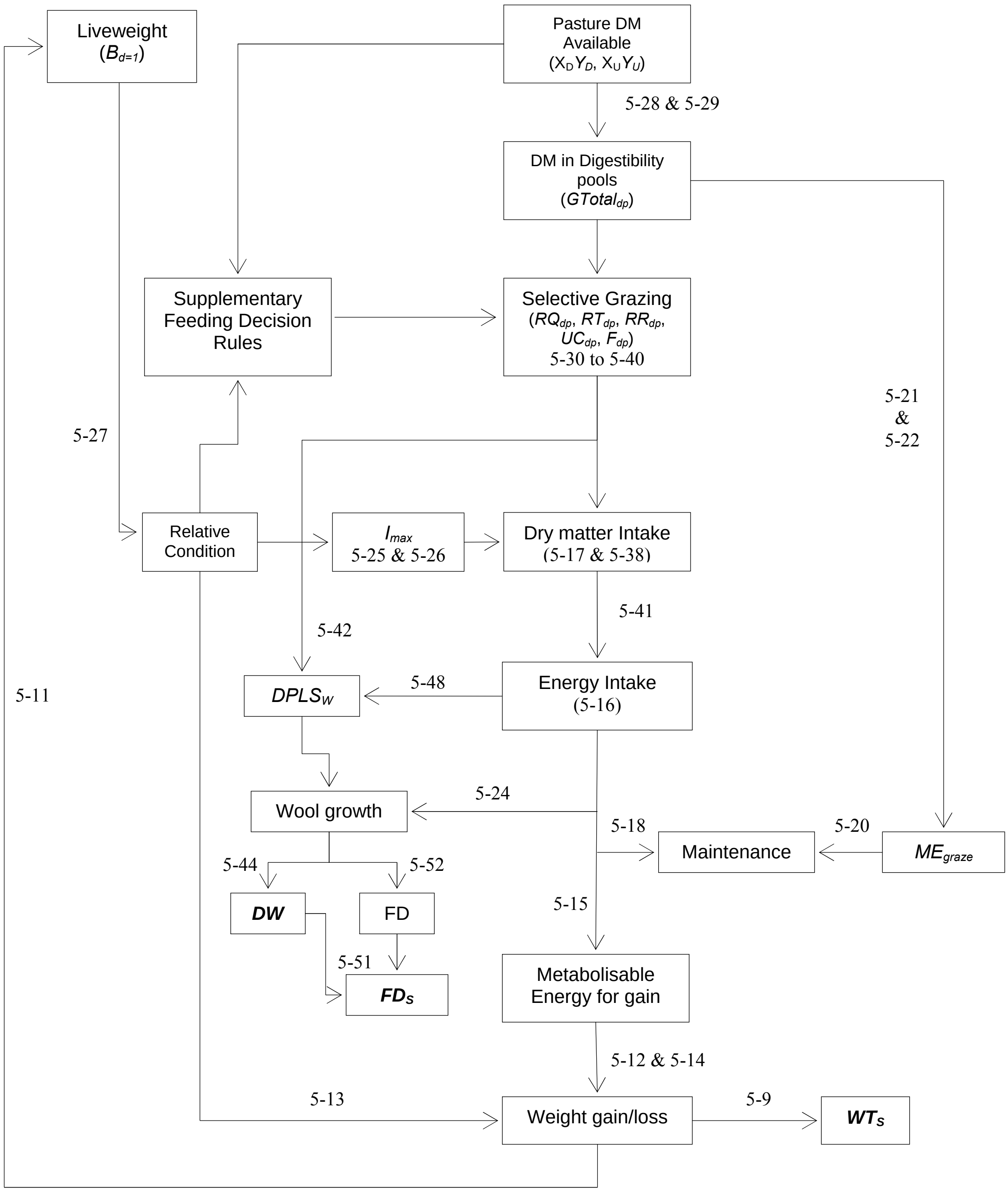

Figure 5-2: Diagrammatic outline of the livestock sub-model. Numbers and variables indicate the corresponding equations.

5.2.2.1 Net liveweight gain or loss

The net production of sheep meat in each season is assumed to be a direct contributor to the economic return for that season. To enable the model to adequately predict the impact of tactical grazing management decisions on livestock production and economic return at a single paddock level, a partial calculation approach has been adopted. In this partial approach livestock production is calculated for each season as the net difference between the liveweight of sheep at the end and the start of the season.

Liveweight gain over the entire season, WT_s enters the economic return sub-model

$$WT_s = B_D - B_0 \qquad 5\text{-}9$$

where B_D is the liveweight of the grazing sheep at the end of the season, and B_0 is the starting liveweight for each season. B_D is a function of daily liveweight gain or loss over the season and is calculated as follows:

$$B_D = \sum_{d=1}^{D} LW_{Gd} \qquad 5\text{-}10$$

where LW_{Gd} is the daily liveweight gain of sheep grazing the paddock during the season. The daily liveweight gain of mature grazing sheep is calculated as outlined in Freer *et al.* (2007).

$$LW_G = \frac{NE_g}{EV_g} \qquad 5\text{-}11$$

where NE_g is the net energy available for liveweight gain (MJ of ME/d), and EV_g is the estimated energy value of liveweight gain (MJ/kg). The net energy available for liveweight gain is calculated as follows:

$$NE_g = k_g ME_g \qquad 5\text{-}12$$

where k_g is the net efficiency of utilisation of metabolisable energy for growth and fattening, and ME_g is the metabolisable energy available for liveweight gain (MJ of ME/d) calculated in equation 5-15.

The estimated energy value of liveweight gain, EV_g (MJ/kg), for mature sheep is a function of the animal's relative body condition and is calculated as follows:

$$EV_g = 0.92(\alpha_E + 13.8BC) \qquad 5\text{-}13$$

where BC is the relative body condition of the animal and is the same as its relative condition, RC, calculated in equation 5-27, and α_E is a constant for sheep.

The net efficiency of utilisation of metabolisable energy for growth and fattening for all diets, k_g, including concentrate or roughage supplements, is assumed to be a function of the diet's metabolisable energy content.

$$k_g = 0.043MD \qquad 5\text{-}14$$

where *MD* is the metabolisable energy content of the diet (MJ of ME/kg of feed DM).

5.2.2.2 Energy for growth

The metabolisable energy available, ME_g, is based on the net energy balance between metabolisable energy consumed and energy used in maintenance and wool production.

$$ME_g = EI - ME_M - ME_W \qquad 5\text{-}15$$

where *EI* is the total metabolisable energy consumed (MJ ME/d), ME_M is the metabolisable energy required for maintenance, and ME_W is the energy used for wool growth.

Energy intake

The total amount of metabolisable energy consumed, *EI*, available for meeting maintenance and production is based on the predicted amount of pasture and supplements consumed and its estimated energy content.

$$EI = DMI \cdot MD \qquad 5\text{-}16$$

where *DMI* is the daily dry matter intake of pasture and supplements (kg DM/hd/d), and *MD* is the mean metabolisable energy content of consumed pasture and any supplements provided (MJ of ME/kg DM) calculated in equation 5-41.

The daily dry matter intake of sheep grazing on pasture, *DMI* (kg DM/hd/d), is a function of both the potential maximum intake of dry matter that may be physically consumed and the cumulative relative intake from the digestibility pools. The pasture is comprised of areas inhabited by both desirable and undesirable species with a known distribution of the proportions of the pastures in defined digestibility pools,

$$DMI = I_{\max}\left(RI_{psum} + RI_S\right) \qquad 5\text{-}17$$

where I_{max} is the maximum potential intake of dry matter (kg DM/d) predicted in equation 5-25, and RI_{psum} is the cumulative relative intake from all pasture digestibility pools estimated in equation 5-30, and RI_S is the relative intake of any supplements provided.

Metabolisable energy for maintenance

The maintenance metabolisable energy requirement, ME_m, is estimated using the following equation:

$$ME_m = \frac{\left(0.26B^{0.75}\exp(-0.03A)\right)}{k_m} + 0.09EI + ME_{graze} \quad 5\text{-}18$$

where B is liveweight (kg) excluding fleece weight, A is age in years with a maximum of 6, k_m is the net efficiency of use of ME for maintenance, EI is total metabolisable energy intake (MJ/d) from equation 5-16, and ME_{graze} is the additional energy expenditure for grazing animals. This modified version of the equation described in Freer *et al.* (2007) assumes only mature castrate sheep graze within their thermoneutral zone.

The net efficiency of use of metabolisable energy for maintenance is predicted as

$$k_m = 0.02MD + 0.5 \quad 5\text{-}19$$

where MD is the metabolisable energy content of consumed pasture and supplement dry matter (MJ/kg DM) estimated in equation 5-41. However under conditions of weight loss, k_m is assumed to be constant at 0.80 (Freer *et al.*, 2007). This represents the efficiency of using body reserves through the catabolism of body fat and protein.

The additional energy expenditure from sheep grazing pasture, ME_{graze}, is predicted by taking into account the slope of the paddock, but excludes any impact of cold stress or any interaction with high density grazing systems often seen under strip grazing.

$$ME_{graze} = B\frac{\left\lfloor \alpha_{ME} DMI_P \left(0.9 - Y_{qP}\right) + 0.0026H \right\rfloor}{k_m} \quad 5\text{-}20$$

where α_{ME} is the scalar for chewing effect in sheep, DMI_P is the dry matter consumed from pasture (kg/d excluding any supplements consumed), Y_{qP} is digestibility of the pasture dry matter consumed from equation 5-43, k_m is the efficiency of energy use for maintenance, B is the fleece-free liveweight (kg), and H is the horizontal equivalent of distance walked, such that;

$$H = \frac{\left(1 + \tan(0.174S)\right)\min\left(1, \frac{SR}{\beta_{ME}}\right)}{0.000057GF + 0.16} \quad 5\text{-}21$$

where S is the mean slope (^{o}) of the grazing area, β_{ME} is the threshold stocking density (hd/ha), and GF is the amount of green forage available (kg DM/ha). The quantity of green forage available is calculated using the total quantity of dry matter in digestibility pools 0.8, 0.7 and half of 0.6, or the total available pasture if the quantity of green forage is less than 100kg DM/ha. The amount of green forage available is calculated as follows:

$$GF = GTotal_{0.8} + GTotal_{0.7} + 0.5 \cdot GTotal_{0.6} \qquad \text{5-22}$$

where $GTotal_{dp}$ is the total amount of dry matter (kg DM/ha) estimated in equation 5-29, to exist in the digestibility pools (*dp*) of 0.8, 0.7 and 0.6.

The dry matter intake from pastures, DMI_P (kg DM/d), excluding any dry matter from supplements offered, is

$$DMI_P = I_{\max} RI_{psum} \qquad \text{5-23}$$

Metabolisable energy for wool

The metabolisable energy requirements for wool production, ME_W, is estimated using the following equation

$$ME_W = \varepsilon_W \left(\frac{DW}{\gamma_W} - \alpha_W \right) \qquad \text{5-24}$$

where *DW* is the amount of wool grown (grams clean wool/d) estimated in equation 5-44, ε_W is the parameter defining the energy content of greasy wool, γ_W is the ratio of clean to greasy wool (or yield), and α_W is the basal rate of wool growth (grams greasy wool/d).

5.2.2.3 Potential intake

The maximum potential intake of grazing sheep is a function of its potential demand for energy and its physical capacity for feed intake. Maximum potential intake, I_{max} (kg DM/d/hd) is calculated as follows,

$$I_{\max} = \alpha_{PI} SRW \cdot 0.7 \cdot CF \qquad \text{5-25}$$

where *SRW* is the standard reference weight (kg liveweight excluding fleece weight) of a mature wether in average condition (condition score 3.0) when skeletal development is complete and it has not been interrupted by under-nutrition during its development, *CF* is the condition factor for non-lactating animals, α_{PI} is a constant defining the effect of relative size of sheep on potential intake. In this application of the intake model, the individual sheep grazing the paddock are assumed to be mature and fully developed, hence their relative size is neutral or equal to a ratio of 1.0 (Freer *et al.*, 2007). This also assumes the grazing animals are within their thermoneutral zone and, of course, are not lactating.

An animal's condition factor, *CF*, is related to its current relative condition, *RC*,

$$CF = \frac{RC(1.5 - RC)}{0.5} \qquad 5\text{-}26$$

where an animals relative condition, *RC*, is the ratio of its current body weight (*B*) to the animals standard reference weight (*SRW*). With the assumption that only mature animals graze the paddock, the normal weight of an animal is assumed to be the same as its *SRW,* which makes *RC* the same as relative body condition (*BC*).

$$RC = \frac{B}{SRW} \qquad 5\text{-}27$$

For animals that are in above-average condition with $RC > 1.0$, *CF* is calculated as described in equation 5-26, otherwise $CF = 1.0$. This method allows for the compensatory gain of animals after a period of weight loss if their $RC \leq 1.0$, if there is sufficient pasture biomass to support higher levels of pasture intake.

5.2.2.4 Selective grazing and relative intake

To adequately represent the impact on livestock performance of changes in the areas of a paddock occupied by either desirable or undesirable pasture species requires the prediction of selective grazing by livestock. This requires the model to predict the selection of sward components by sheep, as they attempt to select a diet higher in digestibility than the mean of the pasture found in the paddock. The adoption of such a method reflects observations from grazing-system studies where the more palatable and digestible pasture species and their components are preferentially grazed, consequently leading to the overgrazing of the more desirable species and the gradual decline in such species.

As in Freer *et al.* (2007), the total amount of pasture biomass found in areas of desirable and undesirable species is allocated to 6 digestibility pools with midpoints of 0.8 to 0.3 Dry Matter Digestibility (DMD) at 0.1 increments. The allocation is based on parameters derived from simulation results using a more sophisticated biophysical model, *AusFarm*, as introduced in Chapter 4 and detailed in Chapter 6.

The allocation of pasture dry matter between the digestibility pools of undesirable and desirable groups within the pasture, GU_{dp} and GD_{dp}, is calculated as follows:

$$GU_{dp} = \delta_{Udp} Y_U X_U \text{ and } GD_{dp} = \delta_{Ddp} Y_D X_D \tag{5-28}$$

where δ_{Udp} and δ_{Ddp} are the relative distributions of dry matter in each quality pool for undesirable (U) and desirable (D) sward components, Y_U and Y_D are the total amount of pasture biomass, and X_U and X_D are the proportions of the paddock occupied by undesirable and desirable species groups. The subscript dp indicates the fixed digestibility pools (DMD_{dp}) of 0.8, 0.7, 0.6, 0.5, 0.4 and 0.3. The total weight of pasture biomass available to grazing livestock in each digestibility pool is:

$$GTotal_{dp} = GU_{dp} + GD_{dp} \tag{5-29}$$

To estimate the actual dry matter intake of grazing livestock and the digestibility of their diets from the dry matter available in each digestibility pool, the model assumes that the animal attempts to consume its potential intake from each pool from the highest to lowest digestibility in succession. The ability of animals to select from each pool is related to the quantity of dry matter in each pool and its digestibility. The more an animal satisfies its potential intake from a higher digestibility pool, the less will be consumed from the lower digestibility pools. The overall cumulative relative intake of pasture, RI_{psum}, is the sum of the relative intakes from each digestibility pool.

$$RI_{psum} = \sum_{dp=1}^{6} RI_{dp} \tag{5-30}$$

where RI_{dp} is the calculated relative intake for each individual digestibility pool

$$RI_{dp} = F_{dp} RQ_{dp} \tag{5-31}$$

where F_{dp} is the relative availability in each digestibility pool, and RQ_{dp} is the relative ingestibility for each pool class and is based on the fixed Dry Matter Digestibility for each pool, DMD_{dp}, such that;

$$RQ_{dp} = 1 - 1.7 \max\left(0.8 - DMD_{dp}, 0\right) \tag{5-32}$$

The relative availability for each digestibility pool is calculated in succession starting with the most digestible first, using the following equation.

$$F_{dp} = UC_{dp} RR_{dp} RT_{dp} \tag{5-33}$$

where UC_{dp} is the unsatisfied capacity, or proportion of potential intake left unsatisfied by the harvesting of dry matter from the higher digestibility pools, RR_{dp} is the relative rate of eating, and RT_{dp} is the relative time spent eating from pool *dp*. To commence the calculation of relative availability for the first digestibility pool ($F_{0.8DMD}$), the unsatisfied capacity ($UC_{0.8DMD}$) is initially set at 1.0. The relative availabilities of the remaining pools are in sequence reduced by the remaining unsatisfied capacity from the previous pools through the cumulative equation which calculates the residual unsatisfied capacity (UC_{dp}) for the current pool.

$$UC_{dp} = \max\left(0, 1 - \sum_{k=1}^{dp-1} F_k\right) \qquad 5\text{-}34$$

The relative rate of eating, RR_{dp}, and the relative time spent eating, RT_{dp}, for each pool is a function of the proportion of dry matter in each pool and total amount of pasture dry matter in each pool, as follows

$$RR_{dp} = 1 - \exp\left(-\left(1 + 0.35GP_{dp}\right) \cdot \alpha_{RE} GTotal_{dp}\right) \qquad 5\text{-}35$$

$$RT_{dp} = 1 + 0.6\exp\left(-\left(1 + 0.35GP_{dp}\right) \cdot \left(\beta_{RE} GTotal_{dp}\right)^2\right) \qquad 5\text{-}36$$

where GP_{dp} is the proportion of dry matter in each digestibility pool, $GTotal_{dp}$ is the amount of dry matter (tonnes DM/ha), and α_{RE} and β_{RE} are constants for grazing sheep. In this instance, the herbage height factor described by Freer *et al.* (2007) has been kept neutral at a value of 1.0 which assumes the ratio of sward height to mass in each of the digestibility pools remains at a constant of 3cm per tonne of dry matter per hectare.

The proportion of pasture dry matter in each quality pool is calculated as follows:

$$GP_{dp} = \frac{GTotal_{dp}}{\sum_{dp=1}^{6} GTotal_{dp}} \qquad 5\text{-}37$$

where $GTotal_{dp}$ is the amount of dry matter in each digestibility pool in tonnes of dry matter per hectare, calculated in equation 5-29.

5.2.2.5 Supplementary feeding

Inclusion of supplementary feeding into the DPRD model is required to avoid both the mortality of sheep grazing the paddock between decision points, and to provide a means of maintaining the pasture sward. To adequately represent the impact of supplements in a grazing system, there is a need to take into account the substitution effect on pasture dry matter intake, as well as its impact on diet digestibility and energy consumption for livestock maintenance and production (Dove, 2002).

This model incorporates supplementary feeding based on the method described in Freer *et al.*(2007). The primary assumption being that the grazing animal will select the supplement before it selects herbage of the same or lower relative ingestibility or quality (RQ_{dp}). To simplify the modelling process, the supplement has been assumed to be cereal grain, such as wheat, which has a dry matter digestibility of 89% and a metabolisable energy content of 13 MJ of ME/kg of dry matter (Alcock and Bell, 2007). This restricts the supplement to a separate digestibility pool, a DMD of 0.9, which will in turn affect the residual unsatisfied capacity, UC_{dp}, for lower quality pasture digestibility pools.

The amount of supplement dry matter intake is determined by the relative intake of the supplement and the potential intake of the sheep, such that

$$DMI_S = RI_S I_{\max} \qquad \text{5-38}$$

where RI_S is the relative intake of the supplement, and I_{max} is the maximum potential intake of the grazing sheep calculated in equation 5-25.

The relative intake of pasture dry matter is estimated as described in equations 5-28 to 5-37, but with the following modifications to incorporate supplements being offered to grazing sheep. As with equation 5-30, the relative intake of supplements, RI_S, is a function of relative availability, F_S, and relative ingestibility, RQ_S. RQ_S is calculated using equation 5-32. Thus, $RQ_S = 1 - 1.7\max(0.8 - \delta_S, 0)$ where δ_S is the dry matter digestibility of the supplement pool.

The relative availability of the supplements provided, F_s, is constrained by either the ingestibility of the supplement (RQ_S) and the amount of supplement offered as a proportion of the grazing sheep's potential intake (I_{max} from equation 5-25), or the metabolisable energy concentration of the supplement. Thus:

$$F_S = \min\left(\frac{SDM}{I_{\max} RQ_S}, \frac{10.5}{\eta_S}\right) \qquad \text{5-39}$$

where SDM is the quantity of supplement dry matter offered (kg DM/hd/d), and η_S is the metabolisable energy content of the supplement (MJ ME/kg DM).

For the pasture digestibility pools (0.8 to 0.3), the residual unsatisfied capacity for each digestibility pool, UC_{dp}, in succession is now calculated as

$$UC_{dp} = \max\left(0, 1 - \sum_{k=1}^{dp-1} F_k - F_S\right) \qquad 5\text{-}40$$

In this instance $UC_{0.8DMD}$ is no longer set equal to 1.0, but is a function of the remaining unsatisfied capacity after the relative availability of supplements (F_S) has been taken into account.

Metabolisable energy content and Diet digestibility

The metabolisable energy content of the diet from both consumed pasture and supplements, MD (MJ of ME/kg of DM consumed), is estimated using the following function

$$MD = 17.2Y_q - 1.707 \qquad 5\text{-}41$$

where the digestibility of the predicted diet, Y_q (DMD), under selective grazing and supplementary feeding (when provided), is based on the distribution of pasture and supplement dry matter in all digestibility pools, and is calculated from the contributions of the different pools to the diet.

$$Y_q = \frac{\sum_{dp=1}^{dp} DMD_{dp} RI_{dp} + \delta_S RI_S}{\sum_{dp=1}^{dp} RI_{dp} + RI_S} \qquad 5\text{-}42$$

where RI_{dp} is the relative intake, DMD_{dp} is the dry matter digestibility of each pasture digestibility pool, RI_S is the relative intake of supplements, and δ_S is the dry matter digestibility of the supplement pool. For the calculation of the metabolisable energy used for the activity of grazing (ME_{graze} in equation 5-20), the digestibility of the dry matter consumed from the selective grazing of pasture is also required and is calculated as follows:

$$Y_{qP} = \frac{\sum_{dp=1}^{dp} DMD_{dp} RI_{dp}}{\sum_{dp=1}^{dp} RI_{dp}} \qquad 5\text{-}43$$

5.2.2.6 Wool growth

The rate of wool growth from sheep grazing the paddock is estimated using the equations described by Freer *et al.* (2007). The quantity of wool grown per day is estimated based on the balance between the amount of energy or protein available for wool growth, and the wool production efficiency of the genotype. In this model, as the animals grazing the paddock are assumed to be mature, age has no impact on wool growth.

$$DW = \frac{SFW}{SRW} DLF \min(1.16 DPLS_W, 14EI) \quad 5\text{-}44$$

where *SFW* is the standard fleece weight (kg greasy fleece weight) of the sheep genotype when it is at its *SRW* (standard reference weight); the ratio defines the wool production efficiency of a genotype. *DLF* is the scaled effect of day length on wool growth, $DPLS_W$ is the amount of truly digestible protein leaving the stomach and available for wool growth net of maintenance protein requirements (grams/d), and *EI* is the amount of energy available for wool production (MJ of ME/d), which is equivalent to the total amount of energy consumed as the wethers are neither lactating nor carrying a conceptus.

The day length factor, DLF, is calculated as follows:

$$DLF = 1 + \beta_W (DL_S - 12)) \quad 5\text{-}45$$

where DL_S is day length in hours and has been given different parameter values for each season, and β_W is the constant describing the response of wool production from different sheep breeds to day length.

The amount of truly digestible protein leaving the stomach which is available, $DPLS_W$ is estimated through the construction of a simplified model of protein intake based on the relationships described in Freer et al. (2007) and generated through the spreadsheet tool SheepExplorer. This is available at www.pi.csiro.au/*GrazPlan* and describes the application of the GrazFeed decision support tool (Freer *et al.*, 1997). The process of estimating $DPLS_W$ is as follows:

$$DLPS_W = DPLS_{MCP} + DUDP \quad 5\text{-}46$$

where $DPLS_{MCP}$ is the amount of truly digestible protein from microbial crude protein (grams/day), and *DUDP* is the amount of truly digestible undegradable dietary protein (grams/day). $DPLS_{MCP}$ has been estimated from the quantity of microbial crude protein leaving the stomach, which is a function of the level of feeding and energy intake. It does not take into account the seasonal fluctuation in microbial output but it does take into account the mean effect of the simulated paddock's latitude (with Armidale being 30^o S). $DPLS_{MCP}$ (g/MJ of energy intake) was estimated as (R^2=0.9998).

$$DPLS_{MCP} = EI\left(-0.112FL^2 + 0.7544FL + 5.079\right) \quad \text{5-47}$$

where *EI* is the total amount of metabolisable energy consumed (MJ ME/d from equation 5-16), and *FL* is the relative level of feeding, such that:

$$FL = \left(\frac{EI}{ME_m}\right) - 1 \quad \text{5-48}$$

where ME_m is the maintenance metabolisable energy requirements for a grazing sheep as calculated in equation 5-18. The amount of truly digestible undegradable dietary protein is calculated as follows,

$$DUDP = \mu_P CP\left(0.0055CP - 0.178\right)DMI \quad \text{5-49}$$

where μ_P is the proportion of crude protein intake that is undegradable protein in the rumen from pastures (McDonald *et al.*, 1988), *DMI* is the dry matter intake (kg DM/hd/d), and *CP* is the crude protein content of the dry matter intake (grams/kg DM). The crude protein content is:

$$CP = \left(0.5264Y_q - 0.1749\right)\cdot 1000 \quad \text{5-50}$$

where Y_q is the digestibility of the predicted diet (DMD as a decimal), under selective grazing when supplementary feeding is provided. This function predicting the crude protein content of the diet has been estimated using data generated from *AusFarm* simulations (R^2=0.9885). The strong relationship between diet DMD and dietary crude protein content is due to the fixed crude protein content assumptions of the digestibility pools described in the *GrazPlan* suite of models (Moore *et al.*, 1997).

5.2.2.7 Fibre diameter

Fibre diameter is the most important wool quality attribute influencing the price received for wool. The diameter of wool grown is strongly influenced by nutrition and genotype, and as such will be sensitive to variations in pasture quantity and quality. To capture these effects on the value of wool production the following calculations have been incorporated into the livestock sub-model to estimate a weighted mean fibre diameter of wool grown in each season, FD_S.

$$FD_S = \frac{\sum_{d=1}^{D} FD \cdot DW}{\sum_{d=1}^{D} DW} \quad \text{5-51}$$

where *FD* is the daily prediction of the fibre diameter of new wool grown (microns) and *DW* is the quantity of new wool grown (grams clean wool/d).

FD, is based on the rate of wool growth relative to the mean fibre diameter of the genotype and its mean greasy fleece weight. The following equations are based on those outlined in SheepExplorer and again assume mature sheep thereby eliminating the age factor on fibre diameter.

$$FD = MFD\left(\frac{0.365DW}{\gamma_W SFW}\right)^{0.333} \qquad 5\text{-}52$$

where *MFD* is the mean fibre diameter of the genotype (microns), *DW* is the rate of daily wool growth (grams clean/d) calculated in equation 5-44, γ_W is the ratio of clean to greasy wool (or yield), and *SFW* is the standard fleece weight.

5.2.3 Pasture sub-model

Changes in botanical composition impact on livestock production and consequently, financial returns. Although a robust and functional model of inter-species competition and growth that can accurately predict changes in botanical composition is not available, development of such a model has not been undertaken. This is because the primary focus of this study is the optimisation of pasture resource development and management, and to develop such a model would be outside the scope of this thesis.

The objectives of this study require a pasture sub-model that enables species groups in the sward to be adequately represented without the need for within sward species modelling, inter-species competition or a detailed biophysical model of plant growth. The outcome from the review of the literature in Chapters 3 and 4 has already shown that multi-species competition itself is not adequately modelled in pastures where more than 2 species exist. Thus an empirical method has been developed which will adequately meet the study objectives.

The method applied in this sub-model is conceptually outlined in Figure 5-3 and incorporates two stages to modelling the change in pasture biomass and composition between seasons. In a single production year, four seasons have been identified that relate to tactical and strategic decision points, and the biophysical characteristics of plant growth and botanical composition change within pastures.

In these four seasons the pasture sward components of the area of the paddock under 'desirable' species and the area under 'undesirable' species, are modelled separately on a daily time step. To the grazing animal, the paddock represents an even distribution of dry matter from the two species groups based on the relative areas of the paddock occupied by each species group.

The changes in the area of the paddock occupied by either the desirable or undesirable species groups is adjusted seasonally in response to the type of year and the relative rate of pasture biomass harvest (grazing management). This 'partial' paddock approach for modelling the areas of a paddock under different species groups was adapted from Loewer (1998).

Seasonal changes in the potential growth of the sward components and their quality are accommodated for by adjusting parameters on a seasonal basis. To model the impact of stochastic climate conditions, these parameters are adjusted using stochastic multipliers as described by Cacho *et al.* (1999).

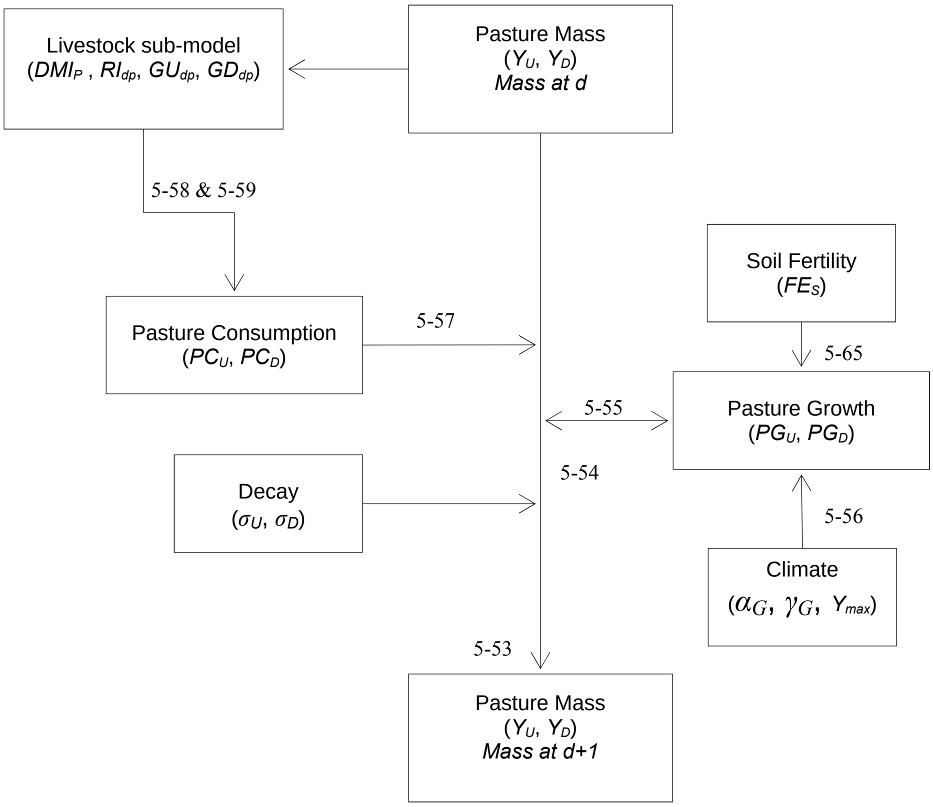

Figure 5-3: Diagrammatic outline of the pasture sub-model. Numbers and variables indicate the corresponding equations.

5.2.3.1 Pasture biomass

The daily change in available pasture dry matter, net of any supplements being fed, is a function of the pasture consumed by grazing livestock and the growth of pastures from the remaining biomass. Pasture growth and consumption is modelled in each of the desirable and undesirable sward components.

The process of pasture consumption and growth assumes that the grazing livestock harvest pasture biomass before its growth for that day is calculated. The change in pasture biomass for desirable (dY_D) and undesirable (dY_U) species at the end of each day is calculated as follows.

$$dY_D = PG_D - PC_D - \sigma_D Y_D \text{ and } dY_U = PG_U - PC_U - \sigma_U Y_U \qquad 5\text{-}53$$

where PG_D and PG_U are the quantities of pasture grown per day (kg DM/ha/d) after grazing by livestock, PC_D and PC_U are the quantities of pasture consumed by the grazing livestock (kg DM/ha/d), and σ_D and σ_U are the daily decay rates of pasture due to microbial breakdown, trampling and defecation by grazing livestock (Alford, *pers. comm.*).

Pasture growth

Pasture growth is based on the sigmoidal pasture growth curve of Cacho (1993). The parameters were estimated using simulation output from *AusFarm* (Moore, 2001) which was calibrated to experimental data from the Cicerone Project. This method has been applied in previous studies and has been found to adequately represent the net growth of different types of pastures under grazing (Alford, 2004). For notational convenience, the *U* and *D* subscripts are not included in the following equations which have been applied separately to each pasture group.

The individual growth of pasture biomass (kg DM/ha/d) for desirable and undesirable species is calculated as follows:

$$PG = \alpha_G \frac{Y^2}{Y_{\max}} \left[\frac{Y_{\max} - Y}{Y} \right]^{\gamma_G} FE \qquad 5\text{-}54$$

where α_G is a growth parameter influenced by the soil fertility effect (*FE*) and climate under stochastic simulations, Y_{max} is the maximum sustainable herbage mass or ceiling yield when an equilibrium is reached between new growth and the senescence of old leaves (but excluding the decay of plant material), γ_G is a dimensionless parameter with a value in the range of $1< \gamma_G <2$ (Cacho, 1993).

Figure 5-4 illustrates the relationship between pasture mass and pasture growth of the sigmoid growth curve. It indicates maximum net pasture growth rate, G^{max}, occurs at pasture mass Y^*. Cacho (1993) showed that the value of α_G effects the height of the growth curve, G^{max}. The parameter γ_G interacts to effect the position of Y^* along Y and the height of the growth curve. The parameter Y_{max} interacts to determine the height of the growth curve and, to a lesser extent, the position Y^* along Y. Seasonal values of these parameters are derived individually for the desirable and undesirable sward components.

The residual pasture mass, Y, in kg DM/ha for day d is the residual amount of pasture mass left after grazing has been accounted for.

$$Y_d = Y_{d-1} - PC_d \qquad 5\text{-}55$$

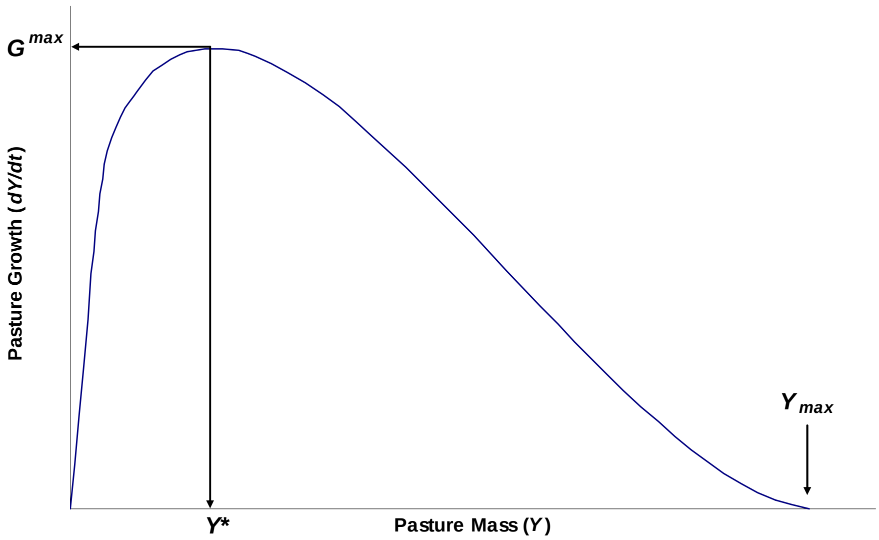

Figure 5-4: Sigmoid pasture growth curve

Stochastic multipliers

Under stochastic climatic conditions, α_G and γ_G are adjusted seasonally to reflect different year types using stochastic multipliers. As described in Cacho *et al.* (1999), when operating the DPR model in a stochastic mode, the mean seasonal α_G and γ_G parameters used under deterministic simulations are multiplied by their respective stochastic multiplier. These stochastic multipliers, $SM\alpha$ and $SM\gamma$, are defined for season i and year t as follows;

$$SM\alpha_{it} = \frac{\alpha_{it}}{\frac{1}{n}\sum_t \alpha_{it}} \quad \text{and} \quad SM\gamma_{it} = \frac{\gamma_{it}}{\frac{1}{n}\sum_t \gamma_{it}} \qquad 5\text{-}56$$

where *n* is the number of years in the sample from which the parameters are derived. During the running of a stochastic simulation these stochastic multiplier values are randomly selected in sets of annual cycles or year types from a uniform distribution. Given that the parameters for each year type have been derived from years simulated using *AusFarm*, each year has the same probability of being selected. Under deterministic simulations the stochastic multiplier values are equal to 1.

Pasture consumption

The differences in quality between the desirable and undesirable species components of the pasture and their impact on livestock production have been estimated through selective grazing. This has resulted in more or less dry matter being consumed from either species group depending on their relative availability and quality, as well as accounting for the substitution effect from the feeding of any supplements on reducing pasture dry matter intake.

The pasture consumption from the desirable and undesirable components of the sward is assumed to be evenly distributed throughout the paddock depending on the weighted consumption from the quality pools and the proportion of the paddock occupied by desirable and undesirable species groups. Pasture consumption from each individual sward component is calculated as:

$$PC_U = \sum_{dp=1}^{6} YC_{dp} PYP_{Udp} \text{ and } PC_D = \sum_{dp=1}^{6} YC_{dp} PYP_{Ddp} \qquad 5\text{-}57$$

where YC_{dp} is the total quantity of pasture consumed per hectare from each digestibility pool (kg DM/ha) with desirable and undesirable sward components combined, PYP_{Ddp} and PYP_{Udp} are the area-weighted proportion of dry matter in each digestibility pool for desirable and undesirable sward components.

The quantity of pasture consumed from each digestibility pool, YC_{dp}, is a function of relative intake from each pool, stocking rate and pasture dry matter consumption per grazing sheep.

$$YC_{dp} = DMI_P SR \left(\frac{RI_{dp}}{\sum_{dp=1}^{6} RI_{dp}} \right) \qquad 5\text{-}58$$

where DMI_P is the total pasture dry matter intake (kg/hd/d), SR is the stocking rate (hd/ha), and RI_{dp} is the relative intake from each of the pasture digestibility pools. The individual area-weighted proportion of dry matter existing in each of the digestibility pools is calculated as follows:

$$PYP_{U\,dp} = \frac{GU_{dp}}{\sum_{dp=1}^{6} GU_{dp}} \text{ and } PYP_{D\,dp} = \frac{GD_{dp}}{\sum_{dp=1}^{6} GD_{dp}} \qquad 5\text{-}59$$

where GU_{dp} and GD_{dp} are the quantities of pasture dry matter (kg DM/ha) in each of the digestibility pools for undesirable and desirable sward components.

5.2.4 Pasture composition sub-model

This sub-model is a critical component in determining the interaction of stochastic climatic conditions and the application of pasture resource development technologies on the profitability of grazing systems. It encapsulates botanical composition changes in pastures on a seasonal time step. The development of this method provides significant opportunities to model the interaction between the tactical management of grazing systems and the long term expected responses in botanical composition (Figure 5-5).

The total area of pasture is comprised of two components, Desirable species and Undesirable species so that $X_D + X_U = 1.0$, where X_D is the proportion of desirable species and X_U is the proportion of undesirable species within the pasture sward. This is a spatial measure of sward composition similar to basal measurement common in agronomic experiments (Whalley and Hardy, 2000). The growth of the sward is independent of area being occupied, as the paddock area is assumed to be homogenous in micro-climate, soil type and fertility.

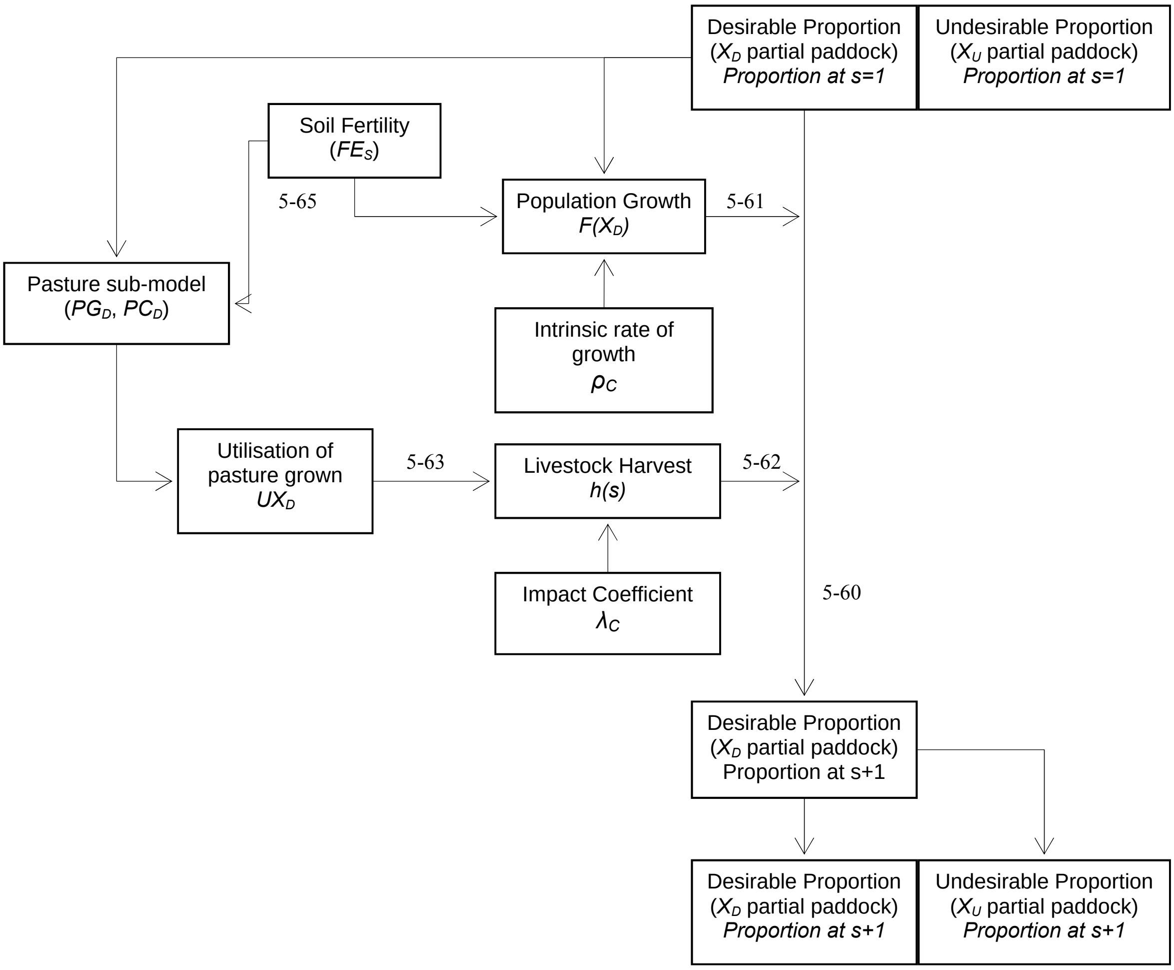

Figure 5-5: Diagrammatic outline of pasture composition sub-model. Numbers and variables indicate the corresponding equations.

Seasonal changes in the botanical composition of the sward are assumed to be driven by the effect of management and climate on the desirable components within the sward, as this group is assumed to have a higher potential growth rate and a higher digestibility and hence is more likely to be consumed than the undesirable species group. A further assumption is that the undesirable species group tends to be invasive and opportunistic wherever there is a decline in the area of the desirable species group. It is also assumed that if desirable species are given the opportunity through adequate soil fertility, tactical grazing rests or reduced grazing pressure during favourable seasons, they will expand their basal cover and move eventually towards attaining dominance of the sward.

The method applied in this study to model pasture resource composition as a renewable resource is similar to that often applied to exploited biological resources (Clark, 1990).

These models are based on differential equations. In this application to the renewable resource of desirable species, the equations are in the form:

$$\frac{dX_D}{ds} = F(X_D) - h(s) \qquad 5\text{-}60$$

where $X_D = X_D(s)$ denotes the proportional area occupied by desirable species within a sward, $F(X_D)$ represents the rate of growth in the area of desirable species, and $h(s)$ is the impact of harvest or grazing on the area occupied by desirable species in a season.

5.2.4.1 Desirable species population growth

The growth in the population of desirable species, measured as the change in the area of the paddock they occupy, is represented by a function describing their rate of growth in the absence of any harvesting or grazing. The rate of growth in the area of desirable species under limited spatial and environmental resources is described using a logistic growth model:

$$F(X_D) = \rho_C X_D \left(1 - \frac{X_D}{\kappa_C FE}\right) FE \qquad 5\text{-}61$$

where ρ_C is the intrinsic rate of growth in the area occupied by desirables species, and κ_C is the environmental carrying capacity, or the maximum area of the paddock that the desirable species may occupy within a sward. The introduction here of a soil fertility effect (*FE* in equation 5-65), potentially limits both the rate of growth in the population and the potential size of the population (Cook *et al.*, 1978a; Dowling *et al.*, 1996; Hill *et al.*, 2005).

The parameter ρ_C is subject to $\rho_C > 0$ and $\rho_C < 1.0$, and is variable as it relates to climate and season. This parameter is varied depending on the type of year and the season in which the shift in botanical composition is being modelled. Figure 5-6 illustrates the impact of different ρ_C values on $F(X_D)$. Higher ρ_C values are expected in favourable years where climatic conditions favour vegetative growth and reproduction of desirable species and lower ρ_C values are expected under poorer climatic conditions.

To enable the application of this method on a seasonal time step, the values of ρ_C for a particular year type have been made in proportion to the potential for vegetative growth and reproduction in a season. This captures the relative importance of season on changes in botanical composition due to tactical grazing rests at different times of the year. Shifts in population in the absence of any harvest or grazing occur mostly in spring, followed by summer with only limited shifts in autumn or winter (Fitzgerald and Lodge, 1997). Values for ρ_C were estimated from the simulation and analysis of in-field experimental data.

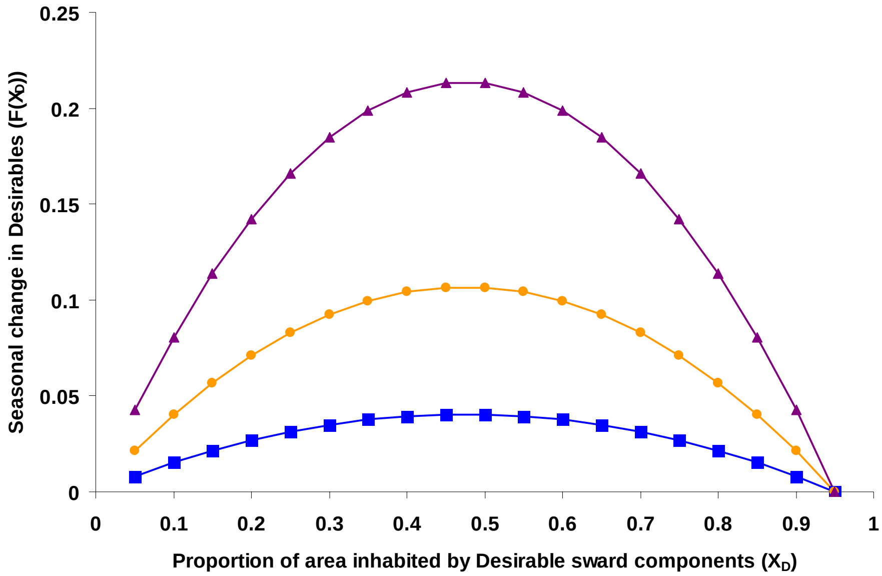

Figure 5-6: Influence of ρ_C and area occupied by desirable species on their rate of expansion in a season; ρ_C = 0.9 (▲),ρ_C = 0.45 (●),ρ_C = 0.17 (■), κ = 0.95 and *FE* = 1.0.

5.2.4.2 Impact of grazing livestock on desirable population

The effect of any livestock grazing on sward structure, *h(s)*, is estimated using the predicted utilisation by grazing livestock of the pasture grown in a season. This takes into account both of the components that make up grazing pressure on the sward, namely stocking rate and grazing time, and the stochastic growth of the pasture in a season.

$$h(s) = UX_D \lambda_{SC} \qquad 5\text{-}62$$

where UX_D is the utilisation of the desirable pasture grown in a season by grazing livestock, and λ_{SC} is the impact coefficient of grazing livestock on the population of desirable species components within the sward. The measure UX_D is similar in principle to the measure of grazing pressure defined by Doyle *et al.*(1994). The parameter λ_{SC} is positive and variable as it relates to the time of year in which the shift in botanical composition is being modelled. The value of the parameter reflects the sensitivity of botanical composition change to seasonal grazing pressure on species phenology.

Figure 5-7 shows that under a constant level of λ_{SC} and with poor seasonal conditions, such as droughts, which induce low intrinsic rates of growth in the population of desirable species (ρ_C=0.17), moderate levels of harvest by grazing livestock (UX_D=0.45) leads to a negative impact ($h(s)>F(X_D)$) on the size of the desirable population. As seasonal conditions improve (ρ_C =0.45 and 0.9) there are states in which moderate harvest levels by grazing livestock allow the proportion of desirable species within the sward to increase (in states when $h(s)<F(X_D)$).

This method encapsulates the effect of different grazing pressures in different seasons on changes in botanical composition. Seasonal values for λ_{SC} were estimated statistically from the simulation of in-field experimental data and guided by expert opinion. An iterative trial and error process was used to estimate the best possible expected outcome for each season and is detailed in Chapter 6.

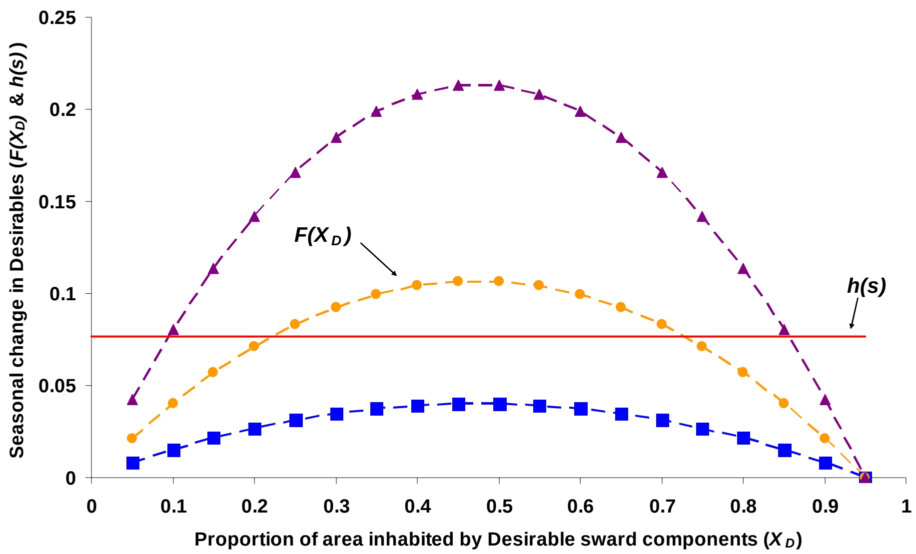

Figure 5-7: Livestock harvesting impact *h(s)* (—) and predicted rates of expansion by desirable species within the sward; ρ_C = 0.9 (▲),ρ_C = 0.45 (●),ρ_C = 0.17 (■), κ = 0.95, *FE* = 1.0; when UX_D = 0.45 and λ_{SC} = 0.17.

Typically the harvesting effect is based on the concept of *catch-per-unit-effort* where the harvest is linearly proportional to the size of the population (Clark, 1990). This has been modified in this application of the model due to the way pasture utilisation by grazing livestock is estimated.

$$UX_D = \max\left(\mu_C, \frac{\sum_{d=1}^{D} PC_{Dd}}{\sum_{d=1}^{D} PG_{Dd}}\right) \qquad 5\text{-}63$$

where μ_C is the maximum utilisation constraint on the impact of grazing livestock on the population of desirables species, PC_D is the quantity of dry matter consumed from only the desirable components of the sward (kg DM/ha), and PG_D is the quantity of dry matter grown from the desirable components of the sward (kg DM/ha). As utilisation over a season is calculated based on the consumption and growth of individuals in the population of desirable species, the need to make *h(s)* a function of X_D is removed. Thus *h(s)* remains constant across all states of botanical composition.

5.2.5 Pasture establishment

In the DPRD model the strategic decision to sow introduced species to replace an existing sward is assumed to occur at the start of a season. The decision to sow causes the adjustment of pasture and stocking rate variables on the first day of a simulated season with the following process occurring:

1. The proportion of the paddock under the desirable species group, X_D is set equal to 0.95 and the proportion under the undesirable species group, X_U is set equal to 0.05.
2. The quantities of pasture biomass available per hectare for the desirable and undesirable swards, Y_D and Y_U, are set equal to 100kg dry matter per hectare.
3. Stocking rate is set to 0 hd/ha from the first day of the season.
4. Monitored on a daily time step, once combined pasture mass, Y_T, reaches 3000 kg dry matter per hectare either in the season in which the pasture is sown or in a following season, sheep stock the paddock at a defined post-sowing stocking rate, SR_S. Y_T is calculated as follows:

$$Y_T = \sum_{dp=1}^{6} GTotal_{dp} \qquad 5\text{-}64$$

where $GTotal_{dp}$ is as defined in equation 5-29.

Steps 1 to 4 occur within the Monte Carlo simulation framework. In the SDP framework only steps 1 to 3 occur as it is assumed that the stocking rate remains at 0 hd/ha only for the season of sowing, after which the dynamic optimisation process identifies future optimal stocking rates.

The costs of sowing pastures, *SCOST*, include the costs of seed, sowing and fertiliser (Scott, 2006). It is assumed these costs occur in the season of sowing and are passed to the economic sub-model. The fertiliser component of the sowing cost is assumed to only be sufficient for the maintenance of the sown pasture in the season of sowing, and as such does not influence soil phosphorus levels. However, additional fertiliser, in the amount of the decision variable P_{FERT}, is applied at the start of each season and is based on the assumed fertiliser input system being tested in either the Monte Carlo or SDP framework.

5.2.6 Soil fertility sub-model

The soil fertility sub-model is similar in nature to the concept of fertility scalars used in more complex biophysical models of grazing systems (Moore *et al.*, 1997), but with the index limiting pasture growth at a daily time step as described in Cacho (1998). This occurs through the inclusion of FE_s in equation 5-54. Figure 5-8 shows a diagrammatic outline of the soil fertility sub-model.

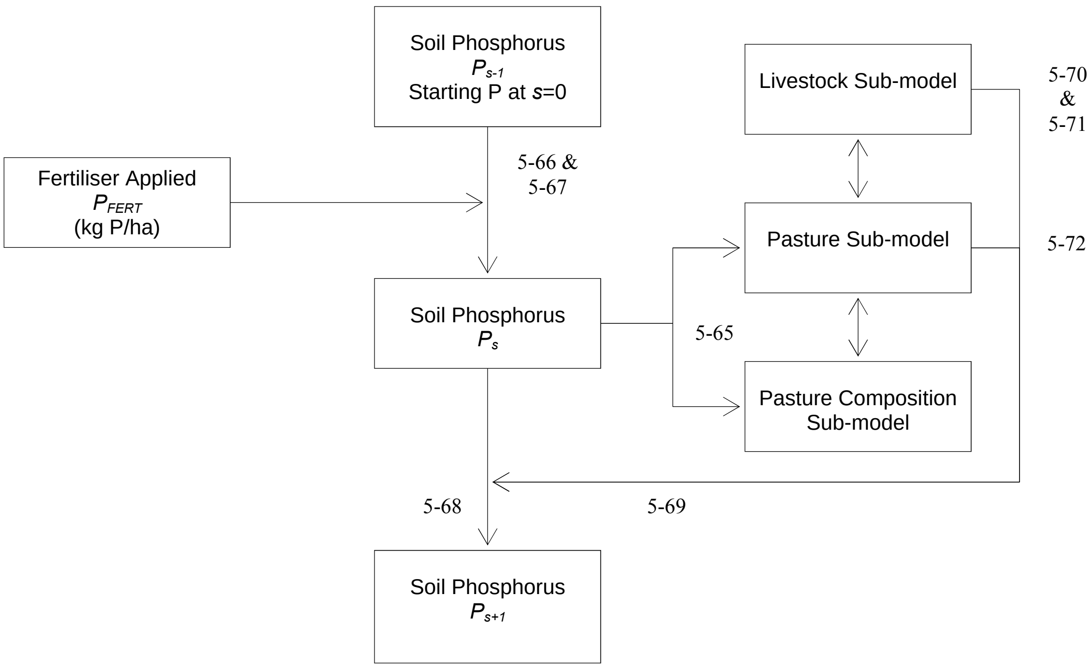

Figure 5-8: Diagrammatic outline of the soil fertility sub-model. Numbers and variables indicate the corresponding equations.

The soil fertility effect for a season, FE_s, is based on the soil phosphorus levels carried over from the previous season and any increases in soil phosphorus from the application of fertiliser. The relative yield restriction is estimated using the Mitscherlich equation (Thornley and France, 2007).

$$FE_s = 1 - e^{\alpha_F P_s} \qquad 5\text{-}65$$

where P_s is the level of soil phosphorus at the start of a season (mg/kg Colwell) and α_F is the parameter describing the rate of change in relative yield response to changes in the levels of soil phosphorus. The parameter α_F is an estimated value which solves equation 5-65 when the relative yield or fertility effect (FE_s) equals 0.95 and P_s equals P_{CF}. P_{CF} is the predicted critical Colwell phosphorus level (P_{CF}) at which 95% of maximum relative yield occurs. P_{CF} is estimated using the following published function derived from the Better Fertiliser Decisions national database (Gourley *et al.*, 2007).

$$P_{CF} = 19.6 + 1.1PBI^{0.55} \tag{5-66}$$

where *PBI* is the Phosphate Buffering Index of a representative soil derived from the Cicerone Project Farmlets database.

Changes to the level of soil phosphorus between seasons are a function of the amount of fertiliser applied and the grazing systems maintenance fertiliser requirements. The level of soil phosphorus for the current season *s*, is calculated after taking into account any applications of fertiliser, whereas the level of soil phosphorus entering the next season, *s+1*, is net of the maintenance phosphorus requirements. This assumes there is an immediate response in pasture growth to any fertiliser applied in the current season, although the residual phosphorus pool for the following season is reduced due to maintenance phosphorus requirements over the season. After the application of fertiliser, the phosphorus level for the current season is calculated as follows:

$$P_s = \max\left[\iota_F, P_{s-1} + \zeta_F\left(P_{FERT}\beta_F\right)\right] \tag{5-67}$$

where P_{s-1} is the soil phosphorus level at the start of the season (mg/kg Colwell), and P_{FERT} is the amount of fertiliser applied (kg of single superphosphate applied/ha). β_F is the proportion of phosphorus available in the fertiliser, ζ_F is a constant that allows for the phosphate buffering capacity of the soil and the response of soil phosphorus levels to applications of fertiliser derived from Burkitt *et al.* (2001), and ι_F is the minimum amount of slow release phosphorus from non-expendable pools available for plant growth.

The amount of soil phosphorus remaining at the end of the season is calculated net of maintenance phosphorus requirements, as follows:

$$P_{s+1} = \max\left(\iota_F, P_s - P_{main}\right) \tag{5-68}$$

where P_{main} is the maintenance fertiliser requirement. The estimation of maintenance fertiliser requirements is derived from the relationships described in Helyar and Price (1999). P_{main} (in mg/kg soil) is a function of phosphorus losses from the paddock system due to livestock product exports and removal of soil phosphorus to sheep camps, and the accumulation of non-exchangeable inorganic and organic phosphorus reserves, and phosphorus gains from non-fertiliser inputs.

$$P_{main} = \frac{\varepsilon_F \left(P_{Exp} + P_{DU} + P_{Acc} - P_{NF}\right)}{\sigma_F} \quad 5\text{-}69$$

where P_{Exp} is the quantity of phosphorus removed through livestock products (kg P/ha), P_{DU} is the removal of soil phosphorus to sheep camps, P_{Acc} is the accumulation of non-exchangeable organic phosphorus, P_{NF} is the non-fertiliser inputs to soil phosphorus levels, ε_F is the proportion of exchangeable phosphorus extracted in the Colwell soil test, and σ_F is the bulk density of the top 10cm of soil (g/cm^3). P_{Exp} is calculated from the amount of product, both wool and sheep meat, removed during the season.

$$P_{Exp} = SR\left[\omega_F \sum_{d=1}^{D} DW_d + \mu_F WT_s\right] \quad 5\text{-}70$$

where DW_d is the daily growth of wool per head, WT_s is net liveweight gain or loss per head, with ω_F and μ_F being the proportion of phosphorus in wool and sheep meat. The calculation of the amount of phosphorus removed through dung and urine to sheep camps, P_{DU}, is based on an assumed constant rate of dung and urine removal per grazing animal.

$$P_{DU} = \frac{\theta_F \sum_{d=1}^{D} 0.1SR}{\left(1 - \upsilon_F\right)} \quad 5\text{-}71$$

where θ_F and υ_F are the proportions of phosphorus in dung and urine that are relocated and concentrated into sheep camps. The quantity of phosphorus immobilised in non-exchangeable organic phosphorus pools is related to pasture production:

$$P_{Acc} = \sum_{d=1}^{D} o_F \left(\frac{\left(PG_U X_U + PG_D X_D\right)}{20.5}\right)_d \quad 5\text{-}72$$

where o_F is the proportion of phosphorus accumulated in the largely non-exchangeable organic phosphorus pool. The non-fertiliser inputs to soil phosphorus, P_{NF} (kg P/ha/season), are based on the quantity of phosphorus in average rainfall.

$$P_{NF} = \sum_{d=1}^{D} \frac{\rho_F AR}{3.65 \times 10^5} \quad 5\text{-}73$$

where AR is the mean annual rainfall (mm/year), and ρ_F is the amount of phosphorus in rainfall (g/mm).

5.3 Summary

The DPRD model developed in this Chapter uses data and models from a range of sources in the literature. Components of the DPRD model have been developed to meet the need for modelling a dynamic pasture resource under stochastic climatic conditions. The model encapsulates the interactions between the production and persistence of the desirable components of pastures, and that of grazing livestock harvesting the pasture resource.

The modelling of interactions between botanical composition in pastures, their productivity and the expected livestock production and subsequent economic returns, has the capacity to adequately test a range of tactical and strategic decisions. The ability of the model to test these decisions in a dynamic pasture resource framework is unique and has the potential to improve tactical and strategic decision making. The robust nature of the functions in the model also ensures the model has broad applicability in the high rainfall temperate pasture zone of Australia and other similar regions.

The DPRD model operates at the paddock level in a broader grazing system. The level of detail in the sub-models and their components is considered appropriate for inclusion into the Monte Carlo simulation and SDP frameworks described in Chapters 6 and 7.

The process of deriving unknown model parameters and evaluating the model is undertaken in Chapter 6. The model is then applied to the case study region to demonstrate and test a range of management options involving the sowing of introduced pastures under different soil fertility input systems and stocking rates. In Chapter 7 the DPRD model is embedded into an SDP framework to identify the optimal management of the dynamic pasture resource.

Chapter 6. Dynamic pasture resource and development model parameterisation and simulation

6.1 Introduction

This chapter describes the parameterisation of the dynamic pasture resource development model (DPRD) and the simulation of a grazing system in the case-study region. The parameterisation of the DPRD model has been achieved through a combination of data analysis from a farming-systems field experiment, expert opinion, and the analysis of the outputs from the simulation of the field experiment using a complex biophysical model (*AusFarm:* CSIRO (2007)).

The calibration and validation of the complex biophysical model and the DPRD model are described. The application of the DPRD model to the high rainfall temperate pasture zone of south eastern Australia is then demonstrated through its incorporation into a Monte Carlo simulation framework. This framework is used to investigate the productivity, profitability and risks associated with pasture improvement technologies and stocking rate policies. The Monte Carlo simulation framework is also used to demonstrate the difference in modelling changes in botanical composition under deterministic and stochastic climatic conditions.

6.2 The Cicerone Project

The Cicerone Project Inc. set up a farming systems experiment to investigate the sustainability and profitability of three farm management systems in the New England region of New South Wales (Gaden *et al.*, 2004; Scott, 2002). The experiment consisted of three farmlets of approximately 50 hectares each. Farmlet A represented a high input flexible grazing system, Farmlet B represented a moderate input system with flexible grazing (described as typical district practice), and Farmlet C represented an intensive rotational grazing system under moderate inputs (for details see Appendix A).

As a high input system, Farmlet A aimed to increase soil fertility and maintain soil test values at 60 mg/kg phosphorus (bicarbonate extract) and 10 mg/kg sulphur (KCI_{40} extract). These levels were considered sufficient to remove most of the growth limitations caused by these two important nutrients (J.M. Scott, *pers. comm.*). Farmlets

B and C were both moderate input systems with soil test targets of 20 mg/kg phosphorus and 6.5 mg/kg sulphur. Over the period of the experiment, soil fertility targets were achieved through a combination of capital and maintenance applications of fertiliser (Guppy, 2005).

The farmlet systems were conducted for July 2000 to December 2006. During this period, cumulative plant available water was modelled based on daily climate records for Armidale NSW, the results showed that the plant available water was at or below long term median conditions throughout the period of July 2000 to April 2005 (Carberry *et al.*, 2005). In combination with periods of moisture stress and utilisation by grazing livestock, there was evidence of reduced pasture persistence of sown and desirable species in all of the treatments (Scott *et al.*, 2005). The measurements made on each of the farmlets provided a diverse source of data for analysis and calibration in the *AusFarm* simulations and DPRD model.

Experimental data were provided through access to a secure on-line database of the Cicerone Project's farmlet experiment (http://www.cicerone.org.au). Access was made available to all collaborating researchers involved in the project. The data queries performed in the database enabled data to be downloaded in a spreadsheet format. However, before it could be used as base data or for calibrating experimental *AusFarm* simulations, the accessed data required sorting and transformation. Other data and information relating to pasture and grazing management within each of the farmlet systems (Mpiti-Shakhane, 2006) and the transformation of farmlet performance to a commercial scale (Scott, 2006) were obtained from collaborating researchers.

6.3 Deriving DPRD model Parameters using *AusFarm* Simulations

AusFarm (CSIRO, 2007), previously known as *Farmwi$e* (Moore, 2001), is the most recent component of the *GrazPlan* suite of decision support tools (Donnelly *et al.*, 2002; Donnelly *et al.*, 1997). *AusFarm* is a complex, multi-function, biophysical model that utilises the climate, soil moisture, pasture and livestock sub-models from other *GrazPlan* decision support tools. This modelling framework is capable of simulating pasture-livestock systems to any level of complexity using daily climate data (Moore, 2001). However, this complexity often limits its application to experimental research by researchers and advisors.

The direct use of *AusFarm* in Monte Carlo simulations and Stochastic Dynamic Programming is limited due to its complexity and resulting computing speed. However, once calibrated to experimental field data, *AusFarm* provides an efficient method of generating parameters for the less complex biophysical models used in the optimisation of farming systems. This is the approach that has been adopted in this study.

6.3.1 Cicerone paddock simulations

The methods of competitive interference between pasture species in the *GrazPlan* suite of models are based largely on light interception and withdrawal of moisture from the soil profile (Salmon *et al.*, 2003). As such, the more complex the sward that is being modelled, the more difficult it becomes for species interactions to be modelled accurately in *AusFarm* and *GrassGro*, particularly in regions where summer-active perennials grow (Salmon, *pers. comm.*).

Commonly, the modelling of grazed pasture paddocks over several years in *Ausfarm* will result in predicted changes to botanical compositions which are often not an accurate reflection of experimental results. Because of the desirability of assessing the impacts of botanical composition change observed on the Cicerone farmlets (Mpiti-Shakhane, 2006), an improved method was needed which would reflect, realistically, the observed changes in botanical composition.

To improve the accuracy of predictions of botanical composition change a partial paddock approach adopted in the DPRD model was also applied to *AusFarm* simulations of the Cicerone Project. This method of simulating more complex pastures is described in section 6.3.1.2 and is supported by others who have discussed the limitations of *GrassGro* in modelling clumpy pastures as well as its rudimentary interspecies competition model (Clark *et al.*, 2000). A single paddock simulation experiment was trialled in *AusFarm*, but predictions of botanical composition change were found to be inferior to those of the partial paddock simulations described in 6.3.2.

The following section details the process adopted for selecting and simulating a Cicerone Project paddock. It describes the base environmental data used, the aggregation of pasture species into functional groups, and the methods used to replicate livestock grazing of the Cicerone paddock.

6.3.1.1 Climate and soil type

The Cicerone project is located at an elevation of 1000 metres above sea level with terrain described as flat to slightly sloping (Mpiti-Shakhane, 2006). The location of the Cicerone Project farmlets 17 km south of Armidale, allowed longer term climate data sets from Armidale to be used in the *AusFarm* simulations. Figure 6-1 shows the mean daily maximum and minimum temperatures for Armidale. The mean annual rainfall over the years of 1968 to 2006 was 745mm per annum with approximately 66% of it falling between October and March (Figure 6-2). The climate is representative of the summer dominant, temperate high rainfall region found in south eastern Australia.

In the *AusFarm* simulations, a default duplex soil profile with a depth of 700mm and 5 layers was used to define the soil type for the Cicerone Project site (A horizon 0-300mm, B horizon 301-700mm). This default profile is supported by earlier research which found a number of duplex soil types in the experimental area (McLeod *et al.*, 1998).

Figure 6-1: Mean daily maximum (—) and minimum (– –) temperatures (^{o}C) for Armidale NSW, over the years of 1968 to 2006 (source: *AusFarm* based on Bureau of Meteorology daily climate records for Armidale, NSW).

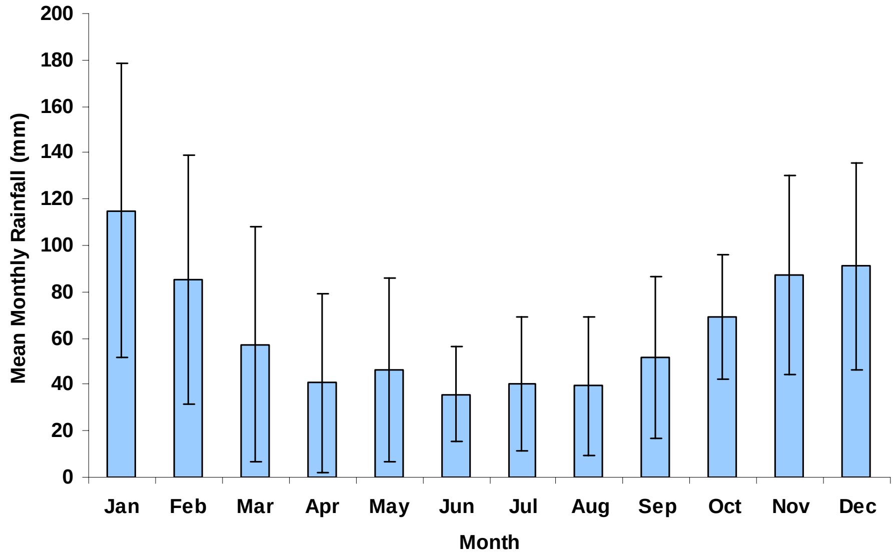

Figure 6-2: Mean monthly rainfall (mm) for Armidale NSW, over the years of 1968 to 2006, +/- one standard deviation shown in the error bars.

6.3.1.2 Pasture species groups

Applying the partial paddock approach required the identification and modelling of two distinct groups of species. These two species groups have been termed "desirable" and "undesirable".

Species that fit within the desirable group are plants that, given good growing conditions, typically produce large amounts of highly digestible and palatable plant material, respond to improved soil fertility, and have the ability to maximise carrying capacity and livestock production.

In contrast, species that have been classified within the undesirable group are plants that are less capable of producing large amounts of highly digestible plant material, tend not to respond greatly to increased levels of soil fertility and are normally associated with lower carrying capacity and livestock productivity.

In other applications of the methodology described in this thesis, these definitions may be extended to include the positive or negative contribution of a particular species towards the perceived sustainability and biodiversity of the pasture. Alternatively, the desirable species group may represent a single species which is the focus of the particular study.

In the Cicerone farmlet experiment, pasture composition was assessed using the Botanal dry weight technique (Scott *et al.*, 2005; Tothill *et al.*, 1978). The allocation of species between the groups and sub-groups was derived from species descriptions documented by Kahn *et al.* (2003), Wheeler *et al.* (1982) and Auld and Medd (1987).

The species identified within the paddocks of the Cicerone Project database (database query: *PastureBotanalSpecies*) were allocated between desirable and undesirable species groups and 6 functional sub-groups (Table 6-1).

Table 6-1: Classification of dominant pasture species into desirable, undesirable, and functional groups. Bolded species indicate those representative species used in the *AusFarm* simulations.

Functional Group	Desirable Species Group	Undesirable Species Group
Annual Grass	*Bromus* spp *Avena fatua*	*Agrostis avenacea* *Briza minor* *Hordeum leporinum* *Setaria* spp ***Vulpia* spp**
Cool Season Species	***Austodanthonia* spp**. *Dichelachne micrantha* *Elymus scaber* *Microlaena stipoides*	*Anthoxanthum odoratum* *Holcus lanatus* *Poa sieberana* *Deyeuxia* spp *Stipa scabra*
Warm Season Species	*Paspalum dilatatum*	*Aristida ramose* ***Bothriochloa macra*** *Chloris truncata* *Cynodon dactylon* *Digitaria sanguinalis* *Eulalia aurea* *Eleusine tristachya* *Eragrostis spp* *Panicum gilvum* *Paspalidium* spp *Pennisetum alopecuroides* *Sorghum leiocladum* *Sporobolus elongatus* *Themeda australis* other unidentified C4 grasses
Introduced Species	*Dactylis glomerata* *Festuca elatior* *Lolium multiflorum* *Lolium perenne* ***Phalaris aquatica***	
Legumes	*Medicago* spp. ***Trifolium repens*** *Trifolium subterraneum*	
Broadleaf & weeds	*Cichorium intybus*	*Carthamus lanatus* *Cirsium vulgare* *Cyperus* spp. *Juncus* spp.

Year-long green perennials were incorporated into cool season species rather than introduced species which predominantly represent previously sown species. The species shown in **bold** text in Table 6-1 were used in the *AusFarm* simulations of the Cicerone paddocks. These species were used as they best represented either the dominant species within the groups or were the most appropriate species available within the limited number of species parameter sets available in *AusFarm*.

6.3.1.3 Representative paddock selection

The Cicerone Project maintained 34 paddocks between the three farmlet treatments. A single paddock, paddock A3 from the Farmlet A treatment, was selected as the most appropriate representative paddock for simulation to derive the required parameters for the DPRD model. The selection of this representative paddock for simulation was based on work by Mpiti-Shakhane (2006) who used multivariate analysis to identify three representative paddocks from each farmlet for further investigation in a detailed biophysical study of pasture and grazing management within each of the farmlet systems. The multivariate analysis considered the criteria of time since sowing, uniformity of species composition, elevation of the paddock, electromagnetic conductivity (soil type), soil phosphorus and sulphur levels. From this work the representative paddocks identified for the three farmlets were A2, A3, A7, B1, B3, B8, C1, C5 and C9.

The final choice of paddock A3 for simulation was based on the quality and quantity of the available data, and especially grazing management and stocking rate records, visual pasture estimates, species composition data, and the period since pasture establishment for each of these identified paddocks. The objective was to identify a paddock representative of the dominant species that could be modelled using *AusFarm* and that had not been resown just prior to, or during the experimental period.

The aggregated functional-group botanical composition data for paddock A3 (Figure 6-3) represent data from individual species recorded for A3 (database query: *PastureBotanalSpecies*) that have been aggregated based on the species allocation (Table 6-1).

The aggregated data for desirable and undesirable species groups over the same experimental period (Figure 6-4), were incorporated into management scripts for

AusFarm that adjusted the respective areas of the desirable and undesirable partial paddocks (Appendix B) during the period 11th December 2001 to 24th January 2006.

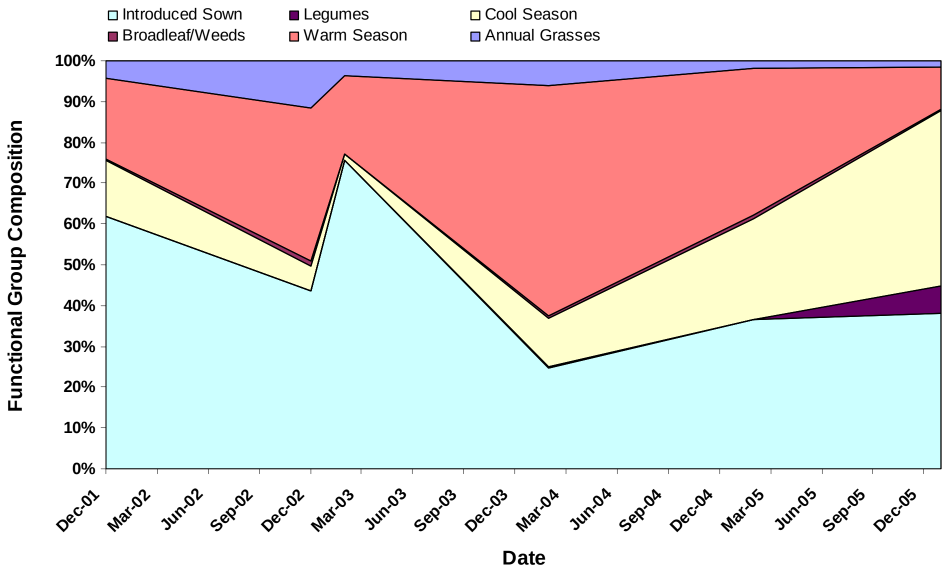

Figure 6-3: Changes in botanical composition summarised as the proportion of functional groups for Cicerone Project Paddock A3, based on classification of individual species outlined in Table 6-1.

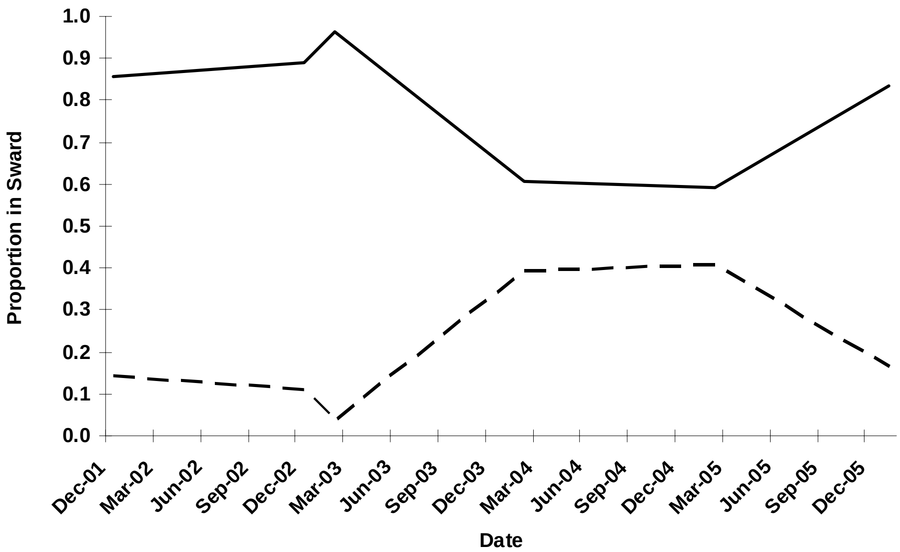

Figure 6-4: Proportion of desirable (—) and undesirable (− −) species groups for the Cicerone Project Paddock A3 based on classification of individual species outlined in Table 6-1.

6.3.1.4 Simulating grazing pressure on Cicerone farmlets

Due to the complex array of livestock types used to graze the Cicerone farmlets, a basic dry sheep equivalent (DSE) substitution method was applied to the Cicerone data (database query: *paddocks_dsegrazingdays_final*). Industry accepted DSE ratings for different stock classes (Table 6-2) were used to calculate the number of DSE days grazed within a paddock over the recorded time period.

The calculated DSE days were transferred into *AusFarm* management scripts to allow automatic running of the software and to replicate the complex movement of livestock in and out of the selected Cicerone paddocks over the entire trial period.

Table 6-2: DSE ratings applied to livestock grazing Cicerone farmlet paddocks. Sourced from Davies (2005).

Animal Class	Physiological Description	DSE Rating
Wethers	50 kg liveweight Mature dry sheep	1.0
Ewes	Pregnant, last 6 weeks bearing single lambs	1.5
	Pregnant, last 6 weeks bearing twin lambs	1.9
	Pregnant, last 6 weeks averaged	1.6
Ewes	Lactating with single lamb	3.0
	Lactating with twin lambs	3.2
	Lactating averaged	3.0
Rams		2.0
Weaners	25 kg & gaining 100grams/day	1.1
Cow & calf	450 kg cow in mid-lactation	16.2
Yearling Cattle	350 kg heifers or steers gaining 1kg/day	10.4
Bulls	800 kg	10

Livestock entering the simulated paddock were allocated between the desirable and undesirable partial paddocks. The proportion of livestock entering the desirable partial paddock, R_D, was calculated using the area-weighted distribution of dry matter and its quality between the two partial paddocks:

$$R_D = \frac{(D_{DD} D_A)}{(D_{DD} D_A + UD_{DD} UD_A)}$$

where D_{DD} and UD_{DD} represent the amounts of available dry matter weighted by the digestibility for desirable and undesirable groups. These are then weighted by D_A and UD_A which represent the area of the desirable and undesirable partial paddocks. The areas of the undesirable and desirable partial paddocks were annually adjusted over the simulation period using data extracted from the Cicerone Project's relational database.

The allocation of total DSEs within the whole paddock was calculated daily, with the livestock entering each partial paddock being of similar average weight. Although this is a simplified version of the selective grazing method described in the DPRD model, it was found to adequately replicate selective grazing pressure for the purposes of calibrating *AusFarm* for long-run simulations in order to derive pasture growth and quality parameters.

6.3.1.5 Supplementary feeding

During the conduct of the Cicerone farmlet experiments significant amounts of supplementary feed were provided to grazing animals. To identify the amounts provided to animals grazing paddock A3, the data from two separate databases were cross-referenced.

The database containing livestock numbers and grazing times within paddocks (database query: *paddocks_dsegrazingdays_final*) were cross referenced with the separate fodder costs database (database query: *Farm_FodderCostsV2*) which contained the number of stock, quantity, timing and type of any supplements fed. Due to inconsistent livestock group referencing between the two datasets, the date of activities, stock number and basic livestock class descriptions were used as the key criteria for identification.

The quantity and type of supplements offered to animals grazing paddock A3 were assembled and incorporated into the *AusFarm* simulation (management scripts shown in Appendix B). Any supplements provided were offered daily to grazing animals in both partial paddocks. The allocation of supplements offered to animals within each partial paddock was based on the daily calculated value of R_D, so that animals in each partial paddock received equal amounts per head.

6.3.2 Calibration of AusFarm

The initial simulations of Cicerone paddock A3 were compared against field experimental data for paddock A3 to determine the level of agreement with the *AusFarm* predictions. Initially *AusFarm* was found to overestimate winter pasture production, leading gradually to the elimination of species such as annual grasses, as well as *Austrodanthonia* and *Trifolium repens*, and concurrently resulting in dominance of *Phalaris* and *Bothriochloa macra*.

In order to improve the level of agreement between the botanical composition data and the *AusFarm* predictions, a combination of developing management scripts and adjusting pasture variables were applied through an iterative trial and error process. A component of the management script was written that maintained less dominant species when necessary through the annual sowing of either ripe soft seed, as was the case for annual grasses and *Trifolium repens*, or the sprouting of rhizome or stolon material common in many perennials, which was the case for *Austrodanthonia* (Garden and Bolger, 2001).

Additional changes to the management script were also written to suppress the winter growth of *Phalaris*, the dominant species within the desirable partial paddock. This was necessary due to the lack of depression during winter of the temperature growth-limiting factor for *Phalaris* in comparison to other C3 species available in the *GrazPlan* suite of decision support software. Within *AusFarm*, *Phalaris* is parameterised to be less sensitive to temperature than other species, based on growth cabinet studies. However, given that growth during winter is also strongly limited by radiation and day length, the relative temperature sensitivities within *AusFarm* may not be appropriately balanced for the Armidale climate (Moore, *pers.comm.*).

The primary pasture variables that can be manipulated in *AusFarm* are the rooting depth and fertility scalars for individual species, as well as the initial amount and distribution of plant material. Initial amounts of plant material were set to represent the aggregated experimental data (database query: *DG_PastureVisualDataComplete*) from paddock A3 of the Cicerone farmlet experiment. This aggregation was based on the allocation of individual species data to the functional and species groups (Table 6-1).

The iterative adjustment of the maximum rooting depth and fertility scalar for the individual representative species allowed the modification of dominance and response between simulated species (Salmon, *pers. comm.*). Appendix B outlines the initial amounts of plant material, final rooting depths and fertility scalars applied to each of the representative species.

A time series comparison between simulated data from *AusFarm* and observed data from paddock A3 is illustrated in Figure 6-5. The predicted *AusFarm* data represent the partial paddock area-weighted mean amount of dry matter available per hectare. The observed data represent the visually estimated amounts of pasture dry matter available that were recorded for paddock A3 from the 1st March 2002 until 12th December 2006.

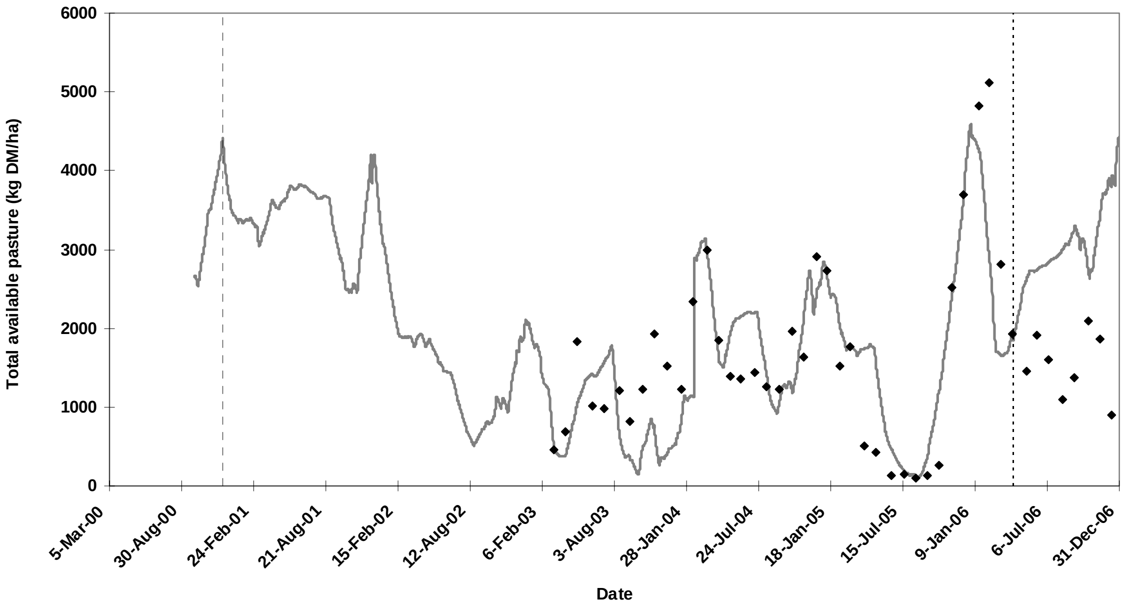

Figure 6-5: Continuous *AusFarm* simulated data and experimental data from the Cicerone Project database indicating change in pasture mass over time for paddock A3. Predicted *AusFarm* (—) and Cicerone Project observed (♦) pasture mass data (available from March 2003 to December 2006). The period between the vertical dashed lines indicates the period for which livestock movement records were available.

Livestock movement records were available for the period 1st February 2001 to 14th April 2006. Outside of this grazing window, the simulated paddock is assumed to remain un-grazed, hence the divergence between the observed and simulated data beyond the 14th April 2006.

Observed data plotted against paired simulated data (Mayer and Butler, 1993) are presented in Figure 6-6. The simulated outputs from the *AusFarm* model are acceptable for their application in this thesis. The slope of the line between observed and predicted data is approximately 1.0 ($p < 0.001$), as would be expected for a good correspondence between observed and predicted data when the intercept is constrained to a value of 0.

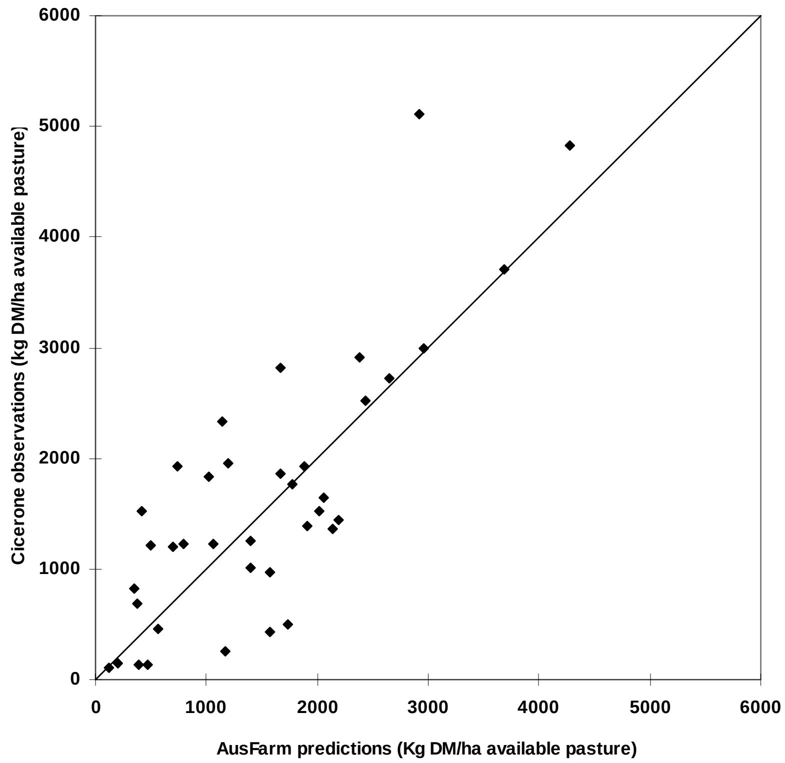

Figure 6-6: Observed Cicerone Project pasture mass data plotted against paired *AusFarm* simulation output for paddock A3 for the period of March 2003 to December 2006.

6.3.3 DPRD pasture parameters

For the DPRD model to operate effectively on a daily time step a range of pasture parameters, identified as 'variable' in Table 5-1 (Chapter 5), were extracted from the *AusFarm* simulations. Parameters were required for the seasonal pasture growth function (equation 5-54), allocation of desirable and undesirable dry matter amongst the digestibility pools (equation 5-28), decay rates for pasture biomass (equation 5-53), and those used to model changes in botanical composition (equations 5-60 to 5-63).

6.3.3.1 Pasture growth

In the DPRD model, as outlined in Chapter 5, the single sigmoid equation described by Cacho (1993) was used to model pasture growth within each season. The three parameters of the pasture growth function, α , γ and Y_{max} were estimated for each season within each year type using data from *AusFarm* simulations. Data for fitting the pasture growth function were derived through a process similar to that described by Alford (2004), and detailed as follows:

1. Four seasonal *AusFarm* simulations were set up based on the calibrated *AusFarm* simulations of the paddock A3, being Autumn, Winter, Spring and Summer. These seasons are designed to represent periods of similar feed quality and production. They also align with periods within a year were the phenology of the species being modelled is consistent. As such the duration and timing of these representative seasons do not match Gregorian calendar definitions.
2. For each seasonal simulation a management script was written to annually cut pastures at heights of 10, 25, 50, 100 and 150mm within a season (detailed in Appendix B). This provided a range of levels for residual dry matter from which the pastures could regrow.
3. The pasture was simulated to be cut daily for 30 days with residual dry matter and daily growth rate recorded. The period within a season to be recorded was identified from an un-harvested 1970 to 2006 *AusFarm* simulation as the period where mean pasture growth rates for that season typically occur. Table 6-3 gives the dates over which measurement of residual dry matter and post-cut pasture growth were averaged. The use of mean residual pasture mass and mean shoot growth rate are justified due to the large volatility in simulated growth rates, where use of a single days measurement, similar to that described by Alford (2004), could lead to erroneous representations of a mean seasonal pasture growth function.
4. Mean residual dry matter (*Y*) and Mean daily growth rate (*dY*) for both desirable and undesirable swards were recorded for each year, season and cut height. Each measurement became an observation, resulting in 5 observations per season within a year.

Table 6-3: Simulated cutting periods for the recording of residual dry matter and post-cutting daily pasture growth rate.

Seasonal Simulation	Season Duration	Simulated cutting and recording periods
Autumn	1st April to 31st May	12th April to 11th May
Winter	1st June to 30th August	25th June to 25th July
Spring	1st September to 31st December	20th October to 19th November
Summer	1st January to 31st March	1st February to 2nd March

The four seasonal *AusFarm* simulation experiments were run over the period 1976 to 2006 with daily climate data for Armidale, NSW. This provided 5 observations for each of the 4 seasons over a 30 year period resulting in a total of 600 observations for the dataset.

Previous studies have suggested that Y_{max}, although rarely reached in a grazing system, is relatively constant within a season and between years (Cacho, 1993), and is lower than the expected theoretical potentials (Harris, 1978). A constant value of Y_{max} was derived for each season and species group. The value for Y_{max} was derived by plotting the *AusFarm* simulation observations from a random selection of years and visually estimating the point at which $dY = 0$ (refer to Figure 5-4). From these estimations of Y_{max} a mean value was derived for each season and species group (Table 6-4). These values are consistent with those found by Alford (2004) and suggested in Harris (1978).

Table 6-4: Seasonal values of Y_{max} (kg DM/ha) applied to each year and seasonal group of observations.

Species Group	Season			
	Autumn	Winter	Spring	Summer
Undesirable	6000	2000	6500	8000
Desirable	5500	5300	8000	5000

Using the statistical package *SAS* (SAS Institute Inc, 2000), the pasture growth coefficients α and γ (equation 5-54) were estimated by fitting actual pasture growth rate observations (dY) against the residual pasture mass (Y) using a non-linear least squares regression based on the Gauss-Newton method. Figure 6-7 illustrates the fitted sigmoid pasture growth curve against *AusFarm* simulation observations for each season in a typical year, with Table 6-5 providing a summary of the coefficient estimates and statistics. The model was found to be highly significant with estimates for α and γ being significantly different from zero ($p \leq 0.05$) for the majority of seasons.

Overall the model was found to best fit the desirable species group. The prediction of winter growth rates for the undesirable species group was the least accurate. Reasons for this may be the species mix of predominantly C4 perennial grasses and to a lesser extent C3 annual grasses found within the undesirable group. Another complicating factor was that increasing the simulated cut height did not significantly increase residual dry matter for the undesirable species group, which resulted in the clustering of dY measurements with only small gains in *Y*. This would be expected given the generally shorter and less erect vegetative growth habit of the dominant undesirable species, *Bothriochloa macra*, being simulated (Whalley *et al.*, 1978). Appendix C details the coefficients for each year and season used in the DPRD model.

Table 6-5: Summary of coefficient estimates and statistics for 2004.

Species Group	Season	Y_{max}	α	$\alpha_{\text{Std Error}}$	γ	$\gamma_{\text{Std Error}}$	Prob. > F
Desirable	Summer	5000	0.0114	0.0006	1.201	0.0567	0.0005
	Autumn	5500	0.0112	0.0011	1.740	0.0377	0.0012
	Winter	5300	0.0085	0.0019	1.375	0.1707	0.0324
	Spring	8000	0.0240	0.0025	1.610	0.0492	0.0017
Undesirable	Summer	8000	0.0229	0.0047	1.599	0.0888	0.0039
	Autumn	6000	0.0076	0.0012	1.736	0.0583	0.0016
	Winter	2000	0.0052	0.0037	1.776	0.2665	0.2061
	Spring	6500	0.0299	0.0014	1.604	0.0217	0.0005

The values of α and γ for the desirable species group are consistent with those estimated by Alford (2004) which were based on *GrassGro* simulation data for Northern Tablelands pastures. The predicted pasture growth rates for desirables and undesirables also correspond to those described by Robinson and Archer (1988) for *Bothriochloa* and *Phalaris* dominated swards at Glen Innes, NSW.

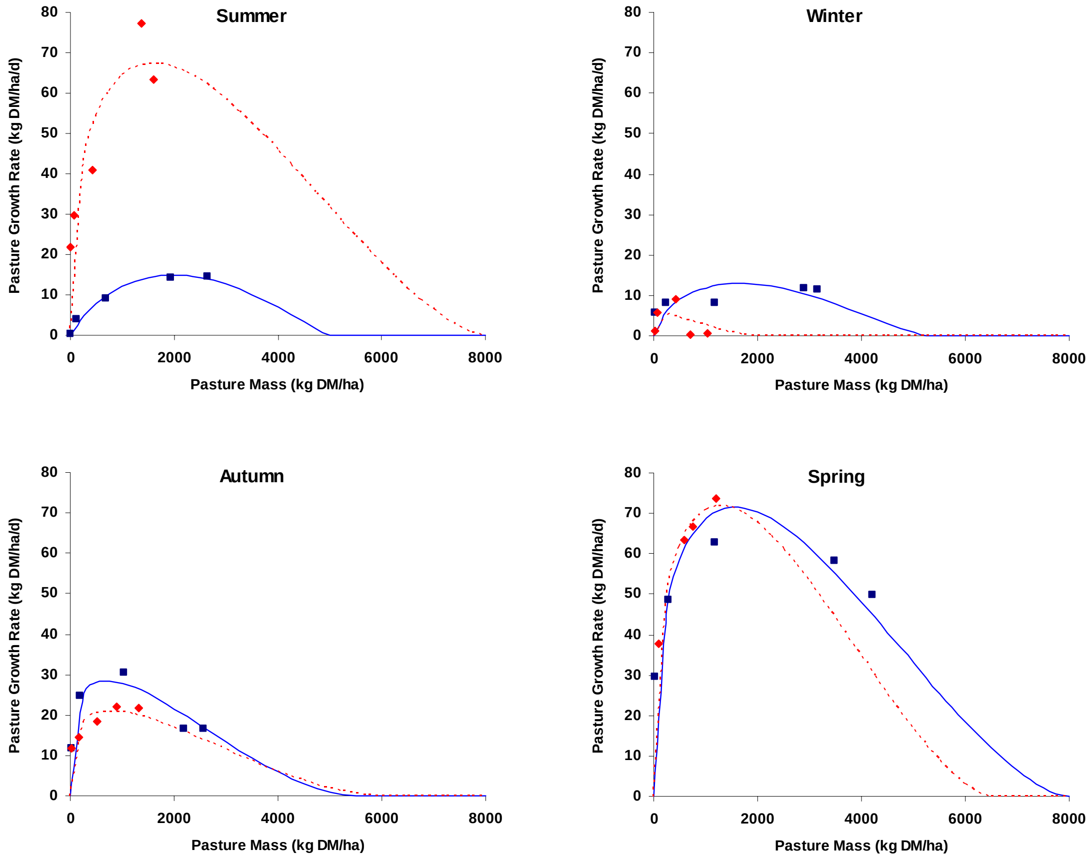

Figure 6-7: *AusFarm* simulation observations for desirable (■) and undesirable (♦) species groups, and the fitted sigmoid growth curve for desirable (—) and undesirable (– –) species groups, for each season in 2004.

6.3.3.2 Stochastic multipliers

When operating the DPRD model in a stochastic simulation, the pasture growth parameters, α_G and γ_G, are adjusted seasonally to reflect different year types using stochastic multipliers. As described in Cacho *et al.* (1999), the mean seasonal parameters, α_G and γ_G, used under deterministic simulations are multiplied by their respective stochastic multiplier to represent a given year type. These stochastic multipliers, $SM\alpha$ and $SM\gamma$, are defined for each season and year (equation 5-56).

For desirable and undesirable species groups, the stochastic multipliers are calculated from the data shown in Appendix C, using each season's value of α_G and γ_G, as well as the mean for that seasonal parameter. Figure 6-8 illustrates the distribution of $SM\alpha_{it}$ and $SM\gamma_{it}$ values for the desirable and undesirable species groups in each season and all these seasonal multipliers have a mean of 1.0.

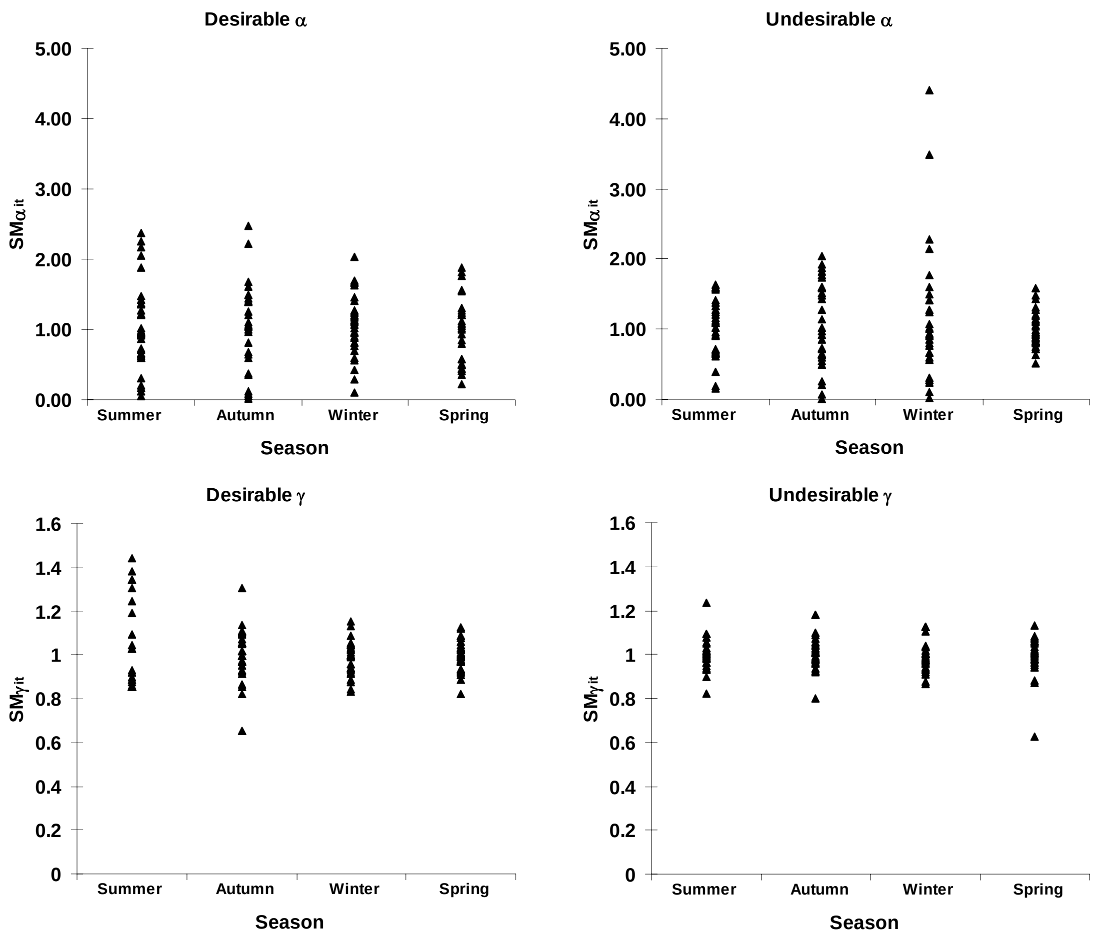

Figure 6-8: Distribution of estimated values of $SM\alpha_{it}$ and $SM\gamma_{it}$ from 30 years of growth coefficients for desirable and undesirable species groups.

6.3.3.3 Pasture quality dry matter distributions

In the DPRD model, δ_{Udp} and δ_{Ddp} are the relative distributions of dry matter in each of the six digestibility pools, denoted by *dp*, for both the desirable and undesirable sward components.

The pasture quality parameters were derived from the *AusFarm* simulations. Due to the complexity of incorporating a variable quality profile into the DPRD model, an average quality profile for each season was estimated from the daily simulation over the period 1976 to 2006 for paddock A3 under a moderate stocking rate of 10 DSE/ha. Figure 6-9 illustrates the average daily distribution of dry matter within each quality pool for both the desirable and undesirable swards. Table 6-6 presents the seasonal parameter estimates for δ_{Udp} and δ_{Ddp} applied in the DRPD model.

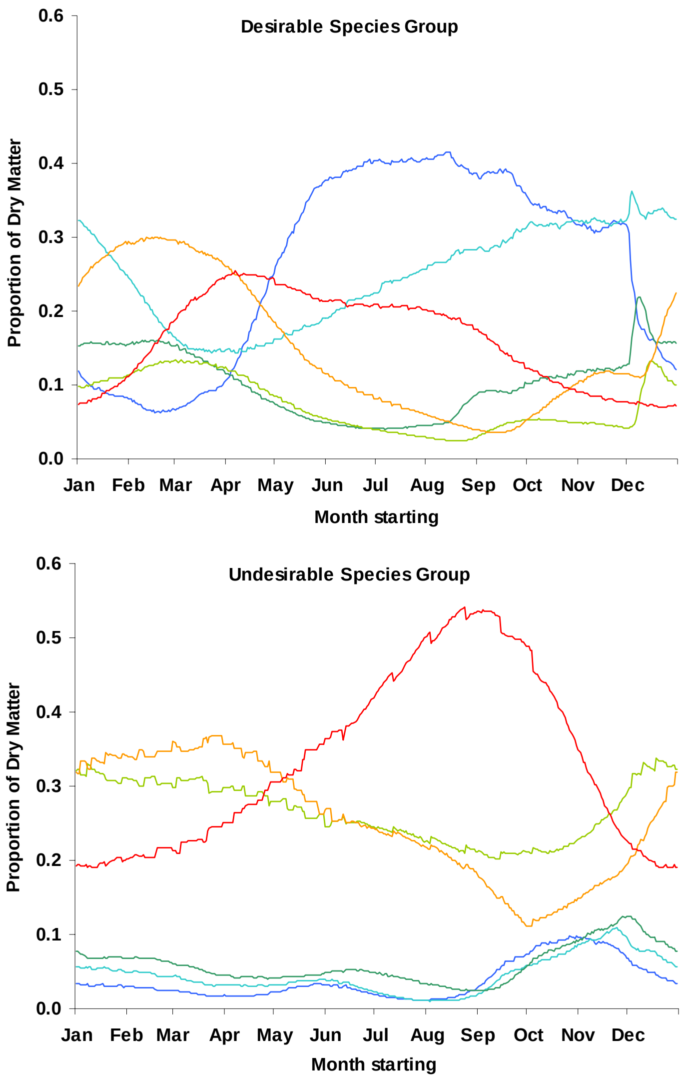

Figure 6-9: Proportion of dry matter in each digestibility pool for Desirable and Undesirable species groups, (—)0.8, (—) 0.7, (—) 0.6, (—) 0.5, (—) 0.4, and (—) 0.3.

Table 6-6: Pasture quality parameters, δ_{Udp} and δ_{Ddp}, the proportions of dry matter in each digestibility pool applied for each season for the desirable and undesirable sward components.

Group	Season	Digestibility pool					
		$\delta_{0.8}$	$\delta_{0.7}$	$\delta_{0.6}$	$\delta_{0.5}$	$\delta_{0.4}$	$\delta_{0.3}$
Desirable	Autumn	0.25	0.16	0.08	0.09	0.19	0.24
	Winter	0.40	0.24	0.05	0.04	0.07	0.20
	Spring	0.30	0.32	0.12	0.06	0.10	0.10
	Summer	0.08	0.21	0.15	0.12	0.28	0.15
Undesirable	Autumn	0.02	0.03	0.04	0.28	0.32	0.30
	Winter	0.02	0.02	0.04	0.24	0.23	0.46
	Spring	0.07	0.07	0.08	0.25	0.18	0.36
	Summer	0.03	0.05	0.06	0.31	0.35	0.21

6.3.3.4 Pasture biomass rates of decay

In the DPRD model, σ_D and σ_U are the mean daily decay rates of pasture for the desirable and undesirable swards respectively. These parameters were estimated from the *AusFarm* simulations described in the previous section. The long-term average daily decay rates for both the desirable and undesirable swards over the simulation period of 1976 to 2006 are illustrated in Figure 6-10. The mean daily decay rates of pasture biomass applied in the DPRD model for each season and sward group are given in Table 6-7.

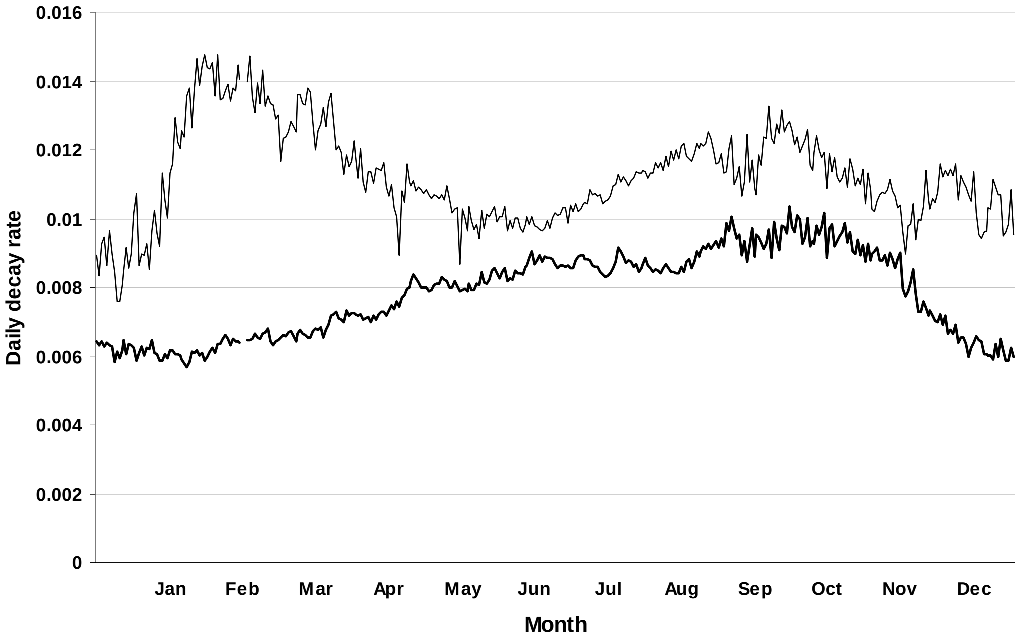

Figure 6-10: Average daily decay rates for desirable (−) and undesirable (—) swards.

Table 6-7: Daily pasture decay rates, σ_D and σ_U, for desirable and undesirable swards.

Season	Species Group	
	Desirable	Undesirable
Autumn	0.0111	0.0076
Winter	0.0107	0.0086
Spring	0.0112	0.0084
Summer	0.0120	0.0063

6.3.4 Botanical composition

As explained in Chapters 4 and 5, a dynamic exploited-population model (Clark, 1990) was applied in the DPRD model to encapsulate the dynamic nature of pasture management, grazing and climate as they affect botanical composition and the subsequent effects of those changes on pasture and livestock production. The application of this model in a grazing system requires the estimation of parameters that predict the intrinsic rate of growth of the desirable population in the absence of grazing (ρ_C) as well as the impact grazing livestock have on the desirable population (λ_{SC}). The parameters have been estimated using a combination of experimental field data, *AusFarm* simulation output and expert opinion.

6.3.4.1 Intrinsic rate of growth in the 'desirable' species population

The intrinsic rate of growth in the basal area of desirable species in the absence of any harvesting by grazing livestock, ρ_C, was estimated from unpublished experimental field trial data from 1967 to 1973 at the long-term grazing trial site 'Big Ridge' (Hutchinson and King, 1980) at the CSIRO Pastoral Research Laboratory, near Armidale, NSW (latitude 30°31'S, longitude 151°39'E, altitude 1000 m). Hutchinson (*pers. comm.*) indicated that, under favourable seasonal conditions, and in the absence of grazing and under high soil fertility, the basal cover of desirable species, in this instance predominantly phalaris, increased from 10% to 80% within 3 years. This is supported by other literature that has indicated introduced species, with adequate soil fertility and favourable environmental conditions, have the potential to rapidly increase their basal cover in degraded pastures (Dowling *et al.*, 1996; Michalk *et al.*, 2003; Virgona and Bowcher, 2000), especially when rested from grazing.

In this analysis it is assumed that the potential intrinsic rate of growth in the basal area of the desirable population is in direct response to the potential vegetative growth of desirable species within a season. The potential for vegetative growth within a season is best represented by α_G which is the pasture growth parameter within the sigmoidal growth function used in the DPRD model. This concept is supported by work which has found that, providing there is the opportunity for pasture growth, there is the potential for the preferred species to increase its size, weight and basal cover when there is reduced defoliation stress (Cook *et al.*, 1978a; Dowling *et al.*, 2005; Dowling *et al.*, 1996).

Analysis of 'Big Ridge' unpublished data

To estimate the intrinsic rate of growth, *AusFarm* was used to simulate the 'Big Ridge' site over the period 1st January 1966 to 31st December 1972. Within the period 1st October 1967 to 1st October 1969 the paddock was simulated to be grazed under a constant stocking rate of 40 DSE/ha, reflecting the actual experimental conditions over that period. From the 1st October 1969 the simulated paddock remained destocked and the method previously described to estimate pasture growth rate from different pasture cut heights and residual masses was applied. This allowed the estimation of a ρ_H: α_T ratio, where ρ_H is the estimated cumulative intrinsic rate of growth at the 'Big Ridge' site and α_T is the cumulative sum of the growth parameter α_S for each season between spring 1969 and spring 1972 as derived from *AusFarm* simulations.

The cumulative intrinsic rate of growth, ρ_H, was estimated by iteratively solving the growth of the desirable population so that the proportion of the paddock occupied by desirable species, X_D, is equal to 0.80 at the end of spring 1972. The intrinsic rate of growth of the desirable population within each season, ρ_S, was estimated as follows:

$$\rho_S = \rho_H \left(\frac{\alpha_S}{\sum_{S=S_1}^{S_T} \alpha_S} \right)$$

where S_T is the total number of seasons from spring 1969 to spring 1972, S is an index for season, and S_1 is the first season (Spring 1969).

Table 6-8 presents the calculated values of ρ_H and ρ_S, and Figure 6-11 illustrates the predicted changes in the proportion of the site occupied by desirable species.

Table 6-8: Estimated α_S, ρ_S and cumulative intrinsic rate of growth ρ_H for the 'Big Ridge' site. *FE = 1.0* and $\kappa_C = 0.95$.

Year	Season	X_D	$F(X_D)$	ρ_S	α_S
1969	Destock	0.10			
	Spring	0.14	0.04	0.476	0.020
1970	Summer	0.16	0.02	0.125	0.005
	Autumn	0.17	0.01	0.058	0.002
	Winter	0.17	0.00	0.005	0.000
	Spring	0.25	0.08	0.579	0.025
1971	Summer	0.32	0.07	0.403	0.017
	Autumn	0.33	0.01	0.041	0.002
	Winter	0.34	0.01	0.048	0.002
	Spring	0.38	0.04	0.185	0.008
1972	Summer	0.45	0.07	0.304	0.013
	Autumn	0.63	0.18	0.772	0.033
	Winter	0.66	0.03	0.158	0.007
	Spring	0.80	0.14	0.681	0.029
Cumulative ρ_H & α_T				3.837	0.163
$\rho_H : \alpha_T$ ratio					23.516

The estimated ρ_H: α_T ratio was then applied to simulated years to derive a climatically adjusted intrinsic rate of growth, ρ_C, for each season and year type (Table 6-9). This was done using the following equation:

$$\rho_C = \min[0.999, \alpha_S(\rho_H : \alpha_T)]$$

The maximum value of 0.999 represents the constant intrinsic rate of growth under the most favourable climatic conditions, but which is adjusted seasonally by the value of α_S.

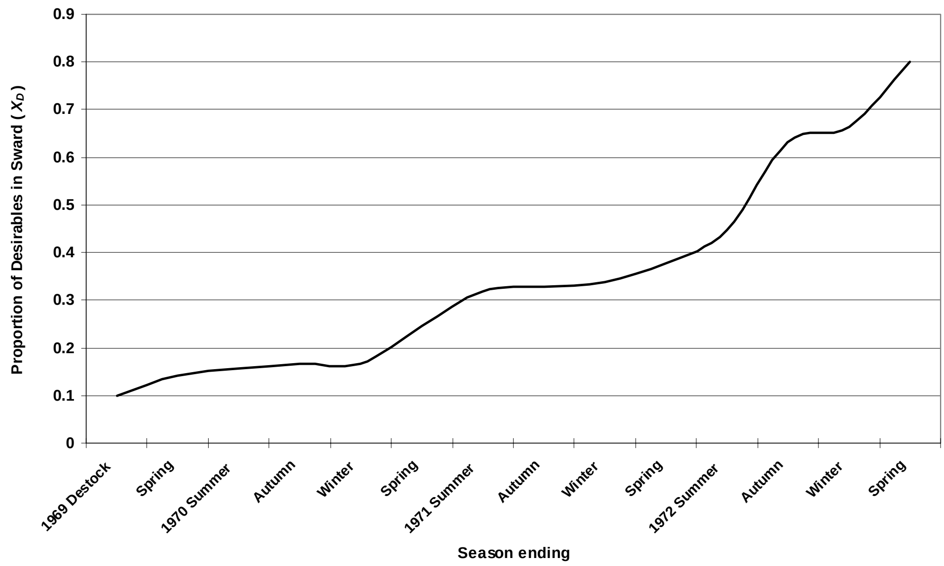

Figure 6-11: Predicted change in botanical composition from Hutchinson (*pers. comm.*) unpublished data.

Table 6-9: Intrinsic rate of desirable population growth, ρ_C.

Year	Autumn	Winter	Spring	Summer
1976	0.625	0.423	0.477	0.426
1977	0.462	0.180	0.269	0.319
1978	0.361	0.076	0.582	0.308
1979	0.481	0.528	0.731	0.460
1980	0.041	0.209	0.229	0.197
1981	0.050	0.144	0.567	0.424
1982	0.160	0.025	0.271	0.207
1983	0.540	0.266	0.512	0.200
1984	0.557	0.248	0.469	0.066
1985	0.668	0.293	0.596	0.037
1986	0.024	0.227	0.194	0.093
1987	0.489	0.325	0.377	0.186
1988	0.633	0.377	0.100	0.017
1989	0.466	0.304	0.440	0.291
1990	0.669	0.210	0.205	0.225
1991	0.472	0.367	0.207	0.288
1992	0.435	0.310	0.508	0.589
1993	0.025	0.434	0.526	0.742
1994	0.623	0.155	0.242	0.294
1995	0.164	0.252	0.565	0.703
1996	0.287	0.439	0.825	0.447
1997	0.305	0.285	0.727	0.395
1998	0.753	0.312	0.880	0.638
1999	0.999	0.324	0.851	0.220
2000	0.997	0.435	0.616	0.185
2001	0.719	0.329	0.394	0.378
2002	0.451	0.109	0.164	0.051
2003	0.642	0.294	0.231	0.269
2004	0.263	0.199	0.564	0.304
2005	0.007	0.231	0.561	0.379

6.3.4.2 Livestock harvest impact coefficient

The negative effect of livestock harvesting plant material on the basal area of desirable species is derived from the simulation of experimental field data. Once the intrinsic rate of population growth is known, the livestock harvest impact coefficient, λ_{SC}, can be estimated through the simulation of the Cicerone farmlet experiment. The *AusFarm* simulation data representing paddock A3, was used to estimate the quantity of pasture consumed (PC_D) and grown from desirable species (PG_D) and also to calculate the seasonal utilisation of desirable species, UX_D.

An important factor in estimating λ_{SC} for each season was that botanical composition is most sensitive to the harvesting of plant material by grazing livestock during the spring, followed sequentially by summer, autumn and winter (Dowling *et al.*, 1996; Kemp, 1993). Table 6-10 gives the estimated values for λ_{SC} for the A3 paddock over the seasons from Spring 2001 and Autumn 2006. The parameter μ_C (see equation 5-62) is the maximum utilisation constraint and reflects the potential maximum changes in botanical composition reported in the literature (Scott *et al.*, 2000b). This parameter was given a value of 2.5 and was guided by expert opinion (J.M. Scott, *pers. comm.*). The final results from this iterative 'trial and error' process, used to minimise the sum of squares of deviations between predicted and observed proportions of desirable species, are shown in Appendix D.

Given the outcomes of the graphical analysis (Figure 6-12) and the limited availability of data from the Cicerone farmlet experiment, with only four periods between botanical composition measures available, these estimates were assumed to be sufficient for the objectives of this study. Paired data for the graphical analysis assumes a linear interpolation between the start and end of the season for predicted data where field experimental data occurred between these points.

Table 6-10: Predicted values of λ_{SC} used in the DPRD model.

Season	λ_{SC}
Autumn	0.060
Winter	0.070
Spring	0.120
Summer	0.082

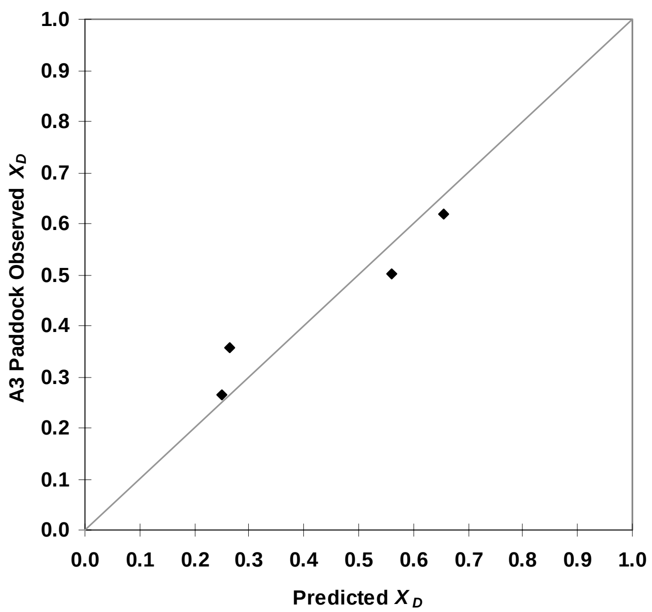

Figure 6-12: Observed Cicerone Project paddock A3 pasture composition data (proportion desirable species, X_D) plotted against predicted data.

6.4 Validation of the DPRD model

The validation of a model through testing and comparison with experimental data is a necessary step for model acceptance (Mayer and Butler, 1993). The statistical validation of the DPRD model is limited due to a number of factors. These include its design for the examination of a dynamic grazing system and resource problem (Harrison, 1990), and the general lack of data available within the case study region to validate the model's predictions.

It has been suggested that the use of visual techniques such as plotting observed against predicted observations provide superior diagnostic capabilities compared to time-series plots (Mayer and Butler, 1993). Both techniques have been applied to the calibration of *AusFarm* simulations and the parameterisation of the DPRD model using the available field experimental data.

The DPRD model contains components that have been extensively validated by other researchers. For example, many of the functions within the livestock sub-model that were adapted from the *GrazPlan* suite of decision support tools, have been extensively tested and found to adequately predict livestock performance (Clark *et al.*, 2000; Salmon *et al.*, 2004). Many of the functions found in the DPRD livestock sub-model are also defined in the most recent edition (Freer *et al.*, 2007) of the original report by the SCA (1990) that describes the feeding standards for Australian ruminant livestock. The *GrassGro* component of the *GrazPlan* suite is also a key component in predicting pasture growth rate parameters for the DPRD model and has been found to be robust under temperate pasture systems (Salmon *et al.*, 2003).

Harrison (1990) suggests that graphical comparison and appraisal of model output during the development process by subject-matter specialists is the most appropriate procedure for validating farming systems models and their components. These techniques have been applied to the parameterisation of the pasture composition sub-model.

Another method of validating and gaining confidence in the DPRD model is by demonstrating its application. This is done through experimental simulation in the following sections.

6.5 Simulation using the DPRD model

A series of simulation experiments were performed to investigate the effects of stocking rate and fertiliser input on wool and sheep meat production, profitability and risk. The series of simulation experiments were conducted for both a newly sown pasture and an existing degraded sward.

To demonstrate the implications of ignoring the interaction of a stochastic climate and the dynamic nature of the pasture resource, the series of simulation experiments were conducted under both deterministic and stochastic conditions. In the deterministic simulations the botanical composition remained at its initial value and climate represented an average year. In addition, to further investigate the sensitivity of model outcomes to the dynamic botanical composition sub-model and the effects of stochastic climatic conditions, combinations of static and dynamic botanical composition were simulated against combinations of deterministic and stochastic climatic conditions.

Each simulation experiment ran over a period of 10 years which corresponds to the perceived persistence of sown perennial pastures by 80% of producers in the high rainfall temperate pasture zone of south eastern Australia (Reeve *et al.*, 2000). Ten stocking rate levels (3 to 30 hd/ha set stocked) were tested against 3 levels of fertiliser application (42, 125 and 250 kg/ha/annum of single superphosphate) for both an existing degraded sward and a sown pasture. The sown pasture remained destocked until pasture mass reached 3000 kg DM/ha, after which the tested stocking rate level was applied. This represents a 10 x 3 x 2 factorial experiment with 300 iterations per treatment in stochastic mode and 1 iteration per treatment in deterministic mode, a total of 60 treatment combinations per mode.

The initial state of the paddock simulated represents what is perceived as typical for the New England region located within the high rainfall temperate pasture zone of south eastern Australia and is based on the starting point for the average paddock in the Cicerone farmlet experiment. The starting soil fertility level was assumed to be moderate with 22 ppm Colwell P and a botanical composition of 44% desirable and 56% undesirable species in the sward. The assumed starting point for the experimental simulations was the 1st April with a pasture mass of 2300kg DM/ha. These initial values represent the mean values extracted from the Cicerone Project database for all paddocks at the start of the field experiment.

The DPRD model has been implemented and solved using Matlab 7 (The Mathworks Inc., 2004). The Matlab code describing all of the DPRD sub-models and the application of the DPRD model to the Monte Carlo simulation framework is detailed in Appendix E.

6.5.1.1 Supplementary feeding policies

The quantity of supplements offered to grazing animals in the DPRD model influences the economics of the grazing system, animal performance, pasture production and botanical composition. Two decision rules are applied in both the Monte Carlo simulation and stochastic dynamic programming framework (Table 6-11).

These decision rules are applied each day in the model with the equivalent of a maintenance ration in cereal grain (wheat) being offered to the grazing animals when applicable. The maintenance ration was been based on the energy requirements for maintaining a wether in condition score 2.0. The quantity of supplements offered to grazing animals, kg DM/animal/day, is calculated using the following equation.

$$SDM = 0.85 SRW \sigma_S$$

where SRW is the standard reference weight of the sheep genotype in condition score 3.0, σ_S is the quantity of supplement required to maintain 1kg of liveweight of a sheep in condition score 2.0 (Freer *et al.*, 2007).

Table 6-11: Supplementary feeding decision rules applied in the DPRD model with the quantity offered being *SDM*.

Supplementary feeding rule	Description
If $B_d < 0.85SRW$	Represents a minimum condition score of 2.0 at which wethers are capable of survival and production, and a reduced likelihood of tender wool (Bell and Alcock, 2007; Morley, 1994). This base feeding rule is applied concurrently with the following pasture mass driven feeding rule.
If $\sum_{dp=1}^{6} GTotal_{dp} < 100$	Minimal supplementation to maintain the existence of a pasture sward in the DPRD model.

6.6 Simulation Results

6.6.1 Pasture resource

The summarised results for the stochastic and deterministic simulations are presented in Table 6-12 and Table 6-13. In the stochastic simulations the proportion of desirables remaining and the level of soil phosphorus after ten years of grazing were affected by both the stocking rate and levels of fertiliser application (Table 6-12). For both the sown and degraded pasture, the proportion of desirables ranged from 0.9 to 0.05. The highest levels of desirables were maintained under low stocking rate and high soil fertility conditions. With increasing stocking rates and decreasing soil fertility, the persistence of desirable species declined to the lower limits within the ten year simulation period.

The proportion of desirables was marginally higher for the sown pasture than the degraded pasture after 10 years. Under low soil fertility conditions, the highest level the proportion of desirables reached was 0.5. This decreased rapidly to the lower limit of 0.05 with stocking rates greater than 12 head per hectare. At higher soil fertility levels, the persistence of desirable species increased, with higher stocking rates capable of being maintained. For the degraded pasture, stocking rates of around 3 head per hectare allowed the pasture to persist in its initial state until the end of the 10-year simulated period. With stocking rates of 15 and 30 head per hectare, moderate and high levels of fertiliser application maintained the pasture in its initial state.

Table 6-12: Results of the stochastic simulation experiments (mean of 300 iterations with one standard deviation in parenthesis). SS is single superphosphate.

Stocking Rate (hd/ha)	Degraded Pasture: Fertiliser applied (kg SS/ha/year) 42	125	250	Sown Pasture: Fertiliser applied (kg SS/ha/year) 42	125	250
Proportion of area occupied by Desirables at the end of the simulation						
3	0.49 (0.06)	0.86 (0.04)	0.89 (0.04)	0.50 (0.06)	0.86 (0.04)	0.90 (0.04)
6	0.28 (0.07)	0.77 (0.06)	0.85 (0.06)	0.31 (0.07)	0.78 (0.06)	0.84 (0.06)
9	0.13 (0.06)	0.70 (0.08)	0.80 (0.08)	0.15 (0.07)	0.71 (0.08)	0.80 (0.08)
12	0.06 (0.02)	0.58 (0.10)	0.76 (0.09)	0.07 (0.03)	0.61 (0.09)	0.76 (0.09)
15	0.05 (0.00)	0.47 (0.11)	0.72 (0.11)	0.05 (0.01)	0.50 (0.12)	0.73 (0.10)
18	0.05 (0.00)	0.35 (0.12)	0.67 (0.13)	0.05 (0.01)	0.40 (0.12)	0.70 (0.10)
21	0.05 (0.00)	0.23 (0.12)	0.65 (0.13)	0.05 (0.01)	0.27 (0.13)	0.65 (0.12)
24	0.05 (0.00)	0.12 (0.08)	0.61 (0.14)	0.05 (0.00)	0.18 (0.11)	0.61 (0.13)
27	0.05 (0.00)	0.07 (0.04)	0.56 (0.16)	0.05 (0.00)	0.13 (0.09)	0.58 (0.15)
30	0.05 (0.00)	0.05 (0.01)	0.50 (0.18)	0.05 (0.04)	0.09 (0.07)	0.55 (0.16)
Soil Fertility at the end of the simulation (ppm Colwell P)						
3	8.3 (1.1)	34.6 (1.8)	81.5 (1.9)	8.5 (1.3)	34.8 (1.8)	81.6 (1.9)
6	5.5 (1.0)	28.5 (1.9)	74.7 (2.2)	5.8 (1.3)	29.1 (2.4)	75.5 (2.4)
9	4.1 (0.8)	23.3 (2.2)	68.5 (2.5)	4.4 (1.0)	24.0 (2.4)	70.1 (2.9)
12	3.4 (0.5)	19.0 (2.3)	63.1 (2.9)	3.5 (0.6)	20.0 (3.0)	64.6 (3.2)
15	3.1 (0.2)	15.7 (2.3)	58.1 (3.2)	3.1 (0.3)	16.6 (2.6)	59.8 (3.6)
18	3.0 (0.0)	12.9 (2.3)	54.3 (3.6)	3.0 (0.2)	14.0 (2.9)	55.6 (3.9)
21	3.0 (0.0)	10.9 (2.3)	50.2 (3.7)	3.0 (0.3)	12.2 (2.6)	52.5 (4.6)
24	3.0 (0.0)	10.5 (2.5)	46.7 (4.1)	3.0 (0.0)	10.8 (2.8)	49.6 (4.5)
27	3.0 (0.0)	9.1 (2.0)	43.7 (4.0)	3.0 (0.1)	9.7 (2.2)	47.0 (4.7)
30	3.0 (0.0)	8.2 (1.8)	41.5 (4.6)	3.0 (0.5)	8.8 (2.0)	44.8 (5.1)
Wool production (kg clean wool/hd/year)						
3	4.4 (0.6)	5.0 (0.5)	5.1 (0.5)	4.4 (0.5)	5.0 (0.7)	5.2 (0.7)
6	3.7 (0.8)	4.7 (0.5)	4.9 (0.5)	3.8 (0.5)	4.7 (0.8)	5.0 (0.7)
9	3.2 (0.9)	4.4 (0.6)	4.6 (0.6)	3.2 (0.5)	4.4 (0.7)	4.7 (0.6)
12	2.9 (0.9)	4.0 (0.6)	4.4 (0.6)	2.9 (0.5)	4.1 (0.7)	4.5 (0.6)
15	2.7 (0.7)	3.7 (0.6)	4.2 (0.6)	2.8 (0.4)	3.8 (0.6)	4.3 (0.6)
18	2.7 (0.6)	3.4 (0.5)	3.9 (0.6)	2.7 (0.3)	3.5 (0.6)	4.1 (0.5)
21	2.6 (0.5)	3.2 (0.5)	3.7 (0.5)	2.6 (0.3)	3.2 (0.5)	3.8 (0.5)
24	2.6 (0.4)	2.9 (0.5)	3.5 (0.5)	2.6 (0.3)	3.0 (0.5)	3.6 (0.5)
27	2.7 (0.4)	2.7 (0.5)	3.4 (0.5)	2.6 (0.3)	2.8 (0.5)	3.4 (0.5)
30	2.7 (0.3)	2.6 (0.4)	3.2 (0.4)	2.6 (0.2)	2.7 (0.4)	3.3 (0.5)
Wool fibre diameter (microns)						
3	20.2 (1.5)	21.2 (1.2)	21.4 (1.2)	20.5 (1.5)	21.6 (1.8)	21.9 (1.9)
6	19.2 (1.8)	20.7 (1.4)	21.0 (1.4)	19.5 (1.4)	20.9 (1.9)	21.4 (1.9)
9	18.3 (1.9)	20.2 (1.5)	20.7 (1.5)	18.5 (1.4)	20.6 (1.8)	21.0 (1.9)
12	17.9 (1.7)	19.7 (1.6)	20.3 (1.6)	18.1 (1.4)	20.0 (1.8)	20.8 (1.8)
15	17.8 (1.5)	19.2 (1.6)	19.9 (1.7)	18.0 (1.3)	19.6 (1.7)	20.3 (1.8)
18	17.8 (1.3)	18.7 (1.6)	19.5 (1.7)	18.0 (1.3)	18.9 (1.7)	20.0 (1.8)
21	17.9 (1.2)	18.2 (1.5)	19.2 (1.7)	18.0 (1.3)	18.6 (1.7)	19.5 (1.8)
24	18.0 (1.1)	17.8 (1.4)	18.9 (1.7)	18.1 (1.3)	18.1 (1.7)	19.3 (1.7)
27	18.0 (1.0)	17.6 (1.3)	18.7 (1.6)	18.0 (1.4)	17.9 (1.6)	19.0 (1.7)
30	18.1 (1.0)	17.5 (1.2)	18.4 (1.5)	18.1 (1.3)	17.8 (1.6)	18.7 (1.8)

Table 6-12 continued

Stocking Rate (hd/ha)	Degraded Pasture: Fertiliser applied (kg SS/ha/year) 42	125	250	Sown Pasture: Fertiliser applied (kg SS/ha/year) 42	125	250
Liveweight change (kg liveweight/hd/year)						
3	16.5 (5.6)	22.0 (4.2)	23.1 (4.2)	15.8 (6.7)	21.2 (6.3)	22.3 (6.4)
6	10.2 (8.2)	19.1 (4.9)	20.7 (4.8)	10.1 (8.2)	18.3 (6.6)	19.7 (6.5)
9	3.7 (10.7)	15.7 (5.5)	18.1 (5.4)	4.2 (10.2)	15.6 (6.2)	17.1 (6.6)
12	-1.5 (11.5)	12.2 (6.1)	15.5 (5.9)	-0.4 (11.4)	12.4 (6.4)	14.9 (6.4)
15	-4.9 (10.8)	8.6 (6.3)	12.8 (6.2)	-3.6 (11.0)	9.1 (6.6)	12.7 (6.5)
18	-7.1 (9.8)	5.0 (6.5)	9.8 (6.4)	-5.8 (10.0)	6.0 (6.6)	10.2 (6.6)
21	-8.4 (8.8)	1.5 (6.7)	7.4 (6.4)	-7.2 (9.1)	2.6 (6.8)	7.7 (6.5)
24	-9.4 (7.6)	-2.6 (7.3)	5.0 (6.4)	-8.2 (8.0)	-0.5 (6.9)	5.1 (6.4)
27	-10.2 (6.5)	-5.5 (7.1)	2.7 (6.3)	-8.9 (7.1)	-3.2 (6.7)	2.8 (6.2)
30	-10.4 (5.7)	-7.9 (6.7)	0.1 (6.0)	-9.5 (6.3)	-5.7 (6.8)	0.8 (5.9)
Gross margin ($/ha/year)						
3	67 (17)	64 (14)	36 (14)	35 (102)	32 (106)	4 (107)
6	131 (42)	161 (31)	141 (31)	94 (120)	122 (134)	101 (134)
9	160 (86)	237 (48)	229 (50)	122 (143)	198 (151)	182 (157)
12	134 (174)	292 (67)	302 (70)	105 (194)	249 (169)	252 (176)
15	72 (269)	325 (88)	357 (91)	51 (261)	282 (183)	306 (197)
18	-16 (352)	341 (109)	390 (114)	-24 (324)	300 (199)	345 (213)
21	-108 (422)	338 (143)	418 (136)	-107 (379)	297 (211)	364 (236)
24	-210 (472)	285 (205)	435 (158)	-198 (429)	272 (235)	370 (248)
27	-309 (511)	227 (267)	438 (185)	-294 (460)	225 (269)	372 (259)
30	-413 (559)	128 (346)	411 (217)	-389 (492)	151 (320)	354 (289)

There was a tendency for the final proportion of desirable species in the sward, after 10 years of set stocked conditions, to be more variable with increasing stocking rates and fertiliser applications. Under low fertiliser applications and moderate to high stocking rates, the proportion of desirables consistently trended towards the lower limit and the expected outcomes were not as variable.

The cumulative distribution functions (CDFs) for mean pasture mass over the 10 year stochastic simulation for four combinations of pasture type (sown or degraded), stocking rate and fertiliser application indicate that, with increased stocking rates and low levels of fertiliser application, mean pasture mass is decreased (Figure 6-13). With increased rates of fertiliser and lower stocking rates, higher mean pasture masses are maintained.

Table 6-13: Results of the deterministic simulation experiments. Proportion of desirables at end of simulation is 0.44 and 0.95 for degraded and sown pastures. SS is single superphosphate.

	Degraded Pasture			Sown Pasture		
Stocking Rate	Fertiliser Applied (kg SS/ha/year)			Fertiliser Applied (kg SS/ha/year)		
(hd/ha)	42	125	250	42	125	250
Soil Fertility at end of Simulation (ppm Colwell P)						
3	8.0	34.3	81.2	7.7	33.7	80.7
6	5.1	28.2	74.6	5.0	27.4	73.8
9	3.8	22.7	68.3	4.2	22.1	67.5
12	3.2	18.0	62.5	3.7	18.0	62.0
15	3.0	14.2	57.0	3.2	15.4	57.4
18	3.0	11.3	51.9	3.0	14.3	54.1
21	3.0	9.6	47.4	3.0	14.4	52.2
24	3.0	8.6	43.3	3.0	14.8	51.9
27	3.0	8.0	39.9	3.0	13.8	52.9
30	3.0	7.6	37.1	3.0	12.7	53.2
Wool production (kg clean wool/hd/year)						
3	4.1	4.4	4.5	4.7	5.1	5.1
6	3.7	4.3	4.4	4.1	4.9	5.0
9	3.2	4.1	4.3	3.4	4.6	4.8
12	2.9	3.9	4.1	3.0	4.3	4.6
15	2.7	3.7	4.0	2.7	3.8	4.3
18	2.7	3.5	3.9	2.7	3.4	4.0
21	2.6	3.2	3.7	2.6	3.0	3.6
24	2.6	3.0	3.6	2.6	2.8	3.3
27	2.6	2.8	3.4	2.7	2.7	3.0
30	2.6	2.7	3.3	2.7	2.7	2.8
Wool fibre diameter (microns)						
3	19.8	20.4	20.5	20.2	20.8	20.8
6	19.1	20.2	20.3	19.3	20.5	20.6
9	18.3	19.9	20.1	18.1	20.1	20.3
12	17.7	19.6	19.9	17.6	19.5	20.0
15	17.7	19.2	19.7	17.4	18.8	19.5
18	17.7	18.8	19.5	17.3	18.1	19.0
21	17.8	18.3	19.2	17.4	17.4	18.4
24	17.9	17.8	19.0	17.5	16.9	17.8
27	17.9	17.5	18.7	17.5	17.2	17.2
30	18.0	17.3	18.4	17.6	17.4	17.1
Liveweight change (kg liveweight/hd/year)						
3	14.3	17.5	18.1	20.8	24.1	24.6
6	10.4	15.9	16.7	14.9	22.1	23.0
9	4.9	14.1	15.3	6.4	19.4	21.0
12	-0.4	12.0	13.9	0.1	15.9	18.6
15	-4.0	9.7	12.3	-4.5	11.4	15.6
18	-6.5	6.9	10.7	-6.8	5.9	12.0
21	-8.3	3.6	9.0	-8.4	0.0	7.7
24	-9.8	-0.1	7.2	-9.0	-5.1	2.6
27	-11.0	-3.5	5.2	-9.3	-7.1	-2.7
30	-12.0	-6.4	3.0	-10.0	-8.5	-6.3

Table 6-13 continued

Stocking Rate (hd/ha)	Degraded Pasture Fertiliser Applied (kg SS/ha/year) 42	125	250	Sown Pasture Fertiliser Applied (kg SS/ha/year) 42	125	250
Gross margin ($/ha/year)						
3	58	47	18	52	43	13
6	126	136	110	123	149	124
9	174	214	194	149	236	221
12	184	277	269	108	293	298
15	130	327	334	33	316	351
18	53	362	391	-66	312	376
21	-35	385	438	-176	298	376
24	-130	397	476	-296	254	355
27	-229	385	505	-416	90	325
30	-331	351	524	-550	-75	215

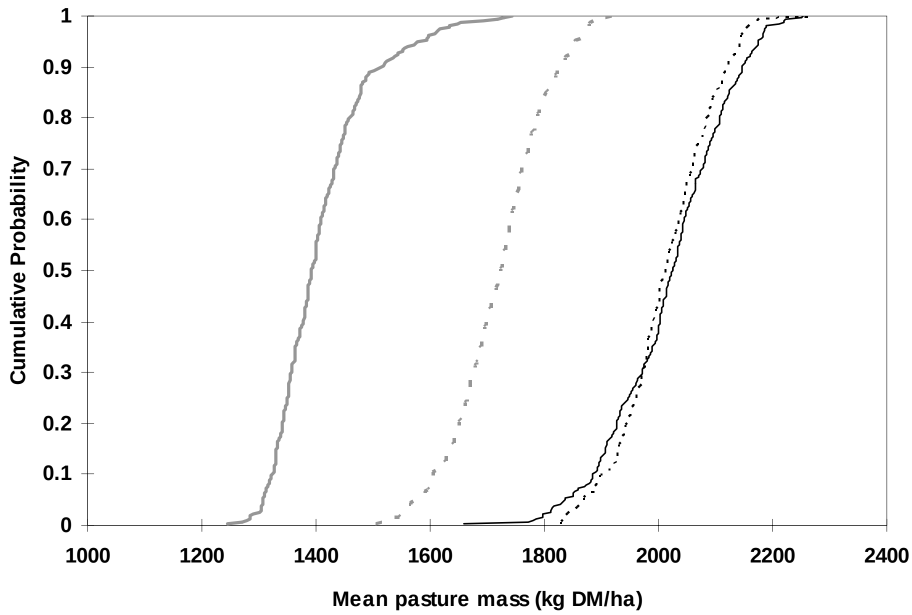

Figure 6-13: Cumulative distribution functions for mean pasture mass under stochastic simulations of different stocking rate, fertiliser and pasture sowing management strategies. Sown/Low fertiliser/SR15 (—), Sown/High fertiliser/SR27 (- - -), Sown/moderate fertiliser/SR12 (—), and degraded/Moderate fertiliser/SR15 (- - -).

A pattern between the mean pasture mass and proportion of desirables at the end of the 10 year simulation also existed (Figure 6-14). This indicated that when a mean pasture mass of less than 1500 kg DM/ha was maintained and received low levels of fertiliser application, the proportion of desirables in the sward degraded to 0.05 within the 10-year simulation. However, with increased mean pasture mass the proportion of desirables in the sward, after ten years, increased. These results suggest that a mean pasture mass of at least 2000kg DM/ha is required to maintain the proportion of desirables at over 0.50. However, as soil fertility improves, the mean pasture mass required to maintain higher proportions of desirables declines.

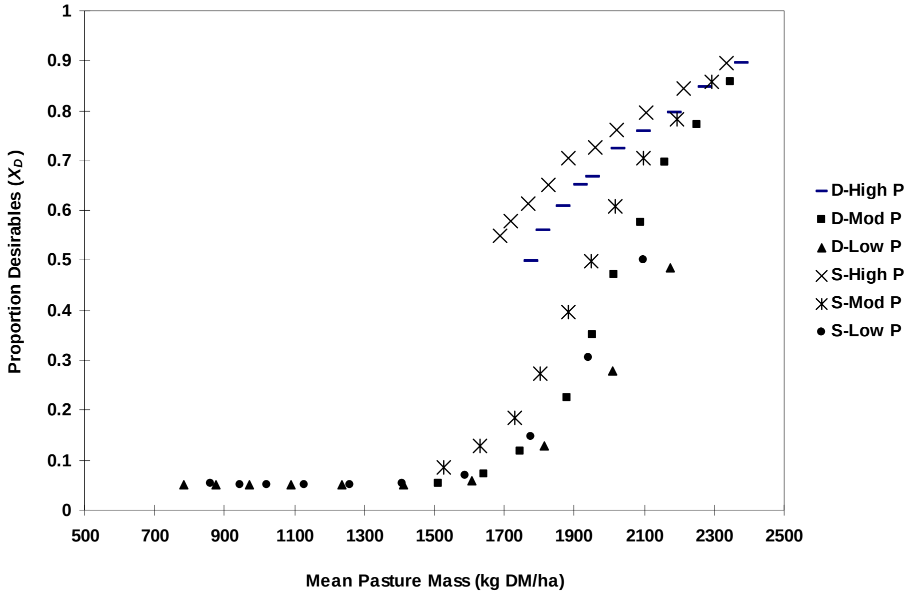

Figure 6-14: Relationship between mean pasture mass and persistence of desirable species measured as the proportion of desirables in the sward after 10 years of grazing under different rates of fertiliser application (High, Moderate, and Low) for a degraded (D) and sown pasture (S).

Soil fertility at the end of the simulation period ranged from 3.0 to 81.6 ppm Colwell P. The levels of soil phosphorus increased with increasing rates of fertiliser application and decreasing stocking rates. With an initial soil phosphorus level of 22 ppm Colwell P, maintenance states of soil fertility were achieved at stocking rates of 9 to 12 hd/ha and superphosphate applications of 125 kg/ha/yr. In the deterministic simulations, final soil phosphorus levels followed a similar pattern with maintenance states of soil fertility being achieved at 9 head per hectare and 125 kg/ha/yr of single superphosphate applied per year.

6.6.2 Wool production and liveweight change

For both the deterministic and stochastic simulations, livestock production was sensitive to stocking rate, fertiliser application and pasture type (sown or degraded). Stochastic wool production ranged from 2.6 to 5.1 kg clean wool/hd with corresponding fibre diameters of 17.5 to 21.4 microns. Wool cut increased with decreasing stocking rates and increasing levels of fertiliser application. Mean wool production was marginally higher for sown pasture and also slightly broader.

Deterministic wool production followed a similar trend to stochastic wool production with wool cut per head ranging from 2.6 to 5.1 kg clean/hd and fibre diameter ranging from 17.3 to 20.8 microns. Over the 10-year simulation, total mean annual wool production increased with increasing stocking rates, albeit at a declining rate of increase with increasing stocking rates for both deterministic and stochastic simulations (Figure 6-15). Wool production was lower under lower levels of fertiliser application.

For sown pastures in the deterministic simulations, wool production was over-estimated compared to stochastic simulations in the stocking rate range of 6 to 21 hd/ha under moderate and high fertiliser rates. Under low fertiliser rates, deterministic simulations over-estimated wool production at all stocking rates. There was very little difference in wool production at the lower stocking rates between fertiliser treatments.

In the stochastic simulations liveweight gain was influenced by stocking rate, level of fertiliser application and pasture type (sown or degraded). On degraded and sown pastures liveweight gain varied between a loss of 10.4 kg and a gain of 23.1 kg over 4 seasons within a year. Maximum liveweight gain per hectare occurred when stocking rates were 6, 12 and 15 hd/ha under low, moderate and high fertiliser rates on degraded and sown pastures (Figure 6-15). These stocking rates correspond to gains per head of 10.2, 12.2 and 12.8 kg to produce a total of 62.5, 146.0 and 192.5 kg liveweight/ha respectively on degraded pasture. Similar maximum weight gains were achieved on sown pastures.

A similar pattern was followed in the deterministic simulations with liveweight gain varying between a loss of 12 kg and a gain of 24.6 kg over 4 seasons. In deterministic simulations the maximum liveweight gains per hectare occurred when stocking rates were 6, 15 and 18 hd/ha under low, moderate and high fertiliser rates on degraded pastures. On sown pastures the corresponding stocking rates to maximum liveweight gain were the same as those described for the stochastic simulations.

Deterministic simulations tended to predict higher liveweight gains on degraded pastures with moderate and high fertiliser rates when stocking rates were higher than 12 and 15 hd/ha. On sown pastures deterministic predictions of weight gain were higher when stocking rates were less than 12, 18 and 21 hd/ha under low, moderate and high fertiliser inputs.

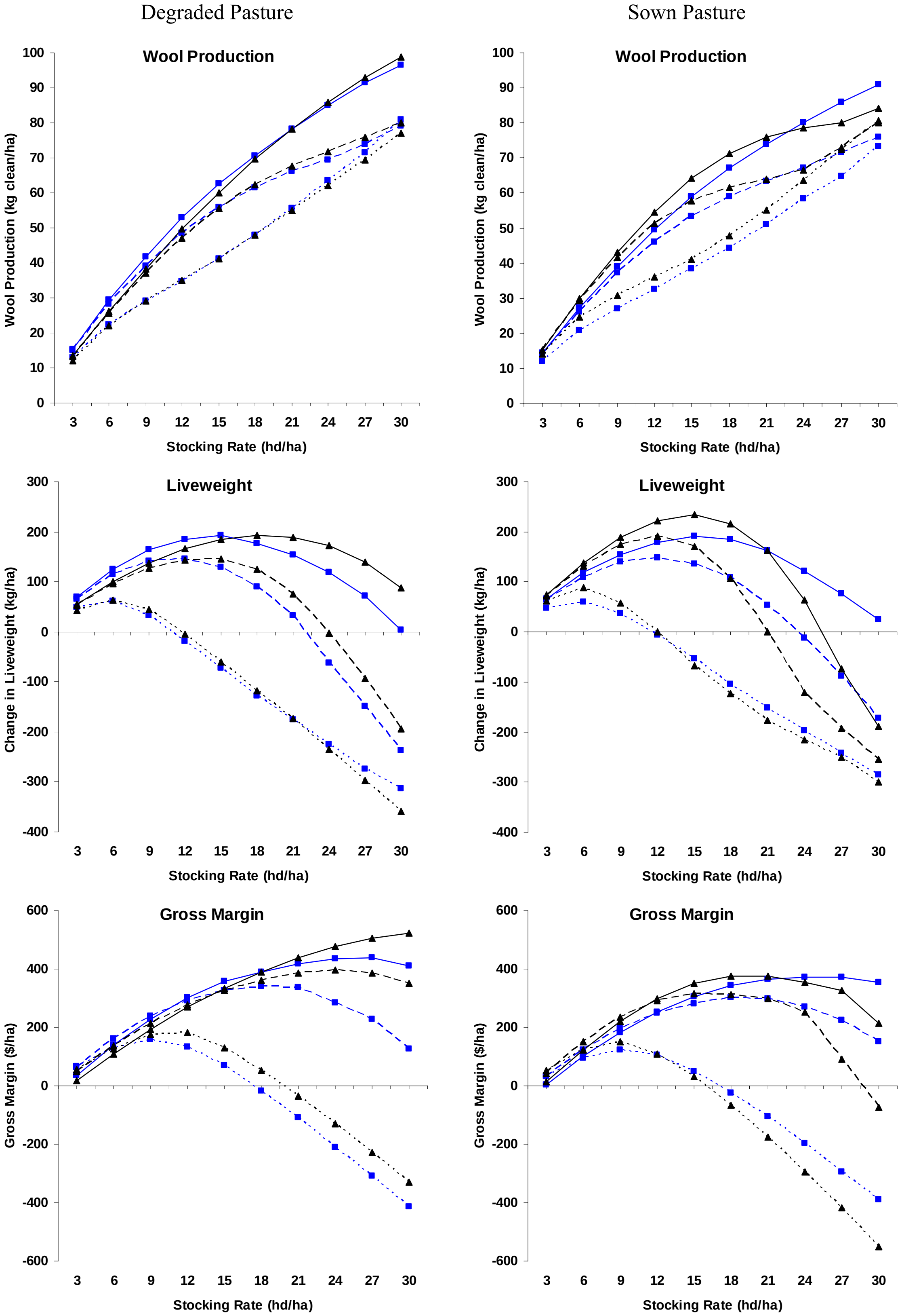

Figure 6-15: Average annual wool production, change in liveweight and average annual gross margin in relation to stocking rate in deterministic (▲) and stochastic simulations (■), at application rates of 42 (- - -), 125 (— —) and 250kg/ha (——) of single superphosphate.

6.6.3 Economic returns and risk

The economic returns, presented as the average annual gross margin ($/ha/yr) were sensitive to stocking rate, level of fertiliser application and pasture type (Figure 6-15). Sown pastures tended to maintain a lower average annual gross margin than the degraded pasture across all fertiliser and stocking rates, except for the highest stocking rate under low and moderate fertiliser input. This was due to the cost of establishment, the opportunity cost of a delay in the time to the first grazing, the rapid degradation of the sown pastures under set-stocking, and the marginal difference in productivity between the degraded and sown pasture types. The variability of annual average gross margin returns, indicated by its standard deviation (Table 6-12), increased with increasing stocking rates for all combinations of sown or degraded pasture, and fertiliser level. There was also a general trend for standard deviations to increase with reduced fertiliser input on degraded pasture. However in a sown pasture under low stocking rates variability increased with increasing fertiliser, while at intermediate stocking rates intermediate fertiliser levels had the lowest variability, and at high stocking rates variability increased with reducing fertiliser levels.

The patterns for annual gross margin were similar to those for meat production, but the influence of wool production (and its fibre diameter) on gross margin increased with increasing stocking rates. Annual gross margins tended to increase with increasing levels of fertiliser application across all stocking rates for both the degraded and sown pastures. At stocking rates of less than 9 hd/ha, moderate and low fertiliser rates achieved higher economic returns than the high fertiliser rate.

In degraded pastures, gross margins ranged from -$413 to $438/ha in stochastic simulations and from -$331 to $524/ha in deterministic simulations (Table 6-12 and Table 6-13). In sown pastures a similar pattern was followed with gross margins ranging from -$389 to $372/ha in stochastic simulations and from -$550 to $376/ha in deterministic simulations. In both the stochastic degraded and sown pastures, maximum gross margins occurred with a stocking rate of 27 hd/ha and high fertiliser applications. Under moderate and low fertiliser levels, the stocking rate to maximise average annual gross margin returns was 9 and 18 hd/ha for both the degraded and sown pasture.

Deterministic gross margin predictions intersected with stochastic predictions when stocking rates were 9, 15 and 18 ha/ha under low, moderate and high fertiliser applications for the degraded pasture. Up to these stocking rates the deterministic gross margins were either very similar their stochastic counterparts or lower, and beyond the intersection they were consistently higher. No economic optimum stocking rate was reached under the deterministic high fertiliser scenario.

The reverse relationship existed in sown pastures when stocking rates were below the intersection between stochastic and deterministic gross margin predictions. Deterministic predictions were consistently higher than stochastic ones, and when stocking rates are higher than the interception, deterministic predictions were consistently lower. Stochastic and deterministic gross margin predictions intersected at stocking rates of 12, 21, and 21-24 hd/ha under low, moderate and high fertiliser applications.

6.6.3.1 Optimal management strategies

To identify the optimal sets of management strategies from those simulated under stochastic conditions, the expected present value of annual gross margins over the ten year simulated period was calculated. To avoid the need for making assumptions about the level of risk aversion of the decision maker, optimal sets of management strategies were identified using a risk-efficient frontier (Cacho *et al.*, 1999). Each point represents a combination of management strategies (pasture type, fertiliser and stocking rate) represented by its expected present value plotted against its standard deviation. Although the standard deviation of present value is a simplified representation of risk, it demonstrates the trade-offs between expected economic return and risk.

Stochastically efficient sets of management strategies lie on the frontier and represent the combinations at which economic return is maximised at the given level of risk. In this experimental analysis, maintaining a degraded pasture was optimal with the stocking and fertiliser rate combinations shown to lie on the frontier (Figure 6-16). Along the frontier, expected returns and risk increased with increasing levels of fertiliser application and increasing stocking rates.

Points that do not lie on the frontier represent stochastically inefficient sets of management strategies. Replacement of the degraded pasture with the sowing of introduced species in this analysis was found to be stochastically inefficient across all combinations of fertiliser application and stocking rates.

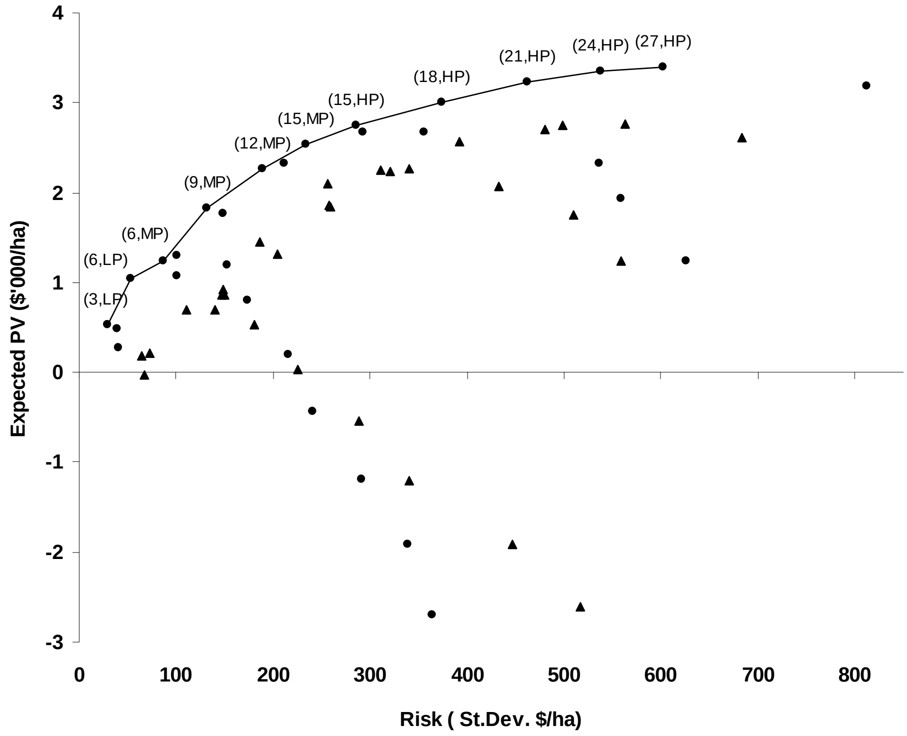

Figure 6-16: Risk -efficient frontier (solid line) for different combinations of stocking rate, fertiliser and pasture sowing management strategies. Efficient sets are all operating on degraded pasture and are identified by stocking rate and fertiliser level (SR/LP=42, MP=125, and HP=250kg single superphosphate/ha/year). Sown pasture combinations are indicated by triangles (▲) and degraded pasture by circles (●)

6.6.4 Model sensitivity to stochastic conditions

In the stochastic simulations there were large changes in the variability of the state of the pasture resource, livestock production and economic returns, between different pasture types and rates of stocking and fertiliser (see standard deviations in Table 6-12). The difference between the maximum deterministic gross margin and the maximum stochastic gross margin indicates the cost of stochastic climatic conditions and a dynamic botanical composition model (Cacho *et al.*, 1999).

The expected cost of a stochastic environment and dynamic pasture resource, in the simulated degraded pasture, increases with increasing stocking rates and fertiliser application rates. For the degraded pasture the maximum deterministic gross margin of $524/ha occurred under high fertiliser inputs and a stocking rate of 30 hd/ha. This prediction was 20% higher than the maximum stochastic gross margin of $438/ha, which occurred under high fertiliser application rates and a stocking rate of 27 hd/ha.

For the simulated sown pasture, the difference between the maximum deterministic and stochastic gross margins was only 1%. The maximum deterministic economic return of $376 occurred at a stocking rate of 18 hd/ha with high fertiliser rates, whereas the maximum stochastic return of $372 occurred at a stocking rate of 27 hd/ha with high fertiliser rates.

The differences between deterministic and stochastic predictions of annual gross margin varied with stocking rate, fertiliser rate and pasture type. Under low fertiliser rates on a degraded pasture the difference in predictions varied between -$9 and $82/ha as stocking rate increased. With moderate fertiliser application the differences ranged from -$17 at the lowest stocking rate up to $223 at the highest stocking rate. Similarly, under the high fertiliser rate, the difference ranged between -$35 to $113/ha.

The difference between deterministic and stochastic sown pastures was influenced by stocking and fertiliser rate. For all fertiliser rates the largest negative difference occurred at the highest stocking rate of 30 hd/ha. The largest positive difference occurred at stocking rates of 6 hd/ha for low fertiliser rates and 12 hd/ha and moderate and high fertiliser rates.

The sensitivity of model outputs to stochastic climatic conditions and the dynamic botanical composition sub-model is illustrated in Table 6-14. It presents the mean percentage differences between the stochastic/dynamic base case predictions and different combinations of a deterministic climate and static botanical composition, across all stocking rates under moderate fertiliser applications. Differences are calculated using the subtraction of the stochastic/dynamic predictions from the deterministic/static predictions.

The results indicated that a deterministic climate, on average, had the largest effect on overestimating production and returns in the degraded pasture. The static botanical composition model led to overestimation of production and profitability, but at a lower level to that of climate. Liveweight change was influenced most by a deterministic climate and static botanical composition, with wool production being less sensitive.

The relationship between stocking rate and varying combinations of static climate and botanical composition, on stochastic predictions of wool growth and present value under moderate fertiliser applications (Figure 6-17) indicates that, for a degraded pasture, at stocking rates of less than 15 head per hectare, a static botanical composition model increasingly caused the underestimation of wool production and present value. When stocking rates were higher, wool production and present value were largely overestimated due to both the deterministic climate and static botanical composition.

Table 6-14: Mean percentage differences in performance measures between the stochastic/dynamic base case and different combinations of deterministic climatic and static botanical composition conditions.

	Deterministic climate & static botanical composition		Deterministic climate & dynamic botanical composition		Stochastic climate & static botanical composition	
Performance Measure	Pasture Type		Pasture Type		Pasture Type	
	Degraded	Sown	Degraded	Sown	Degraded	Sown
Wool	0.0	-2.1	3.7	-2.9	0.5	-1.3
Fibre diameter	-1.1	-3.7	1.0	-4.6	-1.0	-6.1
Liveweight	75.3	-42.8	135.3	44.0	35.8	-15.4
Gross Margin	20.1	-10.0	28.0	26.0	6.2	-29.8
Present Value	18.1	-9.9	25.8	26.0	4.8	-30.4

For a sown pasture, deterministic climatic conditions and static botanical composition, on average, underestimated production and profitability. The results indicated that the static botanical composition model influenced the degree of underestimation, whilst the deterministic climate led to overestimation of production and profitability (Table 6-14).

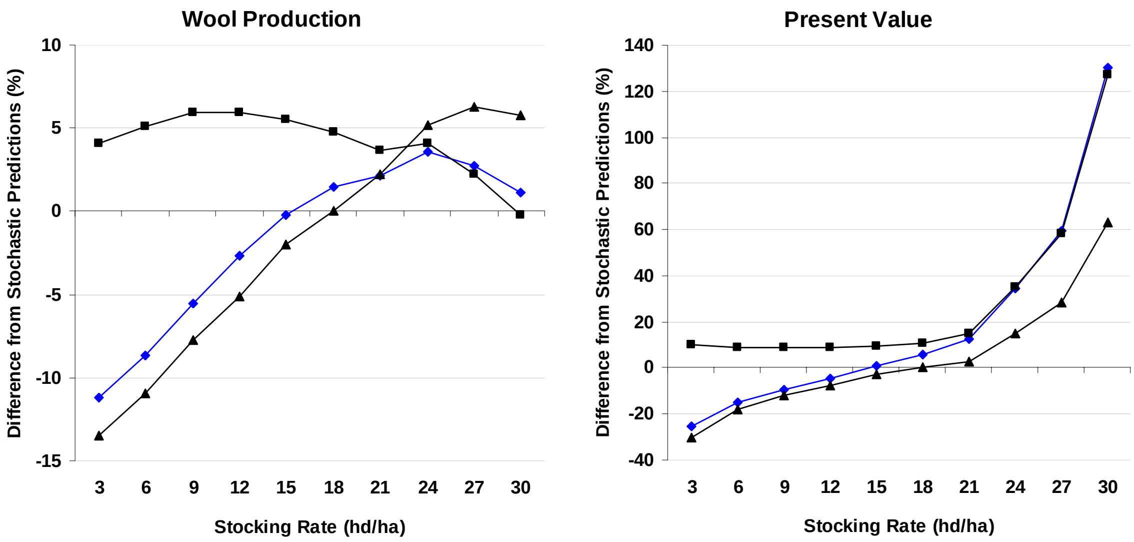

Figure 6-17: Percentage difference between stochastic and dynamic simulation output for wool production and Present Value on degraded pasture under different stocking rates and 125kg/ha single superphosphate application. Combinations of climate and botanical composition conditions are: deterministic climate/static botanical composition (♦); stochastic climate/static botanical composition (▲); and deterministic climate/dynamic botanical composition (■).

6.7 Discussion

The results of incorporating the DPRD model into a Monte Carlo simulation framework presented in this chapter show the model to be capable of simulating the development of a dynamic pasture resource under stochastic climatic conditions. The results demonstrate large differences between deterministic and stochastic simulations. They illustrate the need to consider the interaction between a stochastic climate and a dynamic botanical composition when predicting the production and profitability of a grazing system.

6.7.1 Simulation results

The results of the simulation experiments indicate strong relationships between stocking rate and the rates of fertiliser applied on the persistence of desirable species, and the production from those pastures. Stocking rate affects the level of pasture harvested and, under stochastic conditions, the degree of susceptibility to adverse seasonal conditions such as drought. The persistence of desirables also interacts with soil fertility, which is adjusted by the level of fertiliser applied. These interactions and relationships are supported by experimental work conducted by others such as Cook *et al.* (1978a; 1978b) and Hill *et al.* (2004) who showed the importance of fertiliser application in maintaining the production of pastures and the persistence of sown species, while concurrently reducing the encroachment by undesirable species.

The trends between stocking rate, fertiliser applications and resulting degradation of pastures with increasing stocking rates, also correspond to the results of the long term grazing trial conducted near Armidale over the period of 1965 to 1990 (Hutchinson, 1992). The lack of persistence of sown species also corresponds to that identified in surveys of the NSW HRTPZ which found 66% of the paddocks that contained sown pastures, maintained an average of 27% sown perennial grass species with only 10% of paddocks maintaining greater than 50% of sown perennial grasses (Dellow *et al.*, 2002). Given the divergence between the area sown to introduced species and the area of pastures receiving fertiliser in Australia (Figure 2-3), low to moderate soil fertility levels on average would be expected.

The relationship between mean pasture mass and persistence of desirable species, illustrated in Figure 6-14, suggests that for them to persist at proportions greater than 50%, moderate to high rates of fertiliser are required as a co-requisite to maintaining over 1900-2000 kg DM/ha on average over a year. Given the expected seasonal variation found in pasture mass, this would correspond to the minimum amount of pasture mass (1100-1200 kg DM/ha) required for the persistence of desirable sown species as suggested by field experimentation (Avery *et al.*, 2000; Dowling *et al.*, 1996; Scott *et al.*, 1997).

The results of the simulations suggested a maintenance fertiliser rate in the model of 1.2 to 0.93 kg of phosphorus/ha/yr. This corresponds to identified maintenance rates for sheep grazing systems in the high rainfall temperate pasture zone from long term-grazing trials (Cayley and Saul, 2001) and the predicted maintenance rate of phosphorus application for the Cicerone farmlets of 1.1 kg phosphorus/ha/yr (Guppy, 2005).

The predictions of the stochastic simulations suggested maximum gross margins were achieved at stocking rates of 15-18 hd/ha under moderate rates of fertiliser application. These optimum stocking rates, based on gross margin return, compare favourably to the suggested carrying capacity of sown pastures found on basalt derived soils in the New England region of 15-25 DSE/ha (Lowien *et al.*, 1997). Alford (2004) also proposed, through linear programming of a Northern Tablelands grazing enterprise, that using a minimum pasture mass constraint of 1000 kg DM/ha, the optimal stocking rate, based on economic returns, was 17.2 DSE/ha. This estimate also corresponds to the predicted pasture mass and desirable species persistence described under moderate soil fertility in the results.

Trade-offs between the profitability of the different combinations of strategies and their riskiness were examined through the use of a risk-efficient frontier. This method identifies risk-efficient sets of management strategies or decisions without the need for assuming the degree of risk aversion of the decision maker (Cacho *et al.*, 1999). The method allows the comparison and analysis of large numbers of different sets of decision combinations. Once defined, producers can select from the risk-efficient set of decisions based on the profit they wish to generate and the risk they are willing to accept.

In regard to identifying the optimal development and management of the pasture resource, in this case-study, risk-indifferent producers would choose to operate with high stocking rates (27 hd/ha) and high fertiliser rates (250 kg single superphosphate/ha/yr) on the degraded pasture, rather than replace it with a sown pasture. An extremely risk averse producer would select a combination of low stocking rates (3 hd/ha) with low fertiliser rates (42kg single superphosphate/ha/yr) on a degraded pasture.

The replacement of the degraded pasture through the sowing of introduced species remained within the sets of stochastically inefficient decisions for all post-sowing stocking rates. This was expected due to the direct cost of replacing the existing pasture with a new pasture ($250/ha), as well as the additional cost of reduced production during the establishment phase of the sown pasture. However, it would be expected that the pasture resource would approach a state with continuing degradation, when the sowing of introduced species becomes one of the risk-efficient sets of decisions. This level could be identified with further experimentation by iterative adjustments to the initial state of the pasture resource at levels lower than the state applied in the set of simulated experiments (being 0.44 desirables). In other words, the degraded pasture simulated had not reached a level at which it should be replaced on economic grounds.

The length of the 10-year planning horizon is unlikely to have affected the stochastic efficiency of the sowing option, as there was little difference in botanical composition between sown and degraded pastures at the end of the simulated period. In response to the combinations of stocking rate and fertiliser rate applied, this indicates the convergence of botanical composition for both pasture types within the 10 year period.

6.7.2 Comparison of deterministic and stochastic results

Differences between deterministic and stochastic predictions of production and profit were seen for both degraded and sown pastures. Under a deterministic climate, production and profitability were continually over estimated, whilst under a stochastic environment increasing stocking rates led to increasing costs. Under a static botanical composition model, both over- and under-estimation of production and profit were seen.

For the degraded pasture, a static botanical composition model caused the underestimation of production and profitability at low stocking rates and the over estimation at high stocking rates. The cross-over point was 15 head per hectare with moderate fertiliser application rates. The underestimation of production and profit at low stocking rates was the result of no improvement in the pasture's botanical composition. Any increase in the proportion of desirables would have increased pasture growth rates during autumn, winter and spring, and improved the quality of feed on offer. At high stocking rates the proportion of desirables maintained in the pasture was over estimated and thus growth rates and feed quality were higher than expected. The effect of these changes in pasture production and quality were shown by the differences in stochastic and deterministic livestock production.

For sown pastures, this relationship was largely reversed. Under high stocking rates and low fertiliser applications, a deterministic environment and static botanical composition led to the underestimation of production and profit. With decreasing stocking rates and increasing fertiliser rates, predictions of production and profit were overestimated. This suggests that, in this specific application of the DPRD model, the undesirable proportion of the sward plays a large role in determining the productivity and profitability of the grazing system. It indicates that maintaining high levels of sown or desirable species may not be optimal for the development and management of a pasture resource for a merino wether enterprise. However, this would be expected to change under different sheep production systems which demand different feed profiles. This will be addressed in Chapter 7.

The cost of ignoring climate variability and the dynamics of the pasture resource has been shown to be large under certain conditions. Over- or under-estimations of production and profit would lead to sub-optimal decision making on the development and management of a pasture resource. This is supported by others who have demonstrated the importance of pasture persistence on the economics of sowing pastures (Scott *et al.*, 2000a) and the role of tactical grazing rests to promote the persistence of desirable species (Jones *et al.*, 2006b). However, this is not supported by Torell *et al.* (1991), who suggested that inter-temporal grazing impacts to forage production were not important and there was no benefit from the incorporation of dynamic rangeland models. Their study used an optimal control framework to identify the optimal use of a rangeland resource under both dynamic and static resource models. The limitation of that study was that the framework applied did not include the impact of changes in the quality of forage on livestock performance nor the impact of catastrophic events such as drought. In addition, the applied framework by Torell *et al.* (1991) did not consider the stochastic nature of outcomes between decision points. These limitations have been addressed in the DPRD model.

The dynamic botanical composition model was shown to be less important than a stochastic climate in predicting the production and profit from the application of pasture development and management strategies. The comparison between deterministic and stochastic simulation results indicates that, independent of a producer's attitude to risk, accounting for the dynamic nature of pasture resources and the impact of climate risk is important in the identification of optimal pasture development and management decisions.

6.7.3 Application of the DPRD model

The experimental simulations presented in this chapter are a demonstration of the capacity of simulation models to generate detailed analysis which may assist decision makers better understand the system they are managing. However, the limitation of their use is that the risk to which the decision maker is exposed is not embedded in the decision making process (Hardaker *et al.*, 1991). The tactical-level decisions on stocking rate, as well as the strategic decisions on fertiliser rate and the sowing of pastures, are predetermined and applied with the uncertainty of the decision unfolding over time and being presented as the consequences of the decisions made.

In real farm management situations, these decisions are adjusted over time depending on the state of the system and the future expected economic returns. The riskiness of each decision is embedded into a sequential decision-making process. The economic returns and changes in the state of the system between tactical and strategic decision points are stochastic, being influenced by the effects of climate variability during the period between decision points (Trebeck and Hardaker, 1972).

To solve this dynamic and stochastic pasture resource development problem, the risks associated with decisions need to be embedded in the sequential decision making process. This is achieved in Chapter 7 through the use of a stochastic dynamic programming framework which aims to identify the optimal sequence of decisions for a given state of the pasture resource. The framework uses the DPRD model to define the stochastic nature of economic returns and changes to the state of the pasture resource between decision points.

Chapter 7. Solving the pasture resource development problem using Stochastic Dynamic Programming

7.1 Introduction

In chapter 6 Monte Carlo simulation techniques were applied to investigate the production, economics and risks of different packages of technologies and management strategies applied to a dynamic pasture resource. The effect of taking into account botanical composition change and stochastic climatic conditions on economic returns was demonstrated.

In optimising the development and management of a dynamic pasture resource, the transformation between different states that describe the pasture resource (biomass and botanical composition) depends not only on the initial state of the pasture resource and the tactical or strategic decision taken, but also on the effects of a stochastic climate which is outside the control of the decision maker. The stochastic climate influences pasture growth and feed availability, and the economic returns from the season for the applied tactical or strategic decisions. This process defines conditions whereby the pasture resource problem may be formulated as a stochastic dynamic programming problem (Kennedy, 1986).

This chapter describes the development and implementation of the dynamic and stochastic pasture resource development and management problem using a stochastic dynamic programming (SDP) framework.

7.2 The Stochastic Dynamic Programming model

The SDP solution process uses four seasonal transition probability and biophysical matrices which are applied sequentially to solve a recursive equation with the objective to maximise the expected net present value of returns from sheep production systems over the long run. The SDP model is used to find optimal tactical and strategic decision rules in terms of stocking rates and pasture sowing, as functions of pasture mass and composition (proportion of desirables).

There are two SDP recursive equations that represent the four seasons. This is required due to all four seasons being embedded within a year type, rather than each season remaining stochastically independent.

The SDP recursive equation for the first three seasons starting with autumn is:

$$V_t^s\left(\mathbf{z}_t^s\right) = \max_{\mathbf{u}_t^s}\left[E\left[\pi\left(\mathbf{z}_t^s,\mathbf{u}_t^s\right)\right] + \delta_s E\left[V_t^{s+1}\left(\theta^s\left(\mathbf{z}_t^s,\mathbf{u}_t^s\right)\right)\right]\right];\ \text{for } s\text{=1,2,3} \qquad 7\text{-}1$$

The SDP recursive equation for the final season, summer, in a year is:

$$V_t^s\left(\mathbf{z}_t^s\right) = \max_{\mathbf{u}_t^s}\left[E\left[\pi\left(\mathbf{z}_t^s,\mathbf{u}_t^s\right)\right] + \delta_s E\left[V_{t+1}^1\left(\theta^s\left(\mathbf{z}_t^s,\mathbf{u}_t^s\right)\right)\right]\right];\ \text{for } s\text{=4} \qquad 7\text{-}2$$

where s denotes the season (s = 1,...,4);

t denotes the year;

V_t^s is the optimal value function for the given season and year;

E is the expectation operator;

π is the stage return function for a given season;

$\mathbf{z}_t^s$ is a state vector consisting of three state variables (defined below) for the given season and year;

$\mathbf{u}_t^s$ is a decision vector consisting of two decision variables (defined below) for the given season and year;

θ^s is the transformation function for the given season;

δ_s is the discount factor ($\delta_s = 1/(1+\rho_s)$), where ρ_s is the seasonal discount rate which is pro-rated from the annual discount ρ based on the length of the season in days ($\rho_s = \rho \cdot D_s/365$).

The difference between equations 7-1 and 7-2 is in the season and years indexes of the future value of the system V_t^{s+1} refers to the next season in the current year and V_{t+1}^1 refers to the first season in the next year.

The state vector $\mathbf{z}_t^s$ contains three state variables:

$$\mathbf{z}_t^s = \left(x_t^s, yd_t^s, yud_t^s\right) \qquad 7\text{-}3$$

where x is the proportion of desirable species in the sward; yd is the biomass of desirable species in the sward (kg DM/ha) and yud is the biomass of undesirable species (kg DM/ha). All state variables are measured at the start of season s in year t.

The decision vector $\mathbf{u}_t^s$ contains two decision variables:

$$\mathbf{u}_t^s = \left(sr_t^s, rs_t^s\right) \qquad 7\text{-}4$$

where sr is the stocking rate (hd/ha) and rs is the decision to re-sow the pasture: both decisions are taken at the start of season s in year t.

The transformation functions, θ^s, are represented by the DPRD model described in Chapters 5 and 6. The expected values for a given state/decision are calculated based on Monte Carlo simulation with the DPRD model and using the stochastic multipliers, which were derived from climatic data as explained in Chapters 5 and 6.

The SDP solution process determines the optimal decision for all states at each decision stage. It is assumed that the state transitions and stage returns, which are functions of the current state, decision and stochastic event, are the same for all stages and as such the optimal decisions for all states are the same for all stages. This follows from the decision problem being exactly the same infinite-stage problem whatever the decision stage.

To solve the infinite-stage problem, we can drop the year subscripts and make the value functions dependent only on the state of the system at the beginning of a season. Using the transformation equations we can define the Markovian transition probability matrices $\mathbf{P}^s$ and rewrite the expectation operators in discrete terms. The elements P_{ij}^s of matrix $\mathbf{P}^s$ represent the probability of moving from state i in season s to state j in season s+1. The elements of the transition matrices given the decision $\mathbf{u}^s$ are:

$$P_{ij}^s(\mathbf{u}^s) = P(\mathbf{z}_j^{s+1} \mid \mathbf{z}_i^s, \mathbf{u}^w, r^s) \qquad \text{7-5}$$

where r^s is an index of rainfall and other climatic variables that affect pasture growth.

We can now write the expectations for the recursive equations as:

$$E[\pi(\mathbf{z}_i^s, \mathbf{u}^s)] = \sum_j P(r_j)\pi(\mathbf{z}_i^s, \mathbf{u}^s, r_j) \qquad \text{7-6}$$

$$E[V(\theta^s(\mathbf{z}_i^s, \mathbf{u}^s))] = \sum_j P_{ij}^s(\mathbf{u}^s) V(\mathbf{z}_j^{s+1}) \qquad \text{7-7}$$

subject to:

$$\sum_j P(r_j) = 1 \qquad \text{7-8}$$

$$\sum_j P_{ij}^s(\mathbf{u}^s) = 1 \text{; for all } i \qquad \text{7-9}$$

Since there are only four seasons, the season counter s+1 is set back to 1 when s=4 in the equations above. The rainfall index (r^s) is not explicitly represented as a functional form, but it is introduced through the stochastic multipliers for pasture parameters as explained in Chapter 5.

The SDP model is solved by value iteration (Kennedy, 1986) until policy convergence is obtained, with the resulting $\mathbf{u}^s*(\mathbf{z}^s)$ representing the optimal decision rule contingent on the state of the sward for each season.

7.2.1 State variables

To solve the pasture resource problem numerically requires the restriction of values for the state and decision variables that make up the vectors $\mathbf{z}_t^s$ and $\mathbf{u}_t^s$ to finite sets. Table 7-1 presents the state variables and their boundaries used to generate the Transition Probability Matrices (TPM).

The number of states, n_z, defines the size of the TPM ($\mathbf{P}^s(\mathbf{u}^s)$) for a season and decision, and represents the total number of possible combinations of the initial states that define $\mathbf{z}_t^s$ (equation 7-3). In this case, 10 states of *yd* by 10 states of *yud* by 10 states of *x* make a total of 1000 possible combinations and initial states (Table 7-2). Therefore $n_z = 1000$ and each TPM has dimensions of 1000 x 1000.

Table 7-1: State variables and their boundaries

Pasture Biomass for Desirable (*yd*) and Undesirable (*yud*) swards (kg DM/ha)			Proportion of Desirables (*x*)		
State	Minimum	Maximum	State	Minimum	Maximum
100	0	200	0.05	0.00	0.10
300	200	400	0.15	0.10	0.20
500	400	600	0.25	0.20	0.30
700	600	800	0.35	0.30	0.40
900	800	1000	0.45	0.40	0.50
1250	1000	1500	0.55	0.50	0.60
1750	1500	2000	0.65	0.60	0.70
2500	2000	3000	0.75	0.70	0.80
3500	3000	4000	0.85	0.80	0.90
5000	4000	∞	0.95	0.90	1.00

Table 7-2: Summary of state vector, z.

State	Elements of state vector **z**		
	yud	*yd*	*x*
1	100	100	0.05
2	100	100	0.15
3	100	100	0.25
...			
499	900	5000	0.85
500	900	5000	0.95
501	1250	100	0.05
....			
998	5000	5000	0.75
999	5000	5000	0.85
1000	5000	5000	0.95

7.2.2 Decision variables

There are two decision variables which, in combination, make up the decision vector $\mathbf{u}_t^s$ that influences the distribution of future states of the pasture's botanical composition and dry matter availability, as well as the expected economic returns. One is a tactical decision that defines grazing management and the other a long term strategic decision that defines capital investment in the pasture resource.

1. The stocking rate decision, *sr*, is made at the start of each season and provides the opportunity for the implementation of a range of grazing pressures or tactical grazing rests to benefit production, economic returns and future botanical composition. The values of *sr* used are 0, 2, 4, 8, 10, 15, 20, 30, 40, and 50 hd/ha.
2. The decision to maintain or replace a pasture resource with introduced species, provides an opportunity for the future production of a pasture to be adjusted by the strategic capital investment of sowing a new pasture (*rs*). A stocking rate of 0 hd/ha always accompanies the decision to replace a pasture (*rs* = 1).

In total there are 11 sets of decisions that make up the decision vector **u** (Table 7-3). The decision vector is applied to each season and initial state. This makes a total combination of 44,000 initial states, seasons and decision variables simulated to populate the TPMs required to solve the SDP model.

Table 7-3: Decision variables that make up the decision vector $\mathbf{u}_t^s$.

	Elements of decision vector **u**	
Decision	*sr*	*rs*
1	0	0
2	2	0
3	4	0
4	8	0
5	10	0
6	15	0
7	20	0
8	30	0
9	40	0
10	50	0
11	0	1

7.2.3 Soil fertility

The possibility of including fertiliser application as a decision variable was explored. But this required soil fertility at the start of each season to be included as an additional state variable. When this was attempted the dimensionality of the problem made the SDP impossible to solve because of memory limitations. The inclusion of fertiliser application as a decision variable, and soil phosphorus levels as a state variable, may have been possible by reducing the number of states representing the pasture (*yd*, *yud* and *x*), but the need to ensure the TPM was sensitive enough to reflect changes between pasture states took precedence. As there have been several earlier studies into optimal fertiliser decisions (Godden and Helyar, 1980; Woodward, 1996), it was decided to investigate the impact of different soil fertility regimes by solving a different SDP for each soil fertility level.

Three sets of TPMs were populated with the DPRD model under three different soil fertility regimes:

a. *High input system*: high initial level of soil phosphorus (35 ppm Colwell P) and high application rates of single superphosphate fertiliser (150kg/ha/year) to maintain the required level of soil phosphorus.

b. *Moderate input system*: moderate initial level of soil phosphorus (20 ppm Colwell P) and moderate application rates of single superphosphate fertiliser (100kg/ha/year).

c. *Low input system*: low initial level of soil phosphorus (10 ppm Colwell P) and low application rates of single superphosphate fertiliser (42kg/ha/year).

7.2.4 Supplementary feeding

Supplementary feeding decision rules were not incorporated for similar reasons to those explained above for fertiliser. However, supplementary feeding was also excluded as an endogenous decision to ensure dynamic optimisation of the pasture resource is not skewed by implicit supplementary feeding policies.

To generate the Transition Probability matrices the minimal supplementary feeding rules described in Table 6-13 were applied. That is, supplements were offered to grazing animals when necessary, to ensure they do not fall below a condition score of 2.0, or when total pasture dry matter is less than 100kg DM/ha.

7.2.5 Alternative sheep production systems

A simplified livestock model was used for the integration of the DPRD simulation model into the seasonal SDP framework. This livestock model was only simplified in flock structure and not in the livestock sub-models which predict selective grazing and livestock performance.

To dynamically optimise the pasture resource development and management problem for different livestock production systems, at the paddock level, a method of adjusting the relative value of output was applied. In this method, the value of wool and meat produced from the merino wether enterprise system operating in the DPRD model is adjusted to reflect the relative differences in the value of outputs between the wether enterprise and other sheep production systems.

Although this method is not a precise representation of the actual system, as it assumes similar efficiencies of wool and meat production between different livestock classes and flock structures, it provides an indication of how the optimal decision rules and resulting optimal states are affected by different sheep production systems and their emphasis on different outputs (wool and meat). Industry gross margins for NSW for three sheep production systems (Davies and Scott, 2007) were used to estimate the value adjustment factors for wool and meat. Three different sheep production systems were evaluated; wool production (the wether base case), wool:meat production (based on a self-replacing merino flock) and meat production (based on a second-cross lamb producing flock).

Mathematically these are represented as $VA_{WOOL\,E}$ and $VA_{MEAT\,E}$, and for each alternative sheep production system they were calculated as follows:

$$VA_{WOOL\,E} = \frac{WoolV_E}{WoolV_{Weth}} \text{ and } VA_{MEAT\,E} = \frac{MeatV_E}{MeatV_{Weth}} \qquad 7\text{-}10$$

where $WoolV_E$ and $MeatV_E$ are the value of wool and meat output produced per DSE for each alternative sheep production system (indicated by $_E$); with $WoolV_{Weth}$ and $MeatV_{Weth}$ being the value of output produced per DSE for a standard 19 micron merino wether enterprise. $WoolV_E$ and $MeatV_E$ for each sheep production system are based on the average quantity of wool and meat production. As such:

$$WoolV_E = Wool_q \cdot Wool_p \text{ and } MeatV_E = Meat_q \cdot Meat_p \qquad 7\text{-}11$$

where the values for $Wool_q$ and $Meat_q$ are the quantities of production per DSE for each sheep production system, with $Wool_p$ and $Meat_p$ being the average price received per kilogram of wool and meat output. Table 7-4 gives the derivation of wool and meat value adjustment factors for each sheep production system used in the SDP model. These derived factors are multiplied against the price of wool and meat in equations 5-4 and 5-6 of the economic sub-model.

Table 7-4: Derivation of wool and meat value adjustment factors for different sheep production systems from industry gross margins. Gross margin data sourced from Davies and Scott (2007).

	Sheep Production System		
	Merino Wethers (19 micron Wool)	Self replacing Merino flock (19 micron wool & 6 month old wether weaners)	First Cross ewes & Terminal sires (22kg cwt Lamb production)
Identifier	Wool	Wool:Meat	Meat
$Wool_q$ (kg) /DSE	4.50	2.52	1.36
$Meat_q$ (kg cwt) /DSE	3.95	5.89	11.82
$Wool_p$ (\$/kg)	5.71	5.48	2.19
$Meat_p$ (\$/kg)	1.92	2.18	3.65
$WoolV_E$ (\$)/DSE	25.69	13.82	2.97
$MeatV_E$ (\$)/DSE	7.59	12.82	43.10
Value Adjustment factors			
$VA_{WOOL\,E}$	1.00	0.54	0.12
$VA_{MEAT\,E}$	1.00	1.69	5.68

7.3 Numerical Solution

The linkage between the SDP model and the DPRD model occurs through the estimation of transition probability matrices (TPM) and biophysical matrices for each season.

The model is implemented in Matlab 7 (The Mathworks Inc., 2004). The code is presented in Appendix F. The model was solved by the following steps:

1. Read parameters, set number of states (n_z) and number of decisions (n_u).
2. Run the DPRD model in stochastic mode to derive transition probability matrices and biophysical matrices for each season.
3. Save matrices from step 2 for future use.
4. Set desired prices, costs and discount rate.
5. Read matrices from step 2 into memory.
6. Solve the recursive equation until policy convergence is achieved.
7. Calculate optimal transition matrices.
8. Retrieve optimal solutions for any initial state.

The biophysical matrices created in step 2 have dimensions ($n_z \times n_u$), and they record the expected outcome for each starting state and decision combination for the given season. The biophysical predictions recorded are body weight gain, wool grown, wool mean fibre diameter, and quantity of supplements fed. These matrices are then used to calculate the stage return in step 6 based on equations 5-3 to 5-8 of the DPRD model. This approach allows prices to be changed without requiring the transition probability matrices to be re-calculated, as this step is expensive in terms of time (taking approximately 72 hours to solve).

This method is applied in this chapter to investigate how changing emphasis on the value of production outputs (wool and meat) and input costs (pasture sowing) change the optimal decision vector. The process provides a means of identifying optimal decision rules for different sheep production systems.

The optimal transition matrices (step 7) are created based on the optimal solution $\mathbf{u}^{s}*(\mathbf{z}^{s})$, by selecting the appropriate rows from the transition probability matrices

$\mathbf{P}^s(\mathbf{u}^s*(\mathbf{z}^s))$. The resulting matrices $\mathbf{P}^s*$ have dimensions ($n_z \times n_z$) and represent the state transition probabilities when the optimal decision rule is applied for the given season *s*.

The optimal expected path for any initial state (step 8) is calculated by defining an initial state vector $\mathbf{z}_0$ of dimensions ($1 \times n_z$). This vector contains a 1 in the position representing the initial state and 0 everywhere else. A time sequence of optimal states (in a probabilistic sense) is obtained by matrix multiplication:

$$
\begin{aligned}
w_1^1 &= w_0\,\mathbf{P}^{1*}\\
w_1^2 &= w_1^1\,\mathbf{P}^{2*}\\
w_1^3 &= w_1^2\,\mathbf{P}^{3*}\\
w_1^4 &= w_1^3\,\mathbf{P}^{4*}\\
w_2^1 &= w_1^4\,\mathbf{P}^{1*}\\
w_2^2 &= w_2^1\,\mathbf{P}^{2*}\\
&\ldots\\
w_n^{4*} &= w_n^{3*}\,\mathbf{P}^{4*}
\end{aligned}
\qquad \text{7-12}
$$

Continuing this process will eventually result in convergence in the seasonal values of w_n^s. These values represent the long-term state probabilities when the system is managed according to the optimal decision rule. Its expected value can be interpreted as the optimal target level of pasture mass (*yd** and *yud**) and coverage (*x**) for each season.

In presenting the SDP results, the level of pasture mass is reported as the combined area weighted average pasture mass available in the whole sward, y_C, and is calculated as follows:

$$y_C = yd \cdot x + yud \cdot (1 - x) \qquad \text{7-13}$$

7.3.1 Number of iterations

The appropriate number of Monte Carlo iterations for the creation of the TPMs and the biophysical matrices were determined from calculation of the sum of squared deviations of an arbitrary selection of rows from the $\mathbf{p}^s$ matrices as the number of iterations increased. The process was as follows:

1. A given row $P_{i\bullet}^s(\mathbf{u}^s)$ was selected (see equation 7-5), call this vector $\mathbf{p}_1$;

2. The row was populated by running the DPRD for a given number (m) of iterations starting with state i ;
3. The results were allocated to the corresponding states of $\mathbf{p}_1$ and converted to probabilities;
4. An additional iteration was run (as in step 2) and the probabilities resulting from $m+1$ iteration were allocated to vector $\mathbf{p}_2$;
5. The sum of squared deviations between $\mathbf{p}_1$ and $\mathbf{p}_2$ was calculated, this value was saved as d_K ;
6. The values were updated as $\mathbf{p}_1=\mathbf{p}_2$, $m=m+1$;
7. Steps 4 to 6 were repeated until the value of d_K was sufficiently close to zero.

A selection of the results from this process is presented in Figure 7-1. It is evident that convergence in the value of probabilities occurs with about 200 iterations of the Monte Carlo model, and this was the number of iterations used to generate the TPMs.

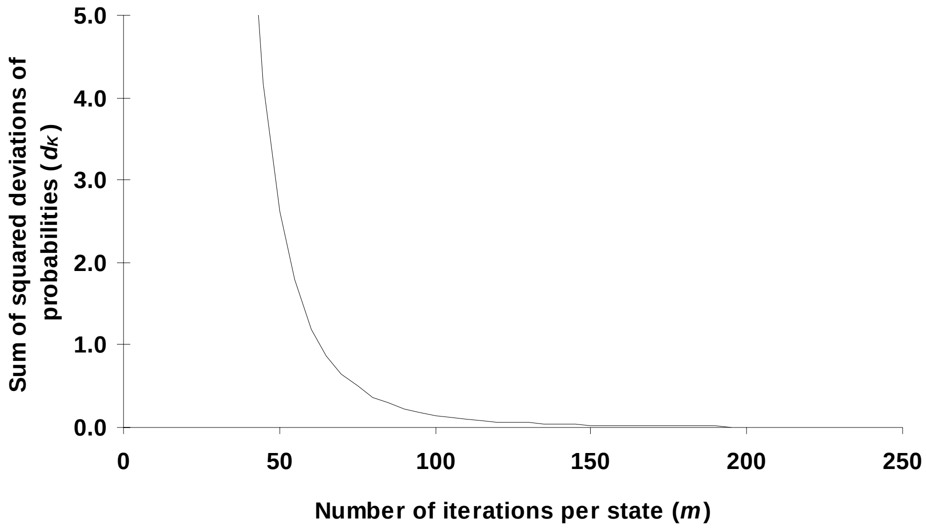

Figure 7-1: Relationship between the sum of squared deviations (d_K) of probabilities and iterations for a given initial state.

7.4 Results

The optimal solutions, $\mathbf{u}^s*(\mathbf{z}^s)$, for any initial state of the pasture resource were identified by solving the SDP model. For any given fertiliser and sheep production system, a total of 4000 optimal solutions exist that describe the optimal stocking rate and re-sow policy for each of the 1000 initial states and 4 seasons. Due to the size of the output dataset, the majority of results are presented through the calculation of expected optimal target levels for the states that describe the pasture resource, and by summarising the states that induce certain decisions, such as tactical grazing rests and the re-sowing of pastures. The results also report the sensitivity of optimal decision vectors and states to different emphases on meat and wool production, the costs of sowing pastures and the discount rate applied.

7.4.1 Optimal trajectories for different input systems

The optimal solutions for any initial state of the pasture resource are used to demonstrate a time sequence of optimal states, based on the state transition probabilities and expected state values (see equation 7-12). The sequences of optimal states have been calculated and plotted for four diverse initial pasture states under each input system from the start of Autumn (Figure 7-2). These values represent the expected values that result from the long-term state probabilities when the system is managed according to the optimal decision rule. The convergence of seasonal values that define the pasture resource ($\mathbf{z}_n^{s*}$) are the expected optimal target levels of pasture mass and proportion of desirables for each season.

From the trajectory of the proportion of desirables it can be seen that in both the low and moderate input systems, at a pasture state of 900kg DM/ha and 0.15 desirables, the optimal decision applied was to re-sow the pasture. Hence its increase to 0.95 desirables in the second season. For this initial state, under the high input system the expected optimal decisions were a combination of tactical grazing rests and reduced grazing pressure to allow both the amount of pasture mass and proportion of desirables to increase to optimal target levels.

For the two pasture states with 2500kg DM/ha and either 0.15 or 0.75 desirables, the optimal decisions were to keep utilising the pastures, albeit at different rates. For the state with 0.15 desirables under all input systems, stocking rates were adjusted to reduce the pasture mass to optimal target levels whilst concurrently increasing the proportion of desirables up to optimal target levels. For the initial state with 0.75 desirables and 2500 kg DM/ha, the highest expected stocking rates were maintained during the period of convergence as the pasture resource moved towards the optimal target state. In this case a lower proportion of desirables and lower amounts of pasture mass were also maintained.

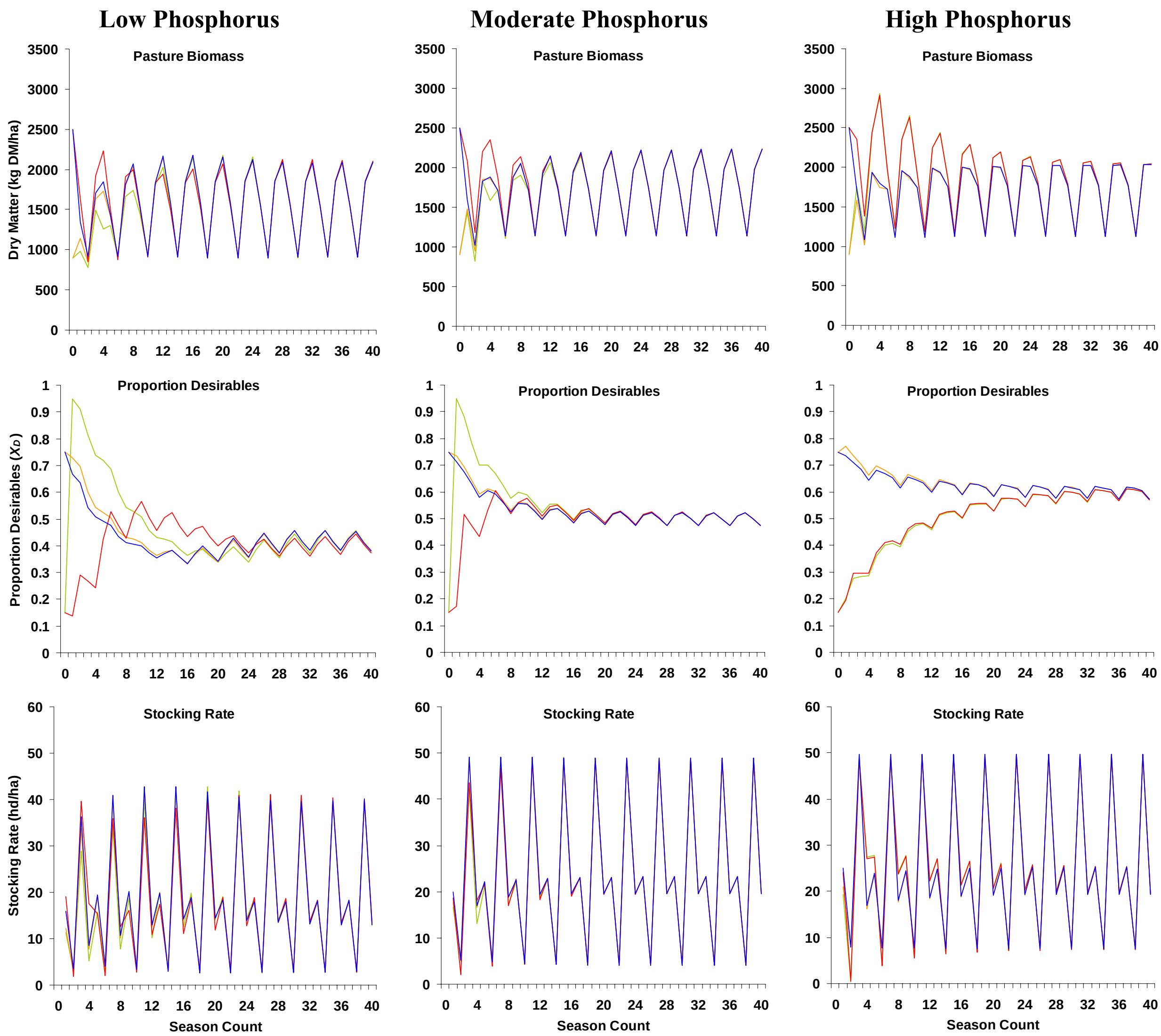

Figure 7-2: Optimal trajectories for high, moderate and low phosphorus input systems, for the initial states of 0.15 desirable/900kg DM/ha (—); 0.75 desirable/900kg DM/ha (—); 0.15 desirable/2500kg DM/ha (—); and 0.75 desirable/2500kg DM/ha (—), under the base merino wether wool production system.

Convergence of botanical composition indicated that, under a low soil fertility system, the identified optimal decision would direct the state of the pasture resource towards maintaining around 40% desirables in the sward. This increased to 50% and 60% for the moderate and high soil fertility systems respectively.

Figure 7-2 also illustrates the optimal stocking rate decisions which were implemented to direct the state of the system towards its optimal state, which maximises the expected present value. It can be seen that the optimal trajectories followed a seasonal pattern for pasture mass and stocking rate. Table 7-5 details the expected optimal target levels for the state of the pasture resource and stocking rate after 20 years (80 seasons). This data corresponds to that presented in Figure 7-2 for the base merino wether 'wool' production system.

Table 7-5: Optimal target levels for the proportion desirables, pasture mass and stocking rate, under alternative sheep production and input systems.

Sheep Production system	Input System	Season ending				Mean
		Summer	Autumn	Winter	Spring	
Proportion Desirables						
Wool	Low	0.38	0.42	0.45	0.41	0.41
	Moderate	0.47	0.51	0.52	0.50	0.50
	High	0.57	0.62	0.61	0.61	0.60
	Mean	0.47	0.52	0.53	0.50	0.51
Wool:Meat	Low	0.51	0.54	0.53	0.51	0.52
	Moderate	0.63	0.65	0.63	0.62	0.63
	High	0.74	0.76	0.74	0.73	0.74
	Mean	0.62	0.65	0.63	0.62	0.63
Meat	Low	0.71	0.76	0.75	0.72	0.73
	Moderate	0.65	0.67	0.65	0.64	0.65
	High	0.75	0.78	0.75	0.74	0.76
	Mean	0.70	0.74	0.72	0.70	0.72
Pasture Mass (kg DM/ha)						
Wool	Low	2092	1550	906	1850	1602
	Moderate	2231	1742	1141	1975	1772
	High	2034	1772	1123	2030	1740
	Mean	2121	1689	1056	1952	1705
Wool:Meat	Low	2205	1944	1194	2136	1870
	Moderate	2302	2098	1329	2247	1994
	High	2051	1976	1257	2270	1889
	Mean	2186	2006	1260	2218	1868
Meat	Low	1753	1685	1081	1981	1625
	Moderate	2285	2133	1337	2338	2023
	High	2054	2009	1279	2351	1923
	Mean	2031	1942	1233	2223	1794
Stocking Rate (hd/ha)						
Wool	Low	13.2	18.3	2.8	40.2	18.6
	Moderate	19.5	23.3	4.0	48.9	23.9
	High	19.4	25.3	7.5	49.7	25.5
	Mean	17.4	22.3	4.8	46.3	22.7
Wool:Meat	Low	1.2	5.7	0.5	24.8	8.1
	Moderate	1.7	12.5	2.5	35.8	13.1
	High	1.7	14.5	3.9	40.2	15.1
	Mean	1.6	10.9	2.3	33.6	12.1
Meat	Low	0.2	5.4	1.0	20.9	6.9
	Moderate	0.5	11.8	2.7	32.9	12.0
	High	1.1	12.9	3.9	34.6	13.1
	Mean	0.6	10.0	2.5	29.4	10.7

Optimal target levels for pasture mass ranged from 906kg DM/ha during winter in the low input system, to 2231kg DM/ha during summer in the moderate input system. On average, the highest target pasture mass was maintained in summer, closely followed by spring, autumn and winter. These end of season optimal pasture mass targets tended to increase with increasing soil fertility in autumn, winter and spring. For summer, the optimal expected pasture mass peaked under a moderate input system, but at a lower proportion of desirables than under the high input system (0.47 versus 0.57).

Optimal expected stocking rates increased with increasing soil fertility for the seasons of autumn, winter and spring. The highest stocking rate was 49.7 hd/ha during spring under high soil fertility and the lowest was 2.8 hd/ha during winter under low soil fertility. The mean target stocking rate, representing all seasons combined, increased with increasing soil fertility. The annual mean optimal target stocking rates were 18.6, 23.9 and 25.5 hd/ha under low, moderate and high input systems respectively.

7.4.2 Sensitivity to different sheep production systems

From Table 7-5 it can be seen that, with an increasing emphasis on meat production the optimal target levels for the proportion of desirables in the sward increased. In a wool production system the mean optimal target level was 0.51, whereas for the wool:meat and meat production systems the mean optimal target levels for desirables increased to 0.63 and 0.72. The seasonal pattern for the proportion of desirables within the sward was similar in all sheep production and input systems, with autumn and winter maintaining higher optimal levels than summer and spring.

Changes to the output of meat and wool for the base wether enterprise led to changes in the present value of the initial state of the pasture resource (Table 7-6). These expected present values represent the maximum profit achieved as the system moved towards the optimal state for the pasture resource. This method was used to indicate the effect of different sheep production systems on optimal decision vectors and target levels.

Profits increased with higher levels of soil fertility and fertiliser inputs within each sheep production system. The present value ranged from $1058/ha under the low input system with the wool:meat production system, to $9045/ha under the high input system with the meat production system. There was also evidence of diminishing returns and a reduction in the variability of the expected present value when the level of fertiliser inputs increased.

Table 7-6: Mean present values ($/ha) for different input and sheep production systems under optimal management across all states of pasture mass and proportions of desirables (coefficient of variation as % in parenthesis).

Sheep Production System	Input System			
	Low	Moderate	High	Mean
Wool	3889 (3.5)	7279 (2.2)	8400 (1.8)	6523
Wool:Meat	1058 (10.2)	2915 (4.1)	3666 (3.4)	2546
Meat	3131 (4.6)	7065 (2.3)	9045 (2.0)	6413
Mean	2693	5753	7037	5161

An index of how the expected profit for each sheep production and input system varied with the initial proportion of desirables that occupied the sward is presented in Figure 7-3. Expected profit increased as the initial proportion of desirables increased. The largest gains in profit occurred under the low input system for each sheep production system. The smallest gains occurred under the moderate and high input systems, with diminishing returns occurring as the proportion of desirables increased.

The wool:meat production system's present value experienced the largest response from increases in the proportion of desirables relative to the base case. The low input system peaked at a PV index of 1.35 and a 0.95 proportion of desirables. For moderate and high input systems the peak was at 1.1.

Optimal target levels for pasture mass represent the expected state at the end of the transition period when the optimal decisions have been applied. On average, the lowest pasture mass targets were in winter with 1260 kg DM/ha for wool:meat production and 1233 kg DM/ha for meat production. The pasture mass targets for winter increased when more emphasis was placed on meat production, with the exception of the low input system.

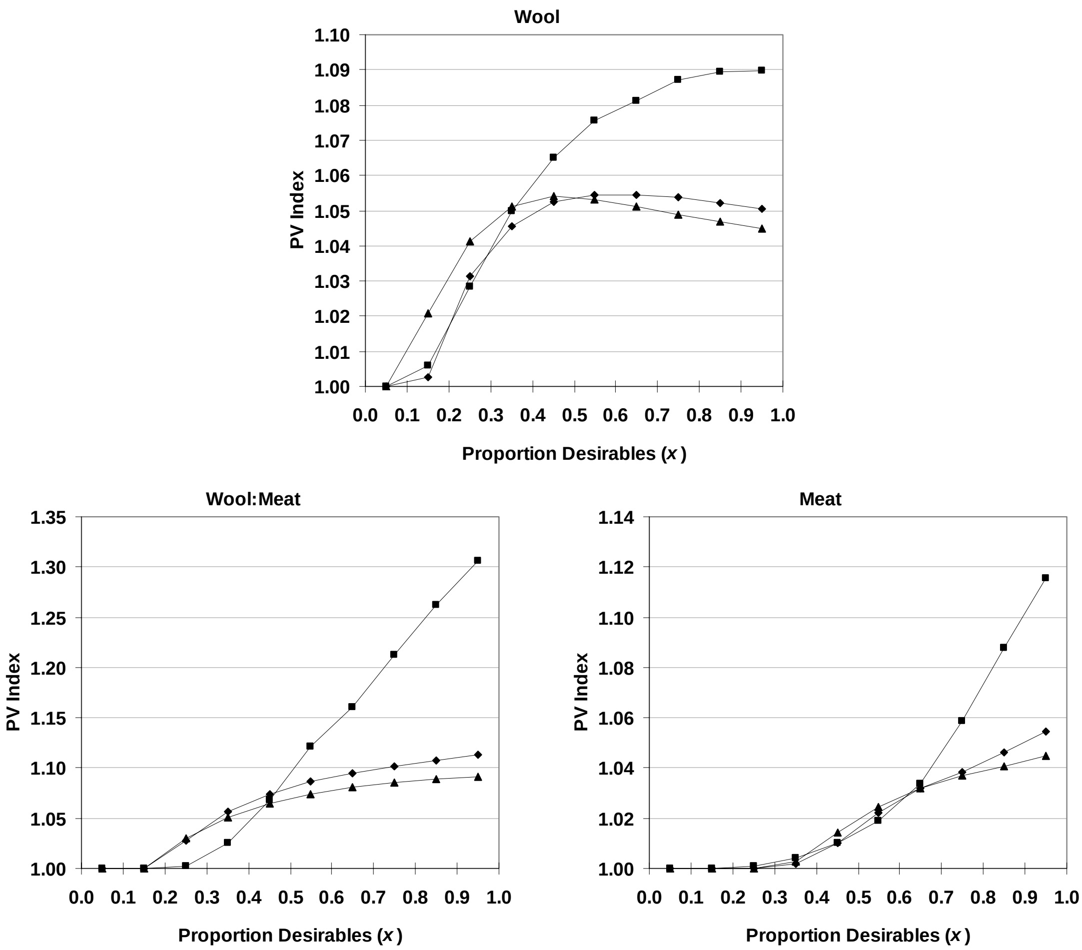

Figure 7-3: Index of present values, *V*, for each sheep production system under different levels of fertiliser input. For each system PV Index =1 with 0.05 proportion desirables. Low input system (■), Moderate input system (♦) and High input system (▲).

Mean pasture mass targets for summer and spring ranged from 1952 kg DM/ha for wool production, to 2223 kg DM/ha for meat production (Table 7-5). Autumn pasture mass targets were similar to spring and summer under wool:meat and meat production systems (2006 and 1942 kg DM/ha), but lower for wool production systems (1689 kg DM/ha).

The highest optimal seasonal pasture mass targets occured for wool:meat production under a low input system. In all seasons but summer, wool production maintained the lowest pasture mass target levels under a low input system. Under a moderate input system, meat and wool:meat production, maintained similar pasture mass target levels for all seasons. Under a high input system, meat and wool:meat production, maintained the highest targets in all seasons except in summer, where all production systems maintained similar target levels.

Optimal stocking rates vary with season, input system and sheep production system. Wool production maintained the highest mean stocking rate at 22.7 hd/ha across seasons and input systems. With more emphasis on meat production, the optimal stocking rate declined to 12.1 hd/ha and 10.7 hd/ha for wool:meat and meat respectively.

The mean optimal stocking rate rose with increasing levels of inputs. The largest increases occurred under wool:meat and meat production systems, which increased by 86% and 90% between low and high input systems. For the wool production system, stocking rate increased by 37% between low and high input systems.

Stocking rate also varied markedly between seasons for different sheep production systems, but exhibited similar patterns in all input systems. For all sheep production systems the highest optimal seasonal stocking rate occurred during spring (Figure 7-4), followed by autumn. Summer stocking rates were markedly lower for wool:meat and meat production systems (1.6 and 0.6 hd/ha), when compared to the wool production system (17.4 hd/ha). A similar pattern also occurred for winter stocking rates, with the wool:meat and meat systems being 48% and 52% of the wool production system's winter stocking rate.

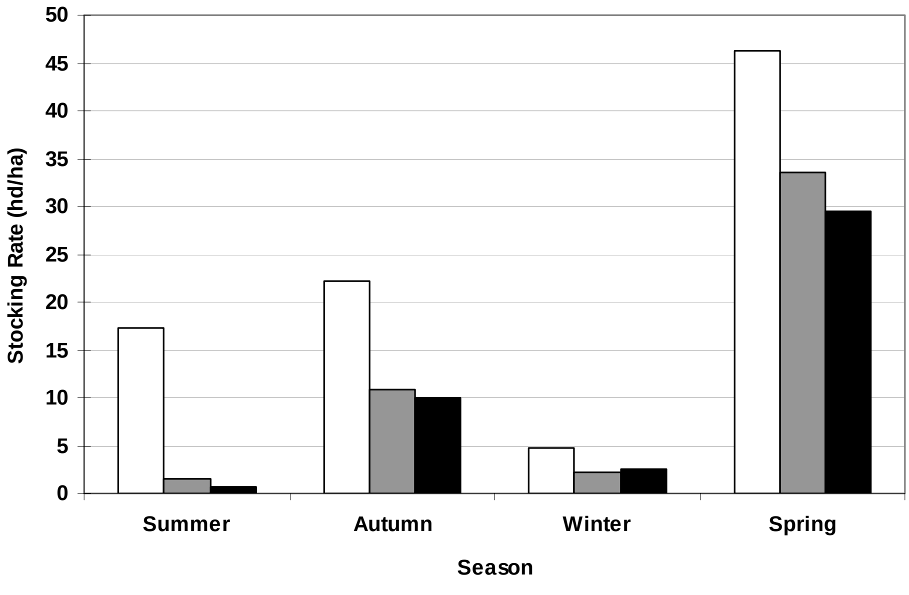

Figure 7-4: Mean optimal seasonal stocking rates (hd/ha) under different sheep production systems, wool (□), wool:meat (■) and meat (■).

7.4.3 Optimal stocking rate decisions

The optimal stocking rate decision varies with season and the state of the pasture. The distribution of optimal stocking rate decisions for each season and pasture state, for the moderate input wool system is presented in Figure 7-5. The initial state of the pasture is defined as pasture mass (*Yc*) on the y-axis, which is the amount of pasture dry matter available at the start of the season, and the proportion of desirables (*x*), that occupy the sward at the start of the season on the x-axis. The spliced-off corners (indicated by *), at the bottom left of each graph for a season, represent the states of pasture when the optimal decision was to re-sow the pasture. Given the dimensions of the SDP outputs, the use of these stocking rate contour plots allowed identification of trends in the optimal decision vector that would not, otherwise, have been detected through statistical analysis. They also provide a quick means of locating optimal decisions by finding corresponding pasture state coordinates.

These graphs represent a simplified presentation of the 4000 optimal solutions. The optimal stocking rate decisions were aggregated into 5 groups. The black regions on the contour plots show the states of pasture where a tactical grazing rest was the optimal decision. The other coloured regions relate to representations of aggregated stocking rate decisions.

Figure 7-5 illustrates that in spring and autumn the optimal stocking rate decision is largely based on the quantity of pasture mass available. The highest stocking rates across all proportions of desirables are maintained in spring, whereas the lowest stocking rates are maintained in winter.

During winter when there are less 0.4 desirables in the sward, there is a band of lower optimal stocking rate decisions and tactical grazing rests across all quantities of available pasture mass. This band also exists for summer and autumn but with higher optimal stocking rates than those shown for winter.

Interestingly, for winter, autumn and summer, tactical grazing rests are optimal when available pasture dry matter is less than 200-500 kg DM/ha across all states of desirables. This is investigated in greater detail in the following section on tactical grazing rests.

The regions of optimal re-sowing are largest in the autumn and winter seasons. If the state of the pasture resource is poor enough, the re-sowing of pastures in those seasons becomes the most profitable decision. This is reviewed in more detail in a following section.

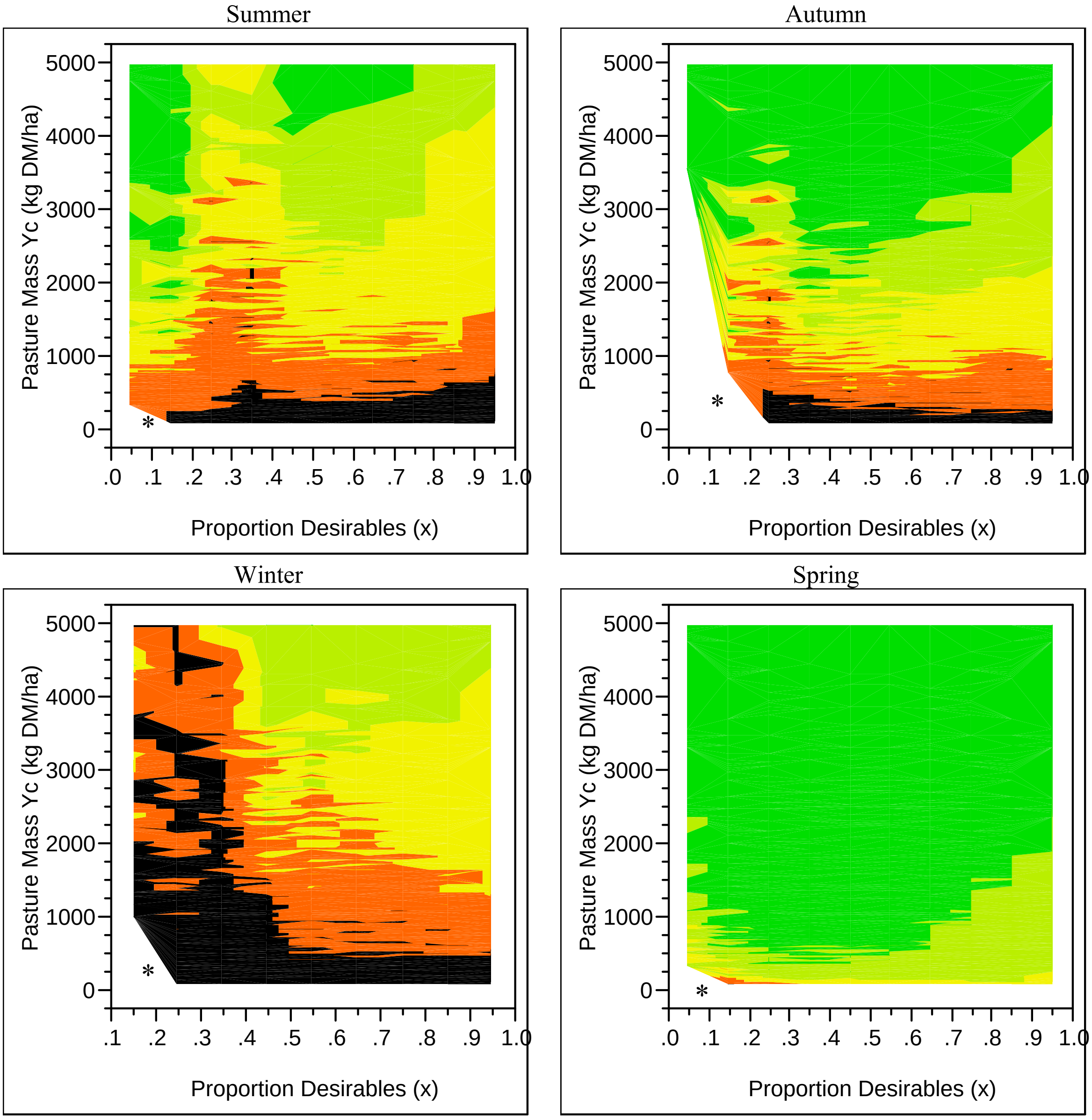

Figure 7-5: Stocking Rate contour plots showing the relationship between the state of the pasture resource, in terms of season, pasture mass and proportion of desirables, on the optimal stocking rate decision for the moderate input wool system. ■ = grazing rest, ■ ≤ 14, ■ ≤ 27, ■ ≤40, ■ > 40 hd/ha, * indicates regions where re-sowing is the optimal decision.

7.4.4 Tactical grazing rest

Extensive areas during the winter, autumn and summer where the optimal policy (*sr**) is the application of low stocking rates (less than 5 hd/ha) are presented in Figure 7-5. Tactical grazing rests occur when sr = 0 hd/ha and their frequency depends upon the state of the pasture resource and season. Figure 7-6 illustrates the relationship between pasture state and tactical grazing rest under the optimal stocking rate policy.

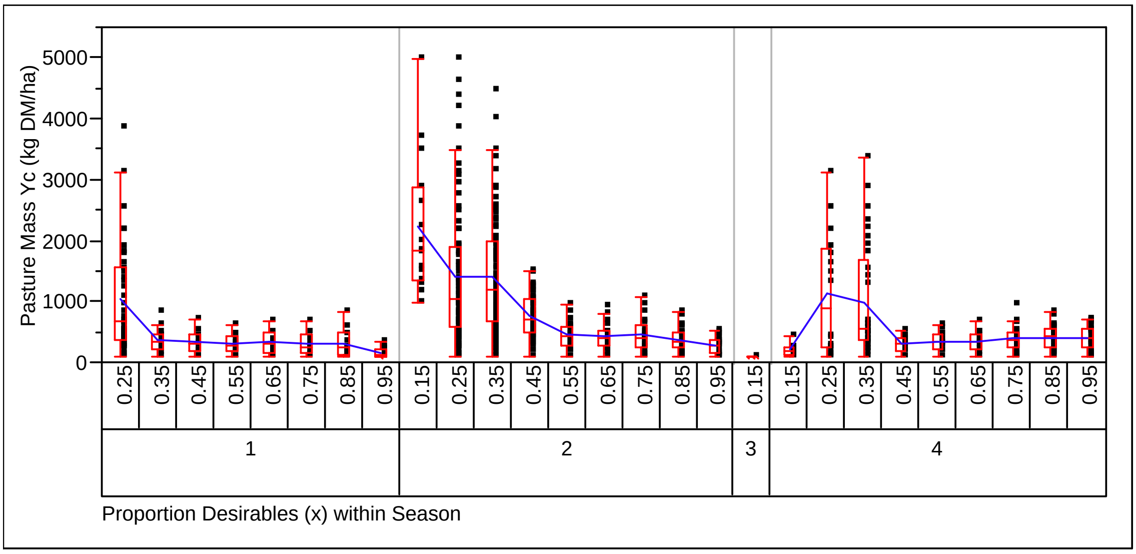

Figure 7-6: Tactical grazing rests (when *sr* = 0 hd/ha) as determined by pasture state, in terms of initial pasture mass and the proportion of desirables, for each season under a moderate input wool production system. Seasons are 1 = autumn, 2 = winter, 3 = spring and 4 = summer. Box plot cell means linked and indicated by joining line (—).

Tactical grazing rests were applied at increasing amounts of pasture mass and decreasing proportions of desirables (Figure 7-6). In autumn, rests were applied when the proportion of desirables was 0.25 and up to a mean of 1046 kg DM/ha. These rests continued to be optimal at higher proportions of desirables but at lower levels of pasture mass (mean of 350kg DM/ha). A similar pattern occurred during winter, but the rest decision remained optimal at pasture masses with a mean of 2240 kg DM/ha when x = 0.15.

During summer the pasture mass that induced grazing rest was highly variable and averaged at 574 kg DM/ha across all proportions of desirables. For spring the only tactical grazing rest occurred when Y_c=100 kg DM/ha and x = 0.15. The box plots within Figure 7-6 indicate that corresponding pasture mass is skewed to very high levels on occasions. This represents cases when there is a large amount of dry matter from undesirable species and very little contribution of desirable species to the sward. The optimal decision under such a state is to provide a tactical grazing rest to enable the recovery of the desirable species.

7.4.5 Re-sowing decision

The decision to re-sow a degraded pasture varies with season, input system, sheep production system, and the state of the pasture resource. Table 7-7 shows the maximum pasture mass up to which re-sowing of the pasture is optimal for different proportions of desirables, seasons, input systems and sheep production systems. Empty cells in the table indicate that even with very low quantities of available pasture, the optimal decision was not to re-sow.

There are some general patterns in the data (Table 7-7). Meat-focused production systems have more states of pasture where re-sowing is the optimal decision. Wool-focused production systems have the least and wool:meat is in between the two.

Table 7-7: Maximum pasture mass quantities below which re-sowing becomes the optimal decision for each season, input, sheep production system and proportion of desirables.

Sheep Production system	Input system	Proportion desirables in the sward (x)						
		0.05	0.15	0.25	0.35	0.45	0.55	0.65
Autumn								
Wool	Low	2420	1503					
	Moderate	3500	1175					
	High	3500						
Wool:Meat	Low	5000	4625	4062				
	Moderate	5000	5000					
	High	5000	3050					
Meat	Low	5000	4775	4187	3687	3155	2415	
	Moderate	5000	5000	4625	3565			
	High	5000	5000	4375	2310			
Winter								
Wool	Low	3340	1503					
	Moderate	5000	2140					
	High	5000						
Wool:Meat	Low	5000	4625	3925	1660			
	Moderate	5000	5000					
	High	5000	5000					
Meat	Low	5000	5000	4375	3688	3155	2415	940
	Moderate	5000	5000	5000	3565	1420		
	High	5000	5000	5000	3285			
Spring								
Wool	Low	320						
	Moderate	690						
	High	870						
Wool:Meat	Low	2420	1502					
	Moderate	4785						
	High	4837						
Meat	Low	4775	3020	1900	1172	732	190	
	Moderate	4925	3050	1337				
	High	5000	4265	962				
Summer								
Wool	Low							
	Moderate	510						
	High	510						
Wool:Meat	Low							
	Moderate	2420						
	High	3330						
Meat	Low							
	Moderate	4755	4325	3925				
	High	4837	4437	3775				

In regards to different input systems, there was a tendency for a higher soil fertility status leading to a higher level of available pasture at which re-sowing is optimal. However, for the majority of cases, re-sowing is only optimal with very low proportions of desirables, when $x = 0.05$ or 0.15.

As the proportion of desirables in the sward increases, the maximum pasture mass state at which re-sowing is triggered declines. This supports the finding discussed in the previous section, that tactical grazing management through complete grazing rests or reduced stocking rates, becomes the optimal decision to rejuvenate degraded pastures.

The majority of re-sowing activity would be expected to occur during the autumn and winter. During summer and spring the re-sowing of pastures is also considered optimal under very degraded pasture states. This represents a limitation of the model as seedling mortality is not considered, only a low starting quantity of pasture mass is used to replicate a germinated pasture. However, these assumptions were required to integrate the DPRD model into the SDP model.

7.4.6 Sensitivity to changes in pasture sowing costs

The base pasture re-sowing cost used in the base case was $250/ha representing the cost of establishment fertiliser, seed, chemicals and sowing (Scott, 2006). To investigate the sensitivity of the optimal decision vectors to changes in the costs of sowing pastures, high and low pasture sowing costs were applied against the moderate input wool production system.

With increasing costs of pasture sowing there was a reduction in the number of pasture states at which the re-sowing decisions were optimal (Figure 7-7). For all seasons there was a reduction in the median pasture mass at which the re-sowing decision was optimal with increasing pasture costs.

In autumn the median pasture mass and corresponding proportion of desirables at which the re-sowing decision was optimal declined with increasing costs of sowing. For low pasture costs, re-sowing occurred at a median pasture mass of 780 kg DM/ha and 0.15 desirables. This declined to a median of 560 kg DM/ha at 0.15 desirables for the base sowing cost. With high sowing costs no re-sowing occurred at 0.15 desirables, but the distribution and median level of pasture mass remained the same as for low and base sowing costs at 0.05 desirables.

The cost of sowing pasture had little effect on the states of pasture mass at which re-sowing in winter was optimal. The median pasture mass that induced re-sowing was 1100kg DM/ha when the proportion of desirables was 0.05. As the cost of sowing increased, the median pasture mass at which re-sowing was optimal for a 0.15 proportion of desirables declined. At low sowing costs a median pasture mass of 870kg DM/ha induced the re-sow decision, with 780 kg DM/ha and 440kg DM/ha at the base and high sowing costs. With the proportion of desirables at 0.15 the range of pasture masses that induced re-sowing decreased with increasing costs of sowing pastures.

Examination of stocking rate contour plots, as described in section 7.4.3, for each season and pasture sowing cost indicated that, for autumn and winter there were reductions in optimal stocking rates when the proportion of desirables were declining and the costs of sowing pastures was increasing. This predominantly occurred through lower optimal stocking rate policies corresponding to higher pasture masses when the proportion of desirables was less than 0.45.

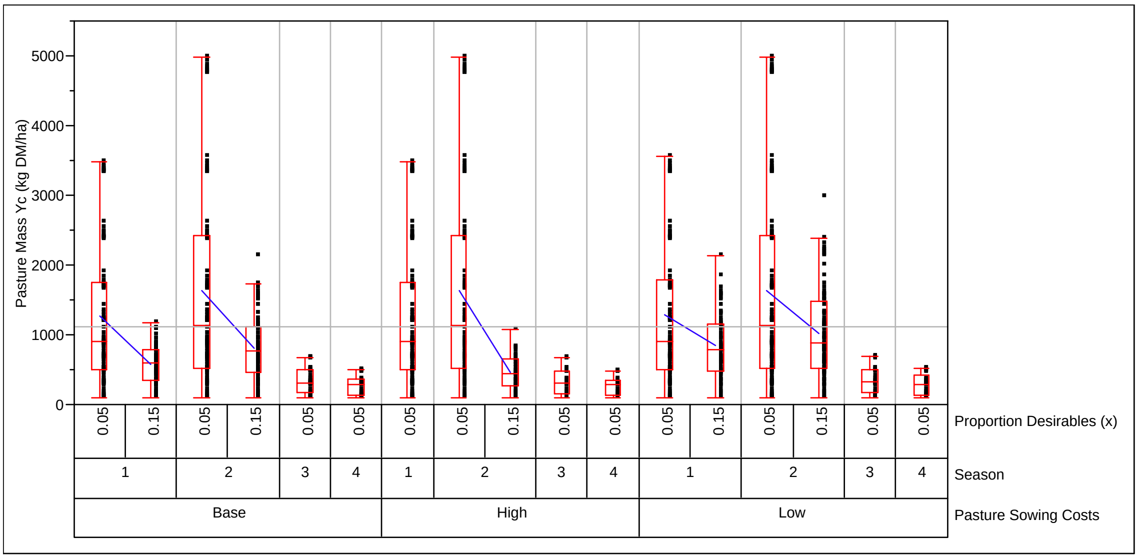

Figure 7-7: Comparison of changes to the state of the pasture when re-sow decisions are optimal under different pasture sowing costs for the moderate input wool system. Seasons are 1 = autumn, 2 = winter, 3 = spring and 4 = summer. Box plot cell means linked and indicated by joining line (—) and grand mean indicated by broken line (- - -).

During spring and summer, the pasture states at which re-sowing was optimal remained insensitive to the costs of pasture re-sowing. Examination of the seasonal stocking rate contour plots for summer and spring indicated that pasture sowing costs did influence optimal stocking rate policies under different pasture states for summer, but did not for spring. In summer there was a tendency for lower stocking rates to occur at higher pasture masses in the region of 0.2 to 0.4 desirables with increasing pasture sowing costs.

7.4.7 Sensitivity to discount rate

The base discount rate used in this analysis was 4.94% and represented the real discount rate calculated from inflation and nominal interest rate data (plus a margin of 1.5%), over the period of 1976 to 2006 (ABARE, 2006). To investigate the sensitivity of the optimal decision vectors to changes in the discount rate, a range of rates were applied against the moderate input wool production system.

With increasing discount rates, there was a reduction in the optimal target level of desirable species in the sward (Figure 7-8). From the range of discount rates tested, 3% to 10%, the response of optimal target levels of pasture mass, proportion of desirables and stocking rates was negligible. However, when examining contour plots of stocking rate for each season and discount rate (not shown), there were subtle differences in the optimal stocking rate policies at lower levels of desirables in the sward. This indicated that, with increasing discount rates, higher stocking rates were optimal at lower proportions of desirables. In addition, with lower discount rates, the states of pasture where the re-sow decision was optimal increased in winter and autumn.

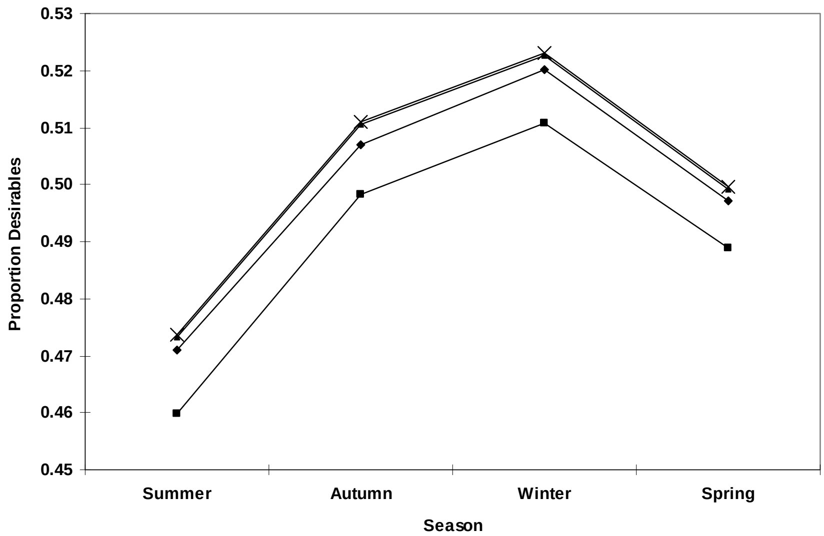

Figure 7-8: Effect of discount rate on the optimal proportion of desirables for each season under a moderate input wool production system. Discount rates are 3% (x), 4.94% (▲), 7% (♦) and 10%(■).

7.5 Discussion

This chapter described the implementation and solution of the dynamic and stochastic pasture resource development and management problem using a stochastic dynamic programming framework. The method demonstrated the integration of the DPRD simulation model developed in Chapters 5 and 6 into a dynamic optimisation framework.

The results of the SDP model presented in this chapter show how the bioeconomic framework developed can be used to identify optimal tactical and strategic decisions in the development and management of a dynamic pasture resource under stochastic climatic conditions. The tactical and strategic decisions relate to the application of technologies that enable the development and management of the pasture resource. The technologies applied in this research are the strategic application of fertiliser, the strategic sowing of introduced species and the tactical use of grazing management to utilise the pasture resource and manipulate botanical composition.

The assumed objective of the decision maker is the maximisation of the expected present value of future returns. The SDP model identified the optimal seasonal stocking rate and pasture sowing polices for each type of input and sheep production system. These optimal policies are derived within a framework where the risks from a stochastic climate are embedded into the decision-making process.

From the application of these optimal decisions the expected optimal state of the pasture resource was defined in terms of pasture mass and botanical composition. The optimal decisions identified balance the economic returns from the present utilisation of the pasture with the dynamic benefits and costs of maintaining a desirable botanical composition.

7.5.1 Optimal botanical composition

Definition of an optimal pasture state is difficult to determine through experimentation given the complexity of a grazing system, livestock production and profitability. The outcomes from this research suggest that the optimal pasture state depends on the level of fertiliser inputs and the type of product from the sheep production system.

The optimal target proportion of desirables in the sward has been shown to vary with soil fertility and sheep production system. The optimal botanical composition varied between 0.40 and 0.80 desirables within the sward. These levels were significantly higher than the average for producers in the HRTPZ (Dellow *et al.*, 2002; Kemp and Dowling, 1991).

The optimal proportion of desirables in the sward increased to between 0.65 and 0.80 when more emphasis was placed on meat production under higher soil fertility systems. The lower proportion of desirables of 0.4 was optimal for low input wool production systems. In this case study, *Bothriochloa macra* and annual grasses contributed significantly to the feed base for the wool production system. However, the ability of this low input system to maintain a higher level of desirables was limited by low soil fertility and the lack of fertiliser inputs (Cook *et al.*, 1978a; Hill *et al.*, 2004). When this was corrected the optimal proportion of desirable species increased by 10% and 20% under the moderate and high input systems. The higher soil fertility increased the growth rate and size of the desirable population. These levels of desirables in the sward correspond to those found by Jones *et al.* (2006b).

The relationship reported between botanical composition and profit is a reflection of sustainable exploitation of the pasture resource can occur and the time that it takes for the system to reach optimal states of pasture mass and botanical composition. When the initial pasture state represents a high proportion of desirables in the sward, exploitation of the pasture resource and the desirable population caused the system to move towards its lower optimal state. When sub-optimal levels of desirables existed in the sward, the pasture resource was improved through either reduced stocking rates or capital investment into re-sowing of the pasture.

7.5.2 Optimal pasture mass

The results from this research indicate that optimal pasture masses vary with input and sheep production system. Their levels were noticeably higher than those suggested by field research as being required for the persistence of sown species (Avery *et al.*, 2000; Dowling *et al.*, 1996) and to maintain groundcover targets of 80% (Salmon, *pers. comm.*), but similar to those found for the persistence of desirable grasses on the Central Tablelands of NSW (Michalk *et al.*, 2003). This indicates that producers in the case study region would maintain optimally higher pasture masses than those recommended as minimum pasture benchmarks for livestock production (Bell and Blackwood, 1993).

Significant differences existed in the digestibility of the pasture on offer due to changes in the proportion of desirables in the sward. This in turn influenced the levels of livestock production the pasture was capable of sustaining. This can be seen in the relationship between pasture mass and the proportion of desirables under sheep production systems with increasing emphasis on meat production. This suggests that, although different input systems and sheep production systems would optimally maintain similar levels of pasture mass within seasons, the critical difference in determining livestock production and profit is the proportion of desirables in the sward.

Interacting with this relationship is the sequence of how the pasture resource is utilised. For meat production systems, lower stocking rates were optimal in summer and winter, which allowed higher stocking rates during autumn and spring. These are periods where the desirable species within the sward maintain highly digestible pasture dry matter and enable higher levels of meat production. This reinforces the importance of the differences in pasture quality between the desirable and undesirable components of the sward in determining livestock production and the optimal development and management of the pasture resource.

7.5.3 Optimal tactical grazing management

Stocking rates for all enterprises and seasons were at their highest levels when the state of the pasture was at its optimal. Sheep production systems, with an increasing emphasis on meat production, had lower optimal stocking rates and maintained higher proportions of desirables in the sward. The meat system was more sensitive to increasing soil fertility with higher present values and lower variability of economic returns. This is in contrast to the results presented in Chapter 6, which suggested both increased returns and risk from increased investment in soil fertility and higher stocking rates. However, those results were derived from set-stocked simulations, which suggest that there is a significant risk-reduction benefit from the integration of tactical grazing management.

The use of complete grazing rest of a pasture as part of the optimal tactical grazing management decision occurs in response to both the proportion of desirables and pasture mass. Low pasture masses of less than 600 kg DM/ha combined with proportions of desirables greater than 0.45 tended to induce the grazing rest decision. As the proportion of desirables in the pasture declined, the pasture mass boundary for inducing grazing rest increased. Through the examination of stocking rate contour plots trends for changes to the optimal decision vector were observed. These suggested that both tactical rests and reduced grazing pressure were optimal stocking rate policies when the proportion of desirables declined to less than or equal to 0.3 in summer and autumn, and 0.4 in winter.

The results of this analysis suggests that for the New England region of NSW, tactical grazing rests and reduced grazing pressure during the autumn, winter and summer are more beneficial than tactical grazing rests during spring. Even though spring maintained the highest intrinsic rates of desirable population growth and the highest livestock harvest impact coefficient, complete grazing rest was only found to be optimal with a pasture state of 100 kg DM/ha and 0.05 desirables. The higher reliability of pasture growth during spring in this environment, and its impact on the production of livestock and economic returns, suggests that the expected benefit from high utilisation outweighs the potential costs of pasture resource degradation.

7.5.4 Optimal re-sowing of pastures

The strategic decision to re-sow a degraded pasture was found to be optimal only when the proportion of desirables was less than 0.15. The exception to this was the low input meat production system, where the re-sowing of pastures remained optimal up to 0.65 desirables in autumn, winter and spring. This suggests if a low-input system is used, repeated sowing of pastures maximises present value and is the optimal method of maintaining higher quality pastures for meat production.

To incorporate the strategic decision of re-sowing pastures into the SDP model, the stocking rate was held at 0 hd/ha in the season of sowing. The dynamic optimisation process then derived the optimal stocking rate for establishing the pasture in the second season. The results from this analysis suggest that, once established, early grazing of newly sown pastures is optimal. In this specific case-study application, the resulting degradation of the newly sown sward would be acceptable as long as the pasture maintains the optimal level of desirables further along the planning horizon.

The relationship between pasture sowing costs and the optimal decision vector indicated that, as the cost of sowing increased, the optimal decision vector adjusted to avoid the cost of re-sowing. This was achieved through the lowering of optimal stocking rates during winter, autumn and summer, when the proportion of desirables was in the region of 0.2 to 0.45. Such a response supports the principles of adopting conservative stocking rates to maintain desirable species within the sward (Dowling *et al.*, 1996).

7.5.5 Application of the SDP results

The sensitivity analysis of the optimal decision vectors to the applied discount rate, suggested optimal stocking rate and re-sowing polices were robust across a broad range of discount rates. The reason for this was that increased stocking rates and the re-sow decision were antagonistic policies in terms of maximising present value. Under high discount rates, there was an increasing emphasis on higher stocking rates to lift pasture resource utilisation and maximise returns in the short term. This was, however, limited by the cost of sowing and the opportunity cost of not grazing during the establishment period under high discount rates.

The extrapolation of the results from this research to other regions with confidence is difficult. Differences in climate, soil type, topography and the species that make up the pasture would influence the optimal decision vector. The relative differences in quality and seasonal growth patterns of the different species groups would influence the optimal target levels of desirable species and the optimal stocking rates achievable. Differences in the rate of response of the desirable species population to tactical grazing rests, soil fertility and livestock harvesting would also affect the long term dynamics of the pasture resource. However, the ability of the framework to adjust the optimal decision vector in response to these variables enables its application in a broad range of situations.

A logical extension to this model is the integration of the optimal decision vectors into a multi-paddock grazing system simulation. This would provide the opportunity to develop a framework that is capable of simulating a complex multi-paddock grazing system that maintains a mosaic of pasture types and compositions. It would also provide the opportunity to simulate the effect of optimal stocking rate and re-sowing policies on the performance of different flock structures and the optimal proportions of tradeable or disposable stock within a grazing system.

Chapter 8. Summary and Conclusions

8.1 The Research Problem

The review of literature indicated that the grasslands of the high rainfall temperate pasture zone (HRTPZ) of south eastern Australia have been transformed through the impacts of grazing and inputs. During the 1950s and 1960s, there were large increases in the areas of sown and fertilised pasture which dramatically increased the carrying capacity of the existing native pasture base. A continuing decline in terms of trade, and increased fertiliser costs are believed to have led to reduced fertiliser inputs which, combined with numerous drought years over the recent decades, has led to degradation of the pasture resource. More recently, the use of more precise tactical grazing management to improve the persistence and productivity of the pasture resource has gained increasing popularity following considerable research.

Nevertheless, the sowing of introduced species and use of fertiliser are still considered important to those producers in the HRTPZ wanting to increase production, but investment in these technologies has been constrained by the perceived and real costs, as well as the risks of not seeing the benefits in dry times.

The dynamics of the pasture resource results in trade-offs between the utilisation of pastures for profit and their persistence. The interaction of technologies such as the sowing of pastures, application of fertiliser and grazing management, influence the potential persistence, productivity and profitability of the grazing system. The trade-offs are inter-temporal as are the benefits and costs of technologies applied to improve the pasture resource.

The decision problem for producers is that the development and management of the pasture resource involves a series of strategic and tactical decisions. There is added complexity in that the stochastic nature of climate introduces production risk between these decision points with both positive and negative feedback consequences. Thus, the optimal development plan will change for each decision point as the state of the pasture resource changes and the expected returns from future decision options change.

To maximise the long-term profitability of sheep producers and solve this sequential decision problem, requires a bioeconomic model that adequately represents the dynamic nature of the pasture resource in terms of both its productivity and composition. These dynamic attributes need to respond to the influences of climate, investments in technology, and pasture resource utilisation.

A review of theoretical frameworks and biophysical models of botanical composition and pasture production suggested that a dynamic pasture resource would best be described through the use of a state and transition framework, coupled with empirical growth models. The need to integrate a dynamic simulation model into economic optimisation procedures precluded the direct use of complex mechanistic models of the grazing system. The bioeconomic framework required to solve the problem needs to integrate a dynamic simulation model of the pasture resource with an economic optimisation procedure that considers the embedded risk of the tactical and strategic decisions of pasture development. A review of previous economic and bioeconomic approaches into pasture resource development and management indicated that few studies have considered the stochastic nature of grazing systems on the benefits and costs of adopting technologies. Even fewer studies have considered the tactical and strategic structure of the sequential decision problem.

The bioeconomic framework developed in this study is unique in that it takes into account the impact of embedded climate risk, technology application and management on the botanical composition of the pasture resource over time. The framework integrates the links between inputs, state of the pasture resource and outputs, which in turn affect the optimal development strategy identified. This process has been achieved through the development of a dynamic pasture resource development (DPRD) simulation model which is integrated into a seasonal stochastic dynamic programming (SDP) framework.

8.2 Discussion of key findings and implications

The working hypothesis that formed the basis of this study was that accounting for a stochastic climate and dynamic relations in pasture composition will improve the estimation of the benefits and costs associated with pasture development technologies. In addition, that through the integration of a dynamic pasture resource simulation model and an economic optimisation model, optimal tactical and strategic decisions would be identified that improve the information available for the management and development of the case-study grazing system. This section discusses the key findings and their implications for sheep meat and wool producers in the high rainfall temperate pasture zone.

8.2.1 Deterministic vs stochastic and static vs dynamic

In chapter 6 the DPRD model was run using a Monte Carlo simulation framework. The objective of this process was to evaluate the application of the DPRD model in the case study region and demonstrate output from the model. Part of the demonstration was to investigate the benefits or costs of including a stochastic climate and dynamic botanical composition model. The results suggested that, independently of a producer's risk attitude, both components impacted on the expected benefits of pasture development technologies. A stochastic climate was shown to have the dominant effect on the predictions of productivity and profitability. There was a general trend for benefits of the applied strategies to be over estimated by a deterministic model, particularly at high stocking rates, which agrees with the findings of Cacho *et al.* (1999). The influence of including dynamic botanical composition in the model is variable, from over estimating benefits under high stocking rates to underestimating benefits at low stocking rates. This reflects the process in the model where either over or under utilisation of the desirable components leads to either a corresponding decrease or increase in the proportions of desirable species in the sward. In combination, the stochastic climate and dynamic pasture composition model had substantial impacts on the predicted benefit and the level of over estimation increased exponentially with stocking rate. With stocking rates of over 18 hd/ha, deterministic predictions overestimated profitability by up to 130%, and with stocking rates below 18hd/ha, deterministic predictions underestimated profitability by up to 25% (under a moderate soil fertility and wool production system).

In this application there were significant benefits from considering botanical composition for inter-temporal decision making. The consideration of botanical composition change has frequently been considered in rangeland studies (Ludwig *et al.*, 2001; Stafford Smith *et al.*, 1995; Torell *et al.*, 1991), but has largely been neglected in temperate grasslands.

In evaluating tactical grazing rests and reduced stocking rates for the benefit of future production and profitability, dynamic pasture models operating under stochastic conditions are required (Jones *et al.*, 1995). From the results of this study, the variability of growth within seasons, such as autumn and summer, determines the benefits from tactical grazing rest on the desirable population. This is supported by research findings which have indicated that the gains from rotational grazing or tactical grazing rests on botanical composition only occur when they coincide with favourable environmental conditions (Dowling *et al.*, 2005). The sporadic effects of drought on botanical composition were also represented in this study and presented the largest risks to maintaining a desirable composition, which is consistent with long-term grazing trials in the New England region (Hutchinson, 1992).

The value of tactical decision making in agricultural production is well supported by previous studies (Kingwell *et al.*, 1993; Marshall *et al.*, 1997). In this study, the costs of not embedding the production risks and tactical decisions into the decision making process are indicated by the differences in the present value results presented in Chapter's 6 and 7. For the wool production system in Chapter 7 there is increasing profitability with increasing soil fertility levels. Chapter 6 suggests the same relationship, but with increasing variability in the profitability of the system. The difference between simulation and optimisation results, being the reduced variability of profitability in the SDP present values, suggests that the ability of the optimisation model to adjust its path as uncertainty unfolds between decision points has a risk-reduction benefit.

8.2.2 Fertiliser application

The Monte Carlo simulation experiments conducted with the DPRD model in Chapter 7 showed a strong relationship between fertiliser input and the persistence of desirable pastures and productivity. This aligns with research that found higher fertiliser inputs were necessary for the maintenance of desirable species and a productive sward (Cook *et al.*, 1978a; Hill *et al.*, 2004).

High fertility systems in both the simulation and SDP model outputs were the most profitable systems. The simulation results indicated that fertiliser strategies that increased phosphorus levels were also required to run higher stocking rates to ensure they remained a risk-efficient strategy. However, low input systems were also found to be risk-efficient strategies. But if consideration is given to the fixed costs of a grazing business, which typically are in the vicinity of \$80-\$150/ha for wool producers in the Tablelands of NSW (Barrett *et al.*, 2003), the lowest combinations of stocking rate and fertiliser inputs (stocking rate of 3 and 6 hd/ha and 42kg single superphosphate/ha/yr) would not be profitable.

The results from the SDP model indicated that the profitability of all sheep production systems increased with increasing soil fertility. This analysis assumed that each of the systems were in a steady state in regards to soil fertility. The application of fertiliser was excluded as a decision in the SDP process due to the issue of dimensionality and the fact that the optimal application of fertiliser inputs has previously been considered (Godden and Helyar, 1980; Woodward, 1996). Instead, soil fertility was maintained at a given level through prescribed applications of fertiliser. However, the assumed steady state of the system in the SDP may have underestimated the maintenance costs of soil fertility under high stocking rates and overestimated under low stocking rates. The reason for this is that the results of the DPRD simulations indicated that over a 10-year period the fertility status of the soil varied with the stocking rate and the fertiliser rate applied. This is a limitation of the SDP process and with improved computing and memory capacity could be addressed in the framework by adding soil fertility as a state variable and fertiliser application as a decision variable.

8.2.3 Sowing pastures

In Chapter 6, the strategy of sowing pastures was less profitable than the maintenance of the degraded pasture. The reason for this involves the cost of sowing the pasture and the marginal difference in productivity between the degraded and the sown pasture over the simulated 10-year planning horizon. The opportunity cost of delaying the grazing of the pasture until it was established would have also contributed to this lower economic performance. However, extension of the 10-year planning horizon would not have influenced the profitability or put the pasture sowing option on the risk-efficient frontier, as botanical composition converged for both pasture types by the end of the simulated period. As such there would have been little benefit to sowing pastures with an extension of the planning horizon. This indicates that post-sowing tactical grazing management is critical to the profitability and maintenance of a newly sown pasture over a degraded pasture. This is supported by earlier work using descriptive deterministic simulations (Scott *et al.*, 2000a) and a dynamic programming approach applied to tactical grazing rests (Jones *et al.*, 2006b).

The slight differences in the simulation analysis between the performance of sown and degraded pastures would have increased if a more degraded pasture had been simulated. There would have also been a greater difference if a more meat-focused sheep production system were operating on the simulated paddock, as wool production was shown to be less sensitive to the proportion of desirables than meat production in the SDP results.

The opportunity cost of delayed grazing also appears to be one of the dominant issues regarding the profitability of sowing introduced species. In the SDP analysis, it was assumed that a newly sown pasture is not grazed in the season of sowing. However, beyond this point the optimisation procedure determined the pasture's future stocking rate. In the majority of cases the re-sown pasture was grazed in its second season. For example, as long as an Autumn sown pasture maintained over 500kg DM/ha by the start of Winter, it was optimal to graze that pasture, albeit at very low stocking rates. The apparent reason for this is that the proportion of desirables in the sward were exploited and it was acceptable for it to decline towards the optimal target levels of botanical composition. This indicates that the undesirable species modelled in this study made a valuable contribution to the feed base and that the cost of maintaining a higher proportion of desirables, through the use of tactical grazing rests or reduced stocking rates, is too high. As such profitability of the newly sown pasture is maximised by utilising and partly degrading the pasture resource to an optimal level.

The importance of botanical composition is highlighted in the comparison between meat and wool production systems. Meat production systems under optimal management maintained slightly higher quantities of pasture mass, significantly lower stocking rates and higher proportions of desirables (72% for meat), than those for wool production (51% for wool). This indicates that it was optimal for meat production systems to operate at lower stocking rates to ensure desirables persist and feed quality remains high.

The SDP analysis also indicated that degraded pastures would only be re-sown when less than 0.15 desirables existed in the sward. This did vary with season, the amount of dry matter present and the grazing enterprise. For example the sowing of introduced pastures was sometimes optimal when there were high amounts of pasture mass (>3000 kg DM/ha), and low proportions of desirables (5%). This represents a pasture with small patches of desirables that no longer contribute significantly to the feed base for grazing livestock. At this state of the pasture resource the profitability of re-sowing the pasture is higher than the benefit of maintaining a degraded pasture.

Autumn and winter were the seasons in which re-sowing of pastures occurred the most, which corresponds to predicted optimum times of sowing pastures in the New England Tablelands (Dowling and Smith, 1976). However, the re-sowing of pastures in summer and spring was also considered optimal under very degraded pasture states (5% desirables and less than 300 kg DM/ha pasture mass). On agronomic principles this may not be optimal and may represent a limitation of the model, as it is assumed the generally strategic decision of re-sowing is available at each seasonal decision stage.

From the SDP results, there were also only relatively small differences observed in the optimal pasture mass targets across the whole range of potential botanical compositions. This lack of difference between the quantities of mean pasture mass would be due to the high amount of summer production from the modelled undesirable species, that is, *Bothriochloa macra* (red grass). This is supported by data from the Northern Tablelands which showed the total production of *Bothriochloa macra* to be similar to that of phalaris but with significantly different growth patterns as well as greater stem to leaf ratios and lower dry matter digestibilities (Robinson and Archer, 1988).

8.2.4 Tactical grazing management

Tactical grazing management in this study was represented by the seasonal adjustment of stocking rates. A range of stocking rates encompassing 0 to 50 hd/ha were available within the decision vector of the SDP model. In solving the pasture resource problem, optimal stocking rates were identified for each pasture state and season. The results indicated that the optimal stocking rates for meat production systems were substantially lower in all seasons when compared to wool production. The lower stocking rates led to slightly higher levels of optimal pasture mass and higher proportions of desirables in the sward. This is to be expected due to the requirement for greater amounts of highly digestible dry matter in order to support weight gain compared to that required to support wool production. These findings are consistent with the published literature on the nutritional requirements of sheep (Dove, 2002; Freer *et al.*, 2007; McDonald *et al.*, 1988).

The relationships described by the optimal stocking rate decision vectors suggest that, with an increasing focus on meat production, maintaining higher soil fertility and higher proportions of desirables in the sward will maximise profit. This is achieved through a trade-off between per head and per hectare weight gains and maintaining the pasture in an optimal state.

The capacity for the bioeconomic framework to seasonally adjust stocking rates unconstrained by flock structure allowed the description of the optimal seasonal harvesting of dry matter. This of course assumes a rotational grazing system may be applied within the whole farm system. From the results of the SDP, it was observed that stocking rates were substantially lower during summer and winter for meat-based production systems. This suggests that the optimal harvest pattern develops a seasonal saving and consumption cycle. In this particular case it was optimal to reduce stocking rates during periods of low growth of desirable species in order to ensure the proportion of desirables in the sward was maintained or increased. This allowed a higher proportion of desirables to be attained in the following seasons of autumn and spring when the growth of desirables was higher with corresponding greater availability of highly digestible dry matter available. This cycle appeared to maximise meat production and profitability from the pasture resource.

The whole farm implications of this are that the management of the enterprise needs to be designed to mimic this optimal harvest pattern as closely as possible. Alternatively, depending on the mosaic of pasture states within the farming system, there may need to be increased emphasis on maintaining a greater proportion of tradeable livestock. There is also the option of transferring the feed between seasons using silage or hay, but the economics of doing this was not considered in this study. The same pattern occurs for wool but to a lesser extent as this enterprise places higher value on the summer feed produced by the undesirable species.

The use of tactical grazing rests has been broadly researched and promoted as a means of maintaining a higher proportion of desirable species (Kemp *et al.*, 2000; Michalk *et al.*, 2003). In this study guidelines for triggering seasonal grazing rests were identified. An alternative strategy to complete grazing rest was the application of low stocking rates (less than 5hd/ha), which occurred frequently at pasture states with low levels of pasture mass and desirables. This especially occurred frequently in winter when there was less than 30% desirables in the sward. These optimal grazing rests and reduced grazing pressure strategies reflect the pasture saving and consumption cycle previously described.

The modelling results suggest that the spring season was the period when livestock had the greatest impact on the desirable population. This indicates that the benefits from spring, being a more reliable season for growth and feed quality with their subsequent effects on livestock production and profitability, outweighed the risk of degrading the desirable population. This is on the proviso that the pasture is rested during other seasons, in particular during winter. This relationship raises questions into the sensitivity of mean seasonal growth rates and the parameter value for the livestock impact coefficient, both of which would be logical areas for further research and development of the model.

With the option of tactical grazing management to enhance botanical composition, it is nearly always more profitable to apply a grazing rest or a period with reduced stocking rate. Although the sowing of pastures has played a major role in the development of grasslands in the HRTPZ (Crofts, 1997; Menz, 1984), it appears from the results of the SDP modelling to be the optimal decision only in severely degraded pastures.

8.2.5 Implications at the whole farm level

The time frame for decision making regarding pasture development has been suggested to be 10-15 years for profit maximisation and 20-30 years for the sustainability and persistence of the pasture system (Lodge *et al.*, 1998; Scott and Lovett, 1997). A key feature of the optimal decision rules that were derived using the bioeconomic framework developed for this study, is that they remain optimal regardless of the time frame being considered as they represent an infinite planning horizon. An interesting outcome is that the discount rate had only a small effect on optimal decision rules, because of the antagonism between the benefits of higher stocking rates and the costs of replacing overgrazed pastures.

The SDP process solved the pasture resource problem to a point of policy convergence. The optimal target levels at convergence indicate a state of the pasture resource which corresponds in principle to that of the maximum economic sustainable yield, whereby the pasture is viewed as an exploited renewable resource (Clark, 1990). As such, each optimal decision rule directs the current state of the pasture towards the optimal and sustainable state. This sustainable state is based on the objective of profit maximisation, but is constrained by the impact of livestock harvesting on the desirable population, the concurrent impacts on the productivity of the grazing system, and the capital cost of resource renewal. The limitations of this analogy are that the method applied did not consider the externalities surrounding the management of a grazing system (e.g. runoff and erosion) (Cacho, 1999; Jones and Dowling, 2004) which is well beyond the scope of this study.

The identified optimal decision vectors are broadly applicable to other paddocks within a farming system that maintain similar species within its desirable and undesirable groups. The seasonal stocking rate contour plots provided a visual guide to all 4000 of the optimal decisions for different states of the pasture resource in each season. Conceptually such a tool could be used to help guide a producer or advisor in deciding the optimal management of a paddock at the start of a season. They provide a guide as to the optimal tactical stocking rate decision, which includes grazing rests, and whether or not to re-sow a pasture. However, outside of these species groupings, the key attributes of pasture growth and quality will play a role in determining the optimal decision vector.

In the application of this method to a whole-farm system, an additional layer of complexity would arise where multiple livestock production systems exist. As each production system, with its own balance of meat and wool production, would maintain different optimal targets for pasture mass and botanical composition.

8.3 Future research opportunities

An issue in the development of this bioeconomic framework was the compromise in deriving time-steps and boundaries. The compromises were made in regards to the frequency of tactical and strategic decisions, as well as the constraint of modelling a single paddock with a representative sheep enterprise. The sensitivity of seasonal pasture growth rates has been identified as an issue and highlights the need to develop the model to handle pasture growth parameters on a shorter time-step, such as on a monthly basis. However, there is a fundamental limitation to operating tactical and strategic decisions in the SDP framework at a shorter time-step; as the memory requirements of maintaining 12 sets of transition probability matrices (one for each month) to solve the sequential decision problem become the main constraint.

A logical development of this framework is its incorporation into a multi-paddock whole-farm simulation model. This would enable the testing of the optimal decision rules, as well as allow the constraint of a simplified flock structure to be overcome and tested to ascertain its interaction with optimal decision vectors. But this would require a different type of optimisation approach, such as an evolutionary algorithm (Mayer *et al.*, 1998).

The issue of dimensionality of the decision problem restricted the incorporation of fertiliser as a decision variable and soil fertility as a state variable in the SDP model. Overcoming this limitation would be a beneficial step in the further development of the bioeconomic framework, but would also require access to much higher levels of computing capacity or simplification of other state and decision variables.

The bioeconomic framework could be further enhanced through further calibration of the botanical composition model. There would also be the potential to modify the model to account for the age of the sown pasture and recruitment. However, such modelling in diverse multi-species swards is limited due to our current knowledge of how plants interact (Kemp and King, 2001).

A key feature of this study was the embedding of production risk into the pasture development decision-making problem with the incorporation of a dynamic botanical composition model. The benefit of this approach is that it considers the inter-temporal trade-offs between investment in pasture development and the utilisation of the pasture resource under climatic uncertainty. The study has shown how we can more realistically model the complex decision process which faces all sheep meat and wool producers and thereby provide readily transferable information to improve decision making.

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Appendices

Appendix A: The Cicerone Project Inc. Farmlet Experiment

Cicerone Farmlet Guidelines

ABC farmlets to be run as individual commercial farms. Each with a self replacing merino flock and opportunity cattle fattening/backgrounding

Farm A High Input/Flexible Grazing

- 8-10 paddocks,
- Aim for 100% of land sown to legumes and nutrient responsive, deep rooted perennial grasses.
- Flexible rotational grazing, more than five mobs in 8-10 paddocks, 10-50 dse/ha stock density.
- Available soil *Phosphorus* level to a target of 60 ppm Colwell.
- Available soil *Sulfate Sulfur* levels to a target of 10ppm.
- Strategic applications of nitrogen fertiliser. Periodic Molybdenum applications.
- Aiming for high legume content (ie. up to 30% of feed on offer)
- *Vulpia* and other weed control as necessary.
- Opportunistic fodder conservation allowed.
- Lime may be considered, depending on soil test.
- Aim for an overall stocking rate of 15 DSE/ha.

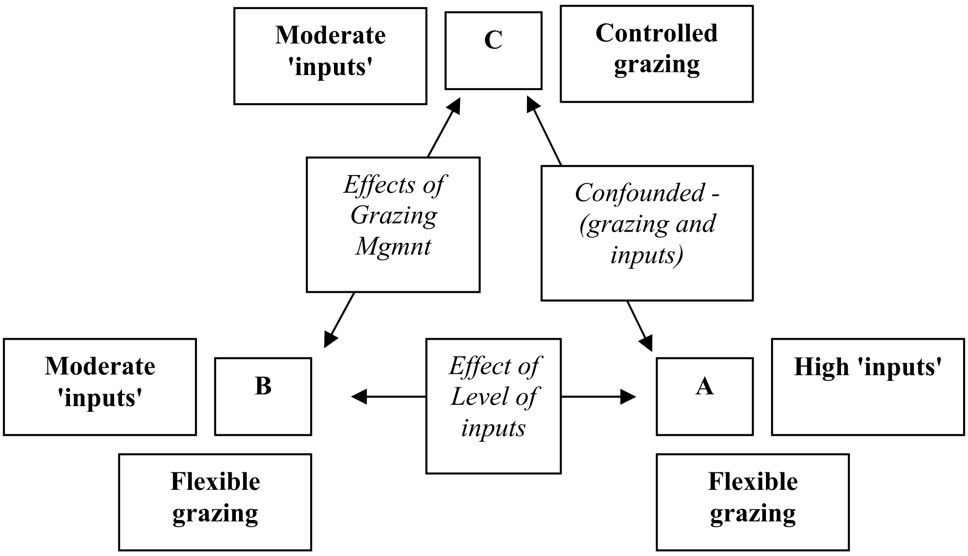
Farm B Medium Input/Flexible Grazing

- 8-10 paddocks,
- Treatment to represent typical district practices
- Flexible rotational grazing, more than five mobs in 8-10 paddocks, 5-30 dse/ha stock density.
- Available soil *Phosphorus* level to a target of 20 ppm Colwell.
- Available soil *Sulfate Sulfur* levels to a target of 6ppm.
- Minimal pasture sowing, *Vulpia* control allowed, Clover may be broadcast.
- Aim for 6-7 DSE per hectare,

Farm C Medium Input/ high stock density grazing.

- Same inputs as B except for the following grazing differences-
- 30-40 paddocks, with electric fencing used to subdivide in order to ensure appropriate grazing pressure, pasture utilisation and rest periods.
- Intensive grazing, less than three mobs in 30-40 paddocks, 50-500 dse/ha stock density.
- Grazing periods to be short and intense, eat 1/3, trample 1/3 and leave 1/3 of pasture on offer.
- Rest periods determined by pasture recovery, do not graze plants growing on root reserve.
- Mobs may be combined to maintain appropriate rest periods and grazing pressure for all paddocks.
- Controlled or planned grazing principles to apply

Thus between Farms A and B we have different levels of inputs, between Farms B and C we have different grazing intensities and between Farms A and C we have the effects of both grazing intensities and level of inputs.

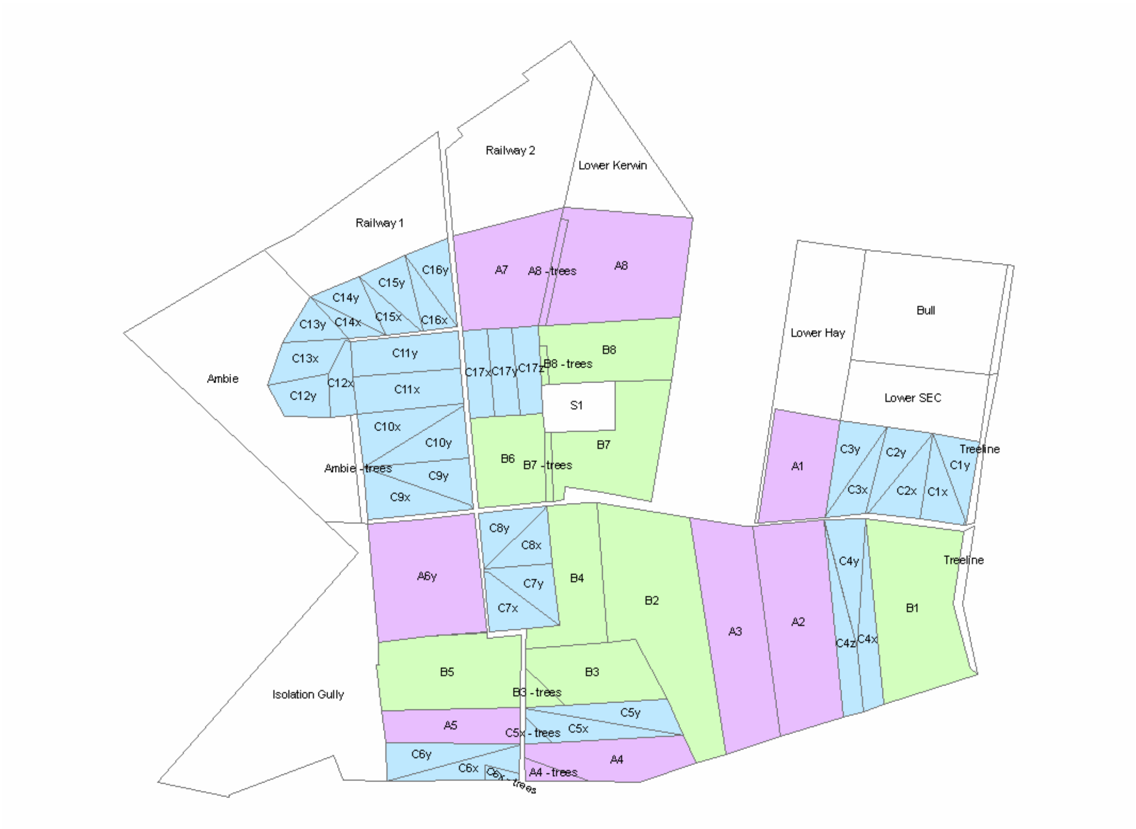


Cicerone Project Farmlet Experimental Area

Total Area = 257.50 hectares

Key

- Farmlet A
- Farmlet B
- Farmlet C
- Runout paddocks/laneways



Appendix B: AusFarm Simulation of Cicerone Paddock A3 (Management Script & Pasture Variable Settings)

The following scripts were used to simulate the A3 paddock over the period 1st October 2000 to 31st December 2006.

Descriptive comments are in *italics* preceded by a '!' symbol.

```
! Livestock management scripts

define i
define n
define d
define ia
define da
define r
define ng
define ta=8.5                              ! total area of paddock being simulated

! Daily drafting of stock into partial paddocks based on DM, DMD & Area of paddock being occupied
{set n=(desirable.Phalaris.avail_dm *desirable.Phalaris.avail_dmd)+(desirable.Legumes.avail_dm
*desirable.Legumes.avail_dmd )+(desirable.Austrodanthonia.avail_dm *desirable.Austrodanthonia.avail_dmd )
    set d=(undesirable.Bothriochloa.avail_dm *undesirable.Bothriochloa.avail_dmd ) +
(undesirable.Annual_grasses.avail_dm *undesirable.Annual_grasses.avail_dmd )
    set ia=desirable.area; set da=undesirable.area
    set r=(n*ia ) / ((n*ia)+(d*da)) }

if stock.number_all >0
  {for i=1 to stock.no_groups
  stock.move group= i, paddock=desirable.name
  set ng = stock.no_groups
  for i=1 to stock.no_groups
  stock.split group=i, type='number', value=r*Stock.number[i]
  for i=ng+1 to stock.no_groups
  stock.move group=i  , paddock=undesirable.name }
!==============================================================
! Partial Paddock area adjustments

on 11 Dec 2001 { reset desirable.area = 0.857 * ta; reset undesirable.area = 0.143 * ta }
on 2 Dec 2002 { reset desirable.area = 0.888 * ta; reset undesirable.area = 0.112 * ta }
on 3 Feb 2003 { reset desirable.area = 0.963 * ta; reset undesirable.area = 0.037 * ta }
on 16 Feb 2004 { reset desirable.area = 0.605 * ta; reset undesirable.area = 0.395 * ta }
on 15 Feb 2005 { reset desirable.area = 0.591 * ta; reset undesirable.area = 0.409 * ta }
on 24 Jan 2006 { reset desirable.area = 0.834 * ta; reset undesirable.area = 0.166 * ta }

!================================================================
! maintaining White clover, Austrodanthonia & annual grasses
each 1 May
    {if desirable.Austrodanthonia.avail_dm <200
    desirable.Austrodanthonia.sow rate= 50
    if undesirable.Annual_grasses.avail_dm  <200
    undesirable.Annual_grasses.sow rate= 10
    if desirable.Legumes.avail_dm <200
    desirable.Legumes.sow rate= 10  }
each 1 Jul
    {if undesirable.Annual_grasses.avail_dm  <200
    undesirable.Annual_grasses.sow rate= 10}

! controlling phalaris winter growth
from 25 May to 15 Sep reset desirable.Phalaris.fertility = 0.4
from 16 Sep to 24 May reset desirable.Phalaris.fertility = 0.85

!====================================================
! Stock movements in and out of A3

on 11 Dec 2000 stock.buy genotype='medium merino', number=162.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 22 Dec 2000 stock.sell group=0, number=162.00
on 11 Dec 2000 stock.buy genotype='medium merino', number=162.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 22 Dec 2000 stock.sell group=0, number=162.00
```

on 11 Dec 2000 stock.buy genotype='medium merino', number=178.20, sex='wethers', age=24, weight=50, fleece_wt=3
on 22 Dec 2000 stock.sell group=0, number=178.0
on 22 Dec 2000 stock.buy genotype='medium merino', number=321.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 2 Jan 2001 stock.sell group=0, number=321.00
on 5 Mar 2001 stock.buy genotype='medium merino', number=213.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 11 Mar 2001 stock.sell group=0, number=213.00
on 11 Apr 2001 stock.buy genotype='medium merino', number=104.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 17 May 2001 stock.sell group=0, number=104.00
on 1 Sep 2001 stock.buy genotype='medium merino', number=210.60, sex='wethers', age=24, weight=50, fleece_wt=3
on 18 Oct 2001 stock.sell group=0, number=210.60
on 19 Dec 2001 stock.buy genotype='medium merino', number=110.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 17 Apr 2002 stock.sell group=0, number=110.00
on 16 Apr 2002 stock.buy genotype='medium merino', number=156.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 26 Apr 2002 stock.sell group=0, number=156.00
on 4 May 2002 stock.buy genotype='medium merino', number=156.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 28 May 2002 stock.sell group=0, number=156.00
on 1 Jun 2002 stock.buy genotype='medium merino', number=40.70, sex='wethers', age=24, weight=50, fleece_wt=3
on 25 Jun 2002 stock.sell group=0, number=40.70
on 1 Jun 2002 stock.buy genotype='medium merino', number=73.70, sex='wethers', age=24, weight=50, fleece_wt=3
on 25 Jun 2002 stock.sell group=0, number=73.70
on 25 Jun 2002 stock.buy genotype='medium merino', number=156.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 29 Sep 2002 stock.sell group=0, number=156.00
on 18 Dec 2002 stock.buy genotype='medium merino', number=74.80, sex='wethers', age=24, weight=50, fleece_wt=3
on 12 Feb 2003 stock.sell group=0, number=74.80
on 24 Feb 2003 stock.buy genotype='medium merino', number=270.40, sex='wethers', age=24, weight=50, fleece_wt=3
on 12 Mar 2003 stock.sell group=0, number=270.40
on 28 Feb 2003 stock.buy genotype='medium merino', number=173.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 21 Mar 2003 stock.sell group=0, number=173.00
on 2 Apr 2003 stock.buy genotype='medium merino', number=31.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 21 Jun 2003 stock.sell group=0, number=31.00
on 30 Jul 2003 stock.buy genotype='medium merino', number=237.50, sex='wethers', age=24, weight=50, fleece_wt=3
on 1 Sep 2003 stock.sell group=0, number=237.50
on 5 Aug 2003 stock.buy genotype='medium merino', number=52.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 20 Oct 2003 stock.sell group=0, number=52.00
on 1 Sep 2003 stock.buy genotype='medium merino', number=93.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 10 Nov 2003 stock.sell group=0, number=93.00
on 10 Nov 2003 stock.buy genotype='medium merino', number=375.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 22 Dec 2003 stock.sell group=0, number=375.00
on 22 Dec 2003 stock.buy genotype='medium merino', number=241.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 2 Jan 2004 stock.sell group=0, number=241.00
on 2 Jan 2004 stock.buy genotype='medium merino', number=54.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 17 Feb 2004 stock.sell group=0, number=54.00
on 16 Mar 2004 stock.buy genotype='medium merino', number=238.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 19 Apr 2004 stock.sell group=0, number=238.00
on 16 Mar 2004 stock.buy genotype='medium merino', number=93.60, sex='wethers', age=24, weight=50, fleece_wt=3
on 27 Apr 2004 stock.sell group=0, number=93.60
on 16 Mar 2004 stock.buy genotype='medium merino', number=72.80, sex='wethers', age=24, weight=50, fleece_wt=3
on 27 Apr 2004 stock.sell group=0, number=72.80
on 22 Jul 2004 stock.buy genotype='medium merino', number=204.80, sex='wethers', age=24, weight=50, fleece_wt=3
on 9 Sep 2004 stock.sell group=0, number=204.80
on 8 Aug 2004 stock.buy genotype='medium merino', number=50.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 9 Sep 2004 stock.sell group=0, number=50.00
on 8 Aug 2004 stock.buy genotype='medium merino', number=27.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 9 Sep 2004 stock.sell group=0, number=27.00
on 22 Sep 2004 stock.buy genotype='medium merino', number=104.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 26 Oct 2004 stock.sell group=0, number=104.00
on 29 Nov 2004 stock.buy genotype='medium merino', number=197.60, sex='wethers', age=24, weight=50, fleece_wt=3
on 9 Jan 2005 stock.sell group=0, number=197.60
on 10 Jan 2005 stock.buy genotype='medium merino', number=190.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 27 Feb 2005 stock.sell group=0, number=190.00
on 1 Feb 2005 stock.buy genotype='medium merino', number=104.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 27 Feb 2005 stock.sell group=0, number=104.00
on 17 Mar 2005 stock.buy genotype='medium merino', number=264.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 25 Mar 2005 stock.sell group=0, number=264.00
on 7 May 2005 stock.buy genotype='medium merino', number=416.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 26 Aug 2005 stock.sell group=0, number=416.00
on 26 Jan 2006 stock.buy genotype='medium merino', number=134.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 3 Mar 2006 stock.sell group=0, number=134.00
on 21 Feb 2006 stock.buy genotype='medium merino', number=260.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 3 Mar 2006 stock.sell group=0, number=260.00
on 10 Apr 2006 stock.buy genotype='medium merino', number=180.00, sex='wethers', age=24, weight=50, fleece_wt=3
on 14 Apr 2006 stock.sell group=0, number=180.00

```
!======================================================================
! Supplementary feeding of stock in paddock

from 30 Jul 2003 to 08 Aug 2003  Supplement.feed supplement= 'lupins', amount= 5.4*r, paddock= 'desirable'
from 08 Aug 2003 to 15 Aug 2003  Supplement.feed supplement= 'lupins', amount= 12.5*r, paddock= 'desirable'
from 15 Aug 2003 to 22 Aug 2003  Supplement.feed supplement= 'lupins', amount= 17.9*r, paddock= 'desirable'
from 22 Aug 2003 to 29 Aug 2003  Supplement.feed supplement= 'lupins', amount= 8.9*r, paddock= 'desirable'
from 29 Aug 2003 to 01 Sep 2003  Supplement.feed supplement= 'lupins', amount= 17.9*r, paddock= 'desirable'
from 22 Jul 2004 to 23 Jul 2004  Supplement.feed supplement= 'lupins', amount= 11.0*r, paddock= 'desirable'
from 23 Jul 2004 to 30 Jul 2004  Supplement.feed supplement= 'lupins', amount= 5.5*r, paddock= 'desirable'
from 30 Jul 2004 to 06 Aug 2004  Supplement.feed supplement= 'lupins', amount= 12.8*r, paddock= 'desirable'
from 06 Aug 2004 to 13 Aug 2004  Supplement.feed supplement= 'lupins', amount= 18.3*r, paddock= 'desirable'
from 13 Aug 2004 to 20 Aug 2004  Supplement.feed supplement= 'lupins', amount= 25.6*r, paddock= 'desirable'
from 20 Aug 2004 to 27 Aug 2004  Supplement.feed supplement= 'lupins', amount= 25.6*r, paddock= 'desirable'
from 27 Aug 2004 to 03 Sep 2004  Supplement.feed supplement= 'lupins', amount= 25.6*r, paddock= 'desirable'
from 03 Sep 2004 to 09 Sep 2004  Supplement.feed supplement= 'lupins', amount= 25.6*r, paddock= 'desirable'
from 08 Aug 2004 to 13 Aug 2004  Supplement.feed supplement= 'lupins', amount= 7.1*r, paddock= 'desirable'
from 13 Aug 2004 to 20 Aug 2004  Supplement.feed supplement= 'lupins', amount= 10.0*r, paddock= 'desirable'
from 20 Aug 2004 to 27 Aug 2004  Supplement.feed supplement= 'lupins', amount= 10.0*r, paddock= 'desirable'
from 27 Aug 2004 to 03 Sep 2004  Supplement.feed supplement= 'lupins', amount= 10.0*r, paddock= 'desirable'
from 03 Sep 2004 to 09 Sep 2004  Supplement.feed supplement= 'lupins', amount= 10.0*r, paddock= 'desirable'
from 08 Aug 2004 to 13 Aug 2004  Supplement.feed supplement= 'lupins', amount= 5.4*r, paddock= 'desirable'
from 13 Aug 2004 to 20 Aug 2004  Supplement.feed supplement= 'lupins', amount= 5.4*r, paddock= 'desirable'
from 20 Aug 2004 to 27 Aug 2004  Supplement.feed supplement= 'lupins', amount= 5.4*r, paddock= 'desirable'
from 27 Aug 2004 to 03 Sep 2004  Supplement.feed supplement= 'lupins', amount= 5.4*r, paddock= 'desirable'
from 03 Sep 2004 to 09 Sep 2004  Supplement.feed supplement= 'lupins', amount= 5.4*r, paddock= 'desirable'
from 17 Mar 2005 to 18 Mar 2005  Supplement.feed supplement= 'lupins', amount= 45.1*r, paddock= 'desirable'
from 18 Mar 2005 to 25 Mar 2005  Supplement.feed supplement= 'lupins', amount= 30.1*r, paddock= 'desirable'
from 06 May 2005 to 06 May 2005  Supplement.feed supplement= 'lupins', amount= 67.6*r, paddock= 'desirable'
from 06 May 2005 to 13 May 2005  Supplement.feed supplement= 'lupins', amount= 60.1*r, paddock= 'desirable'
from 13 May 2005 to 20 May 2005  Supplement.feed supplement= 'lupins', amount= 75.1*r, paddock= 'desirable'
from 20 May 2005 to 27 May 2005  Supplement.feed supplement= 'lupins', amount= 75.1*r, paddock= 'desirable'
from 27 May 2005 to 03 Jun 2005  Supplement.feed supplement= 'lupins', amount= 45.1*r, paddock= 'desirable'
from 03 Jun 2005 to 10 Jun 2005  Supplement.feed supplement= 'lupins', amount= 93.4*r, paddock= 'desirable'
from 10 Jun 2005 to 17 Jun 2005  Supplement.feed supplement= 'lupins', amount= 29.8*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 119.3*r, paddock= 'desirable'
from 17 Jun 2005 to 24 Jun 2005  Supplement.feed supplement= 'lupins', amount= 21.3*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 85.0*r, paddock= 'desirable'
from 24 Jun 2005 to 01 Jul 2005  Supplement.feed supplement= 'lupins', amount= 23.9*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 95.5*r, paddock= 'desirable'
from 01 Jul 2005 to 08 Jul 2005  Supplement.feed supplement= 'lupins', amount= 28.3*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 113.3*r, paddock= 'desirable'
from 08 Jul 2005 to 15 Jul 2005  Supplement.feed supplement= 'lupins', amount= 34.3*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 137.2*r, paddock= 'desirable'
from 15 Jul 2005 to 22 Jul 2005  Supplement.feed supplement= 'lupins', amount= 34.3*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 137.2*r, paddock= 'desirable'
from 22 Jul 2005 to 29 Jul 2005  Supplement.feed supplement= 'lupins', amount= 34.3*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 137.2*r, paddock= 'desirable'
from 29 Jul 2005 to 05 Aug 2005  Supplement.feed supplement= 'lupins', amount= 34.9*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 139.7*r, paddock= 'desirable'
from 05 Aug 2005 to 12 Aug 2005  Supplement.feed supplement= 'lupins', amount= 32.7*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 130.7*r, paddock= 'desirable'
from 12 Aug 2005 to 19 Aug 2005  Supplement.feed supplement= 'lupins', amount= 32.7*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 130.7*r, paddock= 'desirable'
from 19 Aug 2005 to 26 Aug 2005  Supplement.feed supplement= 'lupins', amount= 32.7*r, paddock= 'desirable';
Supplement.feed supplement= 'maize', amount= 130.7*r, paddock= 'desirable'
from 30 Jul 2003 to 08 Aug 2003  Supplement.feed supplement= 'lupins', amount= 5.4*(1-r), paddock= 'undesirable'
from 08 Aug 2003 to 15 Aug 2003  Supplement.feed supplement= 'lupins', amount= 12.5*(1-r), paddock= 'undesirable'
from 15 Aug 2003 to 22 Aug 2003  Supplement.feed supplement= 'lupins', amount= 17.9*(1-r), paddock= 'undesirable'
from 22 Aug 2003 to 29 Aug 2003  Supplement.feed supplement= 'lupins', amount= 8.9*(1-r), paddock= 'undesirable'
from 29 Aug 2003 to 01 Sep 2003  Supplement.feed supplement= 'lupins', amount= 17.9*(1-r), paddock= 'undesirable'
from 22 Jul 2004 to 23 Jul 2004  Supplement.feed supplement= 'lupins', amount= 11.0*(1-r), paddock= 'undesirable'
from 23 Jul 2004 to 30 Jul 2004  Supplement.feed supplement= 'lupins', amount= 5.5*(1-r), paddock= 'undesirable'
from 30 Jul 2004 to 06 Aug 2004  Supplement.feed supplement= 'lupins', amount= 12.8*(1-r), paddock= 'undesirable'
from 06 Aug 2004 to 13 Aug 2004  Supplement.feed supplement= 'lupins', amount= 18.3*(1-r), paddock= 'undesirable'
from 13 Aug 2004 to 20 Aug 2004  Supplement.feed supplement= 'lupins', amount= 25.6*(1-r), paddock= 'undesirable'
from 20 Aug 2004 to 27 Aug 2004  Supplement.feed supplement= 'lupins', amount= 25.6*(1-r), paddock= 'undesirable'
from 27 Aug 2004 to 03 Sep 2004  Supplement.feed supplement= 'lupins', amount= 25.6*(1-r), paddock= 'undesirable'
from 03 Sep 2004 to 09 Sep 2004  Supplement.feed supplement= 'lupins', amount= 25.6*(1-r), paddock= 'undesirable'
from 08 Aug 2004 to 13 Aug 2004  Supplement.feed supplement= 'lupins', amount= 7.1*(1-r), paddock= 'undesirable'
from 13 Aug 2004 to 20 Aug 2004  Supplement.feed supplement= 'lupins', amount= 10.0*(1-r), paddock= 'undesirable'
from 20 Aug 2004 to 27 Aug 2004  Supplement.feed supplement= 'lupins', amount= 10.0*(1-r), paddock= 'undesirable'
from 27 Aug 2004 to 03 Sep 2004  Supplement.feed supplement= 'lupins', amount= 10.0*(1-r), paddock= 'undesirable'
from 03 Sep 2004 to 09 Sep 2004  Supplement.feed supplement= 'lupins', amount= 10.0*(1-r), paddock= 'undesirable'
```

```
from 08 Aug 2004 to 13 Aug 2004  Supplement.feed supplement= 'lupins', amount= 5.4*(1-r), paddock= 'undesirable'
from 13 Aug 2004 to 20 Aug 2004  Supplement.feed supplement= 'lupins', amount= 5.4*(1-r), paddock= 'undesirable'
from 20 Aug 2004 to 27 Aug 2004  Supplement.feed supplement= 'lupins', amount= 5.4*(1-r), paddock= 'undesirable'
from 27 Aug 2004 to 03 Sep 2004  Supplement.feed supplement= 'lupins', amount= 5.4*(1-r), paddock= 'undesirable'
from 03 Sep 2004 to 09 Sep 2004  Supplement.feed supplement= 'lupins', amount= 5.4*(1-r), paddock= 'undesirable'
from 17 Mar 2005 to 18 Mar 2005  Supplement.feed supplement= 'lupins', amount= 45.1*(1-r), paddock= 'undesirable'
from 18 Mar 2005 to 25 Mar 2005  Supplement.feed supplement= 'lupins', amount= 30.1*(1-r), paddock= 'undesirable'
from 06 May 2005 to 06 May 2005  Supplement.feed supplement= 'lupins', amount= 67.6*(1-r), paddock= 'undesirable'
from 06 May 2005 to 13 May 2005  Supplement.feed supplement= 'lupins', amount= 60.1*(1-r), paddock= 'undesirable'
from 13 May 2005 to 20 May 2005  Supplement.feed supplement= 'lupins', amount= 75.1*(1-r), paddock= 'undesirable'
from 20 May 2005 to 27 May 2005  Supplement.feed supplement= 'lupins', amount= 75.1*(1-r), paddock= 'undesirable'
from 27 May 2005 to 03 Jun 2005  Supplement.feed supplement= 'lupins', amount= 45.1*(1-r), paddock= 'undesirable'
from 03 Jun 2005 to 10 Jun 2005  Supplement.feed supplement= 'lupins', amount= 93.4*(1-r), paddock= 'undesirable'
from 10 Jun 2005 to 17 Jun 2005  Supplement.feed supplement= 'lupins', amount= 29.8*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 119.3*(1-r), paddock= 'undesirable'
from 17 Jun 2005 to 24 Jun 2005  Supplement.feed supplement= 'lupins', amount= 21.3*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 85.0*(1-r), paddock= 'undesirable'
from 24 Jun 2005 to 01 Jul 2005  Supplement.feed supplement= 'lupins', amount= 23.9*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 95.5*(1-r), paddock= 'undesirable'
from 01 Jul 2005 to 08 Jul 2005  Supplement.feed supplement= 'lupins', amount= 28.3*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 113.3*(1-r), paddock= 'undesirable'
from 08 Jul 2005 to 15 Jul 2005  Supplement.feed supplement= 'lupins', amount= 34.3*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 137.2*(1-r), paddock= 'undesirable'
from 15 Jul 2005 to 22 Jul 2005  Supplement.feed supplement= 'lupins', amount= 34.3*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 137.2*(1-r), paddock= 'undesirable'
from 22 Jul 2005 to 29 Jul 2005  Supplement.feed supplement= 'lupins', amount= 34.3*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 137.2*(1-r), paddock= 'undesirable'
from 29 Jul 2005 to 05 Aug 2005  Supplement.feed supplement= 'lupins', amount= 34.9*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 139.7*(1-r), paddock= 'undesirable'
from 05 Aug 2005 to 12 Aug 2005  Supplement.feed supplement= 'lupins', amount= 32.7*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 130.7*(1-r), paddock= 'undesirable'
from 12 Aug 2005 to 19 Aug 2005  Supplement.feed supplement= 'lupins', amount= 32.7*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 130.7*(1-r), paddock= 'undesirable'
from 19 Aug 2005 to 26 Aug 2005  Supplement.feed supplement= 'lupins', amount= 32.7*(1-r), paddock= 'undesirable';
Supplement.feed supplement= 'maize', amount= 130.7*(1-r), paddock= 'undesirable'
```

The following code details the scripts used to provide residual pasture mass data and subsequent growth on a seasonal basis over the simulated period autumn 1976 to summer 2006. Only the spring code is shown, but the same script was applied with different dates and cut heights in separate batches of seasonal simulations.

```
define h=50                      ! cut height in mm for all species within partial paddocks
define d_rdm                     ! desirable residual dry matter
define avd_rdm                   ! average residual for desirables (kg DM/ha)
define avud_rdm                  ! average residual for undesirables  (kg DM/ha)
define ud_rdm                    ! undesirable residual dry matter
define d_dgr                     ! desirable average daily growth rate
define ud_dgr                    ! undesirable average daily growth rate
define d_sdgr
define ud_sdgr
define td_rdm1
define td_rdm
define tud_rdm1
define tud_rdm

define avd_sdgr                  ! average post cut growth rate for desirables (kg DM/ha/day)
define td_sdgr
define td_sdgr1
define avud_sdgr                 ! average post cut growth rate for undesirables (kg DM/ha/day)
define tud_sdgr
define tud_sdgr1

! cut event - down to height h
from 20 Oct to 19 Nov repeat 1 days
 {desirable.Phalaris.cut cut_height=h , gathered=1.0 , dmd_loss=0.15 , dm_content=0.86
 desirable.Legumes.cut cut_height=h , gathered=1.0 , dmd_loss=0.15 , dm_content=0.86
 desirable.Austrodanthonia.cut cut_height=h , gathered=1.0 , dmd_loss=0.15 , dm_content=0.86
 undesirable.Annual_grasses.cut cut_height=h , gathered=1.0 , dmd_loss=0.15 , dm_content=0.86
 undesirable.Bothriochloa.cut cut_height=h , gathered=1.0 , dmd_loss=0.15 , dm_content=0.86
```

```
 set d_rdm=desirable.Phalaris.avail_dm +desirable.Legumes.avail_dm +desirable.Austrodanthonia.avail_dm
 set ud_rdm=undesirable.Annual_grasses.avail_dm +undesirable.Bothriochloa.avail_dm
 set d_sdgr= desirable.Phalaris.growth + desirable.Legumes.growth +desirable.Austrodanthonia.growth
 set ud_sdgr=undesirable.Annual_grasses.growth + undesirable.Bothriochloa.growth}

! calculation of average residual pasture mass post cut
from 21 Oct to 19 Nov repeat 1 days
    { set td_rdm1 = d_rdm; set tud_rdm1 = ud_rdm
    set td_rdm = td_rdm1 + td_rdm; set tud_rdm = tud_rdm1 + tud_rdm}
each 20 Nov
  {set avd_rdm = td_rdm/30
  set avud_rdm = tud_rdm/30}
each 21 Nov
  {set  td_rdm = 0; set tud_rdm = 0}

! calculation of average pasture growth rate post cut
from 21 Oct to 19 Nov repeat 1 days
    { set td_sdgr1 = d_sdgr; set tud_sdgr1 = ud_sdgr
    set td_sdgr = td_sdgr1 + td_sdgr; set tud_sdgr = tud_sdgr1 + tud_sdgr}
each 20 Nov
  {set avd_sdgr = td_sdgr/30
  set avud_sdgr = tud_sdgr/30}
each 21 Nov
  {set  td_sdgr = 0; set  tud_sdgr = 0}

! =========================================================
```

The following table details the initial pasture settings derived through an iterative trial and error process to improve *AusFarms* predictions of the Cicerone Projects experimental farmlets paddock A3.

Partial Paddock	Representative Species	Established Plant material (kg DM/ha)	Senescing & Dead Plant material (kg DM/ha)	Litter Material & Seed (kg/ha)	Maximum Rooting Depth (mm)	Fertility Scalar
Desirable (4.5ha, gently sloping)	*Phalaris*	1000	0	0 & NA	510	0.75
	AustroDanthonia	500	400 & 200	200 & NA	500	0.85
	White Clover (Beta)	200	200 dead	200 & 20	150	0.75
Undesirable (4.0ha, gently sloping)	*Bothriochloa macra*	1000	0	0 & NA	350	0.85
	Annual Grass-Early	500	400 & 400	6 & 80	500	0.85

Appendix C: Estimates of pasture growth parameters

Estimates of pasture growth parameters α and γ for undesirable (UD) and desirable (D) species groups, for the DPRD model.

α Estimates

	Summer		Autumn		Winter		Spring	
Year	UD	D	UD	D	UD	D	UD	D
1976	0.0218	0.0289	0.0083	0.0266	0.0025	0.0180	0.0183	0.0203
1977	0.0120	0.0181	0.0260	0.0196	0.0022	0.0077	0.0245	0.0115
1978	0.0215	0.0136	0.0205	0.0153	0.0010	0.0032	0.0208	0.0248
1979	0.0131	0.0131	0.0125	0.0205	0.0079	0.0225	0.0217	0.0311
1980	0.0181	0.0196	0.0008	0.0017	0.0056	0.0089	0.0175	0.0097
1981	0.0190	0.0084	0.0064	0.0021	0.0028	0.0061	0.0282	0.0241
1982	0.0143	0.0180	0.0033	0.0068	0.0002	0.0011	0.0125	0.0115
1983	0.0076	0.0088	0.0145	0.0230	0.0213	0.0113	0.0352	0.0218
1984	0.0239	0.0085	0.0247	0.0237	0.0062	0.0105	0.0236	0.0199
1985	0.0130	0.0028	0.0118	0.0284	0.0026	0.0125	0.0214	0.0254
1986	0.0038	0.0016	0.0027	0.0010	0.0088	0.0097	0.0175	0.0082
1987	0.0133	0.0039	0.0069	0.0208	0.0132	0.0138	0.0255	0.0160
1988	0.0244	0.0079	0.0240	0.0269	0.0150	0.0160	0.0232	0.0042
1989	0.0030	0.0007	0.0203	0.0198	0.0100	0.0129	0.0201	0.0187
1990	0.0322	0.0124	0.0223	0.0284	0.0063	0.0089	0.0199	0.0087
1991	0.0316	0.0096	0.0204	0.0201	0.0414	0.0156	0.0213	0.0088
1992	0.0314	0.0123	0.0093	0.0185	0.0094	0.0132	0.0315	0.0216
1993	0.0279	0.0250	0.0001	0.0011	0.0327	0.0184	0.0296	0.0224
1994	0.0252	0.0315	0.0108	0.0265	0.0073	0.0066	0.0204	0.0103
1995	0.0274	0.0125	0.0163	0.0070	0.0096	0.0107	0.0325	0.0240
1996	0.0310	0.0299	0.0082	0.0122	0.0120	0.0187	0.0389	0.0351
1997	0.0262	0.0190	0.0083	0.0130	0.0087	0.0121	0.0389	0.0309
1998	0.0264	0.0168	0.0193	0.0320	0.0088	0.0132	0.0277	0.0374
1999	0.0222	0.0271	0.0227	0.0471	0.0116	0.0138	0.0226	0.0362
2000	0.0139	0.0094	0.0234	0.0424	0.0084	0.0185	0.0234	0.0262
2001	0.0216	0.0079	0.0188	0.0306	0.0165	0.0140	0.0275	0.0168
2002	0.0178	0.0161	0.0092	0.0192	0.0075	0.0046	0.0156	0.0070
2003	0.0201	0.0022	0.0184	0.0273	0.0140	0.0125	0.0206	0.0098
2004	0.0229	0.0114	0.0076	0.0112	0.0052	0.0085	0.0299	0.0240
2005	0.0133	0.0129	0.0000	0.0003	0.0132	0.0098	0.0365	0.0239
2006	0.0132	0.0161	0.0130	0.0264	0.0201	0.0118	0.0260	0.0208
Mean	0.0198	0.0137	0.0133	0.0193	0.0107	0.0118	0.0249	0.0197
CV(%)	40	61	60	61	82	41	27	46
Min.	0.0030	0.0007	0.0001	0.0003	0.0002	0.0011	0.0125	0.0042
Max.	0.0322	0.0315	0.0260	0.0471	0.0414	0.0225	0.0389	0.0374
n	31	31	31	31	31	31	31	31

Appendix C continued

γ Estimates

Year	Summer UD	Summer D	Autumn UD	Autumn D	Winter UD	Winter D	Spring UD	Spring D
1976	1.6491	1.0001	1.8402	1.4848	1.9999	1.4248	1.7166	1.6183
1977	1.6643	1.0905	1.5813	1.6445	1.9999	1.6235	1.5035	1.6627
1978	1.5602	1.2803	1.6270	1.6909	1.9999	1.7534	1.6954	1.5750
1979	1.7442	1.0001	1.6724	1.4246	1.8376	1.4644	1.6935	1.4277
1980	1.6540	1.0010	1.7003	1.2581	1.8495	1.5554	1.6828	1.7453
1981	1.4590	1.2206	1.7899	1.9999	1.9999	1.6893	1.6150	1.5938
1982	1.6701	1.0075	1.7893	1.6826	1.9653	1.2938	1.8008	1.6826
1983	1.7041	1.0001	1.7128	1.4823	1.6557	1.5472	1.5336	1.6446
1984	1.5666	1.6900	1.6210	1.6139	1.7308	1.4648	1.6188	1.6605
1985	1.5889	1.6148	1.7259	1.5235	1.9999	1.5509	1.7078	1.6235
1986	1.7721	1.5297	1.3518	1.6729	1.5600	1.3579	1.5869	1.7517
1987	1.6022	1.5764	1.5639	1.5217	1.7098	1.5543	1.6712	1.7331
1988	1.6512	1.5751	1.6272	1.6057	1.7443	1.6317	1.0001	1.3233
1989	1.9999	1.0001	1.7129	1.6139	1.7792	1.5358	1.6047	1.5553
1990	1.5370	1.0528	1.7047	1.5555	1.7664	1.5426	1.5352	1.8112
1991	1.5153	1.4616	1.6542	1.6122	1.5374	1.5853	1.5035	1.7018
1992	1.5227	1.0256	1.7890	1.5544	1.7775	1.4843	1.5603	1.5643
1993	1.6174	1.0772	1.9999	1.0001	1.6377	1.5505	1.6261	1.6182
1994	1.6184	1.0001	1.8588	1.5594	1.7296	1.6006	1.5524	1.6545
1995	1.6405	1.2032	1.7056	1.6976	1.7496	1.4843	1.5598	1.5676
1996	1.6241	1.0372	1.7556	1.4557	1.8355	1.4507	1.5818	1.5001
1997	1.6225	1.0001	1.7628	1.4919	1.7340	1.3066	1.5915	1.5051
1998	1.5663	1.0001	1.6479	1.3238	1.6606	1.4161	1.6856	1.4601
1999	1.6115	1.0001	1.6640	1.4028	1.7073	1.5711	1.7295	1.4914
2000	1.7728	1.3945	1.6455	1.3053	1.7253	1.4479	1.6478	1.5651
2001	1.5107	1.0001	1.6562	1.4186	1.6735	1.5926	1.3895	1.4773
2002	1.6099	1.0010	1.8165	1.5611	1.8081	1.7863	1.4089	1.6001
2003	1.3355	1.0001	1.5589	1.5274	1.7948	1.6239	1.6311	1.8037
2004	1.5991	1.2009	1.7364	1.7404	1.7762	1.3747	1.6038	1.6098
2005	1.7093	1.0001	1.9999	1.0001	1.7833	1.6212	1.5140	1.5896
2006	1.6356	1.0001	1.7093	1.5255	1.6136	1.6377	1.5609	1.5612
Mean	1.6237	1.1626	1.7091	1.5145	1.7788	1.5330	1.5843	1.6025
CV(%)	7	20	7	13	7	8	9	7
Min.	1.3355	1.0001	1.3518	1.0001	1.5374	1.2938	1.0001	1.3233
Max.	1.9999	1.6900	1.9999	1.9999	1.9999	1.7863	1.8008	1.8112
n	31	31	31	31	31	31	31	31

Appendix D: Prediction of the livestock harvest impact coefficient, λ_{SC}.

Date	Year	Season	Pasture Consumption (PC_D)	Pasture Growth (PG_D)	Pasture Utilisation (UX_D)	Seasonally adjusted (λ_{SC})	Intrinsic Rate of growth (ρ_C)	Rate of Desirable Population Growth ($F(X_D)$)*	Harvest Impact ($h(s)$)	Change in Desirable population (dX_D/ds)	Predicted X_D	Cicerone Project Observed X_D
31/12/2000	2000	Spring	1854	4297	0.43	0.120	0.75		0.05			
31/03/2001	2001	Summer	218	1017	0.21	0.082	0.23		0.02			
31/05/2001	2001	Autumn	540	2186	0.25	0.060	0.88		0.01			
31/08/2001	2001	Winter	0	1157	0.00	0.070	0.40		0.00			
31/12/2001	2001	Spring	2354	4263	0.55	0.120	0.48		0.07		0.61	0.61
31/03/2002	2002	Summer	1069	1111	0.96	0.082	0.46	0.10	0.08	0.00	0.61	
31/05/2002	2002	Autumn	717	1549	0.46	0.060	0.55	0.12	0.03	0.07	0.68	
31/08/2002	2002	Winter	902	1009	0.89	0.070	0.13	0.03	0.06	-0.04	0.64	
31/12/2002	2002	Spring	534	3058	0.17	0.120	0.20	0.05	0.02	0.01	0.66	0.62
31/03/2003	2003	Summer	913	448	2.04	0.082	0.06	0.01	0.17	-0.16	0.46	0.50
31/05/2003	2003	Autumn	237	1585	0.15	0.060	0.79	0.17	0.01	0.14	0.65	
31/08/2003	2003	Winter	1213	1341	0.90	0.070	0.36	0.09	0.06	0.00	0.64	
31/12/2003	2003	Spring	2187	3570	0.61	0.120	0.28	0.07	0.07	-0.03	0.62	
31/03/2004	2004	Summer	538	1145	0.47	0.082	0.33	0.08	0.04	0.02	0.64	0.28
31/05/2004	2004	Autumn	243	1214	0.20	0.060	0.32	0.08	0.01	0.04	0.32	
31/08/2004	2004	Winter	1259	1266	0.99	0.070	0.24	0.06	0.07	-0.03	0.29	
31/12/2004	2004	Spring	1785	4729	0.38	0.120	0.69	0.16	0.05	0.07	0.36	
31/03/2005	2005	Summer	1378	640	2.15	0.082	0.37	0.09	0.18	-0.11	0.25	0.26
31/05/2005	2005	Autumn	597	708	0.84	0.060	0.01	0.00	0.05	-0.05	0.22	
31/08/2005	2005	Winter	997	1183	0.84	0.070	0.28	0.05	0.06	-0.02	0.20	
31/12/2005	2005	Spring	0	4806	0.00	0.120	0.69	0.11	0.00	0.09	0.28	
31/03/2006	2006	Summer	948	552	1.72	0.082	0.76	0.16	0.14	-0.07	0.22	0.36
31/05/2006	2006	Autumn	77	1686	0.05	0.060	0.46	0.08	0.00	0.14	0.49	

* FE = 1.0, $\kappa_C = 0.95$

Appendix E: Dynamic Pasture Resource Development Model (MATLAB code)

The following code is for the dynamic pasture resource development model and the Monte Carlo simulation framework described in Chapters 5 and 6.

Function names are in **bold**, and descriptive comments are in *italics* preceded by a '%' symbol.

```
%DPRDSim.m
BaseParams
ASM=xlsread('PSM','AlpSM'); % imports alpha data from the same file & different sheet, already transformed into 'stochastic multipliers'
GSM=xlsread('PSM','GamSM');
RSM=xlsread('PSM','RSM');
NSM=size(ASM,1); % sets up year labels for each row
% Initial State variables ======================================================
y=[2300, 2300]; % [U,D] mass in kg DM per hectare
x=[0.56,0.44]; % [U,D] area proportion of paddock.
b=46.25; % starting body weight of animals
w=0; % starting wool qty in grams per head
f=22; % starting level of colwell phosphorus in the soil (mg/kg)
gms=0; % starting GM

% decision variables ================================================
sr=10; % stocking rate in head per ha
fert=10.5; % 10.5, 31.25, 62.5 application of single super phosphate kg/ha
resow=1; % decision to resow a pasture is either 0 for leave as pasture, or 1 for renew pasture
srs=10; % post sowing & pasture mass target sr
%==========================
NYears=10;
NSeas=4;
niter=2; % number of iterations for monte carlo simulation
MaxSeas=NYears*NSeas;

SRtest=[3:3:30]; %sets up sensitivity analysis for changing an initial state or decision variable, subject to SR(1)>0
ntests=size(SRtest,2); % sets size of test

NPV_test=zeros(niter,ntests);
NPV_std=zeros(niter,ntests);
MeanLWG= zeros(1,ntests);
LWG_std=zeros(1,ntests);
MeanWG = zeros(1,ntests);
WG_std=zeros(1,ntests);
MeanWMFD=zeros(1,ntests);
WMFD_std=zeros(1,ntests);
MeanSUPP=zeros(1,ntests);
SUPP_std=zeros(1,ntests);
MeanAGM=zeros(1,ntests);
AGM_std=zeros(1,ntests);
f_XD=zeros(niter,ntests);
f_SF=zeros(niter,ntests);
Y_AV=zeros(niter,ntests);

for i = 1:ntests
   sr=SRtest(i);
   srs=SRtest(i);
   XU=zeros(MaxSeas,niter);
   XD=zeros(MaxSeas,niter);
   YU=zeros(MaxSeas,niter);
   YD=zeros(MaxSeas,niter);
   LWG=zeros(MaxSeas,niter);
   WG=zeros(MaxSeas,niter);
   SF=zeros(MaxSeas,niter);
   WMFD=zeros(MaxSeas,niter);
   SGM=zeros(MaxSeas,niter);
   A_GM=zeros(NYears,niter);
   A_BG=zeros(NYears,niter);
```

```
    A_W=zeros(NYears,niter);
    A_SUPPF=zeros(NYears,niter);
    XDF=zeros(niter,1);
    SFF=zeros(niter,1);
    NPV=zeros(niter,1);
    for j=1:niter;

[X,Y,BG,W,F,MFD,GMs,npv,AGM,ABG,AW,ASUPPF]=DPRD(x,y,b,w,f,gms,PP,PL,PF,PE,sr,fert,resow,srs,MaxSeas,NYears,NSeas,NSM,ASM,GSM,RSM,SP);
        XU(:,j)=X(2:MaxSeas+1,1); % drop year zero
        XD(:,j)=X(2:MaxSeas+1,2);
        YU(:,j)=Y(2:MaxSeas+1,1);
        YD(:,j)=Y(2:MaxSeas+1,2);
        LWG(:,j)=BG(2:MaxSeas+1); % seasonal liveweight gain
        WG(:,j)=W(2:MaxSeas+1); % seasonal wool grown
        SF(:,j)=F(2:MaxSeas+1); % seasonal P levels
        WMFD(:,j)=MFD(2:MaxSeas+1); % wool fibre diameter - seasonal
        SGM(:,j)=GMs(2:MaxSeas+1); % seasonal gross margins
        NPV(j,:)=npv;
        A_GM(:,j)=AGM;
        A_BG(:,j)=ABG;
        A_W(:,j)=AW;
        A_SUPPF(:,j)=ASUPPF;
        XDF=XD(MaxSeas,:)'; % final proportion of desirables
        SFF=SF(MaxSeas,:)';% final level of soil P
        Y=XU.*YU + XD.* YD; % composition weighted paddock dry matter
        av_Y=mean(Y,1)';
    end
NPV_test(:,i)=NPV;
MeanLWG(1,i)= mean(mean(A_BG,1),2);% mean liveweight gain/hd/yr for all iterations
LWG_std(1,i)=mean(std(A_BG),2);
MeanWG(1,i) = mean(mean(A_W,1),2); % mean wool grown/hd/yr for all iterations
WG_std(1,i)=mean(std(A_W),2);
MeanWMFD(1,i)=mean(mean(WMFD,1),2);
WMFD_std(1,i)=mean(std(WMFD));
MeanSUPP(1,i)=mean(mean(A_SUPPF,1),2);
SUPP_std(1,i)=mean(std(A_SUPPF),2);
MeanAGM(1,i)=mean(mean(A_GM,1),2);
AGM_std(1,i)=mean(std(A_GM),2);
f_XD(:,i)=XDF;
f_SF(:,i)=SFF;
Y_AV(:,i)=av_Y;
end;
mNPV=mean(NPV_test,1); % mean NPV for each test
NPV_std=std(NPV_test,1); % standard deviation for each test level
mXDF=mean(f_XD,1); % mean final proportion desirables for each test
XDF_std=std(f_XD,1); % standard deviation for each test level
mSFF=mean(f_SF,1); % mean final SF for each test
SFF_std=std(f_SF,1); % standard deviation for each test level
mY=mean(Y_AV,1); % mean Y for each test - total available kg DM/ha
Y_std=std(Y_AV,1); % standard deviation for each test level

Output=[SRtest',mNPV',NPV_std',mXDF',XDF_std',mSFF',SFF_std',mY',Y_std',MeanLWG',LWG_std',MeanWG',WG_std',MeanWMFD',WMFD_std',MeanSUPP',SUPP_std',MeanAGM',AGM_std'];

************************************************************
function[X,Y,BG,W,F,MFD,GMs,npv,AGM,ABG,AW,ASUPPF]=DPRD(x,y,b,w,f,gms,PP,PL,PF,PE,sr,fert,resow,srs,MaxSeas,NYears,NSeas,NSM,ASM,GSM,RSM,SP)

%DPRD.m
% Dynamic Pasture Resource Development
%using initial assumptions returns results for monte carlo simulation

X=zeros(MaxSeas+1,2);
Y=zeros(MaxSeas+1,2);
YU=zeros(NYears,NSeas);
YD=zeros(NYears,NSeas);
BG=zeros(MaxSeas+1,1);
W=zeros(MaxSeas+1,1);
F=zeros(MaxSeas+1,1);
MFD=zeros(MaxSeas+1,1);
SUPPF=zeros(MaxSeas+1,1);
GMs=zeros(MaxSeas+1,1);
SR=zeros(MaxSeas+1,1);
```

```
SGMs=zeros(NSeas,1);
AGM=zeros(NYears,1);

ABG=zeros(NYears,1);
AW=zeros(NYears,1);
ASUPPF=zeros(NYears,1);
a_BG=zeros(NSeas,1);
a_W=zeros(NSeas,1);
a_SUPPF=zeros(NSeas,1);
X(1,:)=x;
Y(1,:)=y;
B(1)=b;
W(1)=w;
F(1)=f;
GMs(1)=gms;
icount=1;
b0=b; w0=w;
ycount=0;
for iyr=1:NYears
   ry=ceil(rand*NSM); % select random year
   asm=reshape(ASM(ry,:),2,4)'; % reshape data and select random multipliers
   gsm=reshape(GSM(ry,:),2,4)'; % reshape data and select random multipliers
   rsm=RSM(ry,:);
   scount=0;
   for iseas=1:NSeas
      b=b0; w=w0;
      % set parameters for ry
      PP=SP(iseas);
      PP.AG = PP.AG .* asm(iseas);  % mean for season multiplied by stochastic multipliers
      PP.GG = PP.GG .* gsm(iseas);  % mean for season multiplied by stochastic multipliers
      PP.RC = rsm(iseas);
      [x,y,bgain,wgain,f,gms,sr,mfd,sf] = SimSeason(x,y,b,w,f,PP,PL,PF,PE,sr,fert,resow,icount,srs);
      scount=scount+1;
      SGMs(scount)=gms;
      icount=icount+1;
      X(icount,:)=x;
      Y(icount,:)=y;
      BG(icount)=bgain;
      a_BG(scount)=bgain;
      W(icount)=wgain;
      a_W(scount)=wgain;
      F(icount)=f;
      SR(icount)=sr;
      MFD(icount)=mfd;
      SUPPF(icount)=sf;
      a_SUPPF(scount)=sf;
      GMs(icount)=gms;
      YU(iyr,iseas)=y(1);
      YD(iyr,iseas)=y(2);
   end
   ycount=ycount+1;
   AGM(ycount)=sum(SGMs);
   ABG(ycount)=sum(a_BG);
   AW(ycount)=sum(a_W);
   ASUPPF(ycount)=sum(a_SUPPF);
end
[npv]=GetNPV(AGM,PE,NYears); % returns npv

*******************************************************************
function [x,y,bgain,wgain,f,gms,sr,mfd,sf] = SimSeason(x,y,b,w,f,PP,PL,PF,PE,sr,fert,resow,icount,srs)
% runs a whole season on a daily time set using prescribed sets of parameters
Tmax=PP.Tmax;
B=zeros(Tmax+1,1); % saves results
W=zeros(Tmax+1,1);
Y=zeros(Tmax+1,2);
B(1)=b; % starting assumption
W(1)=w;
Y(1,:)=y; % starting assumption for both U & D
y_csum=0; % resets y_cons to zero at start of every season
y_gsum=0; % resets y_grow to zero at start of every season
fddw_sum=0; % resets fibre diameter to zero at start of every season
sdm_sum=0; % resets amount of supplements fed to zero at start of every season
TP(1)=sum(y.*x); % mean area & DM weighted available pasture
if icount==1 % only applied in simulation mode
   if resow==1
```

```
      x(1,:)=[0.05 0.95]; % resets botanical composition
      y(1,:)=[100 100]; % resets available dry matter
      sr=0; % sets stocking rate to zero for at least this season
   end

else
   resow=0;

   x(1,:)=x;
   y(1,:)=y;
   sr=sr;
end

pf = PF.ZF *(fert * PF.BF); % P that enters the plant available pool from fertiliser application (mg/kg colwell)
f = f + pf ; % current season P level after any fertiliser applications & fertiliser P sorption mg/kg colwell

for t = 1:Tmax
  [sdm]=Suppfeed(TP,b,PL); % returns amount of supplement required
  [db,dmi_p,g_dp,ri_dp,dw,fddw]=StockGrowth(b,x,y,sdm,sr,PL,PP);
  [pc] = PastCons(dmi_p,g_dp,ri_dp,sr); %kg DM consumed
  y = y - pc; % change in pasture available after grazing
  [pg,fe] = PastureGrowth(y,f,PP,PF); %kgs DM grown
  dm_surv=[PP.SU PP.SD];
  y=max(0,(y+pg).* dm_surv); % represents the daily survival of old standing dry matter
  b=max(0,b+db);
  w=max(0,w+dw);
  B(t+1)=b;
  W(t+1)=w;
  Y(t+1,:)=y;
  y_csum=y_csum + pc; % calculates rolling sum of consumption
  y_gsum=y_gsum + pg; % calculates rolling sum of growth
  fddw_sum=fddw_sum + fddw; % calculates rolling sum of growth weighted fibre diameter
  sdm_sum=sdm_sum + sdm; % calculates rolling sum of supplements fed
  if sr==0 % only applied when simulating the sowing of pasture & starting with an SR of 0
     if sum((y.*x),2)>3000 %pasture mass at first grazing
        sr=srs;
     end
  end
end;
wgain=W(Tmax+1)-W(1); % total wool grown over season (grams clean wool/hd)
bgain=B(Tmax+1)-B(1); % total live weight gain over season (kgs Lwt/hd)
mfd = fddw_sum/max(wgain,0.001); % mean weight fibre diameter for the season
sf = sr * sdm_sum / PL.AS;  % total supplements fed over the season in kgs dry matter/ha
%Change in pasture composition at the seasonal level
[dxd] = PastureComp(x,y_csum,y_gsum,fe,PP); % returns net change in desirable population
xdi = max(0.05,min(0.95,x(2) + dxd)); % new area of desirables
x = [1-xdi,xdi];

pm=SoilFertility(f,fert,bgain,wgain,sr,y_gsum,Tmax,PF); % change in soil fertility over season
f=max(3,f-pm); % new soil fertility at end of season

[gms]=EconReturn(wgain,bgain,mfd,sr,fert,Tmax,sf,resow,PE); % balance of seasonal value of production and expense

*****************************************************************
function[sdm]=Suppfeed(TP,b,PL)
% based on defined decision rules, returns the quantity of supplements to
% be offered per head (kg DM/head/day) to grazing animals

if TP<=100 % may be adjusted to reflect sustainability targets
   sdm=PL.SRW*0.85*0.0115; % equivalent to full maintenance ration for a wether at base target CS = kg dry matter of
grain supplement offered per head - supplementation rules
elseif b<=(PL.SRW*0.85) % based on minimum condition score of 2.0
   sdm=PL.SRW*0.85*0.0115; % full drought ration to maintain weight
else
   sdm=0;
end

****************************************************************
function [db,dmi_p,g_dp,ri_dp,dw,fddw]=StockGrowth(b,x,y,sdm,sr,PL,PP)
% Livestock sub-model with selective grazing, pasture intake, energy balance,
% wool growth & weight gain functions embedded
% Inputs are body weight (b), pasture mass (y),pasture in diet ME content (md), supplements fed (sdm)
% stocking rate (SR)and parameters
% outputs are change in body weight, fibre diameter, wool growth and pasture consumption
```

```
if b<=0
  db=0;
  dmi_p=0;
  dw=0;
  fddw=0;
  g_dp=[0 0];

  ri_dp=[0 0];
elseif sr<=0
    db=0;
    dmi_p=0;
    dw=0;
    fddw=0;
    g_dp=[0 0];
    ri_dp=[0 0];
    return
end
rc = b / PL.SRW; % relative condition
rci = max(1, rc); % relative condition statement
cf = rci*(1.5 - rci) / 0.5; % condition factor
imax = PL.API * PL.SRW * 0.7 *cf; % potential intake (DM/day)

[md,g_dp,ri_dp,gtot_dp,yq,yq_p,ri_s] = SelectiveGraze(x,y,sdm,imax,PL,PP);

dmi_p = imax * sum(ri_dp); % pasture intake (DM/day) = potential intake * cumulative relative intake
dmi = imax * (sum(ri_dp)+ri_s); % total DM intake
ei = dmi * md; % Total energy intake Mj of ME/day

km = 0.02 * md + 0.5; % efficiency of use of ME for maintenance

if ((sum(gtot_dp(1:2,1))+ gtot_dp(3,1)*0.5)*1000)<100
    gf=1000*sum(gtot_dp); % if green forage < 100kg DM/ha, condition statement to use total available DM/ha in
calculating h factor
else
    gf = (sum(gtot_dp(1:2,1))+ gtot_dp(3,1)*0.5)*1000; % green forage available per hectare (kg DM/ha)
end
h = ((1+tan(PL.SME)*3.14/180)*min(1,sr/PL.BME))/(0.000057*gf+0.16); % horizontal equivalent of distance walked in
relation to Emove
megr = b*(PL.AME*dmi_p*(0.9-yq_p)+0.0026*h)/km; % MEgraze
mem = ((0.26* (b^0.75) * exp(-0.03*PL.A))/km) + 0.09* ei + megr; % ME required for maintenance (MJ ME /day)

% protein balance
fl = (ei/mem) - 1; % Level of feeding (sheep explorer - protein)
dplsmcp = ei * (-0.112*fl^2 + 0.7544*fl + 5.079); % total DPLS available derived from the relationship between MCP -
DPLS and MEI with r2 of 0.9998
cp = (0.5264*yq - 0.1749)*1000; % crude protein intake - relationship between DMD and CP from AusFarm data (rsq =
0.9885)
dudp = PL.UDP * cp * (0.0055*cp - 0.178)* dmi ; % amount of protein from undegradable dietary protein
dplsw = max(0,dplsmcp + dudp ); % dpls available for wool growth

[dw,mew,fd]=WoolGrowth(ei,dplsw,PL,PP); % imports extra wool grown & energy used to grow

% Change in body weight
meg = ei - mem - mew; % Mj of ME/day for weight gain net of maintenance & ME for wool grown
evg = 0.92 * (PL.AE + 13.8*rc); % energy value of live weight gain (MJ/kg gain)
if meg>=0
    kg = 0.043 * md; % net efficiency of utilisation of ME for growth and fattening
else
    kg = 0.80; % net efficiency of body catabolism for maintenance and predicted change of liveweight
end
neg = kg * meg; % net energy available for live weight gain (MJ ME/day)
db = neg / evg; % is LWG or daily change in live weight (kgs)

fddw=dw*fd; % for calculation of mean weighted FD for seasonal wool production

*******************************************************************
function [md,g_dp,ri_dp,gtot_dp,yq,yq_p,ri_s] = SelectiveGraze(x,y,sdm,imax,PL,PP)
% To estimate the selective grazing of DM from different digestibility
% pools and take into account the effect of any supplements fed on pasture
% substitution and change in energy intake (i.e. diet quality
% Inputs are the total herbage masses for D & U species groups (y),
% proportion of paddock occupied by species groups (x) and
% parameters describing the distribution of DM in the pasture digestibility
% pools (PP), amount of supplement offered (sdm) and the max potential
% intake of the sheep (imax).
```

```
% Outputs are ri_dp = relative intake of the different quality pools, relative intake of supplements when offered (ri_s)
% md = energy content of total diet in MJ ME/kg DM, yq = DMD of selected pasture diet, yq_ps = DMD of total diet
% gtot_dp = total DM in each digestibility pool
%wmass=x.*y; % 1*2
%g_dp(:,1)=wmass(1)*PP.RDP(:,1);
%g_dp(:,2)=wmass(2)*PP.RDP(:,2);
g_dp =( repmat(x.*y,6,1)  .* PP.RDP) ./1000; % 6x2 (25, 26)y is total herbage mass (T/ha) within the area of desirable and undesirable species groups

gtot_dp = sum(g_dp,2); % (27) 6x1 Total DM in each digestibility pool
gprop_dp = gtot_dp / max(0.001, sum(gtot_dp)); % (29)proportion of DM in each pool
rr_dp = 1 - exp(-(1+0.35 .* gprop_dp) .* PP.ARE .* gtot_dp); %(30) relative rate of eating
rt_dp = 1 + 0.6*exp(-(1+0.35 .* gprop_dp) .* (PP.BRE .* gtot_dp).^2); %(31) relative time spent eating

% supplements fed
rq_s = 1 - 1.7 * max(0.8-PL.DS,0); % relative ingestibility of supplement
f_s = min((sdm/(imax*rq_s)),(10.5/PL.NS)); % relative availability of supplement
ri_s = f_s * rq_s; % relative intake of supplement

% pasture pools
uc=zeros(6,1);
f_dp=zeros(6,1);
uc(1)= max(0,1-f_s); % 1st digestibility pool in pasture DM
f_dp(1)=uc(1) .* rr_dp(1) .* rt_dp(1); % relative availability for 1st dp
for i = 2:6
   cs=cumsum(f_dp);
   uc(i)=max(0,1-cs(i-1)); % (33)
   f_dp(i)=uc(i) .* rr_dp(i) .* rt_dp(i); % (32)
end;
rq_dp=1-1.7 * max(0.8-PP.DQ,0); % (24) relative ingestibility of pasture dp's
ri_dp = f_dp .* rq_dp; % (34) relative intake of pasture pools, excludes legume content as assumed to be zero

yq_p = sum(PP.DQ .* ri_dp) / max(0.001,sum(ri_dp)); % (36)  - estimated pasture only diet digestibility through selective grazing
yq = (sum(PP.DQ .* ri_dp)+ (ri_s * PL.DS)) / max(0.001,ri_s + sum(ri_dp)); % total diet digestibility
md = 0.172* yq*100 -1.707; % (37) ME content of pastures &  supplements in MJ/kg DM

*******************************************************************
function [dw,mew,fd]=WoolGrowth(ei,dplsw,PL,PP)

% returns the amount, fibre diameter and energy requirement for wool grown
% based on NRDR

dlf = 1+ PL.BW * (PP.DL - 12); % DL is day length in hours, a parameter for the different seasons based on Armidale data
dw = (PL.SFW/PL.SRW) * dlf * min(1.16 * dplsw,14*ei); % wool growth in g clean/day - excludes age affect on follicle development (only up to 1 year of age) and assumes moderate protein supply (8.75g) across all ME available
fd= PL.MFD * ((dw*0.365)/(PL.YW*PL.SFW))^0.333; % predicted fibre diameter of wool grown (Freer etal eqn 84), age factor=1 i.e. mature animal
mew = PL.EW * ((dw/PL.YW)-PL.AW); % net energy used Mj/day for extra wool grown above maintenance

*********************************************************************
function [pc] = PastCons(dmi_p,g_dp,ri_dp,sr)
% returns the quantity of dry matter consumed from each pasture component,
% based on the distribution of DM in the quality pools and between D & U
if dmi_p<=0
   pc=[0 0];
   return
end
if sr<=0
   pc=[0 0];
   return
end

cons_dp = sr*dmi_p .* (ri_dp/sum(ri_dp)); % total kg cons/ha per pool (ri_dp is 6x1)
prop_dp = g_dp ./ repmat(sum(g_dp,2),1,2); % proportion of DM in each pool for D & U (6x2)
pc = cons_dp' * prop_dp; % DM consumed from D & U (kg DM/ha/day) (1x2)

**********************************************************************
function [pg,fe] = PastureGrowth(y,f,PP,PF)
% Function that returns the growth of pasture
% Inputs include PP.AG growth parameter influenced by climate,
% PP.GG gamma growth parameter for Des & Undes, PP.Ymax max herbage mass
% attainable
fe = 1 - exp(PF.AF*f); % fertility effect on pasture growth
```

```
pg = PP.AG .*((y.^2)./PP.YMax).*((max(0,(PP.YMax - y))./ max(y,0.01)).^PP.GG).* fe; % (11) (12) net pasture growth

************************************************************************
function[dxd]=PastureComp(x,y_csum,y_gsum,fe,PP)
% Pasture composition model
% returns the forecasted change in the proportion of desirables at the end of the
% season

fxd = max(0, PP.RC * fe * x(2) * (1 - (x(2) / (fe*PP.KC)))); % logistic growth in the population
u = min(2.5,y_csum(2) / max(0.001,y_gsum(2))); % ratio of pasture utilisation (consumption over growth in season)
hs = u * PP.LC; % seasonally weighted Livestock impact coefficient
dxd = fxd - hs; % rate of change in desirable component

************************************************************************

function [pm]=SoilFertility(f,fert,bgain,wgain,sr,y_gsum,Tmax,PF)
% returns the change in soil fertility level based on phosphorus based
% relationships

pe = (PF.WF * (wgain/1000) + PF.MF * bgain) * sr ; % P export due to livestock products in season (kg/ha)
pdu = (PF.FF * 0.1 * sr * Tmax )/(1 - PF.UF); % p relocation to sheep camps (kg/ha)
pacc = PF.OF*(sum(y_gsum)/20.5); % P accumulated in organic & in-organic pools
pnf = Tmax * (PF.RF * PF.AR)/(3.65*10^5); % p supplied from rainfall
pm = PF.EF * (pe + pdu + pacc - pnf)/PF.SF; % maintenance P requirements for a season in mg/kg colwell

************************************************************************
function [gms]=EconReturn(wgain,bgain,mfd,sr,fert,Tmax,sf,resow,PE)
% returns the balance of revenue and costs from the enterprise operating on
% the paddock within 1 season

wool_p =1793.7207-46.987376*mfd-2.2371866*(mfd-22.1957)^2-0.8693692*(mfd-22.1957)^3+0.3423541*(mfd-
22.1957)^4-0.0224976*(mfd-22.1957)^5; % cents per kg clean median wool price function for period of July 1997 to July
2007 (r2=0.993)
income = sr * (((wgain /1000)* (wool_p/100))+( bgain * PE.BP * PE.MP )); % calculates total revenue on wool & meat
production basis
costs = ((sr * PE.VC)+ PE.PC)*Tmax/365 + (fert * PE.FC) + (sf/1000 * PE.PSF)+ resow*PE.PS; %
gms = income - costs; % representative gross margin of production per hectare

************************************************************************
% BaseParams.m
% Pasture parameters
PP.Tmax=90;
PP.RDP=[
   0.3 0.4
   0.2 0.233
   0.167 0.067
   0.1 0.067
   0.133 0.133
   0.1 0.1]; %proportion in each digestibility pool
PP.ARE = 1.12; % alpha constant for relative rate of eating
PP.BRE = 1.12; % beta constant for relative time of eating
PP.DQ = [0.8 0.7 0.6 0.5 0.4 0.3]'; % DMD of each pool class
PP.DL=15; % base assumption for day light hours
PP.SD=0.996; % sigma is survival of pasture biomass net of decay for improved pastures
PP.SU=0.998; % sigma is survival of pasture biomass net of decay for native/annual grass pastures
%Pasture Composition parameters
PP.RC=0.4;  % rho or r for intrinsic rate of growth of population for year type
PP.KC=0.95; % kappa K is the max population size for desirables
PP.LC=0.08; % Seasonally weighted lamda Lsc is the impact coefficient of grazing livestock on the population of
desirables within a season

% Soil Fertility Parameters
PF.AR=850; % average rainfall in mm per annum
PF.MF=0.006; % Mu F = percentage P in sheep meat
PF.WF=0.000371; % Omega F = Percentage P in clean wool
PF.FF=0.007; % theta F = proportion of P in dung
PF.UF=0.01; % upsilon F = P in urine as proportion of total P excreted
PF.RF=1.5; % rho f = P in rainfall g/mm
PF.EF=0.83; % epsilon f = proportion of p in colwell extract colwell 1963
PF.SF=1.5; % sigma F = bulk density of top 10cm of soil g cm-3
PF.AF=-0.09508; % alpha f for Misterlich equation
PF.BF=0.089; % Beta F = P content of fertiliser
PF.ZF=0.4313; % zeta F = unit colwell shift/kg P applied
PF.OF=0.00685; % kgs of P lost due to pasture DM production
```

```
% Livestock parameters
PL.API = 0.040; % alphaPI or j for sheep
PL.SRW=50; % standard reference weight of mature wether in average condition

PL.AE=13.2; % alpha E for sheep
PL.AME=0.02; % alpha ME MJ kg-2
PL.BME=40; % stocking density threshold (animals/ha) for sheep
PL.SME=2.0; % mean slope of grazing area in degrees
PL.A = 3; % years of age of animals grazing paddock
PL.DS = 0.89; % delta S for DMD of supplement i.e. wheat
PL.NS = 13.0; % Eta S for MD content of grain
PL.AS = 0.9; % alpha S for DM:Wet weight ratio for supplements
PL.UDP= 0.2; % proportion of crude protein intake that is undegradable protein entering the rumen for pastures

% wool production
PL.SFW=5.0; % average annual greasy fleece weight in kg/head
PL.MFD=19.0; % mean fibre diameter
PL.BW=0.03; % breed effect on seasonal wool growth
PL.EW=0.13; % energy content of wool Mj/g greasy fleece weight
PL.AW=6; % basal greasy wool growth rate grams/day
PL.YW=0.7; % clean:greasy ratio

% Economic Return Parameters
PE.BP=0.45; % dressing %, proportion of liveweight gain as saleable meat
PE.MP= 1.52; % 1.52 base meat price in $/kg Dwt (8.6336 for SX sys, 2.5688 for SRsys) - median for July 1997 to July
2007 (source NLRS via Agrorum Consulting)
PE.VC=15.68; % variable costs per head per annum excluding supplementary feeding costs (shearing, animal health)
Scott 2006
PE.PSF=208.60; % $208.60 base cost per tonne wet for supplements assumed feed wheat (average 1997 to 2007)
ABARE 2007 Aust Comm Stats; $110 low price, $310 high price
PE.FC=0.254; % theta SF is cost per kilogram of single superphosphate applied (Ave 1997 to 2007 Source: ABARE
2007)
PE.PC=20; % base pasture costs for pasture & paddock maintenance per hectare/annum
PE.PS=250; % $250/ha base cost of pasture sowing Scott 06, Low price $150 high price $350
PE.A=20; % area of the paddock in hectares
PE.RD=0.0494; % rho is real discount rate (ABARE 2006: calculated from 1976-2006 90 day bank bill+1.5% margin &
inflation)

% Seasonal pasture parameters
SP(1)=PP;
SP(1).Tmax=70; %autumn
SP(1).AG=[0.012801722 0.019018979];
SP(1).GG=[1.691261324 1.530646916];
SP(1).YMax=[6000 5500];
SP(1).RDP=[
  0.0205 0.1472
  0.0301 0.2638
  0.0442 0.1166
  0.2949 0.0947
  0.2528 0.1330
  0.3576 0.2447];
SP(1).DL=11.36;
SP(1).LC=0.06;
SP(1).SU=0.9924;
SP(1).SD=0.9889;

SP(2)=PP;
SP(2).Tmax=90; % winter
SP(2).AG=[0.009375312 0.011054791];
SP(2).GG=[1.77853761 1.55167667];
SP(2).YMax=[2000 5300];
SP(2).RDP=[
  0.0241 0.2889
  0.0264 0.3269
  0.0549 0.0814
  0.2885 0.0433
  0.1818 0.0561
  0.4244 0.2034];
SP(2).DL=10.4;
SP(2).LC=0.07;
SP(2).SU=0.9914;
SP(2).SD=0.9893;

SP(3)=PP;
SP(3).Tmax=115; % spring/summer
```

```
SP(3).AG=[0.02474183 0.019974111];
SP(3).GG=[1.59365715 1.607481541];
SP(3).YMax=[6500 8000];
SP(3).RDP=[
    0.0378 0.2049
    0.0448 0.4124
    0.0612 0.1953
    0.3054 0.0469
    0.1682 0.0354
    0.3826 0.1050];
SP(3).DL=12.85;
SP(3).LC=0.12;
SP(3).SU=0.9916;
SP(3).SD=0.9888;

SP(4)=PP;
SP(4).Tmax=90; % summer
SP(4).AG=[0.019798021 0.013278839];
SP(4).GG=[1.622247108 1.170427213];
SP(4).YMax=[8000 5000];
SP(4).RDP=[
    0.0171 0.0577
    0.0386 0.2887
    0.0541 0.2180
    0.3113 0.1174
    0.2892 0.1771
    0.2897 0.1410];
SP(4).DL=13.5;
SP(4).LC=0.082486;
SP(4).SU=0.9937;
SP(4).SD=0.9880;
```

Appendix F: Stochastic Dynamic Programming Model (MATLAB code)

The following code is for the stochastic dynamic programming framework described in Chapter 7. The function SimStateTrans refers to the transition version of SimSeason described in Appendix E.

Function names are in **bold**, and descriptive comments are in *italics* preceded by a '%' symbol.

```
% TPM.m
% Creates transition probability matrices for seasonal SDP model
niter=200;  % number of random iterations
rand('seed',10);
% Define Y state
ylo=[0,200,400,600,800,1000,1500,2000,3000,4000]';
yhi=[200,400,600,800,1000,1500,2000,3000,4000,inf]';
ny=length(ylo);
yst=(ylo+yhi)/2; yst(ny)=5000;
% Define X state
xlo=[0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9]';
xhi=[0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1]';
nx=length(xlo);
xst=(xlo+xhi)/2;
% Define decisions
u_sr=[0,2,4,8,10,15,20,30,40,50];
u_sow=[0,1];
u=[]; % empty decision matrix
for isr=1:length(u_sr)
   u(isr,:)=[u_sr(isr),0];
end

u=[u; 0,1]; % decision matrix
nu=size(u,1); % number of decision variables
nst=ny*ny*nx; % total number of states
% create state lookup table
%  y1 y2 x
st_idx=zeros(nst,3);
id=0
for i1 = 1:ny
   for i2 = 1:ny
      for i3 = 1:nx
         id=id+1
         st_idx(id,:)=[i1,i2,i3]; % indexes
      end;
   end;
end;
%==============================================
BaseParams;
ASM=xlsread('PSM','AlpSM'); %imports coefficients
GSM=xlsread('PSM','GamSM');
RSM=xlsread('PSM','RSM');
NSM=size(ASM,1); % number of year types
% State variables ====================================================
b=46.25; % starting body weight of animals, 0.925*SRW of CS 2.5
w=0; % starting wool qty in grams per head
f=35; % starting level of colwell phosphorus in the soil (mg/kg)
fert=37.5; % application of single super phosphate kg/ha
%==============================================
% Create TPM and biophysical  matrices
% DP parameters for each season
DPP(1).PM=zeros(nst,nst,nu); % TPM
DPP(1).BG=zeros(nst,nu); % body weight gain matrix
DPP(1).WG=zeros(nst,nu); % wool gain matrix
DPP(1).FD=zeros(nst,nu); % fibre diameter matrix
DPP(1).SF=zeros(nst,nu); % supplementary feed matrix
DPP(2)=DPP(1); DPP(3)=DPP(1); DPP(4)=DPP(1);
```

```
x=zeros(1,2);
y_i=zeros(1,2); % index of pasture mass [u, d]
ry=ceil(rand(niter,1)*NSM); % select sequence of random years

for iseas=1:4  % season
  for i=1:nst % state loop
    y=[yst(st_idx(i,1:2))]'; % extract relevant state
    x(2)=xst(st_idx(i,3)); % extract x for desirables
    x(1)=1-x(2);
    for j=1:nu % decision loop
      bg_sum=0; % physical outputs re-initialised
      wg_sum=0;
      fd_sum=0;
      sf_sum=0;
      sr=u(j,1); % extract stocking rate
      resow=u(j,2); % extract re-sow value
      for k=1:niter
        % select random parameters
        asm=reshape(ASM(ry(k),:),2,4)'; % reshape data and select random multipliers
        gsm=reshape(GSM(ry(k),:),2,4)'; % reshape data and select random multipliers
        rsm=RSM(ry(k),:);
        PP=SP(iseas);
        PP.AG = PP.AG .* asm(iseas);  % mean for season multiplied by stochastic multipliers
        PP.GG = PP.GG .* gsm(iseas);  % mean for season multiplied by stochastic multipliers
        PP.RC = rsm(iseas);
        [xnext,ynext,fnext,bg,wg,fd,sf] = SimStateTrans(x,y,b,w,f,PP,PL,PF,PE,sr,fert,resow);
        y_i(1)=find((ylo<=ynext(1))&(ynext(1)<yhi));
        y_i(2)=find((ylo<=ynext(2))&(ynext(2)<yhi));
        x_i=find((xlo<=xnext(2))&(xnext(2)<xhi));
        icol=find((st_idx(:,1)==y_i(1)) & (st_idx(:,2)==y_i(2)) & (st_idx(:,3)==x_i));
        DPP(iseas).PM(i,icol,j)=DPP(iseas).PM(i,icol,j)+1; % account for this state transition
        bg_sum=bg_sum+bg;
        wg_sum=wg_sum+wg;
        fd_sum=fd_sum+fd;
        sf_sum=sf_sum+sf;
      end; % stochastic loop
      DPP(iseas).BG(i,j)=bg_sum/niter;
      DPP(iseas).WG(i,j)=wg_sum/niter;
      DPP(iseas).FD(i,j)=fd_sum/niter;
      DPP(iseas).SF(i,j)=sf_sum/niter;
    end % decision loop
  end % state loop
end % season loop
for iseas=1:4
  DPP(iseas).PM = DPP(iseas).PM /niter; % calculates probabilities
end;
```

****

```
% SDP.m
% Stochastic DP - Seasonal version
% The transition probability & biophysical matrices (PM) must exist

BaseParams % load base parameters for calculation of economic reward
T=20; % max planning horizon
r=0.0494; % discount rate
delta=zeros(4,1); % discount factor
for i = 1:4
    disct=r*SP(i).Tmax/365; % discount for season
    delta(i)=1/(1+disct); % discount factor
end;

%set matrix dimensions and terminal value
v=zeros(nst,T*4+1);  % value function (zero terminal value)
ustar=zeros(nst,4,T); % decision varies by season
st_opt=zeros(nst,4,T); % store optimal state transition
sid=[1:nst]'; % id numbers for state vector

% Solve DP
tcount=T*4; % count time index for value function
for t=T:-1:1;
for iseas=4:-1:1
  for i=1:nst % from state
      vopt=-10e+15; % large negative number
      for j=1:nu % decisions
```

```
         % calculate current year profit
        bg=DPP(iseas).BG(i,j); % body weight gain

        wg=DPP(iseas).WG(i,j); % wool gain
        fd=DPP(iseas).FD(i,j); % fibre diameter
        sf=DPP(iseas).SF(i,j); % supplementary feed
        Tmax=SP(iseas).Tmax;
        sr=u(j,1);
        resow=u(j,2);
        reward = EconReturn(wg,bg,fd,sr,fert,Tmax,sf,resow,PE);

        vnext = DPP(iseas).PM(i,:,j) * v(:,tcount+1); % expected future value
        vnow = reward + delta(iseas) * vnext;
        if (vnow > vopt)  % maximise
          vopt=vnow;
          uopt=j;
        end;
      end; % decision loop
      v(i,tcount)=vopt;
      ustar(i,iseas,t)=uopt;
      st_opt(i,iseas,t)=DPP(iseas).PM(i,:,uopt) * sid; % optimal state transition
  end;  % state loop
  tcount=tcount-1; % update (season) time count
end; % season loop
end; % t loop
% extract optimal decision rules
sr_opt=u(ustar(:,:,1),1); sr_opt=reshape(sr_opt,nst,4); % stocking rate
rsow_opt=u(ustar(:,:,1),2); rsow_opt=reshape(rsow_opt,nst,4); % resow
% Create optimal state transition matrix
PMstar=zeros(nst,nst,4);
for iseas=1:4;
for i=1:nst
   PMstar(i,:,iseas)=DPP(iseas).PM(i,:,ustar(i,iseas,1)); % insert optimal row
end
end

save MoP_disc10

% To simulate optimal path create initial state
SDPprocess;
```

****

```
% SDPprocess.m
% The SDPSeas model must have been run and results in memory
yvalues=yst(st_idx(:,1:2)); % actual values for states(kg/ha)
xvalues=xst(st_idx(:,3));
% optimal expected state transition
y_und=zeros(nst,4); % DM of undesirables (states x seasons)
y_des=zeros(nst,4); % DM of desirables (states x seasons)
x_des=zeros(nst,4); % area of desirables (states x seasons)
% Optimal (expected) state transitions in terms of actual values
for i=1:4
    ytemp=PMstar(:,:,i)*yvalues;  % DM
    x_des(:,i)=PMstar(:,:,i)*xvalues;  % area
    y_und(:,i)=ytemp(:,1);
    y_des(:,i)=ytemp(:,2);
end
nyears=20;
path_und=zeros(nyears*4+1,4); % optimal path for undesirables
path_des=zeros(nyears*4+1,4); % optimal path for desirables
path_x=zeros(nyears*4+1,4); % optimal path for desirable area
path_sr=zeros(nyears*4+1,4);
path_rsow=zeros(nyears*4+1,4);

st=zeros(nyears*4+1,nst);
st(1,442)=1; % assume this is initial state
icount=1;
for t = 1:nyears
    for iseas=1:4
       icount=icount+1;
       st(icount,:) = st(icount-1,:)*PMstar(:,:,iseas);
       path_sr(icount,1)=st(icount,:)*sr_opt(:,iseas);
       path_rsow(icount,1)=st(icount,:)*rsow_opt(:,iseas);
    end
end
```

```
ytemp=st*yvalues;
path_und(:,1)=ytemp(:,1); % optimal path for undesirables
path_des(:,1)=ytemp(:,2); % optimal path for desirables
path_x(:,1)=st*xvalues;


st=zeros(nyears*4+1,nst);
st(1,448)=1; % assume this is initial state
icount=1;
for t = 1:nyears
   for iseas=1:4
      icount=icount+1;
      st(icount,:) = st(icount-1,:)*PMstar(:,:,iseas);
      path_sr(icount,2)=st(icount,:)*sr_opt(:,iseas);
      path_rsow(icount,2)=st(icount,:)*rsow_opt(:,iseas);
   end
end
ytemp=st*yvalues;
path_und(:,2)=ytemp(:,1); % optimal path for undesirables
path_des(:,2)=ytemp(:,2); % optimal path for desirables
path_x(:,2)=st*xvalues;

st=zeros(nyears*4+1,nst);
st(1,772)=1; % assume this is initial state
icount=1;
for t = 1:nyears
   for iseas=1:4
      icount=icount+1;
      st(icount,:) = st(icount-1,:)*PMstar(:,:,iseas);
      path_sr(icount,3)=st(icount,:)*sr_opt(:,iseas);
      path_rsow(icount,3)=st(icount,:)*rsow_opt(:,iseas);
   end
end
ytemp=st*yvalues;
path_und(:,3)=ytemp(:,1); % optimal path for undesirables
path_des(:,3)=ytemp(:,2); % optimal path for desirables
path_x(:,3)=st*xvalues;

st=zeros(nyears*4+1,nst);
st(1,778)=1; % assume this is initial state
icount=1;
for t = 1:nyears
   for iseas=1:4
      icount=icount+1;
      st(icount,:) = st(icount-1,:)*PMstar(:,:,iseas);
      path_sr(icount,4)=st(icount,:)*sr_opt(:,iseas);
      path_rsow(icount,4)=st(icount,:)*rsow_opt(:,iseas);
   end
end
ytemp=st*yvalues;
path_und(:,4)=ytemp(:,1); % optimal path for undesirables
path_des(:,4)=ytemp(:,2); % optimal path for desirables
path_x(:,4)=st*xvalues;
path_c=(1.-path_x).*path_und + path_x.*path_des;

% Plotting of optimal trajectories
nt=size(st,1);
tv=[0:nt-1];
subplot(2,3,1); plot(tv,path_c);
xlabel('Seasons'); ylabel('Dry Matter (kg/ha)'); title('Pasture Biomass');
subplot(2,3,2); plot(tv,path_und);
ylabel('Dry Matter (kg/ha)'); xlabel('Seasons'); title('Undesirable Biomass');
subplot(2,3,3); plot(tv,path_des);
xlabel('Seasons'); ylabel('Dry Matter (kg/ha)'); title('Desirable Biomass');
subplot(2,3,4); plot(tv,path_x);
ylabel('Area proportion'); xlabel('Seasons'); title('Desirables Coverage');
subplot(2,3,6); plot(tv,path_sr);
xlabel('Seasons'); ylabel('hd/ha'); title('Stocking Rate');
subplot(2,3,5); plot(tv,path_rsow);
xlabel('Seasons'); ylabel('y/n'); title('Re-establish Pasture');
```