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Near - Real Time Financial Assessment of the Queensland Wool Industry on a Regional Basis

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Declaration of Originality

This thesis reports the original work of the author, except as otherwise stated. It has not been submitted previously for a degree at any University.

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Abstract

This thesis describes a systems analysis of the Queensland wool industry at a farm-enterprise level, and development of a computer simulation model designed to provide near real-time physical and financial information to policy makers at a regional level as an aid to decision making.

Extensive reviews of the main biological factors affecting the wool enterprise were completed: diet selection and feed intake, protein digestion and metabolism, energy digestion and metabolism, wool growth, reproduction and mortality.

A sensitivity analysis of three separate bio-economic models was carried out to identify system components having the greatest impact on the financial performance of wool enterprises. Fleece production, wool price and total variable costs were found to be the most important determinants in each model.

Grazfeed, a commercially available software package based on the Australian feeding standards for ruminants, was tested for its ability to simulate animal production as observed in Queensland sheep grazing experiments. A FORTRAN version of the required code for sheep and cattle was written and used in the subsequent analysis. These experiments varied greatly, both temporally and spatially. A number of problems in trial management and methodology were identified, these often required adjustment of recorded data. The collation of trial data was done in a manner that allowed ease of use in computer models. Optimisation software was used to modify parameters and equations within the model in an attempt to improve the agreement between predicted and observed values. Grazfeed was found to be unsuitable using the available test data.

Regression analysis techniques were then used to identify climate, soil water, pasture and dietary variables which were able to explain the observed grazing trial variation in annual fleece production and liveweight change. The dietary variables were estimated using a theoretical diet selection subroutine, and a feed intake subroutine based on

Grazfeed equations. Pasture variables, such as number of growth days, green leaf availability, pasture growth and dietary nitrogen intakes were used in the models. Trial specific annual fleece and liveweight change models were able to explain approximately 70 - 91% and 82 - 93% respectively of observed variation in fleece and liveweight change. Pooling of Mitchell grass and mulga grassland trials resulted in 75 and 63% of the respective variation being explained. Australian Bureau of Statistics (ABS) data were used to test the ability of models developed from the grazing trials to operate at the shire level. The regression developed from the combined Toorak, Burenda and Arabella grazing trials was selected as most suitable for describing wool production throughout the state.

ABS data were used to estimate stocking rates and the number of sheep shorn. Fibre diameter was estimated from wool production and this in turn enabled an economic value to be assigned to the wool grown. Wool prices were the reported micron specific indicator prices where available, or extrapolated prices based on the mean annual market price and the relationship of the mean annual market price to the micron specific indicators. Data from the Australian Bureau of Agricultural and Resource Economics were used to estimate the variable costs per sheep shorn. This enabled a simple gross margin analysis to be carried out. The Queensland farmers index of prices paid was used to express all monetary values to a common base.

Various measures of physical and financial performance of wool enterprises were able to be generated in the format of coloured maps enabling easy comparison of regions within the state. Alternatively, each measure for a specific region was able to be examined relative to historical values predicted by model simulations over the period 1957 - 1995.

The bio-economic model highlighted areas of the Queensland wool production system, such as diet selection and feed intake, where accurate and reliable data are lacking, and therefore, acts as a guide for future grazing sheep research. As more data does become available, those areas of the model judged to be lacking most in accuracy or failing to provide adequate variability will be able to undergo further refinement. Finally, the usefulness and therefore success of the model will probably not be fully evaluated until the next major industry crisis (drought and / or commodity prices) occurs. Until then,

support from relevant funding bodies will be required to ensure data acquisition, and maintenance and development of the model is continued.

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Preface

The work reported in this thesis began in May of 1993 when the author commenced receiving financial support from the Sheep and Wool Division of the Queensland Department of Primary Industries (QDPI) via a scholarship of three years duration. Office space and other numerous forms of support were provided by the Drought Research Group of the QDPI while the author was enrolled through the Department of Plant Production, Gatton College, University of Queensland.

The objective of this work was to couple the pasture simulation work of the Drought Research Group to simulation of wool production and the economics associated with this activity. An 'enterprise stress index' was initially proposed as the final simulation product. This index was planned to incorporate both physical and environmental variables which best represented the conditions under which wool producers were operating. However, initial work quickly resulted in the realisation that such a lofty goal, whilst desirable, was not achievable as part of this thesis. The work presented here does, however, provide the first steps necessary for simulation of an enterprise stress index.

The author, whilst from an animal science background, had no previous experience with computer simulation, and limited experience with computers in general. As such, the development of the bio-economic model described in this thesis has been a learning experience, especially in terms of realising what could be achieved given data and time constraints, as well as the complexity of a model required to generate the desired output. Whilst specific skills such as FORTRAN programming were acquired, the most important benefit in this author's opinion has been the development of a 'systems approach' to problem assessment and solving.

CHAPTER ONE

Introduction

1.1 Aims

The aim of this research was to develop a computer simulation model capable of delivering near-real time physical and financial information for the Queensland wool industry on a regional basis, thus allowing the development of an 'enterprise stress index' to objectively assess the physical and financial difficulties facing producers.

Governments often provide financial support, both direct and indirect during periods of economic hardship. These difficult times have in the recent past arisen due to poor commodity prices and drought. Droughts can be considered to be either climatic droughts, based on rainfall or the resultant soil moisture, or agricultural droughts, normally defined as a combination of rainfall and stock / crop condition (Smith *et al.* 1992). The inclusion of stock and crop condition in the definition of 'agricultural drought' means that property management, e.g. stocking rate management, can interact with climatic variation to influence the severity of 'agricultural droughts' (Smith *et al.* 1992).

The Drought Policy Review Task Force (DPRTF 1990), established by the Commonwealth Government to examine all aspects of Commonwealth and State Government drought policy, considered drought a relative term and gave the following definition:

> *'drought represents the risk that existing agricultural activity may not be sustainable, given spatial and temporal variations in rainfall and other climatic conditions'.*

They recommended drought should be recognised as part of the natural environment for primary production in Australia, and future policy should be aimed at promoting self-reliance and the necessity for individual producers to manage for the risk associated with climate variability. Additionally, the provision of drought assistance, or the manner in which assistance is provided, can lead to uncertainty amongst farmers as they plan to manage the risk associated with drought (Dillon 1986). This may lead to the point where producers taking the most risks in times of drought may benefit most from the provision of government support (DPRTF 1990; Chatterton 1983, cited by MOFAC Consultants Pty. Ltd. 1992). Analysis of drought relief payments on a national basis found the majority of payments were to a minority of land holders, that the system favoured poorer managers, and that climatically marginal areas received proportionally more assistance (Smith *et al.* 1992).

If drought assistance is to be applied on a more limited and / or selective basis, those bodies responsible for doing so will require accurate, real time regional information on the current financial circumstances of producers seeking assistance. The work undertaken and presented in this thesis was aimed at providing such information for the Queensland wool industry via computer simulation techniques.

Governments and other policy makers in the future will make increasing demands upon researchers for prompt up to date information on issues affecting the wool industry and other areas of primary production (Stuth *et al.* 1993). For example, in December 1994, the Strategic Policy Unit, Queensland Department of Primary Industries (QDPI), requested farm financial projections from government officers under two different climate scenarios. Replies were expected within three days of the initial request being made. Requests of this type further highlight the need for a computer model capable of quickly generating farm production and financial information on a regional basis. Additionally, computer models will play an increasingly important role in investigating management options, variability in commodity prices, and climate change at the property, shire and state level. With particular reference to government drought policy, modelling studies have been used to identify strategies that minimise resource damage and financial stress (White 1978, Stafford Smith *et al.* 1995).

1.2 Modelling the Queensland wool industry

The Queensland wool industry covers 600 000 square kilometres, or 35% of the state, and includes many different soil and vegetation types (Weston *et al.* 1981, Carter *et al.* 1996; figure 1.1). During the 12 months to March 30 1994, approximately 12.4 million sheep and lambs were shorn, producing 53 million kg of greasy wool valued at $177 million (Queensland Year Book 1996). Given the relatively low price for wool during this 12 month period compared to the previous 18 years (see figure 3.10), the above figure for gross value of wool production represents the lower end of the range.

The Climate Impacts and Spatial Systems group of the Queensland Department of Natural Resources produce rainfall maps for Queensland, based on data from Bureau of Meteorology recording stations and the use of splining techniques (Hutchinson 1991) to interpolate between stations. These maps allow for examination of current rainfall on a monthly, quarterly or annual basis to be compared between the shires and regions of the state, or compared with historical rainfall data by the use of 'percentile maps'.

The maps present a large amount of information in a format that has been accepted by policy makers, industry and politicians (Brook and Carter 1994). Both State and Federal Government personnel have recently used these maps as an aid in drought funding decision making (K. Brook pers. comm.). Large pastoral companies also receive the rainfall maps and use them as aid in deciding stock movements between their various properties (J. Armstrong pers. comm.).

The Climate Impacts and Spatial Systems group also currently runs the GRASs Production (GRASP) model (McKeon *et al.* 1980, 1982, 1990, 1993, Rickert and McKeon 1982, Scanlan and McKeon 1993, Day *et al.* 1993, Carter *et al.* 1996) throughout Queensland on a 25 km^2 pixel basis. GRASP uses daily climatic data, and information on soils, pastures and tree densities throughout the state. Animal production is determined by both the quantity and quality of forage. Whilst GRASP simulates pasture growth, standing dry matter and nitrogen uptake, it does not simulate dietary quality or animal production. For the wool industry, the next logical step in the development of GRASP was the simulation of wool production, both

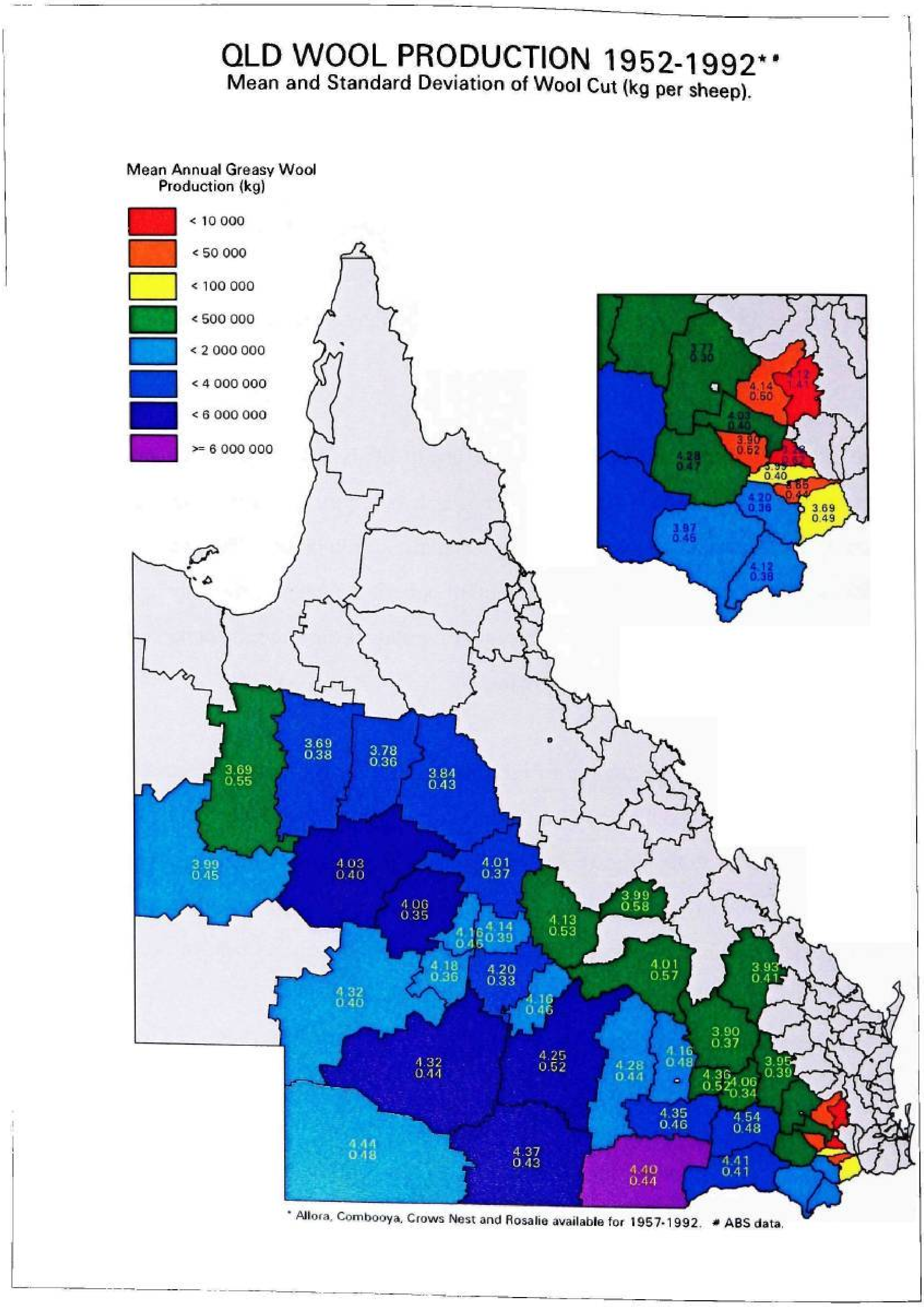

Figure 1.1. Queensland shire greasy wool production total, and per sheep and lamb shorn.

quantity and quality. Combining wool production with data on prices received and paid, allows a simple financial assessment of wool producers to be made. This assessment can then be analysed on both a regional and historical basis.

Reviews of the Queensland wool industry identified the major sources of variability in production as limitations to the spatial distribution of the wool industry, and the impact of seasonal climate variability on wool production, reproduction and mortality (Farmer *et al.* 1947, Moule 1954, 1966, Reid and Thomas 1973, White 1978, Orr and Holmes 1984, McMeniman 1985, Gramshaw and Lloyd 1993). Since the 1940's, intensive field trials have been conducted throughout western Queensland to examine the interaction of management options, pastures, and climate variability on animal production. In reviewing these trials Beale (1985) concluded that there had been a rapid expansion in the state of knowledge of the soil water-plant-animal complex and their interactions in western Queensland. Although this information has been directly extended to graziers, comprehensive models of production systems using this knowledge have only been developed for the north-west Mitchell grasslands (White 1978). Previous studies suggest possible approaches to developing enterprise models include:

- comprehensive reviews of the biology of wool production, reproduction and mortality, with particular reference to the factors dominating in western Queensland (Whelan *et al.* 1984, Morley and White 1985);
- empirical analysis of relationships between functional variables, e.g. pasture availability, dry matter intake, liveweight change, wool growth (following the approach used by White *et al.* 1979); and
- the development of robust relationships and incorporation in computer models simulating the climate-soil-pasture-animal-economic system as demonstrated by White (1978).

All three approaches have been used in this thesis.

The wool production system under analysis is described in figure 1.2. The bio-economic model for this system evolved during the study, the conceptual framework, required inputs, operations

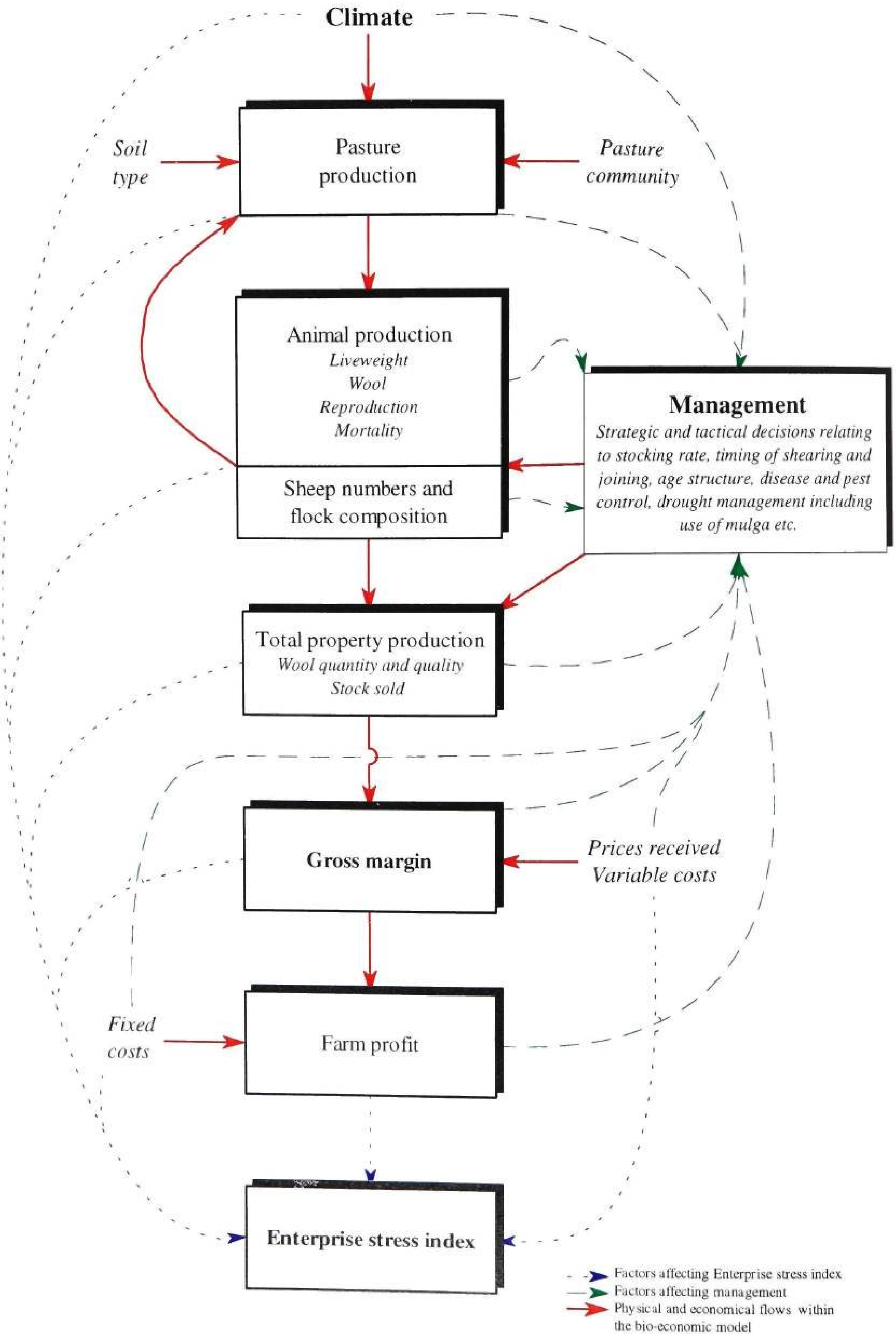

Figure 1.2. Conceptual description of the wool production system for which the model work was carried out.

and outputs were modified as the model developed. These changes have largely arisen due to lack of sufficient reliable data, failure of proposed model components to operate as expected, and the requirement to complete the first attempt of producing a bio-economic model.

The completed model uses simple pasture state variables, generated by GRASP, to estimate wool production per hectare for each pixel in which wool production is carried on. Annual fleece production (and liveweight change) models were developed using data from Queensland grazing trials. These trials were conducted at the 'small paddock' scale and were believed to give the most reliable measurements of animal production. The ability to explain variation at this scale of operation with precision then enabled extrapolation of animal production to the regional and / or shire level.

Australian Bureau of Statistics (ABS) stock data are used to calculate stocking rates, and this in turn, to estimate potential wool production per hectare. Returns from wool sales are calculated largely using micron specific market indicator prices from Wool International, formerly the Australian Wool Corporation (AWC). Australian Bureau of Agricultural and Resource Economics (ABARE) data on the costs of production are used, in conjunction with wool returns, to estimate the gross margin performance on a per sheep, per hectare, or per property basis. Production of thematic maps allows easy comparisons to be made of the various physical and financial components of the model on a regional or historical basis.

1.21. Enterprise stress index

As stated in the first paragraph of this chapter, one aim of this study was to develop a enterprise stress index for the Queensland wool industry. Initially, the index was to consist of a number of climatic, physical (e.g. pasture, stock) and economic variables which best encapsulated the 'stress' experienced by wool producers during periods of adversity and prosperity (figure 1.2).

It is generally assumed that most producers aim for maximum efficiency, which is interpreted to mean maximum profit (Doll and Orazem 1984, Upton 1986). However, this may not always be true (Hill 1990, Makeham and Malcolm 1993). Campbell (1981) drew attention to the difficulty in assessing farm sector financial well-being by looking at one or a group of farm performance figures. He stated that to gain an accurate indication of farm performance, a range of farm financial measures, as well as a knowledge of the composition and stability through time of these measures, were required. Interviews with financial counsellors within the QDPI, and Rural Adjustment Scheme who were dealing with producers in financial difficulty, further emphasised the difficulty of combining various measures into a single index of financial well-being. Other factors such as government aid to farmers and societal views on rangeland sustainability and environmental issues, all of which are subject to change, will also influence a enterprise stress index.

This thesis can be considered as the first step in the development of a enterprise stress index providing the technical and financial component. As will be shown in later chapters, variation in biological rates have a major impact on the economic performance of wool enterprises. Priority has been given to the development of biological models for enterprises representing the range of wool enterprises in the state. Given the rapidity with which economic, social and political factors are changing in the wool industry, the development of a enterprise stress index has not been attempted in this study. Greater attention has been given to developing sound biological models and their further incorporation into spatial models. A preliminary economic evaluation will be presented based on gross margins.

1.3 Thesis outline

Figure 1.3 presents the work undertaken during this research while a short description of the contents of each chapter follows. The overall approach followed that derived from previous studies (White 1978, White 1979, Morley and White 1985): detailed biological review, systems analysis and model development. The review of biology is presented separately in Appendix One.

Chapter Two discusses the role, philosophy and construction of simulation models in agriculture. This includes reasons for building models, types of models, level of model organisation, stages of model development, common reasons for model failure and the applications for which simulation models have been used.

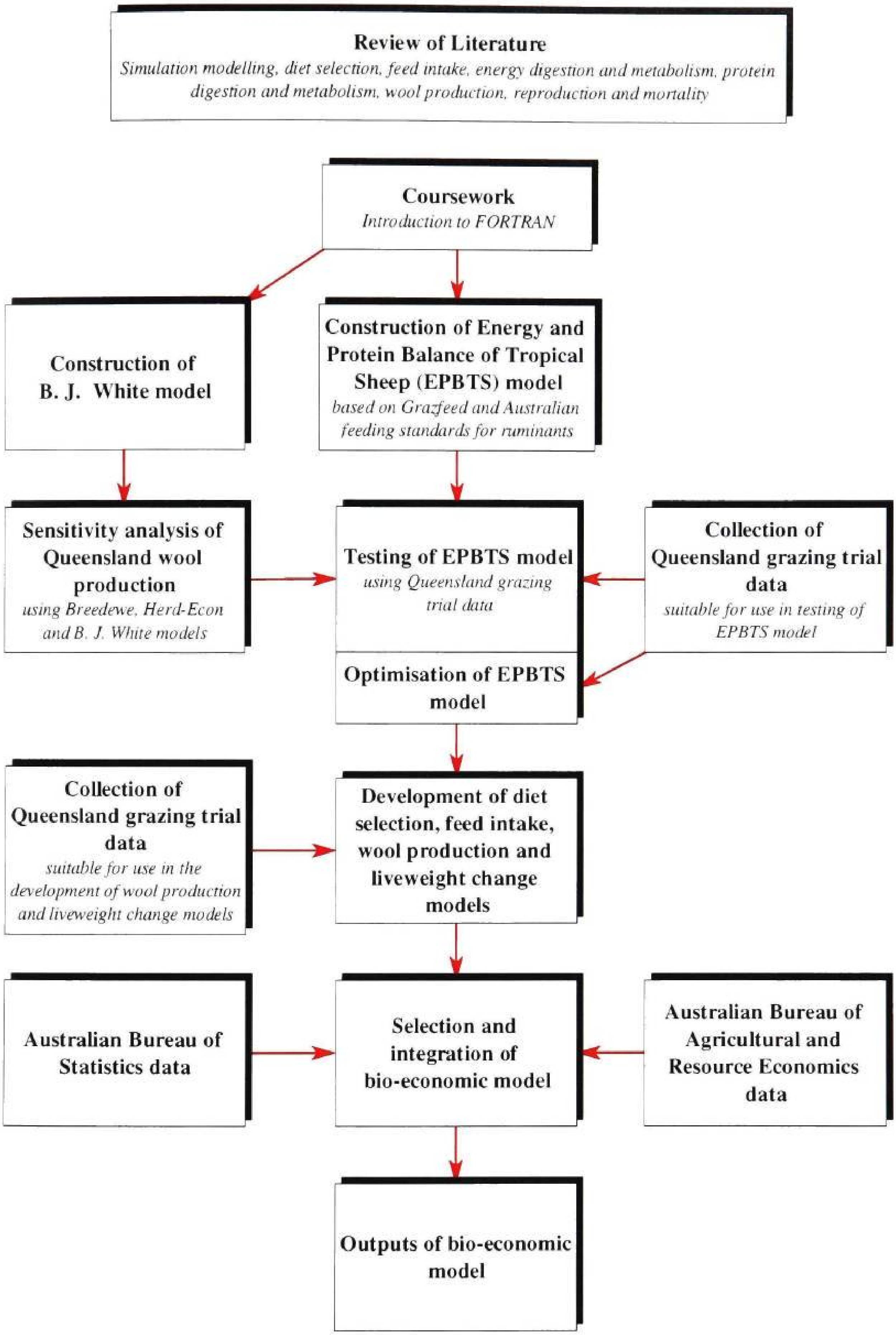

Figure 1.3. Work conducted during the construction of the bio-economic model.

Chapter Three details a sensitivity analysis of wool production in Queensland using three separate bio-economic models: Breedewe, Herd-Econ and the B. J. White model. This analysis was carried out to identify the system components which have the greatest impact on a wool production enterprise and were therefore of greater importance in terms of model development. The three models varied greatly in their operational complexity and required inputs. The most significant difference being the requirement of biological rates (lamb marking, wool production, mortality) as inputs by the Breedewe and Herd-Econ models, whereas the B. J. White model calculated these rates internally. The B. J. White model also had more complex decision or trading (sales and purchases) rules which were able to vary from year to year depending on the season. The three models were highly consistent in identifying sensitive components: wool price received and annual fleece production were the most important followed by variable costs. Variability of the same system components in the real world was also examined.

Chapter Four examines the *Feeding Standards for Australian Livestock: Ruminants* (SCA 1990), the most modern synthesis of nutritional information relating to Australian wool production, and the basis of Grazfeed (Freer and Moore 1990, Freer *et al.* submitted), a commercial software model. As such, the feeding standards and appropriate sections of the Grazfeed model were viewed as being capable of forming the biological basis of the model being developed. The Australian feeding standards have been developed mainly on Australian and international research for temperate production zones. Chapter Four examines their application to the simulation of animal production in the tropics and subtropics. This was done using Queensland experimental grazing trials and a FORTRAN version of the required Grazfeed equations, herein after called the Energy and Protein Balance of Tropical Sheep (EPBTS) model. Based on this evaluation with field data, it was concluded that Grazfeed, as represented by the EPBTS model, was unsuitable for further use in simulation of tropical sheep production. However, sections were later used in the development of a feed intake subroutine. Attempts were made to optimise parameters and modify equations within EPBTS in order to improve the predictive ability of the model, all of which were unsuccessful. Hence, other approaches were needed.

observed annual fleece production and liveweight change. The diet selection subroutine was based on the beef production model of Hendricksen *et al.* (1982) and the feed intake subroutine based on Australian feeding standards / Grazfeed equations.

Chapter Six reports results of the simulation analyses of Queensland grazing trial fleece production and annual liveweight change using simple climatic, soil, pasture and dietary variables. Fleece production and liveweight change were examined on an individual trial basis as well as on a pooled basis. Several suitable models were found to explain a high proportion of the variation in annual fleece production. Similarly, annual liveweight change was generally able to be explained but liveweight changes over shorter time intervals were not. The variability in fibre diameter and clean wool yield were also examined in Chapter Six.

Chapter Seven reports work using Australian Bureau of Statistics (ABS) shire level wool production data to select the most appropriate fleece production model. Also detailed in this chapter are the assumptions and selections relating to shearing dates, time of joining, the effect of gestation and lactation on wool production, the effect of flock age composition on production, calculation of stocking rates and the number of sheep shorn. Gross margins were then able to be calculated based on the wool price received, which in turn was based on fibre diameter, and the variable costs per animal shorn.

Chapter Eight provides examples of the output of GRASP and the bio-economic model in terms of thematic maps showing in detailed resolution regional variation in both physical and financial performance measures. Percentile maps are presented which enable a region's performance to be analysed in a historical context. The problems of map resolution and the level suitable for interpretation are discussed.

Chapter Nine is an overall discussion of the work completed including how the original aims of the model were met, problems encountered in the model development, areas for further research (both model and field work) and alternatives in model operations.

There are four appendices presented as part of this thesis. As previously indicated, Appendix One is a review of literature, with particular relevance to tropical sheep production, dealing with diet selection and feed intake of grazing sheep, energy digestion and metabolism, protein digestion and metabolism, wool, reproduction and mortality. This review was carried out as part of an overall systems analysis and presented here for completeness. Appendix Two is the reconstructed FORTRAN code for the B. J. White model used in Chapter Three, which prior to this work was not available. Appendix Three is the FORTRAN code for the EPBTS model based on the Australian feeding standards / Grazfeed and used in Chapter Four. Appendix Four contains the plots of predicted and observed wool production which were used in Chapter Six to test the wool production models developed using the Queensland grazing trial data, and in Chapter Seven to select the most appropriate wool production regression for the bio-economic model.

CHAPTER TWO

Review of Literature: Construction and Roles of Simulation Models

2.1 Introduction

A review of literature dealing with the philosophy and methodology of simulation modelling as it pertains to agricultural systems is presented here. This review establishes the benefits of the systems analysis approach as a method of organising detailed biological knowledge. Using this approach, the biology of sheep and wool production, especially as it relates to western Queensland, has been reviewed in detail and presented as a separate entity in Appendix One; *Review of the Biology of Sheep and Wool.* In the following discussion, I will concentrate on the basis for the systems analysis approach with particular reference to wool production in western Queensland.

2.2 Modelling in general / agriculture

2.2.1 Why build a model?

Various benefits have been proposed as a result of model development, the more universal ones being (Goodall 1969, Anderson 1974, Ebersohn 1976, Dent *et al.* 1979, Black *et al.* 1982, Morley and White 1985, Trapp and Walker 1986, Blackburn and Cartwright 1987a, Walker 1993, Seligman 1993, Stuth *et al.* 1993, Faichney 1996):

- clarification of one's own understanding of the system;
- synthesis of system fragments into a whole;
- communication of ideas and concepts to others;

- identify gaps or inconsistencies in available information and therefore guide future experimental work;
- provide new insights and better understanding of the system;
- benchmark against which experimental results can be compared;
- aid in management decision making at the farm and regional level;
- allow study of systems where real-life experimentation is impossible, too costly or disruptive (socially or politically);
- prediction of system behaviour following imposition of proposed constraints;
- allow long term effects to be examined; and
- identification of components that affect output of the system in a significant way.

Other less frequently offered reasons for simulation modelling include the desire to seem trendy and examination of systems that do not exist (Dent *et al.* 1979, Morley and White 1985). What is not documented formally in the literature is the apparent positive impact of systems analysis on the careers of some of those involved, and the work that they progressed, based on the insights gained through systems analysis and modelling.

However, it should be noted that simulation models cannot predict the future, replace experiments designed to discover biochemical pathways, ecological processes and site specific system responses to manipulation, or replace subjective assessments and value judgements that affect many management decisions (Seligman 1993).

2.2.2 *What is a simulation model?*

Simulation of agricultural systems can be considered as the formalisation or quantification of ideas, observations, concepts and hypotheses based on experimental data into a series of mathematical equations (Smith and Williams 1973, Black *et al.* 1982, Denham and Spreen 1986, Loewer 1989, Rickert and McKeon 1991). As such, simulation models act as a repository for past research and a guide for future research (Ebersohn 1976, Dent *et al.* 1979). Simulation models use state variables which describe the status of the system at any given point in time. The current value for a state variable is equal to it's starting value, less the flow of material out of the variable, plus the flow of material into the variable (Smith and Williams 1973).

2.2.3 Types of simulation model

There are numerous ways in which models have been classified (Benyon 1983, Loewer 1989, Rickert and McKeon 1991) with most emphasis on the following categories:

- deterministic versus probabilistic (stochastic);
- static versus dynamic; and
- theoretical versus empirical.

Deterministic models are those in which state variables are modified by known biological and physical relationships with no randomly varying elements (Smith and Williams 1973). Probabilistic models are those in which certain inputs or decision rules are generated during the running of the model, generally in line with known statistical values for that variable (Bravo 1972, Anderson 1974, Stafford Smith *et al.* 1995). Goodall (1969) suggested that grazing systems models were perhaps best a combination of deterministic and probabilistic processes. Processes which should be treated as probabilistic are those with greater variability and to which the model is sensitive, e.g. rainfall. Anderson (1974) considered all models dealing with agricultural economics should be probabilistic in nature in order to represent accurately the precision of understanding of the system. For example, RISKFARM (Milham *et al.* 1993), is a dynamic stochastic model for simulating farm financial performance able to estimate uncertain variables such as prices, tax obligations, interest rates etc. from specified probability distributions (Stafford Smith *et al.* 1995). The paper of Stafford Smith *et al.* (1995) shows how complex dynamic soil-pasture-animal models can be used to derive probability distributions of production and resource attributes, and these coupled to complex economic models for sheep enterprises in the arid rangelands.

Static models are those dealing with inputs and outputs over a single production period, generally a year (Upton 1986). Static flock / herd models may be further classified as steady state where the number of animals and composition of the flock / herd is the same at the beginning and end of the production period (Holmes 1988). Dynamic models, those in which the results from one production period flow into and affect the next production period are generally more suitable for simulation of grazing systems (Holmes 1990). As will be examined later (Chapter Three), the difference between static and dynamic models is particularly relevant to western Queensland where there is large year-to-year variation in reproduction and mortality.

Empirical models are those based on equations developed from experimental data by correlation and regression techniques. Theoretical, or mechanistic models go one step further and include hypotheses of what is considered to be happening within the system (Black *et al.* 1982, Poppi 1996). Denham and Spreen (1986) suggested that Decision Support Systems (DSS) are more likely to be empirical than theoretical in nature; empirical models tend to be more concerned with the quality of model output relative to the quality of the theory. However, greater emphasis on theory generally produces a more robust model which is better able to operate under conditions different from those in which it was developed. An example from western Queensland is the DSS developed by Johnston *et al.* (1996) to calculate safe grazing capacity. The DSS contains empirical equations derived explicably for this purpose from the output of a daily soil water-pasture growth model to estimate annual pasture growth, rather than using the complex soil water-pasture growth model itself.

Gaming models are those which require direct human interaction. Anderson (1974) considered gaming models not to be simulation models. However, Freeman and Benyon (1983) believed human interaction replaced the requirement for preset decision rules within the model and potentially resulted in more accurate simulations, provided the participants react in the same way to the model as they would to real life situations (Benyon 1983). To introduce graziers to the concept of simulation, QDPI developed a simulation 'game' of a grazing beef enterprise, BEEFUP (Rickert *et al.* 1989). Extension personnel have found gaming models, such as BEEFUP, a useful way to introduce graziers to the concepts of simulation and DSS (G. McKeon pers. comm.).

2.2.4 Level of model organisation

The level of organisation at which a simulation model operates may vary from molecule to cell, tissue, organ, organism, population and community. Seligman (1993) suggested that 'organisational levels much below the level of interest will not add anything to the understanding of behavioural complexity at a given organisational level'. This is thought to arise because complexity in structure and function is relatively constant between different organisational levels (Seligman 1993).

The level at which modelling occurs should be applicable to the objectives of the model and is generally chosen based on a thorough understanding of the system by the modeller (Morley and White 1985). For example, Black *et al.* (1982) considered higher level models based on empirical equations were adequate for examining the limitations to animal production from pasture, but if the effects of urea supplementation were to be examined, more detailed lower level processes representing the biochemical functions of the rumen and protein flow to the intestines would need to be included. Seligman (1993) also recognised that more detailed models are required in certain situations. However, he warned that greater detail does not necessarily improve predictions because the 'greater detail almost inevitably increases random divergence from whatever "real world" true behaviour may be'. Therefore, modellers should aim to reduce 'complexity to the essential minimum'. In this thesis, both the complex physiological approach to sheep growth and productivity, and empirical equations derived from field data were examined. In previous modelling studies in western Queensland, sound physiological models have been 'forced' to work (White 1978), whilst other studies (Reid and Thomas 1973), did not progress past empirical multiple regression equations.

Models developed to aid decision making, as already stated, are often based on empirical equations. These equations provide descriptions of the relationship between two or more variables but tell us little about the underlying mechanisms (Black *et al.* 1982). It is these underlying mechanisms which research orientated models are used to investigate, and hopefully improve, our understanding of, e.g. mechanistic models may help identify why feed intake is less than expected but do not usually provide better predictions of intake (Poppi 1996). Incorporation of larger complex models into management models is generally not feasible because they are cumbersome, difficult to understand and parameterise, and also less reliable predictors (Seligman 1993, Stafford Smith *et al.* 1995).

2.2.5 Stages of model development

The first stage of model development is definition of the model objective, or the problem the model will help solve. Secondly, an analysis of the system needs to be completed and the necessary inputs and processes identified. Thirdly, the system processes from inputs to outputs are quantified. Finally, the outputs from the model need to be interpreted in terms of the model objectives (Morley 1987). Anderson *et al.* (1985) considered these steps may occur in a cyclical manner. Similarly, Goodall (1969) recommended that data collection and simulation should be carried out concurrently in order to identify data that are lacking and need to be collected. Further, Bravo (1972) considered that, only after a conceptual model was in an advanced stage of development, was it possible to decide on the type and accuracy of data required. This approach was not possible here because of the limited time available to complete a Ph.D. In fact, this thesis relies on animal production data already collected; the consequence of which is that the data collected may be imperfect for model development.

Model validation is an activity that is perhaps more 'art' than 'science', the process itself means different things to different modellers with no set 'recipe' for new modellers. A closely related process which is considered by some as a form of validation is model verification, sometimes called design validation. Model verification involves testing the computer program to ensure it is working as it was intended at the conceptual stage, and that the program mechanisms are logical and consistent (Anderson 1974, Dent *et al.* 1979). Model verification becomes more important in data poor areas where output validation is unable to be carried out (Noble 1975).

Validation, or output validation, is the stage whereby model outputs are compared to those of the real world (Anderson 1974, Noble 1975, Dent *et al.* 1979, Black *et al.* 1982, Loewer 1989). The importance of this stage, the manner in which it is carried out, and associated statistical tests vary greatly; some animal production models undergoing little or no validation (Chudleigh and Cezar 1982, De Leeuw 1986). Validation and the associated requirement for accuracy should be carried out bearing in mind the objectives of the model (Dent *et al.* 1979, Poppi 1996).

Harrison (1990) pointed out the dangers in using statistical tests to check the ability of models to simulate real world systems, and in particular, the theoretical and practical problems associated with regression of model on real world outputs. Harrison (1990) argued that the confidence built up by modellers as their models undergo repeated modifications, often over a long period of time should be recognised. Similarly, Noble (1975) considered validation to be 'any process which increases the user's confidence that the model reflects the parts of the real world it was designed to model'. Loewer (1989) considered validation of a model using data from grazing trials, which themselves are scaled-down physical models, to be of limited value and that the term field comparison was more appropriate. A more subjective validation test, based on graphic appraisal has been suggested by numerous authors (Noble 1975, Dent *et al.* 1979, Harrison 1990). In this case, an expert or panel of experts is provided with both model and real world output. If they are unable to distinguish between the model and reality, then the model is considered realistic.

Model validation is generally carried out using real-world data not used in the process of the model development (Bennett and Macpherson 1985). However, Christian (1981) stated that 'using part of a set of data to construct the model and the rest to validate it is testing not the model but the homogeneity of the data'. He further considered it 'absurd' that modellers should conceal information from themselves whilst trying to find the best solution to a problem. The real issue about validation is the degree of confidence the modeller has in extrapolating outside the range of conditions experienced during data collection, and from which the model was calibrated or derived. Thus, a completely independent test may give false confidence in terms of the ability to extrapolate. In this thesis, Christian's (1981) views are particularly relevant to the extrapolation of complex physiological models as compared to empirical equations.

The 'bottom line' in terms of model validation is that model output should not be different from the real world to an extent that will distract from the objectives for which it was developed, and that the decisions based on the model will not be inferior to those made without the model (Dent *et al.* 1979).

2.2.6 Reasons for model failure

Failure of models to adequately predict may occur for various reasons (Loewer 1989):

- initial status of system incorrectly defined;
- functional relationships not specified correctly;
- timing and / or level of changes to the system are incorrectly given; and
- combinations of the above.

Whelan *et al.* (1984), in a critique of the Texas A&M University model for grazing cattle, emphasised that to avoid problems, model builders need:

- complete familiarity with the bio-economic system;
- to appreciate uses and limitations of model; and
- to ensure adequate validation in the appropriate environment and production system.

Inappropriate model type may also lead to problems. Black *et al.* (1982) considered it seldom possible to obtain an empirical relationship which would describe the behaviour of a complex, interacting system over a wide range of environments. Lack of adequate data upon which models can be developed is a common problem that may lead to erroneous models (Forbes and Oltjen 1986).

The issue of scale, i.e. shifting up or down in time or space, needs to be considered during both the model development and output interpretation phases of model development (Passioura 1996, Boote *et al.* 1996). As stated earlier, Loewer (1989) considered grazing trials were able to be classified as scaled down physical models of grazing systems. Paddock or property level pasture and animal production may not be properly represented by grazing trials for numerous reasons: rainfall variation; effects of water and soil run-on-runoff; differing soil types and pasture communities; greater potential for diet selection; preference of livestock for certain paddock features, e.g. camping under clumps of trees; and, number and location of watering points and the subsequent gradient of grazing pressure. Conversely, the use of production and economic data from the shire or regional scale at the property level also requires consideration because the variation within this type of data is often severely restricted (Meinke and Hammer 1995).

2.2.7 Uses of simulation models

There have been numerous animal production and bio-economic models developed over the past 25 years, most of which evaluate 'what if' scenarios. A short description of the use to which some of these models have been put include:

- evaluation of changes in the physical nature of farms, e.g. pasture type, genotype (Beck *et al.* 1982, Blackburn and Cartwright 1987b, White 1988, Foran *et al.* 1990);
- evaluation of alternative farm management practices (Chudleigh and Filan 1972, Smith and Williams 1973, White *et al.* 1983, Späth *et al.* 1984, White and Bowman 1987, Blackburn and Cartwright 1987b, Stafford Smith and Foran 1988, 1992, White 1988, Foran *et al.* 1990, Foran and Stafford Smith 1991, Stockwell *et al.* 1991, Stafford Smith *et al.* 1994, Conner and Stuth 1995, Carande *et al.* 1995);
- evaluation of changes in government policy (Beck and Dent 1987, Stafford Smith *et al.* 1995);
- evaluation of new technologies (Bowman *et al.* 1989a, b);
- functioning of markets and government intervention (Hermans 1986);
- prioritising of research areas (Chudleigh and Filan 1972);
- estimation of sustainable land uses (Christie and Hughes 1983, Stafford Smith *et al.* 1995, Hansen and Jones 1996);
- increased understanding of the system being modelled (Vickery and Hedges 1972, Arnold *et al.* 1977);
- value of seasonal forecasting in wool enterprises (Bowman *et al.* 1995); and
- effect of changing economic and climatic environments (Reeves *et al.* 1974, Carande *et al.* 1995).

The bio-economic model described in this thesis is initially best classified with the last application group as it provides physical and financial information in response to changes in commodity prices, variable costs of production, and rainfall associated with wool production. However, with minor changes to the manner in which the model operates, or how the output is interpreted, it could also be applied to many of the above issues.

CHAPTER THREE

Sensitivity and Variability Analysis

of

Wool Production in Queensland

Important causes of variation in a systems performance require identification, and then examination of how they vary in reality. Sensitivity analyses are used to identify these attributes (Goodall 1969, Simpson *et al.* 1977, Upton 1986, Foran *et al.* 1990, Stafford Smith and Foran 1992). Sensitive attributes, when varied, have greatest impact on output of the system and are required to be modelled accurately if a model is to mimic a real system. In this chapter, sensitivity of wool producing enterprises is simulated and, 'real world' variability of these important attributes is examined.

3.1 Sensitivity analysis

3.1.1 Introduction

Sensitivity analyses were carried out on three different bio-economic enterprise models in order to identify components having the largest effect on enterprise financial performance, as measured by gross margins[1]. Each model simulates a self-replacing breeding ewe flock which contains various classes of stock:

- breeding ewes (> 2 years old);

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[1] Gross margins are calculated as the gross income from wool production less total variable costs. Variable costs are those directly related to the level of production, e.g. shearing and crutching costs (Hill 1991).

- wethers (optional, > 1 year old);
- rams;
- lambs (prior to weaning);
- weaner ewes (weaning to 1 year old);
- weaner wethers (optional, weaning to 1 year old); and
- maiden ewes (> 1 year old and prior to lambing which generally occurs when 2 years old).

Flock models represent the flow of sheep through these distinct classes. In static models, constant reproduction, mortality and trading rules lead to a steady state structure. In dynamic models, year-to-year variation in reproduction, mortality and trading rules lead to fluctuating flock composition. The three models (Breedewe, Herd-Econ, B. J. White) are quite different approaches to representing sheep and wool enterprises. This study identifies and compares the sensitive components of each model.

Given the mathematical nature in which gross revenue (wool cut * wool price) and subsequently gross margin are calculated, there are a number of points that need to be considered in this chapter:

- sensitivities of the models to wool price and wool cut will be equivalent (shown later in tables 3.6, 3.7 and 3.8); and
- the sensitivities of wool price, wool cut and variable costs are related to variable costs as a proportion of gross revenue, therefore, use of realistic values for costs and prices is essential.

3.1.2 Model description

3.1.2.1 Breedewe

Breedewe (Holmes 1987) was developed to enable financial implications of management decisions to be examined prior to their introduction. Breedewe is a steady state model which produces one year of output, and where flock composition and size is the same at the beginning and end of a year. Biological rates (reproduction, mortality, fleece weight) are required as inputs.

3.1.2.2 Herd-Econ

Herd-Econ is an integrated flock / herd dynamics and property economics model (Stafford Smith and Foran 1990b). Herd-Econ simulates varying farm situations and allows management options to be chosen and examined over a range of time periods. The effect of one year's production is carried over to the following year. Accompanying the increased model complexity is an increased requirement for inputs of both economic and animal population data. Biological rates (reproduction, mortality, fleece weights) are required as inputs. Herd-Econ is one module of the CSIRO RANGEPACK system, a group of decision support models developed for use by pastoralists, extension workers and researchers.

3.1.2.3 B. J. White model

The B. J. White model is a dynamic, whole-property, simulation model, developed to investigate the interaction of drought, management and taxation on Mitchell grasslands in north-west Queensland (White 1978). Climatic data are the driving inputs with simulation of soil water balance, pasture production, feed intake, sheep liveweight, wool production, mortality and reproduction. Complex decision rules affecting stocking rate, sheep trading and flock composition also operate within the model.

At the beginning of this work no computer version of the B. J. White model was available. The model was reconstructed from the monograph, 'A Simulation Based Evaluation of Queensland's Northern Sheep Industry' (White 1978) which was identical to the Ph.D. thesis by the same author. A printed copy of code was provided by the author but it was impossible to determine whether this was the final version used in his simulation studies or an earlier developmental version. Differences existed between the two sources, in such cases the reconstructed code was based on that which gave the best validation and / or which seemed to be more logical (see Appendix Two for model code).

Weekly rainfall, and monthly Australian sunken tank evaporation, are used as inputs to a soil water subroutine which operates on a weekly time step. Tank evaporation values are used rather than Class A Pan evaporation, to avoid the need for recalibration, and actual evapotranspiration is passed to the pasture growth subroutine in those weeks when available soil water is greater than zero. Evaporation is used as a substitute variable for temperature.

The pasture growth subroutine operates on both a weekly and monthly time step. New pasture growth is simulated on a weekly basis. The efficiency of water use by pasture for new growth is modified by soil water stress, current green pasture biomass, evaporation, and pasture utilisation. At the end of each month the green pasture biomass is recalculated based on weekly pasture growths, intake, trampling by grazing sheep and death of green pasture. Dead pasture biomass calculations also occur at the end of each month, based on green pasture death, intake, trampling and loss due to decay.

The sheep liveweight subroutine operates on a monthly time step. Potential dry matter intake, actual dry matter intake, green / dead pasture intake, and digestibility of intake are modelled. The energy balance is calculated from metabolisable energy intake, metabolisable energy requirements of maintenance, and metabolisable energy used in wool growth. Weight change is calculated from the energy balance.

The sheep flock subroutine operates on a monthly time step, parasite and bogging indexes are updated at the end of each month. Lamb marking, mortalities and flock wool production are modelled within this subroutine for a flock of average composition. Vectors based on the data of Riches (1958), Moule (1966), Rose (1972) and White (1978) are then used to modify the average values depending on actual flock composition. Mortalities are calculated twice yearly, at the end of July and December.

Sheep sales and purchases occur as determined by decision rules. The decision rules for trading, together with mortalities and reproduction, determine the sheep population and flock composition.

The complex economic / tax module of the original model was not used because of the many tax changes since the model was developed. Instead, a gross margin subroutine that operated in the same manner as the Breedewe model was used. Annual gross margin was calculated at the end of each financial year, as well as accumulated gross margin for the duration of the model run.

At the start of this study, the B. J. White model was viewed as a likely base model upon which the final product could be developed.

3.1.3 Property simulation methodology

The three models were used to simulate a breeding ewe flock in as similar conditions as was possible, given the marked difference in type, operation and complexity of the models. Sensitivity analyses were carried out by modifying biological rates, prices and management options of the system, and comparing output with the unmodified model.

3.1.3.1 Breedewe

A 'typical' self replacing breeding ewe flock situated in the Longreach region was used in all work. Most property data were from economic profiles (EP1 and EP2) produced by Newman (1992a). The simulated property, based on Newman's (1992a) 'typical' property, had a maximum carrying capacity of 6560 dry sheep equivalents (DSE) and an initial breeding ewe flock of 4000. At lower lambing rates and higher mortality rates, the flock DSE was lower than the maximum possible carrying capacity. At higher lambing rates and lower mortality rates, the breeding ewe flock was reduced to keep the total flock DSE below the maximum allowed. The prices for stock, produce, and management procedures are shown in table 3.1. Production and management options are shown in table 3.2. An explanation of terms is presented in table 3.3.

3.1.3.2 Herd-Econ

The Herd-Econ model required more specification of management options than the Breedewe model. These were based on QDPI recommendations from work with the Toorak Research Station commercial flock (Cobon *et al.* 1994b). Table 3.4 shows the timing of procedures for the Herd-Econ model.

Table 3.1. Prices for stock, produce and management procedures for the simulated property. All prices on a per head basis except for wool which is on a per kg basis.

Stock / Produce / Procedure	**$**
cull maiden ewes (1.5 years old)	3.00
cast for age ewes (6.5 yo)	0.00
weaner wethers (0.5 yo)	8.00
rams	200.00
wool[1] (type 79 clean)	4.62
shearing - weaners	2.50
shearing - ewes / wethers	2.70
shearing - rams (twice yearly)	4.00
crutching - ewes / wethers	0.50
mulesing and marking	0.70
casual labour - ewes	0.40
casual labour - wethers	0.25
ram supplements	1.50
veterinary - weaners/ewes/wethers/rams	0.50

[1] *Sydney price as reported in Queensland Country Life, 1-7-93. No age or sex group factors taken into account for wool price received. A wool basis factor of 42% was used to apply the clean price ($4.62) to the whole greasy clip including selling and freight costs.*

Table 3.2. Production values and management options for the simulated property.

Variable / Option	**Value**
wool cut - weaners[1]	1.5 kg
wool cut - ewes[1]	4.2 kg
wool cut - wethers[1]	5.1 kg
wool cut - rams[1]	6.0 kg
mortality rate[2,3] (all age groups)	9.2%
lamb marking rate[2] (all age groups)	51.0%
DSE - weaners	0.75
DSE - joined ewes (1.5 yo plus)	1.35
DSE - wethers (1.5 yo plus)	1.00
DSE - rams	2.00
ram flock replaced annually	25.0%
ram ratio	2.5%

[1] *Wool cuts are based on an unclassed flock.*

[2] *Mortality and lamb marking rates are 10 year averages (1980-1989) from a review of western Queensland pastoral statistics for the Longreach shire (Newman and Carson 1992).*

[3] *mortality rate of rams assumed to be 0% due to supplementation, for Breedewe and Herd-Econ models.*

Table 3.3. Explanation of commonly used terms.

Term	Definition
cull	To remove from the flock, often associated with classing whereby better individuals are identified and retained whilst the remainder are sold or slaughtered.
cast for age	Refers to the removal of animals from the flock due to their age, sets an upper limit to the age of a particular class of sheep.
weaner	Refers to the class of sheep between weaning, often at about three months of age, and until approximately 12 months of age.
shearing	Removal of wool from sheep on an annual basis. May be done twice yearly with rams.
crutching	Generally refers to the removal of wool from around the anus, vulva / prepuce, and facial areas in order to avoid problems with flystrike. Usually done mid-way between shearings (more precise definitions may be used, e.g. refers to removal of wool from around the anus and vulva only).
mulesing	Procedure whereby the skin on either side of the anus (and vulva) toward the tail region are removed in order to permanently prevent wool growth in this region, thereby reducing the risk of flystrike and the need to remove wool from this region between shearings. Carried out generally at marking, usually 4 - 8 weeks of age.
marking	Usually carried out between 4 - 8 weeks of age and generally includes removal of the tail (to avoid flystrike), castration of males, and tagging / notching of ears.

Table 3.4. Timing of management procedures for the Herd-Econ model flock.

Procedure	Timing
ageing of stock	1st of March
financial year	both July - June and October - September examined
DSE calculated and checked against property carrying capacity	31st October
joining	October / November
crutching / ram shearing	February
lambing	March / April
lamb marking	May
weaning and sale of weaner wethers	July
ram sale / purchase	August
shearing	September
maiden ewe selection	September, following shearing
casting aged ewes	September, following shearing

Unlike Breedewe, Herd-Econ did not allow rams to be bought / sold depending on breeding ewe numbers. Instead, ram numbers were maintained at 100 or 2.5% of the maximum breeding ewe flock size. Weaner ewes were also able to be sold ($10.00 per head) in order to avoid overstocking. Otherwise, the values in tables 3.1 and 3.2 were used in the Herd-Econ sensitivity analysis. The time required for a new equilibrium in age class numbers to be reached, following changes in the number of maiden ewes entering the breeding flock due to modified mortality rates, was also examined.

As Herd-Econ was a dynamic model it was possible to run the model for any number of years. The approach adopted was to run the model for one year, record the gross margin, then run the model for a further nine years. The annual gross margin for the final year and the ten year accumulated gross margin were also recorded. This approach provided three gross margin values for the sensitivity analysis.

To evaluate the impact of year-to-year variation in biological rates, historical time series data (lamb marking, mortality, fleece weight) for the years 1980-81 to 1989-90 (figure 3.1, Newman and Carson 1992) were used as inputs to Herd-Econ. Lamb marking, mortality and fleece weights were varied in turn by ± 10% from their historical values and the resultant accumulated gross margin recorded. Finally, two runs were carried out where all three variables were modified by ± 10% from their historical values so as to give the best and worst possible combination of rates.

3.1.3.3 B. J. White model

The 'typical' breeding ewe flock used in the B. J. White model differed from that used in the Breedewe and Herd-Econ models. The modelled flock was run on 7340 hectares at an initial stocking rate of 0.64 DSE per hectare (4710 DSE in total), which was also the long term stocking rate for the flock. The flock was allowed to expand during appropriate seasons up to 1.5 times the long term stocking rate, i.e. 0.96 DSE / ha (7066 DSE in total). The initial flock composition was 100 rams, 921 one year old ewes and 3823 joined ewes spread over six age classes. Rams were used at a ratio of 2.5% with 25% replaced annually.

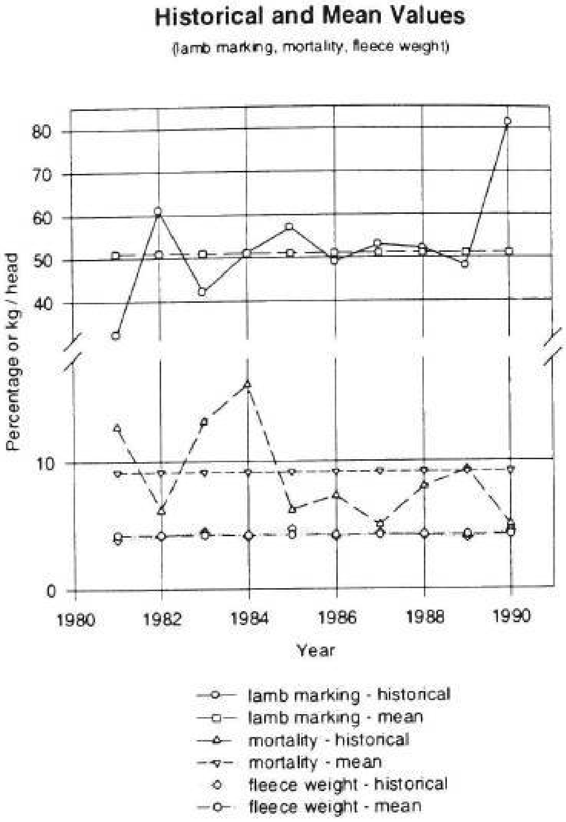

Figure 3.1. Historical values for lamb marking, mortality and wool production for the Longreach shire (1980-81 to 1989-90) compared with mean values.

Because the B. J. White model was specific to the north-west Mitchell grasslands, management was also markedly different from that of the previous models. Twenty percent of maiden ewes were classed when conditions allowed. Ewes were preferably cast for age at seven years of age and wethers shortly after weaning, depending on the current stocking rate relative to threshold rates. Classing of maiden ewes occurred if the current stocking rate was above the long-term stocking rate. Sheep were cast for age, wethers first beginning with the oldest age group, if the current stocking rate was above that which triggered culling (150% of long term stocking rate). However, eight year old wethers and 11 year old ewes were sold after shearing and ageing, irrespective of stocking rate. Forced sales occurred when dictated by poor body condition. The timing of model operations are set out in table 3.5.

One of the most important features of the B. J. White model was the ability to simulate lamb marking, mortality and wool production for the modelled flock. Variation in these calculated rates were applied to all classes, depending on age and sex.

Table 3.5. Timing of management and model operations for the B. J. White model flock.

Procedure/Calculation	**Timing**
forced sales	March and July
lamb marking	April
mortalities	July and December
shearing	July
ageing of stock	July
normal sales	July
ewe purchases	July
ram purchases	July
financial year	August - July

The B. J. White model simulated clean wool production and required a different conversion or wool basis factor to that listed in table 3.1, in order to convert clean wool price to a price for the whole clip, less freight and selling costs. Assuming a yield of 70%, a wool basis factor of 60% gave the appropriate conversion. The DSE equivalence of stock were as for table 3.2, apart from ewes and lambs. Dry ewes (two years plus) were equivalent to 1.0 DSE, while joined ewes increased from 1.0 to 1.4 DSE during the four months prior to marking (late gestation / lactation). All joined ewes were treated as pregnant. Lambs on ewes (post marking) were equivalent to 0.3 DSE.

Toorak Research Station daily rainfall records for 1977 - 1992, and average Australian sunken tank evaporation figures for north Queensland Mitchell grasslands, were used in the simulations. The model was run initially for 5.5 years to allow the property to equilibrate and the accumulated gross margins for the following 10 years were used in the sensitivity calculations.

Prices were kept constant during all runs to avoid interactions between historical prices and climatic data which would have confounded the sensitivity analysis. The prices for weaner wethers, cull maiden ewes, cast for age ewes (> 6.5 years old) and rams were those listed in table 3.1. When other classes of sheep were sold, as dictated by stocking rate and body condition, a price vector was used to calculate the sale price based on a sheep value of $8.00 per head. This vector was developed from a survey carried out on western Queensland saleyard prices during 1966 and 1967 (Beck 1970) and provided variation in prices for sheep of different ages but not sex. Rams were considered to be without value at the end of their working life. Sheep sold at March forced sales received 75% of their normal value, while July forced sales received 50% of their normal value. An additional $3.00 was added to the price for all sheep purchased apart from rams.

3.1.4 Results

3.1.4.1 Breedewe

The sensitivity of the Breedewe model to selected system components is shown in table 3.6. Clean wool price had the greatest effect on gross margin performance. Of the biological rates, wool production was the most important followed by lamb marking and then mortality rate.

Using the Longreach shire 10 year mean lamb marking and mortality rates, it was impossible to maintain a breeding ewe flock, and maiden ewes (120 head) were required to be purchased to maintain flock numbers. When lamb marking rates were increased to 65% and mortality rates reduced to 5% (Newman 1992a), it became possible to maintain numbers and carry out classing of maiden ewes. For this reason, maiden ewe cull prices were negatively related to gross margin using mean 10 year lamb marking and mortality rates (table 3.6). However, at 65% lamb marking and 5% mortality rates, the relationship was positive, excess maiden ewes being sold and the property benefiting from increased prices.

Non-linear relationships between gross margin and the age at which ewes were cast, and the effect of retaining varying proportions of wethers within the flock to 5.5 years of age were examined in detail but not presented here. It was concluded that these non-linear relationships were not likely to influence the conclusions from this sensitivity analysis.

Simulations across a wide range of values showed annual gross margins were linearly related with clean wool price, wool cut per head, variable costs, mortality rate, maiden ewe cull price, cast for age ewe price and weaner wether price (results not shown).

Table 3.6. Breedewe model components evaluated and their impact on property gross margin performance following a 10% increase in their values.

System Component	Original value	Value after 10% increase	$ Change in Annual Gross Margin	% Change in Annual Gross Margin
wool price / kg clean	$4.62	$5.08	4 299	22.95
wool cut / ewe[1]	4.2 kg	4.6 kg	4 299	22.95
variable costs / DSE	$4.98	$5.48	-2 631	-14.05
lamb marking rate[2]	51.0%	56.1%	1 174	6.26
weaner wether price	$8.00	$8.80	740	3.95
mortality rate[3]	9.2%	10.12%	-728	-3.89
cast for age ewe price[4,5]	$1.00	$1.10	59	0.30
cast for age ewe price[4,6]	$1.00	$1.10	68	0.26
maiden ewe price[5]	$3.00	$3.30	-36	-0.20
maiden ewe price[6]	$3.00	$3.30	87	0.34

[1] *wool cuts for other classes of stock were also increased by 10%.*

[2] *base lamb marking rate was 51%, a 10% increase would give a lamb marking rate of 56.1% (51+51*0.1).*

[3] *base mortality rate was 9.2%, a 10% increase would give a mortality rate of 10.12% (9.2+9.2*0.1).*

[4] *ewes cast for age in all other runs had no value, to examine sensitivity a nominal price of $1 / sheep was used as the base price .*

[5] *lamb marking rate 51%, mortality rate 9.2%.*

[6] *lamb marking rate 65%, mortality rate 5%.*

The relationship between gross margin and lamb marking rate was approximately linear (figure 3.2). The Breedewe model simulated increased fleece weights above those specified (table 3.2) when classing of young stock occurred. This affected the positive relationship between lamb marking rates and whole flock gross margin because the increased lamb marking allowed greater selection for higher wool producing sheep. At lamb marking rates greater than 70%, the flock reached its maximum size allowable under the property carrying capacity. As a result, the breeding ewe component of the flock, the group which benefited from classing in terms of wool production, was reduced in size as lamb marking continued to rise. Gross margin increased most for each percentage point change in lamb marking rates in the range of 60 - 70%, followed by 0 - 60%, and least for lamb marking rates greater than 70%.

The effect of interactions between lamb marking and mortality rates on gross margin were examined in a series of 208 runs where lamb marking and mortality were varied against each other (figure 3.3). The Breedewe model was most sensitive, as indicated by the slope of the response surface, to a combination of moderate lamb marking (40 - 70%) and low mortality rates.

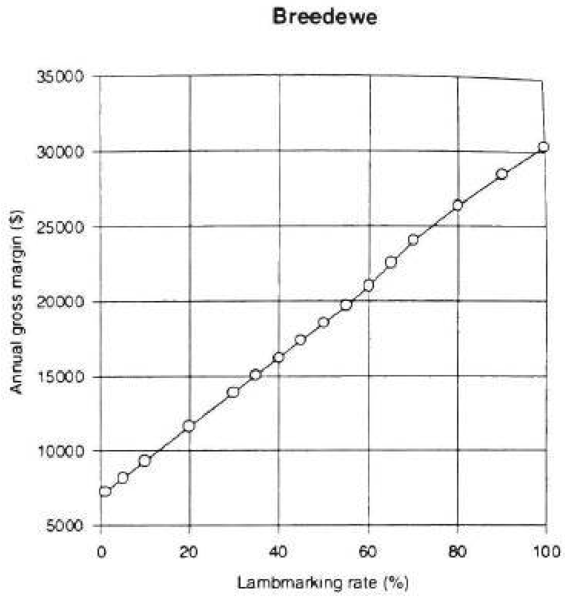

Figure 3.2. Effect of variation in constant year-to-year lamb marking rate on Breedewe annual gross margin.

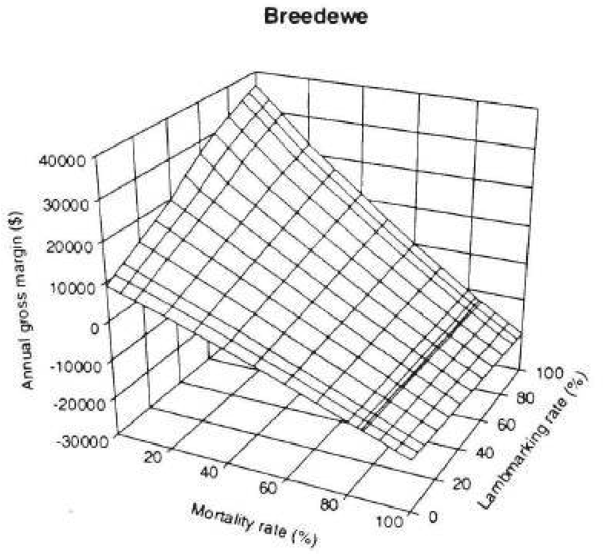

Figure 3.3. Effect of variation in constant year-to-year lamb marking and mortality rates on Breedewe annual gross margin.

3.1.4.2 Herd-Econ

The sensitivity of the Herd-Econ model to selected system components is shown in table 3.7. Clean wool price and wool cut per head had the greatest effect on gross margin performance.

Table 3.7. Herd-Econ model components evaluated and their impact on property gross margin performance following a 10% increase in their values.

System Component	Original value	Value after 10% increase	$ Change in Annual Gross Margin	% Change in Annual Gross Margin
wool price	$4.62	$5.08	3 999	20.60
wool cut / ewe[1]	4.2 kg	4.6 kg	3 617	20.44
variable costs / DSE	$4.98	$5.48	-2 390	-13.50
lamb marking rate[2]	51.0%	56.1%	1 122	6.27
weaner wether price	$8.00	$8.80	708	4.01
mortality rate[2]	9.2%	10.12%	-451	-2.55
cast for age ewe price[4,5]	$1.00	$1.10	59	0.33
cast for age ewe price[4,6]	$1.00	$1.10	68	0.29
maiden ewe price[5]	$3.00	$3.30	-53	-0.30
maiden ewe price[6]	$3.00	$3.30	74	0.32

[1] *wool cuts for other classes of stock were also increased by 10%.*

[2] *base lamb marking rate was 51%, a 10% increase would give a lamb marking rate of 56.1% (51+51*0.1).*

[3] *base mortality rate was 9.2%, a 10% increase would give a mortality rate of 10.12% (9.2+9.2*0.1).*

[4] *ewes cast for age in all other runs had no value, to examine sensitivity a nominal price of $1 / sheep was used as the base price.*

[5] *lamb marking rate 51%, mortality rate 9.2%.*

[6] *lamb marking rate 65%, mortality rate 5%.*

There were no important differences between the three measures of economic performance (first year annual gross margin, final year annual gross margin, ten year accumulated gross margin) because mean biological rates were used for all ten years of the simulation run. All values reported here and used for comparison with the other models are sensitivities based on final year gross margins, except where historical biological rates (figure 3.1) were used. In the latter case, accumulated ten year gross margins were used. Also, use of different financial years (July - June, October - September) had no effect on the sensitivity of the Herd-Econ model to those system components examined. A non-linear relationship between gross margin and the age at which ewes were cast was examined in detail but is not presented here because it does not influence the conclusions from this sensitivity analysis.

The typical reproduction (51%) and mortality (9.2%) rates resulted in Herd-Econ simulations where flock numbers were unable to be maintained without purchasing maiden ewes. Increased lamb marking rates (65%) and reduced mortality rates (5%) made it possible to maintain numbers and carry out classing of maiden ewes.

Annual gross margins were linearly related with clean wool price, wool cut per head, variable costs, mortality rate, maiden ewe cull price, cast for age ewe price and weaner wether price (results not shown).

The relationship between lamb marking and gross margin was linear up to a rate of 75% (figure 3.4). Beyond this level the property carrying capacity was reached. The Herd-Econ property avoided overstocking by sale of weaner ewes down to 1280 head, resulting in a new linear relationship, with an increased slope.

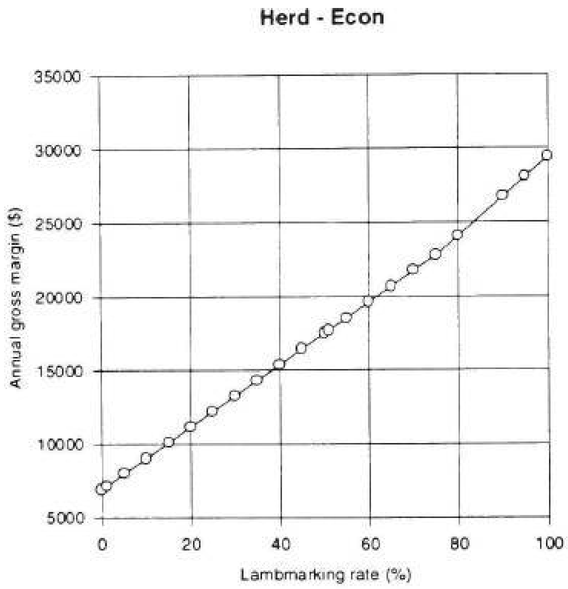

Figure 3.4. Effect of variation in constant year-to-year lamb marking rate on Herd-Econ annual gross margin.

The effect of interactions between lamb marking and mortality rates on gross margin were examined in a series of 208 runs where lamb marking and mortality rates were varied against each other (figure 3.5). The Herd-Econ model was most sensitive, as indicated by the slope of the response surface, to a combination of high lamb marking and low mortality rates.

The effect of using historical values for lamb marking, mortality, wool production (figure 3.1), and modifications to these values on accumulated gross margin are shown in figure 3.6. Accumulated gross margin was most sensitive to wool production (18.5%) followed

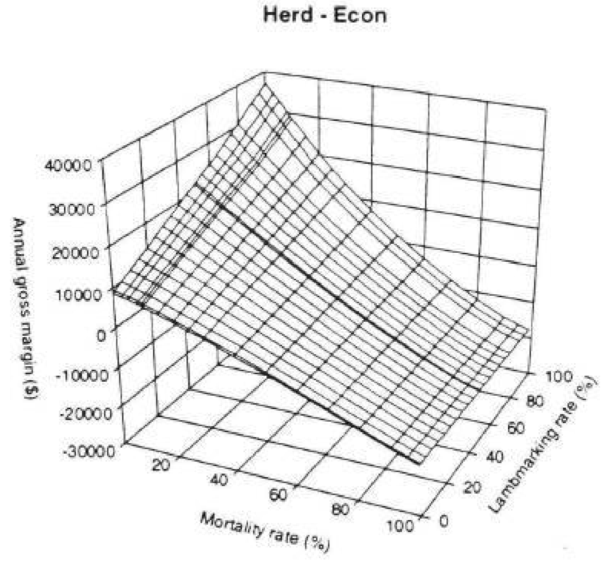

Figure 3.5. Effect of variation in constant year-to-year lamb marking and mortality rates on Herd-Econ annual gross margin.

by lamb marking (5.6%) and mortality (2.4%). Similar ten year accumulated gross margins resulted when either historical biological or mean values for the biological rates were used in the model. The effect of using dynamic biological rates versus mean values in simulation modelling is an area outside the scope of this thesis, although it is generally accepted that dynamic models are more suitable for simulation of grazing systems (Holmes 1990).

3.1.4.3 B. J. White model

The sensitivity of the B. J. White model to selected system components is shown in table 3.8. Clean wool price and wool cut per head had the greatest effect on gross margin performance.

Ten year accumulated gross margin was linearly related to clean wool price, wool cut per head, variable costs, sale price of all sheep, wether sale price, cast for age ewe price and maiden ewe price (results not shown).

The decision rules of the B. J. White model were complex and resulted in different management options being carried out in each year of the run. Sheep sales occurred in six

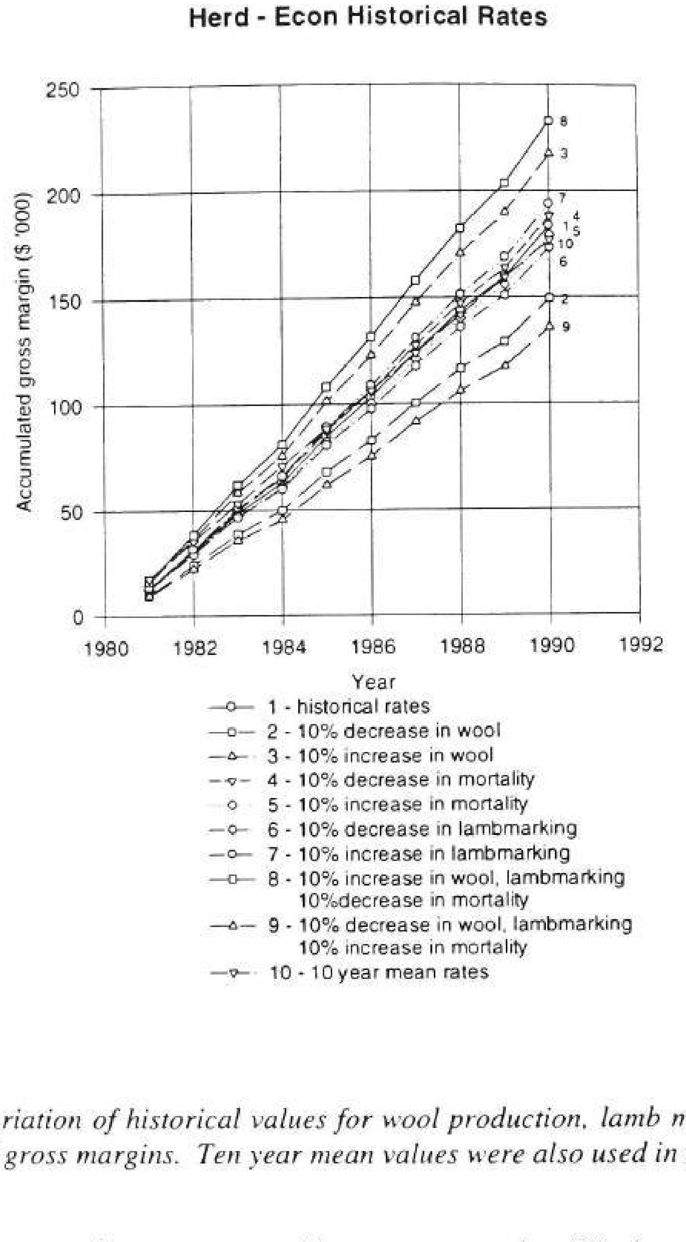

Figure 3.6. Effect of variation of historical values for wool production, lamb marking and mortality on Herd-Econ accumulated gross margins. Ten year mean values were also used in the model.

out of 10 years. Sheep purchases occurred in one year only. Wether sales occurred in two years, maiden ewe in six years, while cast for age ewe sales (excluding ewes aged 11 years with no value) occurred in only one year. No weaner wethers were sold during the course of the run because of the low lamb marking and high mortality rates. Hence, the nil impact of weaner wether price on gross margin.

Accumulated gross margin was not linearly related to variation in lamb marking (figure 3.7) and mortality rates (figure 3.8). The base model gave unexpected results especially when lamb marking rate was varied. Inspection of the year-by-year financial output of the model identified areas of model construction which were contributing to the non-linearity of the responses. Modifications, to be described, were made to the model and the degree of linearity increased.

Table 3.8. B. J. White model components evaluated and their impact on property gross margin performance following a 10% increase in their values.

System Component	Original value	Value after 10% increase	$ Change in 10 Year Accumulated Gross Margin	% Change in Accumulated Gross Margin
wool price / kg clean	$4.62	$5.08	39 655	24.80
wool cut	na	na	39 655	24.80
variable costs	na	na	-22 089	-13.80
lamb marking rate[1]	na	na	8 076	6.39
mortality rate[1]	na	na	-7 342	-5.81
sheep prices (all)	na	na	2 108	1.32
wether prices	na	na	1 582	0.99
CFA ewe price (> 6 years old)	$1.00	$1.10	337	0.21
maiden ewe price	$3.00	$3.30	220	0.14
weaner wether price	$8.00	$8.80	0	0.00

[1] *lamb marking and mortality sensitivities were calculated using a modified version of the model - costs / returns from July sales / purchases were carried over to the following financial year. July normal sales occurred with 'tenths' of age classes sold until stocking rate reduced to appropriate level. sale of maiden ewes. 8 year old wethers and 11 year old ewes occurred as before. Values reported are the mean values resulting from a range of changes - see figures 3.7 and 3.8 below.*
na - not available as these rates and prices were calculated within the model - see 'Property simulation methodology' for more details.

Components within the model contributing to the non-linearity of the response between lamb marking / mortality rates and accumulated gross margin were as follows. Returns from lamb wool production were less than the costs of lamb shearing, lamb marking and other lamb husbandry costs, therefore increased lamb marking rates initially had the potential to reduce annual gross margins. Variations in lamb marking and mortality rates resulted in flocks reaching threshold stocking rates which triggered culling of whole classes in order to avoid overstocking at different times. The sale of these classes occurred until the current stocking rate was below the threshold stocking rate. This resulted in a marked variation in yearly flock numbers, flock composition and gross margins. Forced sales when they occurred exacerbated this variation. Returns from both normal and forced sales were included in the same financial year as the wool returns from those same sale sheep and this further contributed to marked variation in annual gross margins. The major impact of variable flock composition was through the wool production vector, flocks shearing similar numbers of sheep, but with different compositions resulted in different average fleece production, and hence, annual gross margin. Ram purchases for the coming joining season were included in the calculations for the previous financial year. This resulted in years when trading gain, and wool returns for flocks with different biological rates, were similar. However, because the number of ewes that were to be joined the following financial year were greater in flocks with lower mortality rates and / or

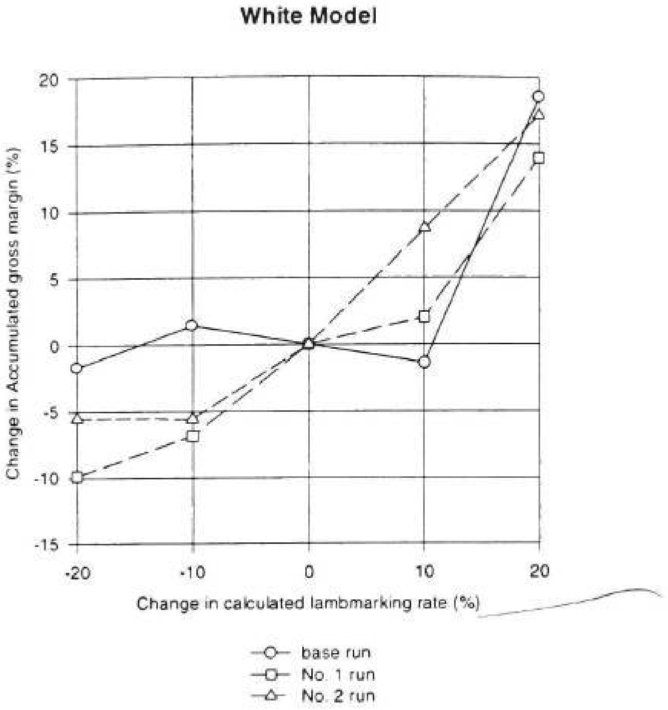

Figure 3.7. Effect of variation of B. J. White model calculated lamb marking rate on accumulated gross margin. No. 1 run. Costs / returns from July sales / purchases were carried over to the following financial year. No. 2 run. As for No. 1 run but with July normal sales occurring with 'tenths' of age classes sold until stocking rate reduced to appropriate level. Sale of maiden ewes, 8 year old wethers and 11 year old ewes occurred as before.

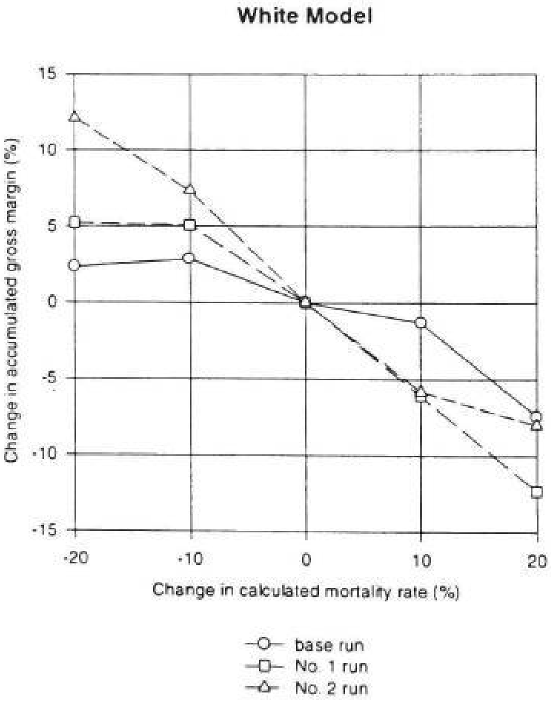

Figure 3.8. Effect of variation of B. J. White model calculated mortality rate on accumulated gross margin. No. 1 run. Costs / returns from July sales / purchases were carried over to the following financial year. No. 2 run. As for No. 1 run with July normal sales occurring with 'tenths' of age classes sold until stocking rate reduced to appropriate level. Sale of maiden ewes, 8 year old wethers and 11 year old ewes occurred as before.

higher lamb marking rates, ram purchase costs and variable costs were increased, resulting in a lower annual gross margin.

3.1.5 Discussion

The results of the sensitivity analyses of the three models were consistent, despite the variation in complexity, input required, internal structure and output. The models were most sensitive to wool cut per head and wool price followed by variable costs (figure 3.9). Gross margin was less sensitive to lamb marking rate, mortality rate and sheep prices.

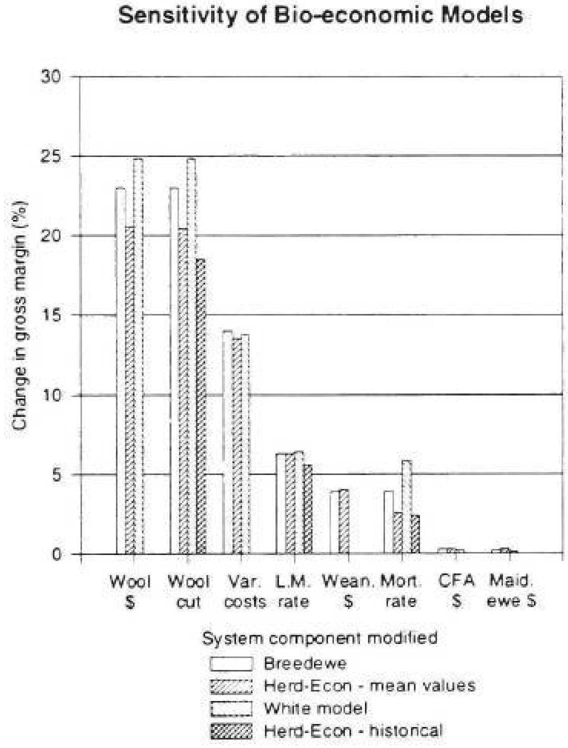

Figure 3.9. Comparative sensitivity of bio-economic models to a 10% increase of system components.

Both wool price and wool cut modifications were applied to all classes of sheep in the three models giving an equivalent effect on gross margin. This was to be expected as wool returns were the product of wool cut per class, number of sheep shorn per class, wool basis factor, and clean wool price.

The effect of weaner wether price and mortality of the B. J. White model were the most marked differences between the models (figure 3.9). Weaner wether sales in the B. J. White model did not occur due to the decision rules operating. Had they occurred, it could be expected that the model would be insensitive to weaner wether price given large numbers were unlikely to be sold, and therefore the contribution to gross income would be minor. The increased effect of mortality on gross margin was associated with stocking rate decision rules, as shown by the lower impact of mortality of the base B. J. White model in figure 3.8. Other differences which affected gross margin results to a lesser extent than those described above were:

- the 'classing effect' of Breedewe where the wool cut per head increased as a result of selection of maiden ewes; and
- the manner in which excessive stocking rates were avoided, Breedewe reduced the breeding ewe flock size as the property carrying capacity was reached, Herd-Econ sold weaner ewes as necessary and the B. J. White model sold age classes (wethers first).

Differences in Breedewe and Herd-Econ sensitivities to variation in lamb marking and mortality rates, as shown in figures 3.2, 3.3, 3.4 and 3.5, are due to the method adopted to avoid overstocking. Breedewe increased wool cut as classing of maiden ewes occurred, giving an initial increase in sensitivity. The reduction in breeding ewe numbers with maximum stocking rate reduced the sensitivity. Herd-Econ sold weaner ewes to avoid overstocking, the returns increasing the sensitivity of the model to increased lamb marking and / or decreased mortality rates. A potential draw back of the property simulation and assumptions used in the Herd-Econ model would exist if this model also increased wool production due to maiden ewe classing. Sale of weaner ewes would reduce the classing of maiden ewes and hence, any potential increase in wool productivity. However, in these Herd-Econ simulations no increase in wool productivity occurred due to classing.

The evaluation of buying and selling decisions should be the subject of detailed evaluation especially considering the interaction of climate and management expertise. This evaluation of trading rules can only be done by detailed surveys and interaction with individual property owners, e.g. Holmes (1986), Newman (1992b), Buxton *et al.* (1995a, b), and is therefore outside of the scope of this thesis.

Long time periods (10+ years depending on actual changes) were required for Herd-Econ flock class numbers to stabilise following variation in the number of young animals entering the breeding class (details not shown). RANGEPACK Herd-Econ Technical Reference Manual (v 1.01, Stafford Smith 1988) recommends that after entering approximate animal numbers for the various classes, the model should be run for 10 - 15 years, or actually for just more than the age of the oldest group, to allow numbers to stabilise. However, the User's Guide for the later version (v 2, Stafford Smith and Foran 1990a) states that following any change in the number of young animals entering the breeding group, the model should be run through nearly twice as many years as the oldest age group to allow animal numbers to stabilise. Also, depending on the complexity of the property management, it may take even more years to stabilise as waves of variation flowing through the breeding class. The later statements are more consistent with the findings from this work. Variation in Herd-Econ flock composition impacted minimally on gross margin because mortality rates, lamb marking rates and wool growth rates between different classes of ewes were the same. In the B. J. White model, where mortality rates, lamb marking rates and wool production varied between age groups (and sexes), there was great variation in annual gross margin as a result of variation in flock composition (results not shown).

Breedewe and Herd-Econ both require the user to supply biological rates (reproduction, mortality, fleece weight). Therefore, no linkage exists within the models between climate or pasture conditions and animal production as is the case with the B. J. White model. For this reason, while these two models were suitable for use in the sensitivity analysis, they were not able to be considered as possible 'base' models from which the final bio-economic model could be developed. The B. J. White model energy balance calculations were based on those of Vickery and Hedges (1972) which have long since been updated. However, Grazfeed (Freer and Moore 1990, Freer *et al.* submitted), which is based on the current Australian feeding standards for ruminants (SCA 1990) was considered a likely base model for the biological component, the testing of which is described in Chapter Four.

Herd-Econ has the potential to simulate most management scenarios in terms of the sale and purchase of livestock. Similarly, the B. J. White model has complex trading rules which are linked to the condition of the stock. However, during the course of this work, no information was found that would enable decision rules to be quantified for a particular region, let alone all wool producing areas of the state. This lack of information restricts the use of dynamic models for simulation modelling at the shire or regional level. A more simplistic approach, such as in Breedewe, which does not require as much information is more applicable to the aims of the bio-economic model being developed in this thesis.

3.2 Real world variability of important enterprise attributes

3.2.1 Introduction

The sensitivity analysis has shown the three models were most sensitive to variation in wool price, wool production and variable costs. It is also important to consider the amount of variation in these variables which occurs in the real world. The importance of a system attribute in simulation modelling is affected by both its sensitivity and real-world variation.

3.2.2 Methodology

3.2.2.1 Wool prices

Weekly national wool indicator prices for the 1976-77 to 1993-94 selling seasons were available for analysis (AWC 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, Wool International 1994). The Consumer Price Index (CPI), as reported in the Commodity statistical bulletin (1994), was used to modify the reported values for inflation using 1992-93 as the base year. Additionally, changes in the method by which the indicator price was calculated occurred in 1983-84 and 1991-92; adjustments were made to the reported values as noted in the Commodity statistical bulletin (1993). Figure 3.10 shows the national wool indicator prices:

- as reported;
- modified for inflation; and
- modified for change in methodology and inflation.

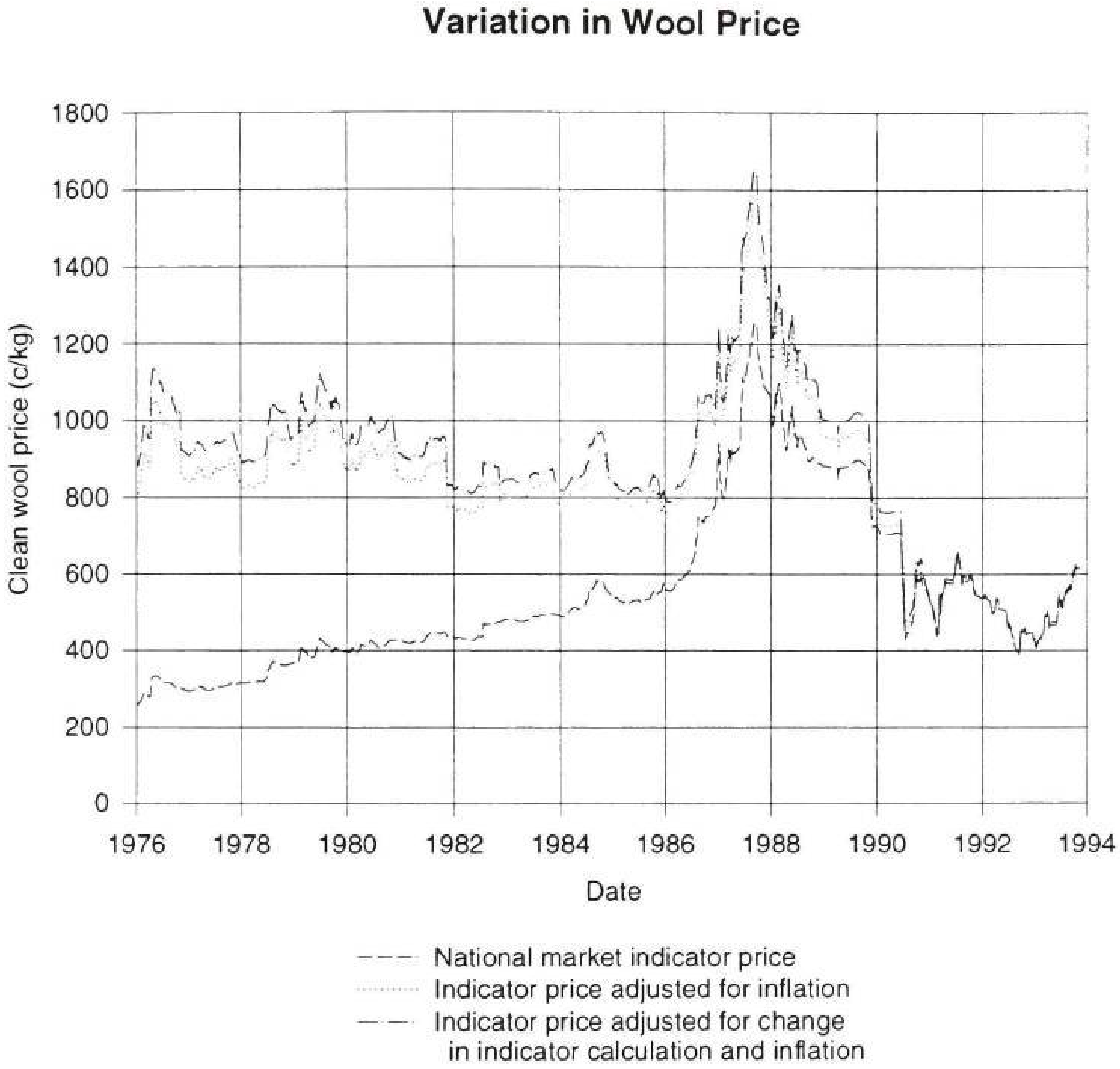

Figure 3.10. Weekly national wool indicator prices as reported, modified for inflation (base 1992-93), and, modified for changes in method of indicator calculation and inflation.

3.2.2.2 Wool production

ABS[2] (1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987b, 1988, 1989, 1990) shire statistics were used to examine the amount of variation in annual greasy fleece weights for all wool producing shires in Queensland. Inspection of the data showed that the highest and lowest calculated fleece weights were from shires in which small numbers of sheep were shorn and low tonnage of wool reported. This occurred because wool production was reported by ABS in whole tonnes of greasy wool; when shearing small numbers of sheep,

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[2] ABS data for the period 1951-52 to 1973-74 obtained directly from archival records of ABS, Brisbane office. Data for the census years 1989-90 to 1993-94 were purchased directly from ABS in electronic format.

depending on whether the actual wool production was rounded up or down, greatly influenced the calculated per head production. ABS data for 1951-52 to 1993-94 were examined:

- as reported; and
- less those records where the annual shire greasy wool production was less than 20 tonnes.

Four individual large wool producing shires (Balonne, Longreach, McKinlay, Murweh) were also selected and the amount of variation in their mean fleece weights examined. Variation in fleece weights were also examined at the property (R. Buxton unpublished data) and paddock level (see table 6.1 for grazing trials).

Total wool production per property or shire is a function of fleece weight and the number of sheep shorn. For this reason, the variability in the number of sheep shorn, and total greasy wool production, were also examined using ABS statistics.

3.2.2.3 Costs of production

ABARE conducts an annual Australian agricultural and grazing industries survey which covers broadacre agriculture. This information was initially published in the Quarterly Review of the Rural Economy, and later in the Farm surveys report. Physical and economic data on an 'average per farm' basis were available for the Queensland sheep industry from 1982-83 through to 1993-94, the last year being preliminary estimates (Tucker and Davenport 1985, Farm surveys report 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995).

Farms in the surveys are classified into various industries on the basis of the Australian and New Zealand Standard Industrial Classification which replaced the former Australian Standard Industrial Classification. Farms classified in the sheep industry are 'farms engaged mainly in running sheep' (Farm surveys report 1995). The sheep-beef industry data were not examined as the variable costs reported were not attributed to their respective enterprises.

Costs are outlays during the year for goods or services that have been sold, in this case sheep and wool. Costs may be divided into fixed and variable; fixed costs remain fairly constant irrespective of the level of farm production, e.g. rates and rental charges, whereas variable costs are directly related to the level of production, e.g. shearing and crutching costs (Smith 1991).

Classification of costs into large groups such as 'repairs and maintenance', 'other materials' and 'other services' made it difficult to accurately identify variable costs. The amount of variation in the reported costs, adjusted to a base of 1992-93, were examined using the following cost classifications:

- variable costs;
- cash costs less stock purchases; and
- cash costs, plus depreciation, plus owner / operator labour, less stock purchases.

3.2.2.4 Lamb marking and mortality rates

ABS statistics for the period 1951-52 to 1993-94 were used to examine the variability in lamb marking and mortality rates across all Queensland wool producing shires, and for selected individual shires (Balonne, Longreach, McKinlay, Murweh).

3.2.2.5 Coefficient of variation

The coefficient of variation (*CV*) is a statistical value which can be used to compare the amount of variation between two different measures and is calculated as (Doll and Orazem 1984):

$$CV = standard\ deviation / mean * 100$$

The *CV*, a measure of the variability of a system attribute, is combined with the results from the sensitivity analysis to provide an indication of the overall importance of each attribute to the system model. The importance of each attribute is calculated as:

$$Importance\ of\ attribute = CV / 10 * sensitivity$$

where *CV* is the coefficient of variation, a measure of the real world variability of the attribute,

10 is the percentage change in model attributes during the sensitivity analysis, and

sensitivity is the change in gross margin resulting from the 10% change in model attributes found in the sensitivity analysis.

The above calculation has the effect of modifying the results of the earlier sensitivity analysis as if each model attribute was modified by one standard deviation, rather than a uniform 10%.

3.2.3 Results

3.2.3.1 Wool prices

Wool prices adjusted for inflation (figure 3.10) fluctuated more than the unadjusted prices in the first half of the time period covered by the graph. Most of this fluctuation can be attributed to the use of a single annual CPI value applied to all wool prices in each selling season. For example, similar wool prices prior to and following the end of June (end and start of wool selling season) may show more variation following modification for inflation as two different CPI values would be used in their adjustment. The *CV*s for national wool indicator prices are presented in table 3.9, together with the sensitivities of the three models calculated in the first part of this chapter to wool prices.

3.2.3.2 Wool production

Shires removed by the weight restriction described in 'methodology' were all from the Darling Downs and Fitzroy regions. Because of the large number of records in the data set (1911), and the relatively small number removed by the tonnage restriction (155 or 8.1% of total records), the coefficients of variation for the complete and tonnage restricted data sets were very similar, 13.0 and 11.8% respectively. The latter *CV* and those for the four selected individual shires are shown in table 3.9. *CV*s for property and paddock fleece weights are also presented in table 3.9.

Table 3.9. Real world variability of important enterprise attributes as measured by coefficients of variation, and the sensitivity of simulation models to these attributes.

Model	Sensitivity to a 10% increase in attribute (%)	Description of real world attribute	*CV* (%)	[1]Importance of attribute (%)
Wool price				
Breedewe	22.95	national wool indicator price as reported	38.9	[2]51.5 - 64.9
Herd-Econ	20.60	national wool indicator price adjusted for inflation	25.2	
B. J. White	24.80	national wool indicator price adjusted for inflation and change in methodology of indicator calculation	26.2	
Fleece weights		**Shire level data**		
Breedewe	19.40	mean shire fleece weights (tonnage restricted)	11.8	16.3 - 29.5
Herd-Econ	20.44	Balonne - mean shire fleece weight	9.8	
B. J. White	24.80	Longreach - mean shire fleece weight	8.4	
		McKinlay - mean shire fleece weight	9.9	
		Murweh - mean shire fleece weight	11.9	
		Property level data		
		property No. 1	15.4	30.0 - 92.0
		property No. 2 - adult sheep	13.9	
		property No. 2 - weaners	20.2	
		property No. 3 - adults	14.9	
		property No. 3 - hoggets	15.8	
		property No. 3 - weaners	37.1	
		property No. 4	18.1	
		Paddock level data		
		Burenda - 10% utilisation	14.5	12.4 - 58.5
		Burenda - 20% utilisation	14.5	
		Burenda - 30% utilisation	15.1	
		Burenda - 50% utilisation	21.6	
		Burenda - 80% utilisation	23.4	
		Burenda - all utilisation paddocks	15.5	
		Toorak - 10% utilisation	21.1	
		Toorak - 20% utilisation	20.1	
		Toorak - 30% utilisation	21.3	
		Toorak - 50% utilisation	19.1	
		Toorak - 80% utilisation	14.9	
		Toorak - all utilisation paddocks	11.8	
		Arabella - 20% utilisation	21.0	
		Arabella - 35% utilisation	18.4	
		Arabella - 50% utilisation	17.2	
		Arabella - 80% utilisation	23.6	
		Arabella - all utilisation trials	13.5	
		Gilruth Plains - 1 ha / sheep	10.4	
		Gilruth Plains - 2 ha / sheep	9.2	
		Gilruth Plains - 3 ha / sheep	6.4	
		Gilruth Plains - all paddocks	16.3	
		Eastwood - 0.1 ha / sheep	21.4	
		Eastwood - 0.2 ha / sheep	13.5	
		Eastwood - 0.4 ha / sheep	11.0	
		Eastwood - 0.8 ha / sheep	10.5	
		Eastwood - all paddocks	13.5	
		grazing trials - all paddocks	19.5	37.8 - 48.4
Number of sheep shorn				
		all Queensland wool producing shires	29.8	
		Balonne	24.0	
		Longreach	18.3	
		McKinlay	44.1	
		Murweh	27.4	
Total greasy wool production				
		all Queensland wool producing shires	20.6	
		Balonne	20.3	
		Longreach	16.7	
		McKinlay	40.5	
		Murweh	21.9	
Variable costs				
Breedewe	-14.05	total variable costs[3]	31.3	-41.3 - -49.0
Herd-Econ	-13.50	variable costs per sheep shorn[3]	34.9	
B. J. White	-13.80	variable costs per kg wool[3]	30.6	

Table 3.9 continued.

Model	**Sensitivity** to a 10% increase in attribute (%)	**Description of real world attribute**	***CV* (%)**	**[1]Importance of attribute (%)**
Lamb marking rate				
Breedewe	6.26	all Queensland wool producing shires	28.1	10.6 - 15.9
Herd-Econ	6.27	Balonne	24.9	
B. J. White	6.39	Longreach	22.5	
		McKinlay	16.9	
		Murweh	22.2	
Mortality rate				
Breedewe	-3.89	all Queensland wool producing shires	66.5	-8.64 - -38.6
Herd-Econ	-2.55	Balonne	61.7	
B. J. White	-5.81	Longreach	33.9	
		McKinlay	43.3	
		Murweh	53.9	

[1] *Range for 'importance of attribute' estimated by using the minimum and maximum values in calculations.*

[2] *Unadjusted wool prices not included in calculations for range.*

[3] *Variable costs are usually expressed on a per head basis. Total and per kg wool variable costs are also used here to account for any correlations between sheep numbers, season quality and variable costs.*

CVs for the number of sheep shorn, and total wool produced, in Queensland and the four individual shires are also shown table 3.9. The amount of variation in the number of sheep shorn in the individual shires varied greatly, and was similar to or greater than the variation in wool prices. Variation in sheep numbers includes, not only the effects of season, but also management decisions such as changes in enterprise mix on beef / sheep properties. McKinlay shire had far greater variation in numbers of sheep shorn relative to the other three shires examined; much of this difference can be attributed to the increase in cattle and the reduction in sheep numbers since the early 70's (figure 3.11).

3.2.3.3 Costs of production

The amount of variation in reported costs of production, adjusted to a base of 1992-93, is shown in table 3.10, and the variable costs (unadjusted for cattle) included in table 3.9. Production costs per sheep and lamb shorn for the period 1982-83 to 1993-94 are shown in figure 3.12. The upsurge in costs in 1988-89 was associated with a dramatic increase in those costs grouped under 'other materials'. Variable cost *CVs* were in the range of 28.8 - 34.9% which were greater than that for wool prices (25.2 and 26.2%) and shire fleece weights (8.4 - 13.0%) but within the range for numbers of sheep shorn (18.3 - 44.1%). Inclusion of fixed costs in the *CV* calculations, as would be expected, reduced the amount of variation. Adjusting costs for the number of cattle present on the property had minimal impact due to the relatively minor size of the herd.

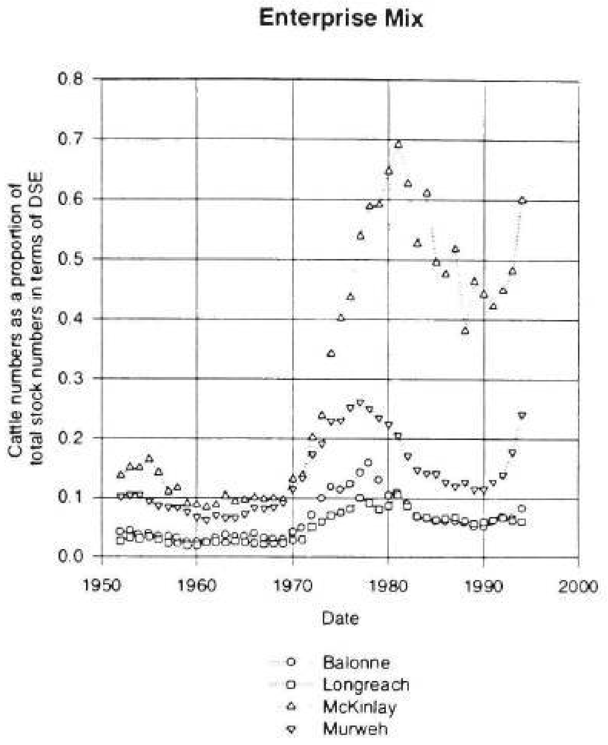

Figure 3.11. Enterprise mix of selected shires; cattle numbers as a proportion of total stock numbers in terms of dry sheep equivalents.

Table 3.10. Coefficient of variation of costs for an average Queensland sheep industry farm for the period 1982-83 to 1993-94 based on ABARE data (base 1992-93).

Cost classification	***CV* - average QLD sheep industry farm**	***CV* - average farm adjusted for cattle costs[1]**
Total variable costs	31.3	29.1
Variable costs per head shorn	34.9	33.5
Variable costs per ha	31.0	29.0
Variable costs per kg wool	30.6	28.8
Total cash costs less stock purchases	19.4	17.3
Cash costs less stock purchases per head shorn	22.5	21.3
Cash costs less stock purchases per ha	17.6	17.4
Cash costs less stock purchases per kg wool	17.1	17.2
Total cash costs plus depreciation plus owner / operator labour less stock purchases	15.7	13.4
Cash costs plus depreciation plus owner / operator labour less stock purchases per head shorn	20.0	19.0
Cash costs plus depreciation plus owner/operator labour less stock purchases per ha	15.0	15.4
Cash costs plus depreciation plus owner / operator labour less stock purchases per kg wool	14.6	15.4

[1] *the average Queensland sheep industry farm included in all years a small beef cattle herd, all costs apart from shearing and crutching were proportioned assuming 1 cow equivalent to 7 DSE.*

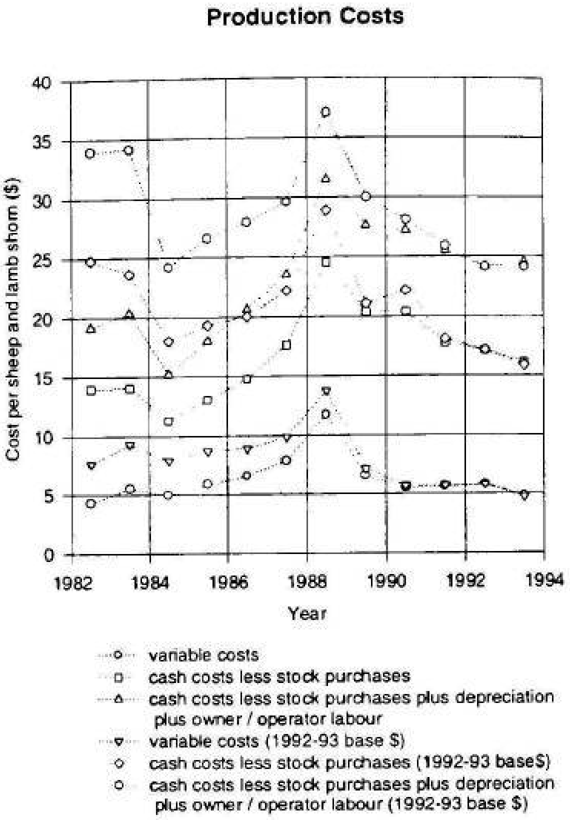

Figure 3.12. ABARE production costs per sheep and lamb shorn for the period 1982-83 to 1993-94.

The possibility that wool prices, fleece weights and variable costs were correlated was also examined. Results of the examination of the relationships between wool prices , fleece weights and variable costs are shown in table 3.11. There was a positive correlation between the wool indicator price and variable costs, whereas no significant relationship (r=-0.236 P=0.384) existed between the wool indicator price and the index of prices paid by Australian farms (Commodity statistical bulletin 1993, Indexes of prices received and paid by farmers: December quarter 1995 - published 1996) over the same time period. The survey variable costs includes prices of services and materials and quantities purchased, while the index of prices paid monitors only price trends of a selected basket of goods and services. This suggested the relationship between wool indicator price and variable costs was the result of producers modifying their spending patterns in response to changes in wool prices.

3.2.3.4 Lamb marking and mortality rates

Variation in lamb marking and mortality rates for all Queensland shires and four individual shires are listed in table 3.9.

Table 3.11. Pearson correlation matrix for wool prices adjusted for inflation, fleece weights and variable costs adjusted for inflation for the period 1982-82 to 1993-94.

	Mean national market indicator price - c/kg clean (July 1 - June 30)	**Mean QLD greasy fleece weights (April 1 - March 31)**	**Mean variable costs per sheep and lamb shorn (July 1 - June 30)**
Mean national market indicator price - c/kg clean (July 1 - June 30)	1.0		
Mean QLD greasy fleece weights (April 1 - March 31)	0.28^2	1.0	
Mean variable costs per sheep and lamb shorn (July 1 - June 30)	0.83^1	0.09^2	1.0

[1] *P<0.001.* [2] *not significant (P>0.05).*

3.2.4 Discussion

The data used to calculate attribute *CVs* differed in size (see Section 3.2.2), and hence, *CVs* for attributes with small data sets would have higher sample errors. However, as a general guide in terms of real world variability, Queensland shire mortality rates had the highest coefficient of variation (66.5%), with the values for the individual shires also large (34 - 62%). Following this were the number of sheep shorn (McKinlay - 44%), total greasy wool production (McKinlay - 40%), and then variable costs (31 - 35%). Shire lamb marking rates and wool prices (excluding prices as reported) were of a similar overall magnitude, 16.9 - 28.1% and 25 - 26% respectively. Fleece weights were overall the least variable, although there were a number of exceptions. Within the fleece weight group, property and paddock fleece weights were of a similar general magnitude with shire values the least variable.

The issue of scale as discussed in Chapter Two, and therefore, the problems of comparing data from paddocks, properties, shires and larger regions need to be borne in mind. The dampened variation in shire fleece values relative to property and paddock values probably occurs because shire values incorporate a range of climates (especially rainfall), soil and pasture communities, sheep classes, genotypes and stock management. Adjusting the shire mean greasy fleece weights for the apparent increase in fleece weights over time (see Chapter Six) would be expected to further decrease the amount of variation. However, given that the main focus of this work is at the property level, attention needs to be focused on property level variability.

The *CVs* calculated for the national wool indicator price are lower than the reported 45.2% for the mean annual Victorian greasy wool price over the period 1885 - 1969 adjusted using the CPI (Bardsley and Olekalns 1996). However, the latter authors probably increased their variation by restricting their analysis to the period prior to the introduction of the wool price stabilisation scheme. With the loss of the reserve price scheme, there is the possibility that wool price variation calculated here may be misleading in terms of future wool price variation. In contrast, the extreme variation in shire values for the number of sheep shorn, and therefore total greasy wool production, were shown to be heavily influenced by management decisions relating to enterprise mix, rather than seasonal conditions alone. Thus in terms of wool enterprises, the effective variation in sheep numbers and total greasy wool numbers is probably less than that calculated here.

The importance of each attribute as estimated by the product of the model sensitivity, and the *CV* as a proportion of 10% (the value used in the model sensitivity), resulted in changes in the ranking of attributes. Although property fleece weights had the highest maximum range, 92% (table 3.9), inspection of the data reveals a lower value is perhaps more representative of the importance of property fleece weights. The 92% was for weaners from property No. 3 while the next highest maximum was 50.1% for property No. 2 weaners, and the maximum range for other sheep classes from property No. 3 was 39.1%. Overall, wool price would appear to be the most important attribute in terms of simulation modelling followed by variable costs, fleece weights, mortality rates, and lamb marking rates.

Wool prices and variable costs are direct inputs to the model being developed while the number of sheep shorn, which was also highly variable, is a function of mortality, reproduction and management decision rules. Thus, fleece weights were the most important attribute to be simulated and were the focus of this thesis, while simulation models for sheep reproduction and mortality were being developed elsewhere (Moore *et al.* 1995, Pepper *et al.* 1996).

CHAPTER FOUR

Evaluation of Equations Derived From the Feeding Standards for Australian Livestock: Ruminants

4.1 Introduction

Chapter Three established the need to model the variation in animal reproduction, mortality and wool production. The models by White (1978) and White *et al.* (1983) suggest that modelling animal production via energy balance is the soundest physiological approach, as outlined in the *Feeding Standards for Australian Livestock: Ruminants* (SCA 1990). The feeding standards were prepared by the Animal Production Committee through a working party which developed a uniform feeding system based on metabolisable energy for ruminants, and a corresponding system for protein. The working party reviewed all available literature, including feeding standards developed from the Agricultural Research Council (UK; ARC 1980, 1984), National Research Council (USA; NRC 1985) and the Institut National de la Recherche Agronomique (France; INRA 1978). Thus, SCA (1990) represents the most up to date review and analysis of data with an emphasis on Australian experimental results.

The feeding standards formed the theoretical basis for Grazfeed, a computerised nutritional management system for grazing ruminants (Donnelly *et al.* 1994). Grazfeed predicts animal performance on a daily basis, and as such, it was considered a likely model for simulating the performance of sheep in Queensland. However, because of a strong bias within the Australian feeding standards toward temperate systems relative to subtropical and tropical systems, reflecting the degree of research into each system, uncertainty over the relevance of Grazfeed to subtropical / tropical grazing systems exists (Clewett 1994, Thompson submitted). Therefore, it was necessary to fully test the ability of Grazfeed to simulate animal production for the wool producing regions of Queensland.

The Queensland wool industry is based on a very wide range of pastures including C_3 and C_4 grasses, C_3 and C_4 forbs, and shrubs / trees such as *Acacia aneura* (mulga) and *Acacia nilotica*. The erratic rainfall of western Queensland causes pulses of forage growth and dynamic changes in pasture composition. Thus, variability in nutritional supply is compounded by both erratic growth patterns and varying nutritional quality of species of grasses, forbs and shrubs (Orr 1986). Because the environment is highly variable, modelling animal production is a greater challenge than modelling animal production in less variable environments of the temperate or higher rainfall zones. To help with the complexity, the wool industry is divided into two major pastoral zones: mulga grasslands, and Mitchell or non-mulga grasslands.

Mulga grasslands occur in the south-west of the state. *Acacia aneura* (mulga), which gives its name to the pasture community, is a shrub or tree which varies in density from sparse (1 / ha) to very dense (8000 / ha; Perry 1970). Since Grazfeed is not designed for semi-arid rangelands where shrubs and forbs make up a large part of the vegetation' (Freer and Moore 1990), mulga grasslands may be unsuitable for the application of Grazfeed.

The Mitchell grasslands are an important wool producing area. Trees and shrubs are sparse in the northern Mitchell grasslands, while further south, grasslands merge with open wooded areas. Mitchell grass (*Astrebla* spp.) is the dominant pasture species but forbs and annual grasses grow in response to rainfall at specific times of the year (Orr and Holmes 1984). Mitchell grasslands may be suitable for Grazfeed.

Reported here are the results of a comprehensive testing of the ability of Grazfeed equations to predict animal production as observed in Queensland grazing trials. The analysis was carried out using a FORTRAN model incorporating the relevant equations. The grazing trials covered a large range of seasons, soil and pasture communities. Since many of these trials were conducted to study long term stability and productivity of pasture, animal records did not receive the attention expected in an animal production trial.

As will be described, the inability of the FORTRAN version of Grazfeed to satisfactorily predict animal production resulted in an attempt to optimise parameters and modify equations within the model in order to improve the model. Additionally, Grazfeed generated feed intake / metabolic variables and trial observations were examined for their ability to explain recorded variation in animal production. A diet selection subroutine, detailed in Chapter Five, was also used in conjunction with GRASP to supply daily estimates of dietary information in an attempt to improve predicted animal production. The field data sources, model development, and results from these simulation experiments are described sequentially, as a logical development process.

4.2 Grazfeed - the model

Grazfeed (V2.0.6) uses climatic, pasture and animal data to calculate the feed intake, diet selection, energy / protein digestion and metabolism, and animal performance. Animal performance is expressed as liveweight gain, milk production and wool growth. Table 4.1 shows inputs for Grazfeed. Calculations performed and output depend on whether or not supplements are fed. When supplements are fed, a user may either feed various levels of supplement and monitor animal performance or, define a performance target and calculate the level of supplementation to achieve the target. If supplements are not fed, only animal performance is calculated. Grazfeed outputs are shown in table 4.2.

4.3 Data sources

Sheep grazing trials with appropriate data to evaluate Grazfeed are detailed in table 4.3. Their locations, including the Eastwood and Gilruth Plains grazing trials used in Chapter Six, are shown in figure 4.1.

4.3.1 Data reliability and problems

Use of oesophageal fistulated (*OF*) animals, the best method for obtaining information on the diet selected by grazing animals, is based on the assumption that these animals will exhibit the same diet selection as the experimental animals (Hogan 1996). However, *OF*

Table 4.1. Inputs required to run the Grazfeed model.

Animal Inputs	**Pasture Inputs**
• species (ovine / bovine)	• green pasture yield and digestibility
• breed type eg. small merino	• dead pasture yield and digestibility
• standard reference weight[1] (*SRW*, value is suggested but may be altered)	• percentage legume in pasture
• standard fleece weight[2] (*SFW*, value is suggested but may be altered)	• pasture native or improved
• animal class eg. wethers, mature ewes	• steepness of land
• if ewes, pregnant / lactating	**Climatic Data**[3]
• if pregnant, time since mating and ram breed type	• maximum and minimum daily temperature
• if lactating, ram breed type, condition score of ewes at mating, mean age of lambs and mean weight of lambs	• mean wind speed over 24 hours
• mean shorn weight	• rainfall over 24 hours
• mean weight	**Supplements**[4]
• mean depth of fleece	• concentrate / roughage type
• highest weight achieved by animals to date	• percentage of each supplement if mixture is being fed
Miscellaneous	• cost per tonne
• month of year	• nutritional information for each supplement supplied but may be altered

[1] *SRW* is the weight of a non-pregnant fleece free mature ewe in average condition, [2] *SFW* is the greasy fleece weight produced by a non-pregnant / non-lactating mature ewe in average condition, [3] optional input, [4] supplements may be fed.

Table 4.2. Outputs of the Grazfeed model.

• potential dry matter intake	• *ME* requirements for maintenance and lactation
• herbage and supplement eaten	• crude protein requirements for maintenance, wool production, lactation and weight gain
• digestibility of herbage and supplement eaten	• rumen degradable protein intake and requirements
• crude protein percentage of herbage and supplement eaten	• net energy required for heat production due to low environmental temperature
• percentage of crude protein of herbage and supplement that is degradable	• daily weight loss/gain
• metabolisable energy (*ME*) content of diet	• wool production per day
• metabolisable energy intake	• milk production per day
• efficiency of use of *ME* for maintenance and gain	• supplement cost per head

Table 4.3. Sheep grazing trials used in testing of GRASP.

Location and Source	Pasture Type	Period of Trial	Observations - Type and Number	Comments and Corrections
'Halton' - Charleville, Beale (1975)	mulga grassland association	Oct. 1971 - Jan. 1974	Liveweights with fleece (10), *DMI*, *OMD* and *CP* (13), pasture yield (13).	Beale (1975) noted the possibility of the *in vitro* digestibility technique he used underestimating total digestibility when mulga was present in the diet. This resulted in a variable reduction in the estimation of dry matter intake depending on the mulga content of the diet. Also, there were problems with incomplete faecal collection using the faecal harness bags. Therefore, when comparing Grazfeed to data from Halton, the field data were supplemented by two modified sets of data: 1. digestibility and dry matter intake as reported; 2. digestibility and dry matter intake modified assuming mulga digestibility of 45%; 3. digestibility and dry matter intake modified assuming mulga digestibility of 50%. Modification of the Halton field data was done on the assumption the *in vitro* technique used by Beale (1975) estimated digestibility of mulga at 39% (McLeod 1973 cited by Beale 1975). It was assumed a more correct level of digestibility for mulga was in the range of 45 - 50% which were values from the work of Norton *et al.* (1972) and McMeniman (1976) cited by Beale (1975) carried out using *in vivo* digestibility techniques. The observed digestibilities and feed intake were then modified depending on the amount of mulga present in the diet. At the time of the first three dietary samplings no liveweights were recorded. A liveweight of 42 kg which was similar to that recorded at the two following weighings was assumed at these times. The *SRW* used was 47.0 kg, the *SFW* was 5.2 kg (N. O'Dempsey pers. comm.). Liveweights were recorded unadjusted for fleece with little information available as to wool growth rates and shearing times (I. Beale pers. comm.). The liveweights of the three groups of sheep used were adjusted assuming they were shorn prior to entering the trial paddock and that mature sheep produced 14 grams greasy fleece / day (5.2 kg / 365 days) and weaners 8 g greasy fleece / day.
Toorak Research Station - Julia Creek, Lorimer (1976, unpublished data)	Mitchell grass	Dec. 1970 - Jan. 1973	Liveweights fleece free (30), *DMI*, *OMD*, *DMD* and *CP* (25), pasture yield (19).	A *SRW* of 44 kg and a *SFW* of 4.2 kg was considered appropriate (D. Cobon pers. comm.).
Toorak Research Station - Julia Creek, Pritchard *et al.* (1986) and Pritchard (1988)	Mitchell grass	March 1979 - Dec. 1979	Liveweights fleece free (3), *DOMI*, *OMD* and *CP* (3), pasture yield (3).	Measurements were made in March, October and December. The long time period between the March and October weighings meant that a number of changes in feed quantity, quality, and therefore liveweight may have occurred. For this reason only the liveweight change between October and December was considered useful. Unfortunately, dates at which liveweight measurements were made were not listed. Wool growth measurements for the same period were reported as being made from 17/10 to 2/12, an interval of 46 days (Pritchard 1988), while pasture yields were measured on 30/10 and 17/12 , an interval of 48 days (Pritchard unpublished data). Obviously the number of days over which the liveweight change occurred was crucial: an assumption of 48 days was used to calculate the mean daily liveweight gain for both groups of sheep. Pasture yield and diet quality for the period were taken as the mean of that recorded in October and December. Although digestible organic matter intake was reported, no ash or organic matter content of diet was reported, making conversion to dry matter intake and comparison with EPBTS predicted feed intakes difficult. The feed intake used in the comparison of predicted and observed mean daily liveweight gain was that calculated by EPBTS. *SRW* and *SFW* were as for Lorimer (1976).

Table 4.3 continued.

Location and Source	Pasture Type	Period of Trial	Observations - Type and Number	Comments and Corrections
'Burenda' - Augathella, McMeniman *et al.* (1986a, b)	Mitchell grass	Nov. 1976 - Aug. 1979	Liveweights fleece free (21). *DMI*, *OMD* and *CP* (5 per utilisation), pasture yield (1).	Two pasture utilisation rates were used, 30% and 50% based on pasture yield at the end of the growing season. Fleece free liveweight measurements covering 21 time periods were available from November 1976 through to April 1979 (McMeniman unpublished data) which meant the dietary data collected in August 1979 could be used to compare predicted and observed feed intakes but not liveweight gain. Unfortunately, only one pasture yield was available for April of each year from 1975 through to 1979 (range 1230 - 2210 kg DM / ha). With pasture height set at 10 cm / tonne DM / ha, the impact of pasture yield on the availability of pasture was markedly reduced, potential dry matter intake calculated by EPBTS being almost entirely dependent on digestibility of the feed and animal factors. A pasture yield of 1000 kg DM / ha was chosen (relative availability = 0.99, maximum 1.0), a level at which there was no impact on EPBTS potential dry matter intake. A *SRW* of 55 kg and *SFW* of 6.0 kg was considered appropriate (N. O'Dempsey pers. comm.).
'Arabella' - Charleville, McMeniman *et al.* (1986a, b)	mulga grassland association	Nov. 1978 - Nov. 1979	Liveweights with fleece (12), *DMI*, *OMD* and *CP* (3), pasture yield (2).	Three diet digestibility and 12 liveweight measurements (not corrected for fleece) were collected from November 1978 to November 1979 (N. McMeniman pers. comm.). Two pasture yields were recorded in April 1978 and 1979 (264 - 798 kg DM / ha). McMeniman *et al.* (1986a) reported the mulga grassland association pastures were in 'good to excellent condition during November 1978 and February 1979, but had deteriorated to drought conditions by November 1979'. On this basis, a pasture yield of 1000 kg DM / ha (relative availability = 0.99) was adopted for November 1978 and February 1979 data while 300 kg DM/ha (relative availability = 0.93) was used for November 1979. A *SRW* of 45 kg and *SFW* of 4.8 kg was considered appropriate (N. O'Dempsey pers. comm.). Arabella liveweights (N. McMeniman pers. comm.) were not reported corrected for wool. Adjustments were made assuming a wool production rate of 14 g greasy fleece / day.
'Biddenham' - Augathella, Orr *et al.* (1988)	Mitchell grass	April 1979 - Dec. 1983	*DMI*, *OMD* and *CP* (11), pasture yield (9), liveweights with fleece (37).	Breeding ewe trial. Unfortunately, EPBTS was only able to simulate wethers / non-breeding ewes and the information available from this ewe trial was unsuitable for use at this stage for feed intake and liveweight gain comparisons. The dry matter digestibility and crude protein content data of the diet were used to examine the relationship between these two components of diet quality.
Blackall, McMeniman *et al.* (1989)	Mitchell grass and small areas of open gidgee woodland	May 1976 - Dec. 1976	*OMD* and *CP* (1), liveweights with fleece (1).	Breeding ewe trial. A single dietary sampling was collected using *OF* wethers in October. The dry matter digestibility and nitrogen content data of the diet were used to examine the relationship between these two components of diet quality.
Toorak Research Station - Julia Creek, Cobon *et al.* (1994a)	Mitchell grass	June 1993	*DMI* and *DMD* (1), pasture yield (1), liveweight with fleece (1).	24 day grazing trial. A *SRW* of 47.0 kg and *SFW* of 4.8 kg was considered appropriate (D. Cobon pers. comm.). Liveweights corrected assuming greasy wool growth rate of 14 g day, time of shearing provided by author.
'Rosebank' - Longreach, Cobon *et al.* (1994a)	Mitchell grass	Nov. 1991	*DMI* and *DMD* (1), pasture yield (1), liveweight with fleece (1).	24 day grazing trial. A *SRW* of 52.0 kg and *SFW* of 5.2 kg was considered appropriate (D. Cobon pers. comm.). Liveweights corrected assuming greasy wool growth rate of 10 g day, time of shearing provided by author.

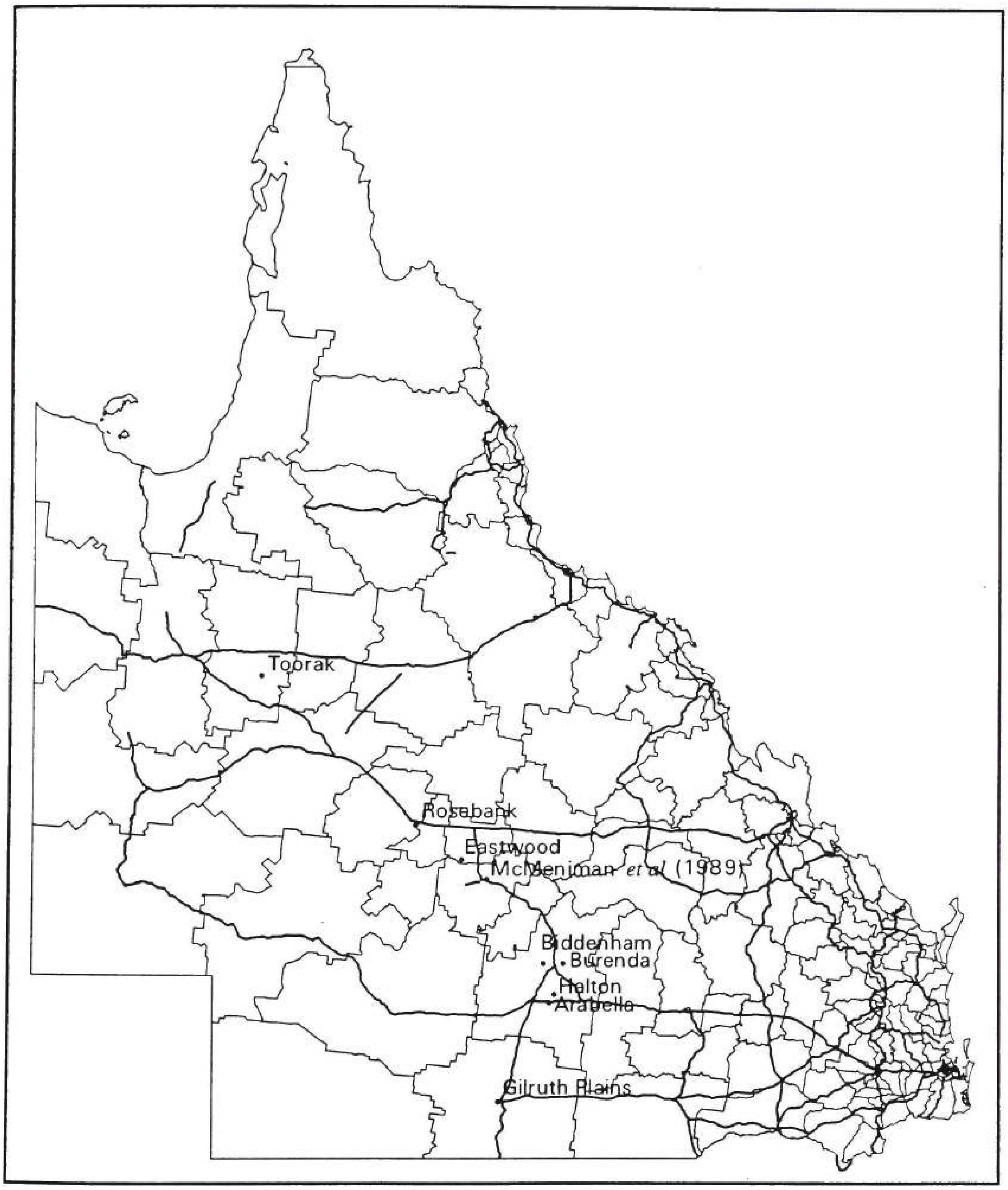

Figure 4.1. Location of sheep grazing trials.

animals are often not the same age, and are usually separated from experimental animals except when measurements are being made. Hogan (1996) recommended that additional independent tests, such as identification of plants from faeces or delta carbon-13 techniques, should be performed to confirm the above assumption.

Two records of liveweights existed for the Burenda and Arabella trials which differed on occasions (N. McMeniman unpublished data). The source used was that which reported liveweights most frequently, and therefore, gave a potentially more accurate picture of changes in liveweight.

The Halton grazing trial data should be viewed with caution due to problems with faecal collection and the impact of dietary mulga on the organic matter digestibility (I. Beale pers. comm.). The largest content of mulga in the diet, 67%, was recorded in June 1972. Assuming a mulga digestibility of 0.5 rather than the measured value (0.39), resulted in an increase in total diet digestibility of 8 points (0.44 → 0.52) and an increase in feed intake of 0.123 kg / day. The lowest content of mulga in the diet, 3%, was recorded in December 1972 and had negligible effect on total diet digestibility and feed intake.

Pritchard (1988) noted that his digestible organic matter intakes were higher than those found by Lorimer (1976) at Toorak. Pritchard's (1988) recorded digestible organic matter intakes were in the range 0.889 - 2.187 kg / day (mean 1.5 kg / day) while Lorimer's (1976) intakes were in the range 0.105 - 0.456 kg / day (mean 0.331 kg / day). The sheep in both trials were of similar weights: 31.5 - 46.8 kg. Lorimer's (1976) mean dry matter intake was 0.84 kg / day (range 0.32 - 1.17), which was closer to those reported for the other trials and the oft used 'rule of thumb' value, 1.09 kg / day (400 kg DM / year). Estimates of the dry matter intakes of Pritchard (1988) are approximately 2.14 - 3.0 kg / day assuming 50 - 70% dry matter digestibility. The Australian feeding standards (SCA 1990) predict dry matter intakes of 0.75 - 1.22 kg for 50 kg sheep (*SRW* 50 kg) grazing abundant pastures (> 2 tonnes DM / ha) and selecting a diet of 50 - 70% dry matter digestibility. Pritchard (1988) attributed the marked difference in dry matter intakes between his and Lorimer's (1976) to three possible causes:

- loss of chromium sesquioxide from faecal samples during grinding leading to a possible overestimation of intake. Lorimer (1976) used faecal bags in combination with *OF* digestibility to calculate intake levels;
- rumen liquor used for calculating digestibility was from sheep being fed lucerne leading to a possible overestimation of true digestibility; and
- diurnal variation in the concentration of chromium in the faeces may have led to overestimation of faecal output since samples were only collected at 0600 hours. Herd *et al.* (1993) reported afternoon faecal samples had 2.5% ($P<0.01$) higher chromium concentrations compared with morning samples.

Although no comparison could be made with dry matter intake, overestimated digestibilities would cause mean daily liveweight gains to be overestimated. Pasture yields, being greater than 1000 kg DM / ha, had little effect on animal performance.

Unfortunately, source data are unreliable due to problems with methodology, (Halton and Toorak - Pritchard *et al.* grazing trials) and with the passage of time, it is difficult to identify and correct this problem (Blackall, Toorak - Pritchard *et al.*, Burenda and Arabella grazing trials).

4.4 FORTRAN version of Grazfeed

4.4.1 Methodology

As Grazfeed (version 2.0.6) is a proprietary computer software package, only available in a compiled form, and is not suitable for research that examines production over long time periods (3 - 12 months), it was necessary to construct a separate FORTRAN version of Grazfeed to allow the grazing trial data to be examined. The new code was based on a number of sources of information (SCA 1990, Freer *et al.* submitted, A. Moore pers. comm., M. Freer pers. comm.). The parameter and functions of Grazfeed V2.0.6 were included in the FORTRAN version, the code for which is presented in Appendix Three. From this point on, the FORTRAN version of Grazfeed will be referred to as EPBTS (Energy and Protein Balance of Tropical Sheep).

The ability of sheep and other grazing ruminants to select a higher quality diet than the average of the available herbage has been noted by many workers (Beale 1975, Mulholland *et al.* 1977, Jung and Sahlu 1986, Jung *et al.* 1989). Diet selection at the plant-animal interface is one of the major problems encountered when modelling animal production (Black 1984). The Grazfeed equations for diet selection, and therefore the quality of the diet ingested, were based on improved pastures and may not be applicable to semi-arid environments (Freer and Moore 1990, Dove 1996).

It was decided to avoid possible problems with diet selection, and to test the production components of EPBTS, by using grazing trial data in which *OF* sheep were used to collect information on dietary quality and feed intake. This allowed EPBTS to treat available herbage as a single pool, the dry matter digestibility (*DMD*) of the diet selected by the *OF* sheep was attributed to this herbage pool. Thus quality of the diet was the same as that recorded during the grazing trial without requiring calculations of diet selection, thereby avoiding additional sources of error.

The grazing trials suitable for testing EPBTS calculations (table 4.3) were those in which sheep liveweights, herbage yield, dry matter intake, digestibility and crude protein content (optional) of the diet were recorded. Frequent measurements of liveweight were preferred so that a realistic mean daily liveweight gain (*LWG*) could be calculated. During the interval between weighings, and preferably at a point centrally located, information was collected on pasture yield, digestibility of intake and dry matter intake (using *OF* sheep). Large time periods between weighings increased the possibility that the calculated mean daily gain was not representative of what occurred in the field, and that the instantaneous pasture and dietary data would not explain the observed change in liveweight.

EPBTS simulated daily wool production based on *metabolisable energy intake* (*MEI*) or *apparently digestible protein leaving the stomach* (*ADPLS*), whichever was the most limiting. Wool production was then adjusted for age (if less than two years), and time of the year (photoperiod), before being included in a 25 day running mean which allowed for the lag affect associated with changes in rate of wool production. Preliminary work with wool production found EPBTS was under estimating production. Unfortunately, the amount of information on wool growth rates (mg / cm^2) within the growing season is limited and comparison between trials may be difficult. For example, White (1978) found that two trials with similar fleece weights at shearing had reported markedly different growth rates.

The accurate simulation of liveweight change was necessary to simulate mortality and reproduction. Also, sheep liveweight influences wool production through potential dry matter intake and body surface area calculations. For these reasons, it was decided to concentrate on feed intake and liveweight gain in terms of model testing, the equations concerned with wool production were also included.

To ensure EPBTS was the same as the commercial version, feed intake and liveweight gain predicted from this version, were compared with that of Grazfeed (V2.0.6) using test data which varied in time of year, latitude, climate, pasture and animal information.

4.4.2 Results

The relationships between feed intake and animal production (liveweight gain is shown in figure 4.2) predicted by Grazfeed and those predicted by EPBTS had correlations of approximately 1.0, slopes of 1.0 and intercepts of 0.0. These indicated that EPBTS was an accurate reflection of the commercially available Grazfeed.

4.5 Dry matter digestibility / crude protein relationships

The crude protein content of forage is normally calculated within EPBTS using the relationship with dry matter digestibility shown in figure 4.3 for Grazfeed, assuming no legume is present in the pasture. The protein level of the ingested feed is important because it can limit both liveweight gain and wool production, and also lead to a reduction in feed intake if the rumen digestible protein intake is less than that required by the rumen microbes for normal activity (see Appendix One, Parts A and B for more details).

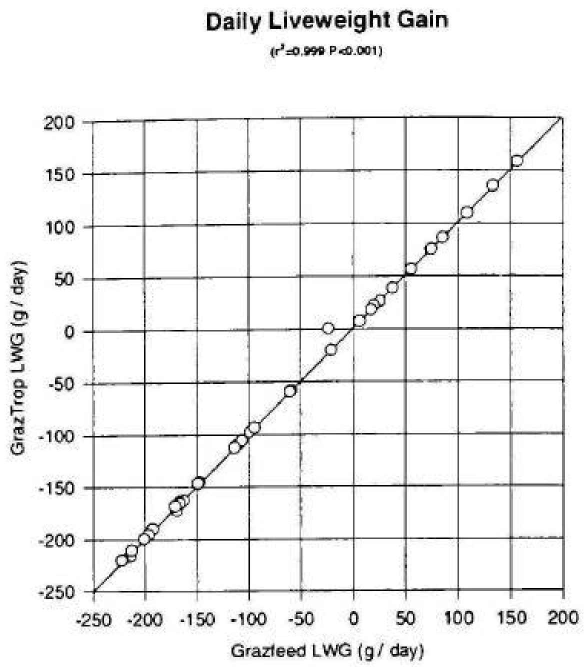

Figure 4.2. Comparison of Grazfeed and EPBTS liveweight gain calculations.

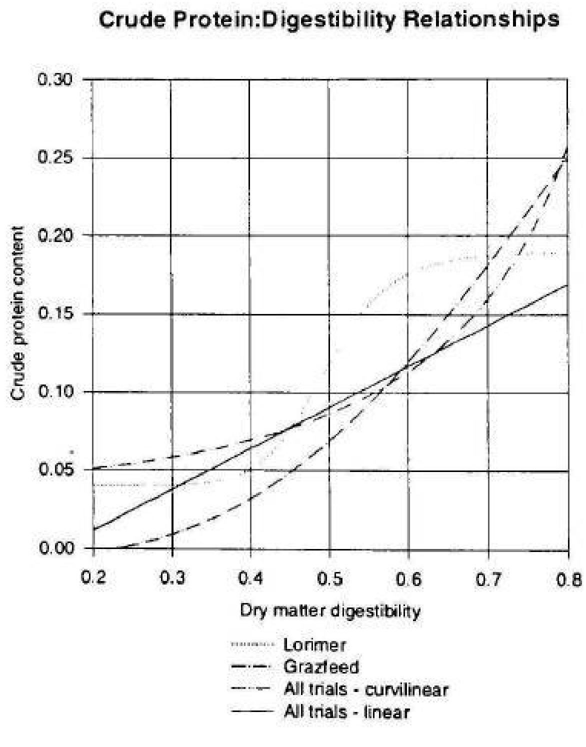

Figure 4.3. Functions describing the relationships between crude protein content and dry matter digestibility.

Reduced feed intake will further limit liveweight gain and wool production. For these reasons a number of relationships with digestibility were used to estimate crude protein levels of the single herbage pool / diet for use in the model analysis. These included the function present in EPBTS as well as crude protein information directly from the grazing trials. There was wide variation within the trials, between the trials, and with EPBTS in their *DMD / CP* relationships (figures 4.3 and 4.4). Lorimer's (1976) work had the most comprehensive data set, and the highest crude protein value per unit of digestibility for the range within which most digestibility observations fell, and therefore, would be the least limiting in terms of protein supply:

$$CP = 0.0402 + 0.1494 / (1.0 + (DMD / 0.4964)^{-11.913}) \qquad (4.1)$$

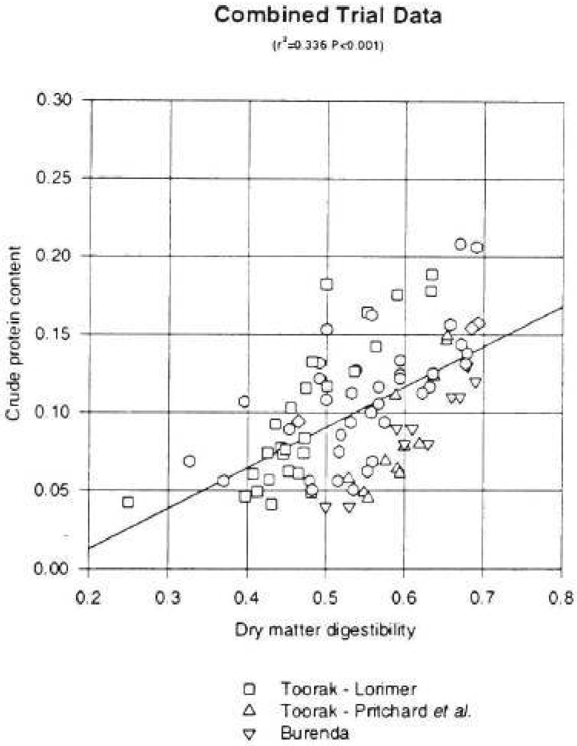

Figure 4.4. Relationship between crude protein and dry matter digestibility for the combined trial data set: Halton, Toorak - Lorimer, Toorak - Pritchard et al., Burenda, Arabella, Biddenham and Blackall. Halton data were used assuming a 50% digestibility for any mulga present in the diet.

4.6 Feed Intake

4.6.1 Methodology

Comparisons were made between EPBTS predicted and grazing trial observations of feed intake using the following assumptions and adjustments. Where digestibility was measured in terms of organic matter, this was related to dry matter digestibility using the following equations:

$$ME_{diet} = 16.0 * OMD - 1.8 \qquad \text{(1.13B, SCA 1990)}$$

$$ME_{diet} = 17.0 * DMD - 2.0 \qquad \text{(1.13C, SCA 1990)}$$

Combining the two equation gave:

$$DMD = (OMD + 0.0125) / 1.0625 \qquad (4.2)$$

where ME_{diet} is metabolisable energy content of the diet,
OMD is organic matter digestibility, and
DMD is dry matter digestibility.

The various combinations of *OMD, DMI* and *CP* that were used in the comparisons of EPBTS and the Halton data are shown in table 4.4. For Toorak - Lorimer, crude protein content of the diet was calculated from digestibility using the EPBTS function (figure 4.3) and the nitrogen content of diet as recorded. For Toorak - Pritchard *et al.*, Burenda and Arabella, crude protein of the diet was calculated using the equation 4.1 from Lorimer (1976) and the crude protein content of diet as recorded. For Toorak - Cobon *et al.* and Rosebank, no crude protein information was reported, therefore equation 4.1 was used to estimate levels from digestibility.

Grazfeed assumes a pasture height of 3 cm per tonne of pasture dry matter (DM) yield but allows this to be corrected where appropriate. A pasture height of 10 cm (range 10 - 30 cm) per tonne of pasture dry matter yield is more appropriate for tussock grasses (G.

Table 4.4. Combinations of OMD, DMI and crude protein used in the comparisons of EPBTS output with Halton observations.

Comparison number	Organic matter digestibility	Dry Matter Intake	Crude Protein
1	recorded *OMD*	recorded *DMI*	recorded crude protein
2	recorded *OMD*	recorded *DMI*	crude protein calculated using *DMD* and Lorimer's (1976) regression (equation 4.1)
3	modified *OMD*, assuming mulga digestibility 0.45	modified *DMI*, assuming mulga digestibility 0.45	recorded crude protein
4	modified *OMD*, assuming mulga digestibility 0.45	modified *DMI*, assuming mulga digestibility 0.45	crude protein calculated using *DMD* and Lorimer's (1976) regression (equation 4.1)
5	modified *OMD*, assuming mulga digestibility 0.50	modified *DMI*, assuming mulga digestibility 0.50	recorded crude protein
6	modified *OMD*, assuming mulga digestibility 0.45	modified *DMI*, assuming mulga digestibility 0.45	crude protein calculated using *DMD* and Lorimer's (1976) regression (equation 4.1)

McKeon pers. comm.). Additional grazing trial data such as latitude, sheep breed / type etc. required by Grazfeed were provided. Maximum and minimum temperatures for the period during which the trial work was carried out were obtained; actual temperatures if available (e.g. Toorak research station), otherwise interpolated temperatures were used (N. Flood pers. comm.).

4.6.2 Results

All dry matter intake predictions are compared with observations in figure 4.5, there was reasonable agreement (predicted mean 0.86, observed mean 0.96) with a tendency for EPBTS to underestimate dry matter intake by about 10%.

For Halton, the EPBTS functions were unable to predict feed intake (figure 4.5) using any combination of organic matter digestibility, dry matter intake and crude protein (table 4.4). The Halton values shown in figure 4.5 were predicted using recorded crude protein values while *OMD* and feed intake were modified assuming a mulga digestibility of 0.5 where appropriate (comparison five - table 4.4). This was the combination which later gave the best agreement in terms of Halton liveweight gain.

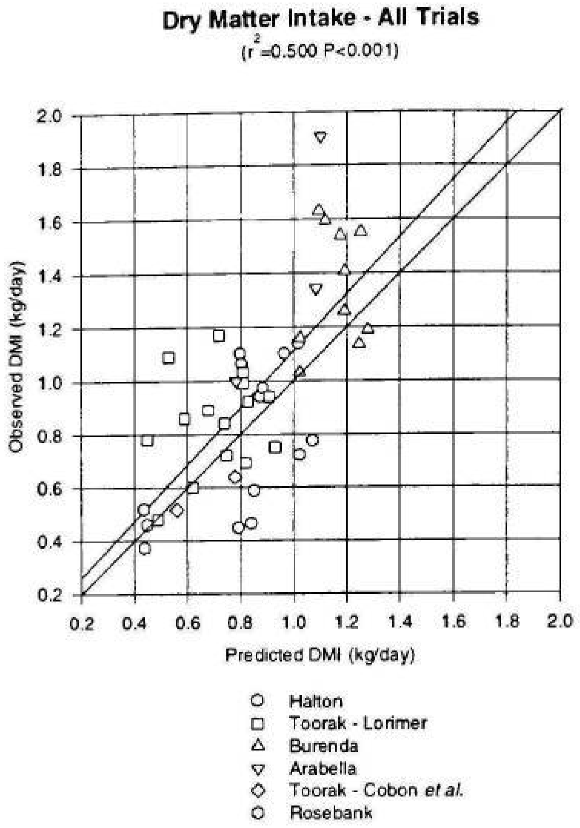

Figure 4.5. Predicted and observed dry matter intake for all trials. Halton data in the graph modified assuming a digestibility of 50% for any mulga in the diet and recorded crude protein values. All other comparisons made with Lorimer's (1976) crude protein values or Lorimer's (1976) regression relating crude protein to dry matter digestibility.

EPBTS tended to slightly underestimate Toorak - Lorimer dry matter intake on the whole although no consistent pattern was obvious (figures 4.5 and 4.6). Burenda predicted feed intake values (figure 4.5), obtained using equation 4.1, were generally less than those recorded. Use of recorded crude protein content of the diet produced worse results overall including two marked outliers (not shown). There were insufficient data points to draw any definitive conclusions from the comparison of observed and predicted Arabella dry matter intakes although there was a tendency for EPBTS to underestimate feed intake. There was no benefit in terms of predicted dry matter intakes from using the Lorimer digestibility / crude protein regression compared with the reported crude protein values (results not shown). Toorak - Cobon *et al.* and Rosebank grazing trials also have too few data points to be conclusive. EPBTS tended to slightly overestimate dry matter intake for Toorak - Cobon *et al.*, while for the Rosebank trial there was reasonable agreement between the mean observed and predicted dry matter intakes.

Effect of the relationship between digestibility and crude protein on EPBTS predicted dry matter intakes is shown in figure 4.6. Better results were obtained using the Lorimer (1976) reported crude protein values when predicting feed intakes.

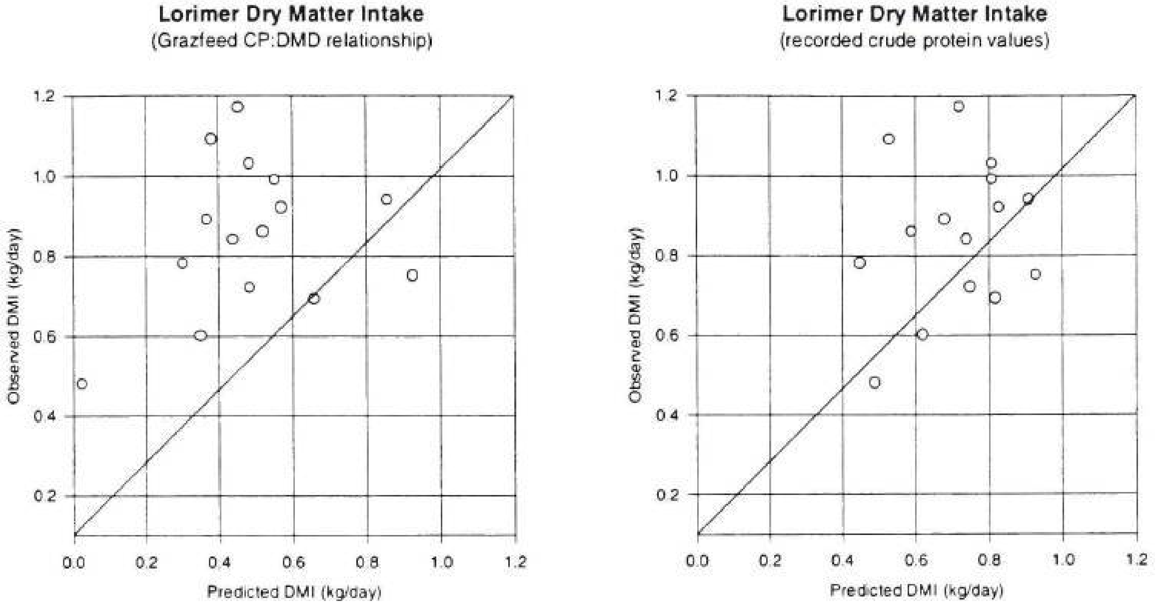

Figure 4.6. Toorak - Lorimer predicted and observed dry matter intakes using Grazfeed crude protein / DMD relationship and recorded crude protein levels.

4.7 Liveweight Gain

4.7.1 Methodology

When comparing EPBTS predicted liveweight gain and grazing trial observations of liveweight gain, the observed feed intake was used as an input to avoid carrying over of errors from feed intake prediction. As such, feed intake and digestion, and metabolism of energy / protein, were tested as separate model components.

4.7.2 Results

Observed and predicted mean daily liveweight gains for all grazing trials are shown in figure 4.7. EPBTS markedly overestimated mean daily liveweight loss and underestimated liveweight gain, using the same digestibilities and crude protein levels as for the feed intakes.

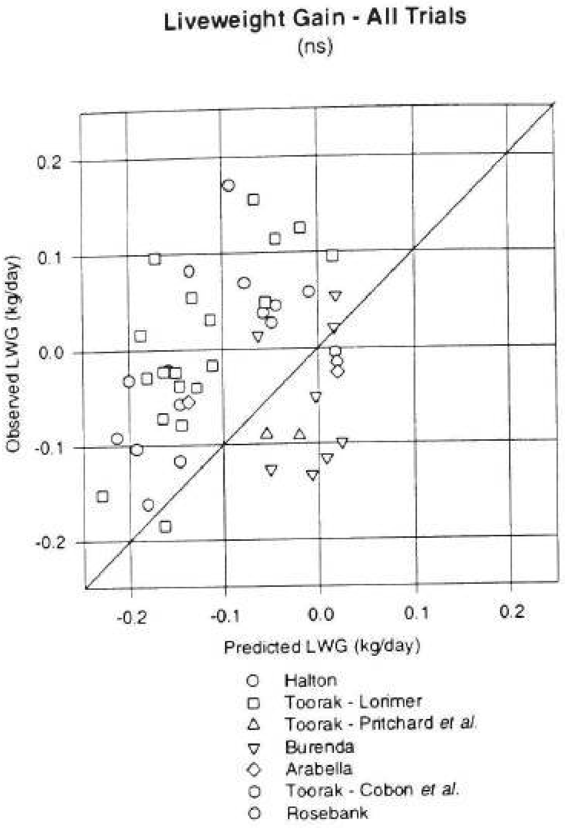

Figure 4.7. Predicted and observed mean daily liveweight gain for all trials. Halton calculations done assuming mulga digestibility of 0.5 and using recorded crude protein values. All other comparisons made with Lorimer's (1976) crude protein values or Lorimer's (1976) regression relating crude protein to dry matter digestibility.

This tendency for EPBTS functions to predict lower mean daily liveweight gains and greater mean daily liveweight losses than were observed was seen in the Halton, Toorak - Lorimer and Rosebank trials. The trend was different for the Burenda and Toorak - Pritchard *et al.* trials, predicted liveweight gain was greater and liveweight loss less than that observed. For Arabella and Toorak - Cobon *et al.*, there were also insufficient data points to draw any definitive conclusions although in the case of Toorak - Cobon *et al.* the two predicted values were very close to the observed values.

As shown previously in figure 4.6, better results in terms of predicted feed intake values were obtained from use of Lorimer's (1976) crude protein / digestibility relationship compared with actual crude protein values. However, there was limited effect of using Lorimer's (1976) crude protein digestibility relationship on liveweight gain calculations (figure 4.8).

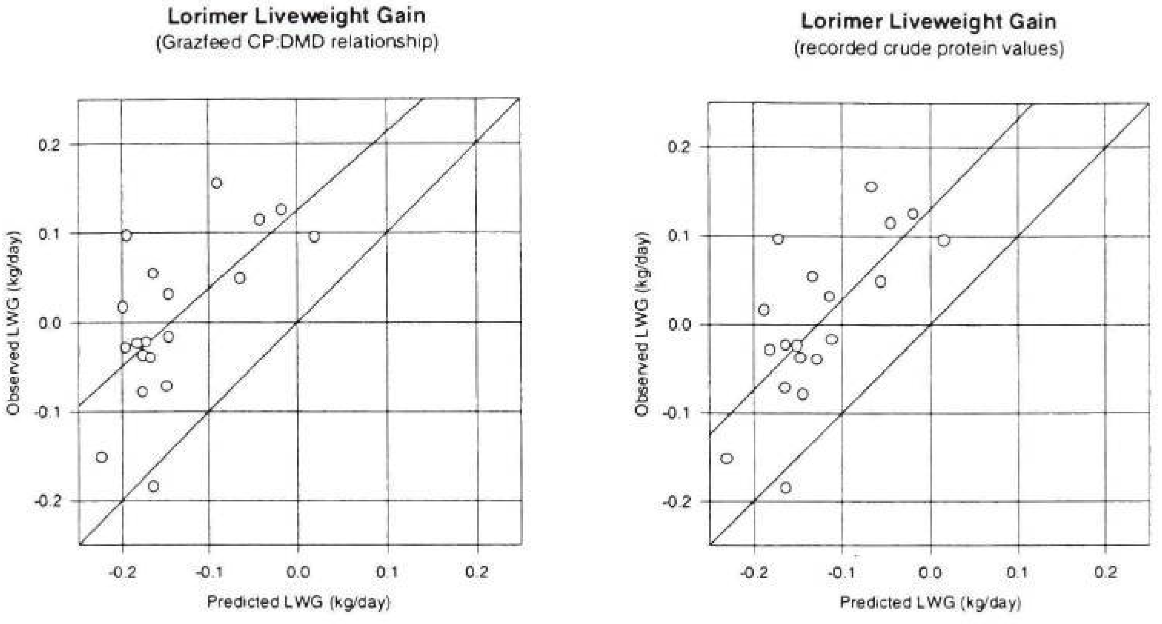

Figure 4.8. Toorak - Lorimer predicted and observed mean daily liveweight gains using Grazfeed crude protein / DMD relationship and recorded crude protein values.

Halton, Arabella, Toorak - Cobon *et al.* and Rosebank liveweights were not reported corrected for fleece weights. Correction of recorded liveweights and mean daily liveweight gains for wool growth, as described earlier, had negligible effect on the comparison of observed and predicted mean daily liveweight gains (not shown).

4.8 Further experimentation - dynamic EPBTS

4.8.1 Methodology

Because of the high frequency of sampling carried out by Lorimer (1976), it was considered most fluctuations in pasture yield, dietary quality and liveweight during the course of the trial would be reflected in the data. EPBTS was modified to allow it to cycle through a specified number of daily time steps and thereby simulate animal production continuously. This modified version of EPBTS will herein be referred to as the 'dynamic EPBTS' while the original version will be referred to as the 'static EPBTS' or simply EPBTS.

The daily input of pasture yield (*TSDM*) and digestibility of herbage were estimated by a series of linear interpolations between the sampled values. Crude protein content of herbage and diet was calculated daily from the digestibility of diet and the regression equation relating Lorimer's (1976) recordings of digestibility of diet and crude protein content of diet (equation 4.1). As previously stated, this regression produced higher crude protein levels than the function present in Grazfeed over the digestibility range in which we are interested. The initial liveweight for each new day was the calculated liveweight at the end of the previous day. Hence, liveweight calculation errors were allowed to compound during the course of the simulation. Linear interpolations of recorded feed intake and liveweight were also carried out to allow comparisons with the predicted values on a daily basis. This interpolated data set for use in dynamic EPBTS will be called 'Lorimer's (1976) time series data', and the original data prior to interpolation, will be called 'Lorimer's (1976) daily data', and where combined with data from the other grazing trials will be called 'pooled daily data'.

The following modifications were also made to dynamic EPBTS and their impact on animal performance examined:

- effect of high environmental temperature on potential dry matter intake was removed;
- pasture height set at 20 cm / tonne of pasture dry matter yield; and
- efficiency of use of energy for gain (k_g) calculated according to equation 1.41 of the Australian feeding standards (SCA 1990).

4.8.2 Results

The dry matter intakes predicted by the dynamic EPBTS and the observed Lorimer (1976) time series values are shown in figure 4.9. The predicted values generally follow the observed value trends but were not quantitatively the same. The major divergence in trends occurred at a period 1 - 2 weeks after heavy rains at the beginning of the wet season. The pasture was of good quality. Lorimer (1976) attributed this low intake to the high water content of the pasture preventing sheep from ingesting adequate dry matter despite grazing for long periods of time (see Appendix One, Part A). Unfortunately no pasture water content measurements were made. Modifications to dynamic EPBTS for

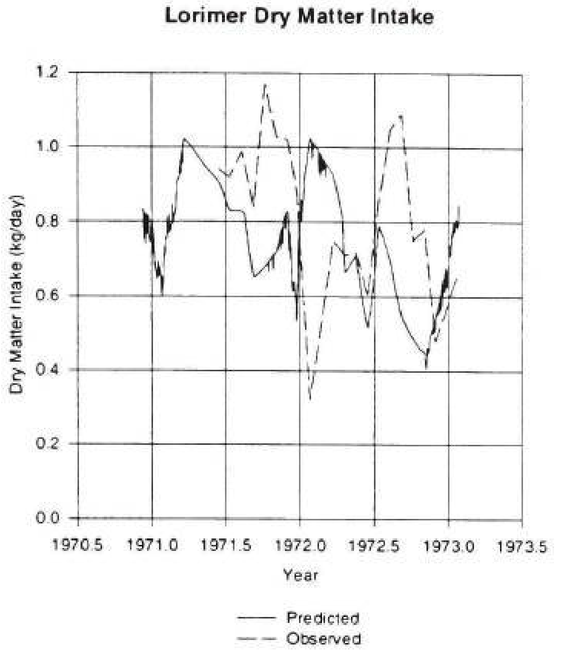

Figure 4.9. Toorak - Lorimer predicted and observed dry matter intake using dynamic EPBTS.

the affect of high environmental temperatures on potential dry matter intake and pasture height on predicted dry matter intakes showed the effects of these factors were minimal.

Mean daily liveweight gain was also markedly underestimated and liveweight loss overestimated by the dynamic version of EPBTS. Predicted liveweight changes by the dynamic version of EPBTS (figure 4.10) resulted in liveweights at which death would have occurred. Modifications to dynamic EPBTS for k_g and ME_{diet} calculations on predicted liveweight gains showed the effects of these factors were minimal.

4.9 Optimisation of EPBTS

4.9.1 Methodology

Figure 4.8 showing Lorimer's (1976) liveweight gain data appeared to identify a systematic bias in the calculation of liveweight gain by EPBTS. The linear regression between predicted (x) and observed (y) mean daily *LWG* had a slope of approximately 1.0, y intercept of 0.13 and an r^2 of 0.5. Thus a simple modification to EPBTS would be to add 0.13 kg / day to the calculated value for liveweight change (figure 4.11).

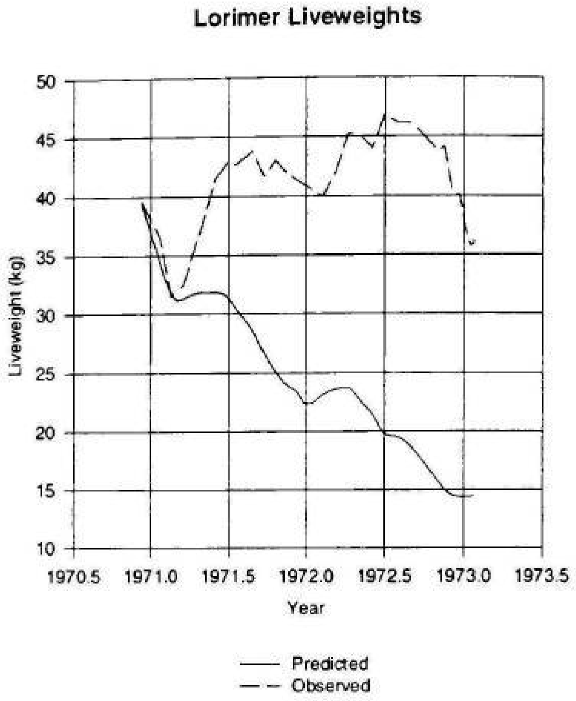

Figure 4.10. Toorak - Lorimer predicted and observed liveweights using dynamic EPBTS.

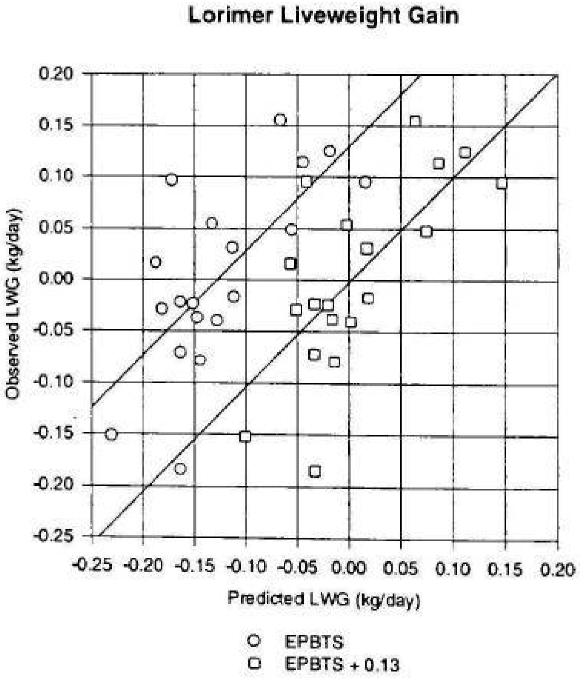

Figure 4.11. Predicted and observed Lorimer (1976) mean daily LWG using EPBTS and EPBTS + 0.13 kg / day. Predicted values calculated using observed crude protein levels.

The dynamic version of EPBTS used with Lorimer's (1976) time series data was also modified to increase calculated *LWG* by 0.13 kg / day. The results from the original work (figure 4.10) and the modified EPBTS (+0.13 kg / day) are shown in figure 4.12. Over the two year period of the experiment the modification resulted in predicted liveweights greater than those observed. However, the addition of 0.10 kg / day to predicted *LWG* gave better results.

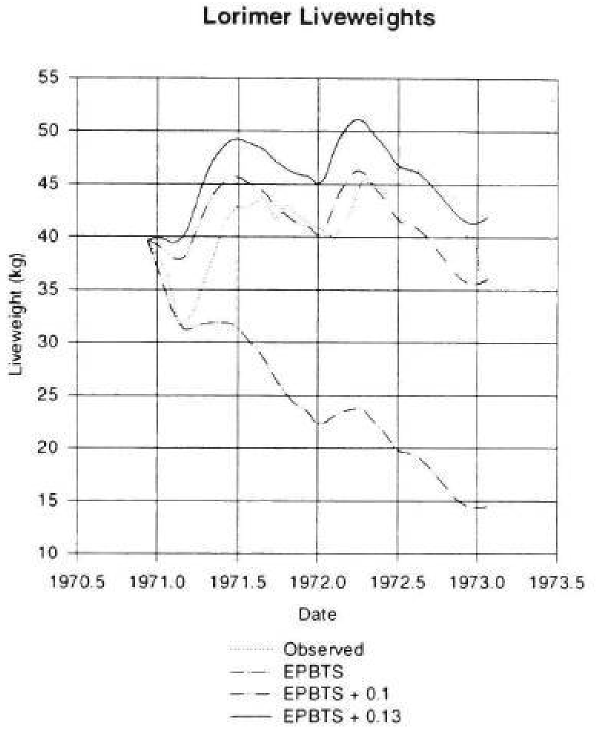

Figure 4.12. Predicted and observed Lorimer (1976) liveweights using the dynamic version of EPBTS, EPBTS + 0.10 kg / day and EPBTS + 0.13 kg / day.

This simple modification does not have a sound biological explanation. EPBTS was not a linear model and there was no simple way to adjust, for example, a parameter or equation to decrease the *metabolisable energy requirements for maintenance* (ME_{maint}) and produce the same results achieved by adjustment for bias of the predicted EPBTS *LWG* value. It may be expected that reducing ME_{maint} would correct the underprediction of EPBTS, however, changes in ME_{maint} also affects efficiency of energy use, *rumen degradable protein intake* (*RDPI*), *rumen degradable protein required* (*RDPR*), energy and protein content of liveweight gain, and hence simple changes in prediction do not occur.

The different adjustment values which gave the best results for the static and dynamic EPBTS indicate the two input data sets are different despite the time series data being derived directly from the daily data. This difference arose because the interpolation process in essence acted as a weighting system on the recorded data points depending on the interval between data recordings.

An investigation was carried out into the possibility of optimising EPBTS parameters and / or modifying equations in order to give an improved fit with the observed data. Variables generated within EPBTS, and recorded grazing trial data, were also examined for their ability to explain variation in the recorded feed intake and liveweight data.

The feed intake analysis used the Halton, Toorak - Lorimer, Burenda and Arabella data. Feed intake data from Toorak - Pritchard *et al.*, Toorak - Cobon *et al.* and Rosebank were not used at this stage because they were 'one off' dietary measurements and it was considered the time series feed intake data from the other trials were more reliable. When *fleece free liveweights* and *fleece free metabolic weights* were used, the Arabella data were also excluded as there was limited information upon which to base the fleece corrections. The liveweight gain analysis used only the Lorimer (1976) time series data (and dynamic EPBTS).

Crude protein (*CP*) content of the diet was calculated as a function of dry matter digestibility using the combined linear regression from all trials (figure 4.4). This function was chosen because of the large number of data points from which it was derived as well as the geographical and pasture community diversity over which theses trials were carried out. Both modified (mulga digestibility 0.45 and 0.5) and 'as recorded' Halton data sets were used. However, because of the limited difference in results, only those using the input data, adjusted assuming 0.5 mulga digestibility, are presented here.

The methods analysed to improve predictions in feed intake and liveweight gain are presented in tables 4.5 and 4.6 respectively. For feed intake, manual optimisation, commercial optimisation software (PEST, Watermark Computing 1994), linear and non linear regression analysis outlined in table 4.5 were applied to both the static and dynamic versions of EPBTS and their respective data sets. Linear regressions developed using pooled daily data and variables generated from static EPBTS were used with data and variables generated from the dynamic version, and vice versa, to see if regression equations developed from one were applicable to the other.

4.9.2 Results

The results of the attempts to improve feed intake and liveweight gain data are presented in tables 4.5 and 4.6. Sixty-three percent of the variation in feed intake of the pooled daily data set was found to be explained by liveweight (*fleece free* or *fleece free metabolic)* and dry matter digestibility / *relative ingestability* (figure 4.13). All other attempts were unsuccessful.

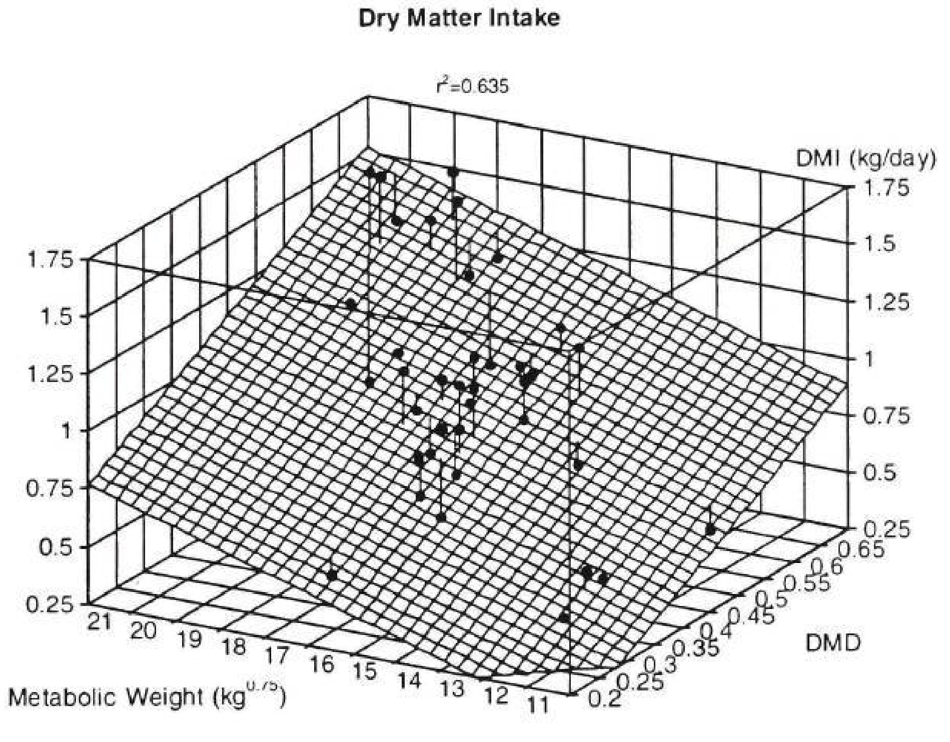

Figure 4.13. Linear relationship existing between observed DMI, DMD and fleece free metabolic weight (modified Halton mulga digestibility). No difference was found with respect to r^2 values when either DMD or relative ingestability was used.

Table 4. 5. Methods, results and comments on attempts to improve feed intake predictions including optimisation of EPBTS parameters.

Improving feed intake predictions		
Method used	**Results**	**Comments**
Manual adjustment of parameters within the EPBTS equations describing *rate of eating, time spent eating, relative ingestability* and *potential dry matter intake* (*PDMI*)	No improvement in predictive ability.	Optimisation of parameters only allowed to occur over a biologically valid range.
A computer software optimisation package (PEST, Watermark Computing 1994) based on a Gauss-Marquardt-Levenberg algorithm was used in an attempt to improve the predictive capability of the feed intake equations within EPBTS.	No improvement in predictive ability.	Optimisation of parameters only allowed to occur over a biologically valid range.
Both manual and PEST optimisation of parameters used in feed intake calculations were repeated while other key EPBTS equations were varied e.g. the limiting affect of ratios of '*rumen digestible protein required* to *rumen digestible protein intake*' greater than one on feed intake was modified in various ways as well as being completely 'turned off'.	No improvement in predictive ability.	Optimisation of parameters only allowed to occur over a biologically valid range.
Linear regressions were used to identify variables recorded in the trials and selected internal variables generated by EPBTS which best explained the recorded feed intake values. The ability of high temperatures (*TF*) to reduce *PDMI* was removed from model calculations at this stage because of its' limited affect (not shown) and because it was preferred to have two separate variables; *PDMI* and a temperature variable. The temperature variable (*Tplus*) was calculated as the number of degrees the mean temperature was greater than 26^{0}C. Two groups of variables were used with the regression analysis to predict feed intake. The first group of variables (variable group one) included those recorded during the grazing trials: *PDMI*, without the reducing affect of *TF*, *with fleece weight / fleece free weight / fleece free metabolic weight*, *DMD* of the diet, *CP* of the diet, *age*, *TSDM*, *Tplus*, *latitude* where pooled grazing trial data were used. The second group (variable group two) included those generated by the EPBTS model: *PDMI*, without the reducing affect of *TF*, *with fleece weight / fleece free weight / fleece free metabolic weight*, *time spent eating*, *rate of eating*, *relative ingestability*, *relative availability*, which is the product of *time spent eating* and *rate of eating*, *age*, *Tplus*, *latitude*, where pooled grazing trial data were used. Metabolic weight was calculated as *fleece free weight* raised to the power of 0.75. *With fleece weight*, *fleece free weight* and *fleece free metabolic weight* were tested in all calculations.	*DMD / relative ingestability* and weight (*with fleece*, *fleece free*, *fleece free metabolic*) were chosen in all stepwise forward regressions and explained 54.3 - 63.5% ($P<0.05$) of the variation in observed feed intake using static EPBTS (figure 4.13). *Fleece free* and *metabolic fleece free weights* explained more of the variation in feed intake than did the *with fleece weight*; 63.4 and 63.5 *vs.* 54.3% respectively. Using the above linear regressions, but with Lorimer's (1976) time series data set and dynamic EPBTS generated variables, resulted in significant ($P<0.0001$) negative Pearson correlations between predicted and observed feed intake values. As well, the static linear regression failed to simulate the degree of variation in *DMI* as was recorded. Using dynamic EPBTS and group 1 variables, the forward stepwise regression selected *DMD*, *TSDM* and *Tplus* which explained 43.8% ($P<0.05$) of the variation in Lorimer's (1976) time series data of feed intakes. Using group 2 variables, *relative ingestability*, *fleece free / fleece free metabolic weight* and *Tplus* explained 30.3% ($P<0.05$) of the variation in feed intake. Using the above linear regressions, but with the pooled daily grazing trial data and static EPBTS generated variables, also resulted in significant ($P<0.05$) negative Pearson correlations between predicted and observed feed intake values.	Use of either *fleece free weight* or *fleece free metabolic weight* gave negligible differences in correlation values for the resultant equations using static EPBTS. *Relative ingestability* was linearly related to *DMD* and therefore gave essentially the same results. Use of the unmodified or modified (mulga digestibility 0.5) Halton data in the pooled data set gave very similar correlation results, the unmodified data generally resulted in a very small (0.01) improvement in correlation values. The negative correlation values arose when applying the static EPBTS linear regression to the time series data because of the influence of the one observation at which *DMD* was at its peak yet *DMI* at its minimum. As there was only one trial used with dynamic EPBTS, *latitude* was not included as a variable. Age of sheep did not vary much within Lorimer's (1976) trial and was also excluded as a variable. The negative correlation values also arose when applying the dynamic EPBTS linear regression to the pooled daily data because of the influence of the one observation at which *DMD* was at its peak yet *DMI* at its minimum.
Once the individual variables having greatest influence on dry matter intake were identified by the regression analysis, they were used together in multiple non-linear regressions in an attempt to improve their explanatory power. The variable combinations used were: *DMI = f(fleece free weight, DMD/relative ingestability)* *DMI = f(fleece free metabolic weight, DMD/relative ingestability)*	No improvement in predictive ability for both the static and dynamic versions of EPBTS and their respective data sets.	Slight improvement occurred in terms of r^2 values but these non-linear regressions were not biologically valid.

Table 4. 6. Methods, results and comments on attempts to improve liveweight gain predictions including optimisation of EPBTS parameters.

Improving liveweight gain predictions		
Method used	**Results**	**Comments**
Manual adjustment of parameters within the EPBTS equations relating to liveweight gain calculations.	No improvement in predictive ability.	Optimisation of parameters only allowed to occur over a biologically valid range.
A computer software optimisation package (PEST, Watermark Computing 1994) based on a Gauss-Marquardt-Levenberg algorithm was used in an attempt to improve the predictive capability of the liveweight gain equations within EPBTS. With PEST, both the observed liveweights on actual recording dates and the time series of observed liveweights were used as the test data in the optimisation process.	No improvement in predictive ability.	Optimisation of parameters only allowed to occur over a biologically valid range.
Given the observed time series of daily liveweight gains, metabolisable energy intake and an assumed mean energy value of gain (*EVG*) of 26.4 MJ / kg, values for ME_{gain} and ME_{maint} which would have allowed for the observed liveweight gain were calculated. This allowed EPBTS predicted ME_{maint} values calculated from the observed trial data to be compared with ME_{maint} values calculated given the observed liveweight gain ($ME_{maintobs}$). Multiple linear regressions were carried out using $ME_{maintobs}$ as the dependent variable and the following groups of independent variables: EPBTS predicted values for ME_{metab}, ME_{eat} , ME_{move} and *MEI;* observed *Wt*, *DMD* and *DMI;* observed *Wt*, *DMI* and EPBTS predicted ME_{diet} ; observed *Wt*, *DMD*, *DMI* and *TSDM*. Because of the limited impact of *fleece free metabolic weight* on the feed intake analysis (table 4.4), the *fleece free liveweights* only of Lorimer (1976) were used in the analysis of liveweight gain.	Examination of $ME_{maintobs}$ values required in order to allow for the rates of liveweight gain observed given *MEI* and assuming *EVG* = 26.4 MJ / kg, showed that at times negative maintenance costs were required. Dynamic EPBTS generated variables and time series data were found to explain 48 - 50% of the variation in $ME_{maintobs}$ but the coefficient values for certain variables were biologically invalid, e.g. *fleece free weight* had a negative coefficient indicating that as liveweight increases, the maintenance costs of the animal would decrease.	In this case we have accepted the recorded liveweight gain values, the feed intake and *DMD* and therefore *MEI*. We have assumed an *EVG* of 26.4 MJ / kg which is the value for a mature sheep weighing 40 kg at maintenance. For Lorimer's (1976) data, *EVG* ranged between 26.38 - 26.42 MJ / kg. The $ME_{maintobs}$ represents the maintenance costs that would allowed the animal to gain weight as observed given the assumptions stated. By regressing model generated and grazing trial data against $ME_{maintobs}$, we are forcing these combinations of variables which we know are highly implausible, or impossible. It is to be expected that biologically invalid coefficients will be produced.
Pest was used to optimise the components of the *ME* costs of maintenance where those costs were the product of the EPBTS equations and a dummy parameter, using the recorded liveweights as the test data: $ME_{maint} = par(82) * ME_{move} + par(83) * ME_{eat} + par(84) * ME_{metab} + par(85) * (MEI * 0.09) \quad (4.3)$ *MEI* is included in the maintenance calculations to account for the variation in maintenance costs with the level of feeding (SCA 1990). Optimisation of equation 4.3 was repeated while key EPBTS equations were varied giving six sets of optimised parameters which were then used with the maintenance cost outputs calculated using static EPBTS and the pooled daily data set.	The predicted dynamic EPBTS liveweight gains were highly correlated with observed values (r^2=0.823 P<0.001) when equation 4.3 was used to calculate maintenance costs following optimisation. Application of this optimised equation to static EPBTS and the pooled daily data set also improved the agreement between predicted and observed liveweight gains. Unfortunately, the coefficients for the components of ME_{maint} were biologically invalid.	It is to be expected that the agreement between predicted and observed liveweight gains was improved given we optimised our equation using the observed liveweight gains as the test data. The biologically invalid coefficients are to be expected given we have in effect carried out a similar but slightly different procedure to that described above.
The grazing trial input variables used by the EPBTS equations to calculate the various components of ME_{maint} were used in the following equation and the parameters optimised using PEST with recorded liveweights as the test data: $ME_{maint} = \mathrm{par}(75) * Wt + \mathrm{par}(76) * TSDM + \mathrm{par}(77) * DMI + \mathrm{par}(78) * DMD + \mathrm{par}(79) * age \quad (4.4)$	Predicted liveweight gains were highly correlated with observed (r^2=0.796 P<0.001) but again the coefficients for the components of ME_{maint} were biologically invalid.	The biologically invalid coefficients for equations 4.3 and 4.4 are to be expected, as the optimisation process by virtue of what it does, is combining variables in such a way as to estimate maintenance costs which themselves are biologically invalid.
Equation 4.4 was modified to predict *LWG* from the same independent variables, and the parameters optimised using PEST: $LWG = \mathrm{par}(75) * Wt + \mathrm{par}(76) * TSDM + \mathrm{par}(77) * DMI + \mathrm{par}(78) * DMD + \mathrm{par}(79) * age \quad (4.5)$	Predicted liveweight gains were highly correlated with observed (r^2=0.854 P<0.001) but again the coefficients for the components of the equation were biologically invalid.	Comments as above.
Linear and non-linear regressions of Lorimer's (1976) *LWG* on *DMD* and *DMI* were carried out using both liveweights on recording days and time series liveweights.	Linear regressions explained 10.5 - 20.6% of the variation in *LWG*. Non-linear regressions were better but not biologically valid.	

4.10 Use of GRASP and a diet selection subroutine with EPBTS

4.10.1 Methodology

Use of simple linear interpolations of recorded data as input to dynamic EPBTS was considered a possible reason why the model failed to adequately simulate liveweight gain (figure 4.10). GRASP, and an associated diet selection subroutine (see Chapter Five), were used to provide input data on a daily basis and the ability of EPBTS was again tested. EPBTS was included in the GRASP model as a subroutine (figure 4.14).

The GRASP model assumed a standard dry sheep equivalent had a daily intake of 1.096 kg (400 kg / 365 days), this value being modified by a restriction index calculated from forage utilisation. This provisional calculated daily dry matter intake was then passed to the diet selection subroutine where a provisional dietary crude protein concentration was calculated. In the diet selection model, to be described in detail in Chapter Five, growth was also added to youngest age pools, ageing of pools occurred and the dietary nitrogen value for each age pool was recalculated. The provisional dietary crude protein was passed to the EPBTS subroutine along with pasture yield and used to estimate digestibility using the linear regression based on pooled grazing trial data (figure 4.4).

Dry matter digestibility was then used in the calculations of dry matter intake. Calculations of dry matter intake in the EPBTS subroutine were on a per head basis. The value for the dry matter intake was then passed to the *DMI* subroutine where the actual intakes from individual pasture age pools was calculated and dietary crude protein concentration was recalculated. The final calculated dietary crude protein concentration would only vary from the provisional value if individual age pools in either calculation were completely consumed. Using the Toorak utilisation trial data set there was no difference in provisional and final calculated dietary crude protein values at the lower utilisation levels while only a few were recorded whilst running the 80% utilisation data set (see figure 5.17). In all 13 cases, the provisional dietary nitrogen concentration was less than the final calculated value.

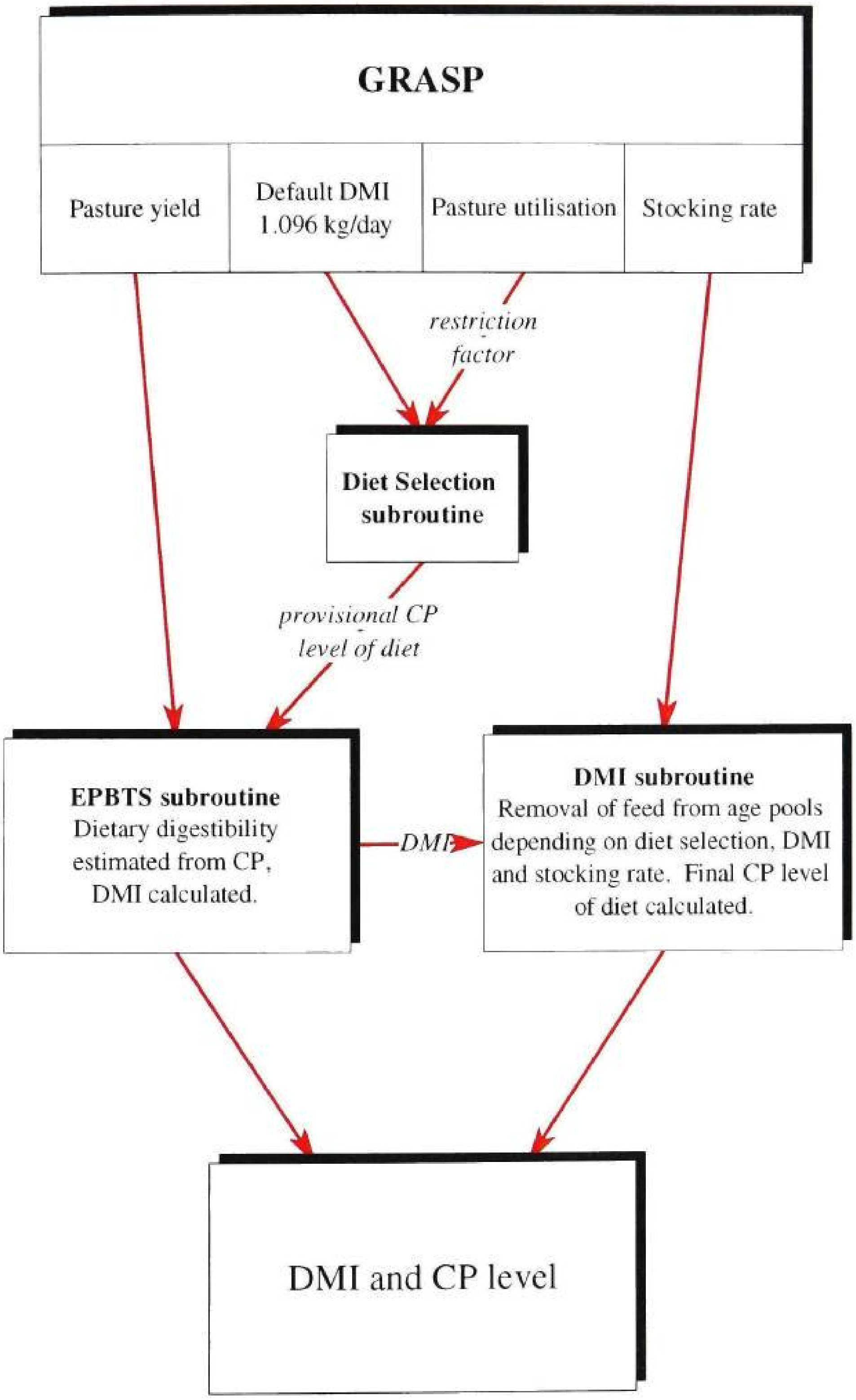

Figure 4.14. Information flow between GRASP, the diet selection, EPBTS, and dry matter intake subroutines.

4.10.2 Results

Using GRASP daily input compared with interpolated recorded data did not improve the ability of dynamic EPBTS to simulate liveweight gain (not shown).

4.11 Testing Lorimer's (1976) data reliability

4.11.1 Methodology

In order to ensure a procedural or systematic error was not present in the recorded *DMI* and *DMD* values of Lorimer (1976), dummy parameters were used to decrease or increase the recorded values. *DMI* and *DMD* dummy parameters were optimised in turn using the recorded liveweights as the test data.

An additional check was carried out by developing a cubic polynomial function which described Lorimer's (1976) *DMI* as a function of *DMD* and *CP* ($r^2 = 0.48$). The parameters of this function were optimised against the recorded liveweights using PEST. The optimised cubic polynomial regression was then used in EPBTS to compare the predicted and observed liveweights.

4.11.2 Results

Modification of Lorimer's (1976) feed intake or digestibility values by a constant value arrived at by optimisation against recorded liveweights, in the assumption of possible systematic errors in the data, did not improve model predictions of liveweight variation.

Using PEST to modify a cubic polynomial in which *DMI* was a function of *DMD* and crude protein content of the diet resulted in *DMI* values which were nearly always greater than those recorded by Lorimer. Whilst the use of these increased feed intakes in EPBTS did improve liveweight predictions, the agreement between predicted and observed values was still unsatisfactory.

There does not appear to be a systematic error in the *DMI* or *DMD* values recorded by Lorimer (1976).

4.12 Discussion

All relevant available data have been collected and collated in order to test the ability of Grazfeed to simulate Queensland grazing trials. Where necessary, reasonable adjustments have been made to overcome limitations in the data.

Whilst the analysis of the grazing trial data was done using EPBTS and not the commercially available Grazfeed, both models produced almost identical results on testing (figure 4.2). This indicated there was no reason to suspect Grazfeed would produce different results had it been used in the analysis.

Both the static and dynamic versions of EPBTS were run with the efficiency of use of energy for gain (k_g) calculated as in Grazfeed for temperate pastures, and as recommended by SCA (1990) for tropical pastures (SCA equation 1.41), with negligible differences in results. Calculation of *rumen degradable protein required* (*RDPR*) and k_g for temperate pastures in Grazfeed produce peak values in spring. Modifications were made to both functions so that peak values were obtained during autumn, in phase with pasture growth following late summer / autumn rain. Differences between outputs were negligible.

4.12.1 Digestibility / crude protein relationships

The crude protein level predicted for a given level of digestibility is important, since low levels may reduce rumen microbial activity and therefore dry matter intake, while at other times, liveweight gain and wool production may be reduced if insufficient protein is available for deposition. The relationship for all grazing trial dry matter digestibility / crude protein content data is shown in figure 4.4. The linear relationship had an r^2 value of 0.336, while a curvilinear regression was able to increase the correlation slightly (r^2=0.358). A comparison of these regressions with Lorimer's (1976) regression and the function within Grazfeed is shown in figure 4.3.

For digestibilities lower than 0.6, the Grazfeed function calculated a lower crude protein content than the regression from the grazing trial data. The Lorimer (1976) regression, which has been used in the comparisons, predicted a higher crude protein content than the Grazfeed function for all feeds with a digestibility of less than 0.7. It also predicted a higher crude protein content than the combined regression for digestibilities between approximately 0.45 and 0.73, the range in which most of the grazing trial digestibilities fell.

The Lorimer (1976) equation was preferred to the combined regression or the Grazfeed function for the grazing trial analysis because initial work with EPBTS indicated it tended to underestimate feed intake and liveweight gain. By using the crude protein / dry matter digestibility relationship which gave the higher crude protein values, this reduced the risk of crude protein deficiencies reducing EPBTS predicted values. The sigmoidal nature of the Lorimer (1976) regression, although dependent on one point and not fitting the generally accepted protein to digestibility (energy) pattern, was not a reason for failure of EPBTS to simulate adequately for the reason stated above. Also, the use of this relationship allowed the Lorimer (1976) interpolated time series data to be used without predicting excessively low protein levels relative to those which would have been predicted by use of the EPBTS equation.

4.12.2 Feed intake

The agreement between predicted and observed dry matter intake shown in figure 4.5 was reasonable given the errors in measuring feed intake under field conditions, e.g. Pritchard (1988), Murray (1994). The general trend in the individual trial comparisons was for mean dry matter intakes of predicted and observed to be similar. Two trials in which this trend was not evident were the Burenda and Arabella grazing trials, where mean predicted dry matter intakes were less than mean observed values, but the predicted mean daily liveweight gains were more in agreement with observed mean daily liveweight gains.

Lorimer's (1976) feed intake values were calculated using faecal harness bags (10 sheep harnessed out of a total of 25 sheep) to estimate total faecal output, and digestibility of the diet. Murray (1994) has shown that the presence of harness bags on penned sheep may reduce intake by up to 10%. It would be expected that any such bias would have been removed by optimising the recorded feed intake values against recorded mean liveweights for all sheep. However, scaling intakes was not sufficient to enable liveweight change to be predicted. Therefore, inability to predict liveweight change may be due to either errors in recorded feed intake or liveweight change.

4.12.3 Liveweight gain

The ability of EPBTS to predict changes in liveweight gain was poor (figure 4.7). The general trend in the individual comparisons was for predicted mean daily liveweight gain to be markedly smaller than the observed mean daily liveweight gain. Two trials in which this trend was not seen were the Burenda and Arabella grazing trials, where predicted mean daily liveweight gains were more in agreement with observed mean daily liveweight gains. As stated, the feed intakes used in this analysis were those recorded in the trial work, and in the case of Burenda and Arabella, these values were generally greater than predicted by EPBTS.

Hogan (1996), recently drew attention to the poor reliability of SCA (1990) equations for predicting fat and protein content of liveweight change, and therefore the level of liveweight gain / loss for grazing cattle in northern Australia. Cattle on temperate pastures, from which these equations were developed, do not experience the same fluctuations in pasture quantity and quality and the associated fluctuations in liveweight. Hogan (1996) considered the lack of quantifiable information on the physiology of liveweight loss and compensatory liveweight gain limited SCA (1990), and other similar models, to use as general guides only. Similar conclusions are probably also applicable to grazing sheep in Queensland which experience extended periods of low nutrient quality and availability.

4.12.5 Optimisation

The different versions of EPBTS, static and dynamic, produced different results when simple modifications (+ 0.10 - 0.13 kg / day) were made to the predicted Lorimer (1976) *LWG* as shown in figures 4.11 and 4.12. Addition of 0.13 kg / day worked best in static EPBTS and 0.10 kg / day in dynamic EPBTS, in terms of agreement between predicted and observed liveweights. These results indicate the daily and time series data are different, despite the time series data being derived from the daily data.

The grazing trial data used in static EPBTS assumed that the recorded pasture and dietary factors at a single point represented what existed over the period between liveweights measurements, from which the mean daily liveweight gain was calculated. Also, the interpolation of Lorimer's (1976) data assumed the grazing trial variables were measured frequently enough to capture temporal fluctuations. Both assumptions may be incorrect, especially during periods prior to and following rainfall when the pasture quantity / quality and dietary intake may change rapidly.

Optimisation, both manually and with the use of PEST, did not improve the agreement between observed and predicted feed intake and liveweight values. Although not fully reported here, extensive modifications were made to EPBTS equations and the optimisation process repeated with each change. Bounds for parameter optimisation values were based on published values or best judgement following visual inspection of the relationship. The optimised parameter values resulting from these biologically sensible constraints did not improve the predictive ability of EPBTS. More liberal bound setting eventually gave predicted values in very close agreement with observed values, but the optimised values were either not biologically valid, or resulted in internal variables which were not biologically valid. Additionally, repeating the optimisation process with different initial parameter values resulted in different optimised parameter values, indicating there were non-unique solutions to the problem, or that the optimisation procedure could not distinguish local optima from the best global solution.

The inability of regressions developed from static EPBTS to explain variation in *DMI* when used in the dynamic version, as indicated by negative Pearson correlation values, and vice versa, arose largely because of a single Lorimer (1976) data point. At this point, shortly after rain, the *DMD* was at it's highest recorded level (0.633), but *DMI* at it's lowest level (0.32 kg DM/day). Given current understanding of the effects of *DMD* on *DMI* this was completely unexpected. The author (Lorimer 1976) suggested this anomaly may have temporarily arisen because of high pasture water content (not measured) in combination with rumen volume limiting dry matter intake. Using the pooled daily data, the influence of this point was markedly reduced compared with the time series data. This would suggest feed intake regressions developed from the pooled daily data would be preferable to those developed from the time series data.

Feed intake levels were most closely related to *DMD / relative ingestability* and liveweight (*with fleece, fleece free, fleece free metabolic weight)*, explaining between 54.3 - 63.5 % of the variation when using the pooled daily data (figure 4.13). It is therefore essential that dietary quality and liveweight need to be modelled accurately if they are to be used to predict feed intake. A model was developed to predict the dietary dry matter digestibility (Chapter Five), but daily liveweight change could not be modelled accurately (Chapter Six). Other variables did not improve the prediction of intake (*rate of eating, time spent eating* and their product, *relative availability*) when pasture height is set at 10 cm per tonne of dry matter. Non-linear regressions involving *DMD / relative ingestability* and liveweight were not able to improve the explanatory power of these variables relative to the linear regression and still be biologically valid.

Modification of Lorimer's (1976) time series data by excluding the point at which peak *DMD* / minimum *DMI* was recorded, and interpolation between the two adjoining recording dates had little effect on the ability of EPBTS to simulate *DMI* or *LWG* (results not shown). However, interpolation over such a long period (approximately 90 days) ignored the assumption upon which linear interpolation was carried out, especially at the time of year in which it occurred (December - March). This problem has highlighted the importance of making frequent pasture / animal measurements during grazing trials, especially during periods when rapid changes in the grazing environment can be expected.

Using the interpolated time series data and comparing EPBTS calculated ME_{maint} with derived $ME_{maintobs}$ again highlighted the inability of EPBTS to simulate the observed grazing system or, conversely, unsuitability of the data for validation / optimisation of a daily time step model such as EPBTS.

Regressions of $ME_{maintobs}$ against dynamic EPBTS generated variables, and grazing trial measurements, gave correlation values (r^2) of 0.4 - 0.5. However, coefficients of many of the selected variables were not consistent with accepted theories of animal nutrition. SCA (1990) also highlighted the dangers of attempting to attach biological significance to coefficients of statistical descriptions of data sets. They stated such descriptions 'do not provide a viable framework for the generation and incorporation of new information, nor promote understanding of the biology'.

Equations 4.3, 4.4 and 4.5 (in table 4.6) all produced very good results on optimisation. However, the results were not biologically valid and not unique. Constraining the parameters to values that were biologically realistic resulted in predicted values that were poorly correlated with observed values.

4.13 Conclusions

Tests show the EPBTS model gave identical results to the commercial version, Grazfeed (V6.0.2), and hence is an accurate representation of modern theory on energy / protein systems.

EPBTS was unable to predict liveweight gains of sheep grazing native Queensland pastures. EPBTS was better able to predict dry matter intakes, especially when crude protein / digestibility relationships based on actual data from tropical pastures were used. Examination of the most comprehensive and reliable data set (Lorimer 1976) showed a systematic bias in the prediction of mean daily liveweight gain by EPBTS (figures 4.8 and 4.11). Optimisation of parameters and modification of functions within EPBTS were not able to explain this bias.

The grazing trial data used in the testing of EPBTS were not without problems in terms of reliability. Data collected at regular intervals over an extended time period may not adequately represent changes in the grazing environment and therefore were not ideal for the purposes of testing a daily time step model. This was emphasised with the time series data of Lorimer (1976) which were used to test the dynamic EPBTS. Components of the model relating to feed intake were used in further work, as described in Chapter Five, but alternative approaches to EPBTS simulation of animal production were required, as described in Chapter Six.

CHAPTER FIVE

Diet Selection and Feed Intake

5.1 Introduction

Because of the failure of EPBTS to adequately simulate animal production as tested in Chapter Four, it was decided to examine the usefulness of simple climatic, soil, pasture and dietary variables in explaining the variation in observed animal production.

In rangelands rainfall can be considered the primary determinant of pasture growth and hence potential animal productivity. The modelling of pasture production (GRASP), which includes other factors such as soil and pasture type, temperature, humidity and the presence of trees, provides a further refinement of this indicator. The differential selection of plant parts and plant species by grazing sheep, and the level of feed intake, are the main interactions between the pasture community and grazing animals. As a result of this interaction, nutrients are supplied to the forestomachs and intestines, digestion and absorption occurs, and the supply of protein and energy determines to what extent sheep are able to grow wool to their genetic potential. Therefore, development of a model which simulated the diet selection and level of feed intake by grazing sheep was the next logical step to link pasture models to animal production models. A diet selection model should produce variables which are better indicators of animal production than those produced by the pasture production model. Also, better models of intake of pasture by animals should more correctly account for feedbacks on water balance and pasture production.

Modelling of diet selection and feed intake has been identified by numerous workers as a major challenge to the successful modelling of grazing animal production systems (White *et al.* 1979, Black *et al.* 1982, Kenney and Black 1984, Ketelaars 1986, Ungar and Noy-

Meir 1986, Denham and Spreen 1986). Factors affecting diet selection are discussed in Appendix One, Part A. Often in pen experiments examining diet selection, one factor is examined in isolation, whereas grazing sheep are influenced by a wide range of factors. Dove (1996) suggested the need for further experimental work to measure 'available herbage in botanical, physical, chemical, and spatial terms, and to conduct experiments in which factors influencing diet selection are examined in an unconfounded way'. However, a pasture production model that included the major pasture species, or groups of species (perennials, annuals, forbs), would be a necessary precursor to diet selection models simulating botanical composition of the diet.

Few models exist which link the grazing animal to the pasture community. Grazfeed (Freer *et al.* submitted, Dove 1996) requires the user to enter the mean digestibility and yield of the green and dead pasture pools. For example, mean digestibility of the green pool (range 0.5 and 0.8) is entered and the mass of green pool is partitioned into four digestibility classes: 0.5, 0.6, 0.7, 0.8. Similarly, the mean digestibility of the dead pool (range 0.3 - 0.7) is used to proportion the dead pool mass into five digestibility classes: 0.3, 0.4, 0.5, 0.6, 0.7. Dove (1996) noted that in the 'absence of appropriate data, the distributions are conceptual'. Sheep are assumed to select their diet from the highest digestibility class first, moving to less digestible classes as dictated by the availability of feed in each class and their predicted feed intake. Grazfeed calculates the potential feed intake of sheep based on their size and condition assuming *ad lib.* access to a forage of high digestibility (>0.8). This potential intake is then adjusted for physiological state, presence of supplements, and pasture quality and availability. As GRASP does not estimate the mean digestibility of green and dead pools, and the distribution of the green and dead pools in Grazfeed is conceptual only, no work was carried out using the Grazfeed methodology of diet selection. Instead, a diet selection model was developed using existing equations for diet selection of beef cattle which had been part of the early development of GRASP (Hendricksen *et al.* 1982, McKeon *et al.* 1982) but had not received any further testing or development. This model of diet selection was based on the following concepts:

- nitrogen content and digestibility of plant components declines with age (Wilson and Mannetje 1978);

- animals prefer and select for these higher quality components as demonstrated by the high green leaf content of diet found by Ash *et al.* (1982); and
- the age classes of a sward can be simulated, and the preferences of animals for younger ages can be described mathematically (Hendricksen *et al.* 1982, McKeon *et al.* 1982).

GRASP is a single sward model with parameters optimised for specific pasture communities often representing the average across a range of species in the sward. For example, the maximum possible nitrogen content of a sward (e.g. 1.7% N for Mulga grasslands) is likely to be less than the maximum nitrogen content of some species (e.g. forbs 2.6% N) which may make up a small fraction of the sward (Beale 1975). These differences in nitrogen content are also likely to be reflected in digestibility, as suggested by figures 4.3 and 4.4. However, whilst simulation models of botanical composition exist in early developmental stages for other pasture systems, e.g. Ash *et al.* (1994), conceptual models only exist for Mitchell and mulga grasslands (Jones and Burrows 1994, McArthur *et al.* 1994). Hence, in this chapter the amount of variation in diet quality that can be explained by age alone is examined.

The development of the diet selection and feed intake models, as subroutines within GRASP, is presented here. Use of variables from these two subroutines, and other variables in the soil-plant system, to explain variation in observed wool production and liveweight change is detailed in Chapter Six.

5.2 Diet selection - model development

5.2.1 Mitchell grasslands

The initial approach was to optimise the existing GRASP diet selection equations relating to preference and nitrogen content of age pools, using data from oesophageal fistulated (*OF*) sheep on Mitchell grasslands. The relationship between the proportion of green in the diet relative to the pasture was then examined and optimised in line with available field data. Because of feedbacks in GRASP, modifications to calculations of green in the diet required re-analysis of the diet selection equations. This was performed separately for Mitchell grass and mulga *OF* data.

The initial diet selection model was developed using pasture age pools derived from GRASP simulations. The first age pool was accumulated daily growth (kg DM / ha) for a five day period. The age of the pool was calculated by weighting for daily growth. After each five day period the age and mass of pasture was passed to the next age pool; the seventh pool (pasture >30 days) was a terminal pool weighted for age (figure 5.1a).

Four versions of a diet selection model with a daily time step were developed and tested using the following three functions:

1. A preference index from the beef production model of Hendricksen *et al.* (1982) was used as the starting point for the differential selection of material from each age class (figure 5.2a):

$$Pref = 0.0211 + (1.0 - 0.0211) * \exp(-0.0286 * age) \qquad (5.1)$$

where *Pref* is the preference rating for a particular age pool, and
age is age in days of material in each pool.

2. A dry matter availability index, represented by a simple ramp function, with no restriction when age pools exceeded 50 kg DM / ha. Below 50 kg DM / ha, the index declined linearly to a value of 0.0 at 0.0 kg DM / ha;

3. The nitrogen content of the material selected from each age pool was calculated based on the following equation from Hendricksen *et al.* (1982, figure 5.2b):

$$Nit = 0.462 + 3.47 \exp(-0.1024 * age) \qquad (5.2)$$

where *Nit* is the nitrogen content (%) of material selected from each pool.

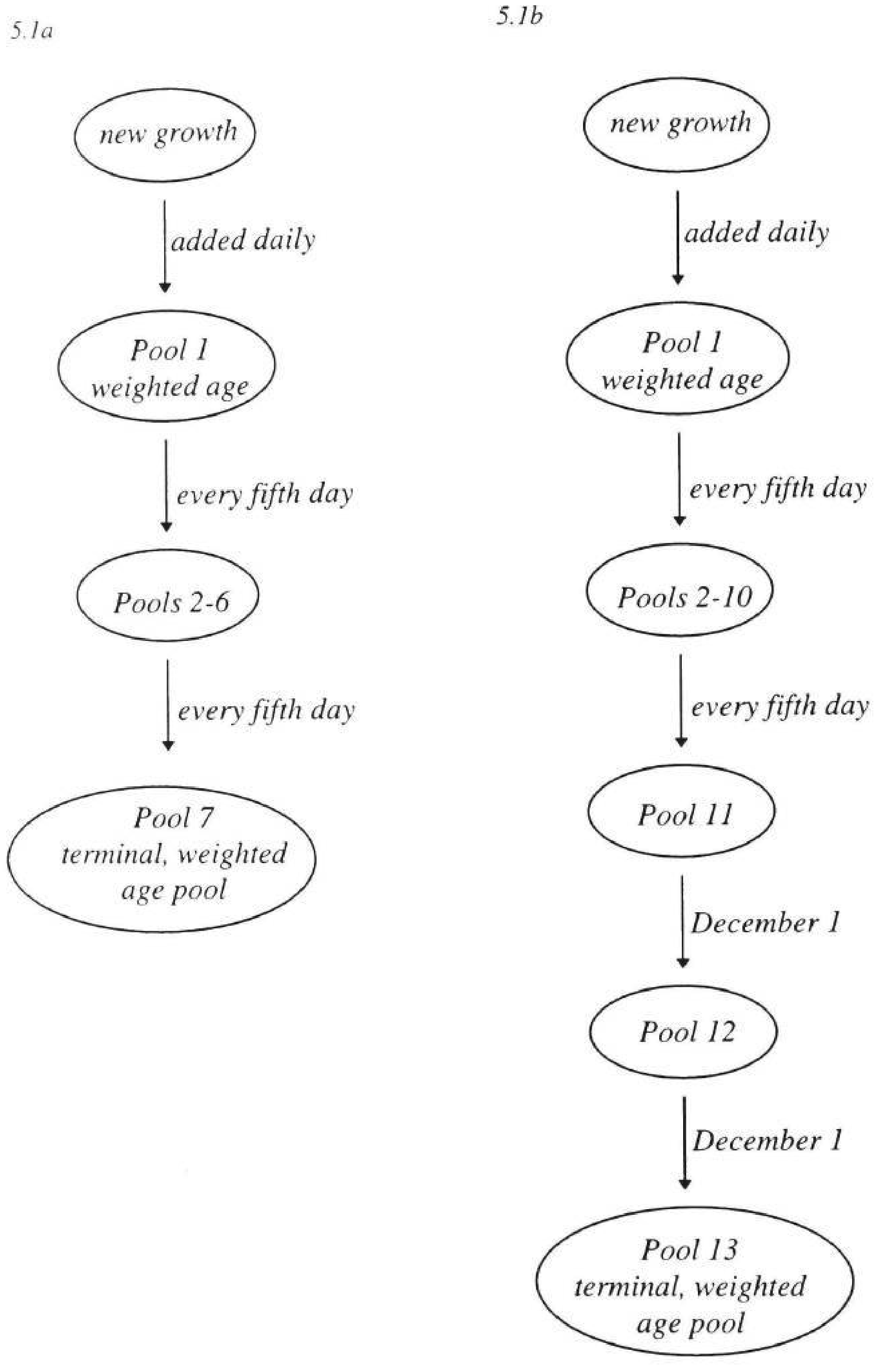

Figure 5.1. Schematic representation of flow of pasture through the age pools of the initial diet selection model (5.1a) and the final diet selection model (5.1b).

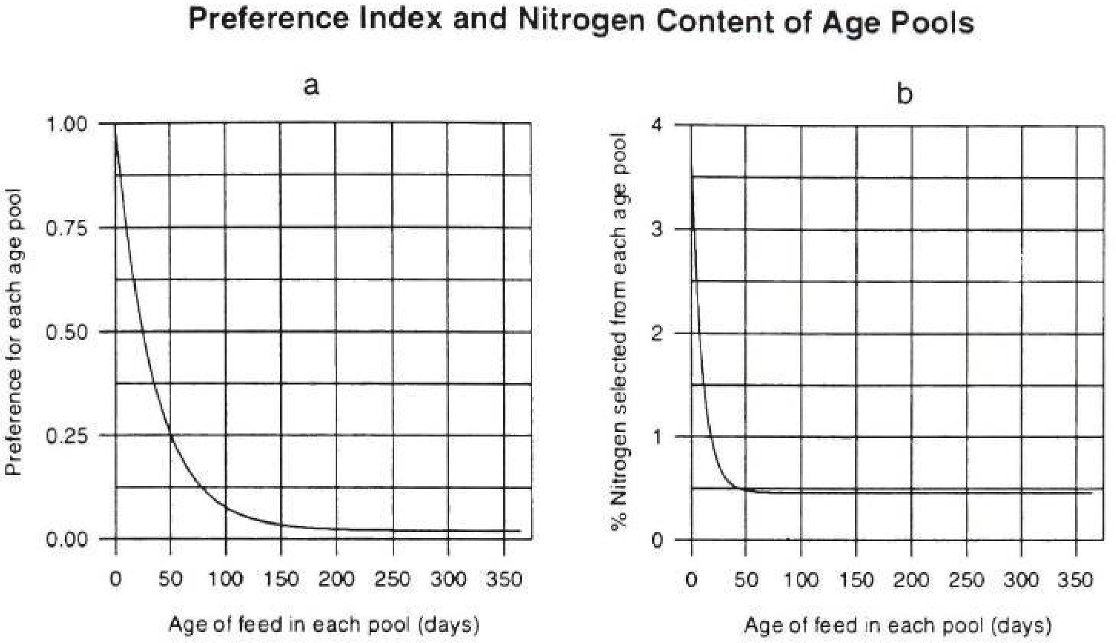

Figure 5.2. Relationships between preference index and age of pasture pool (a), and nitrogen content of the material selected from the pasture pool and age of pasture pool (b) (Hendricksen et al. 1982).

The four versions of the diet selection model varied slightly in their structure with *Diet Selection I* being the base model:

Diet Selection I

- preference for each age pool calculated as a function of age (figure 5.2a);
- preference modified by dry matter availability index;
- preference for each age pool then recalculated as a ratio of each pool's preference to the sum of preferences for all age pools;
- dry matter intake of 400 kg / 40 kg DSE / 365 days assumed;
- nitrogen concentration of material selected from each age pool calculated as a function of age (figure 5.2b); and
- nitrogen intake from each pool and daily nitrogen intake calculated.

Diet Selection II

- sum of preferences for all age pools had maximum value of 1.0, and the preference calculations began with youngest age pools (beginning the preference calculations with the youngest age pools, with the sum limited to 1.0, provided further emphasis of preference for younger pools);

- preference for first age pool calculated as function of age, then modified by dry matter availability index;
- if sum of preferences was less than 1.0, the next pool's preference was calculated and then modified by dry matter availability. Preference for a pool was the minimum of pool preference or (1.0 - provisional sum of preferences);
- if sum of preferences at end of calculations less than 1.0, the remaining preference was attributed to the oldest pool having dry matter available; and
- dry matter nitrogen intake then calculated as for *Diet Selection I*.

Diet Selection III

- as for *Diet Selection II,* but if sum of preferences less than 1.0 after all pool calculations, the remaining preference (1.0 - sum of preference) distributed to those pools having a preference as a proportion of their contribution to the sum of preference.

Diet Selection IV

- sum of dry matter availability indices had maximum value of 1.0;
- preference for youngest age pool calculated and modified by dry matter availability index;
- sum of preferences able to be of any value i.e. does not have to equal 1.0;
- for each subsequent pool, the dry matter availability index is the minimum of that calculated or (1.0 - provisional sum of dry matter availability); and
- dry matter intake must exceed 0.5 kg / day.

Initial work found that long intervals occurred when there was no plant growth. All feed was in the seventh age pool and the weighted age of this pool did not allow for adequate diet selection in terms of preference and nitrogen content of diet. Thus, the number of age pools was increased to thirteen, the first eleven pools being updated every five days (figure 5.1b). This number of pools with a turnover of five days allowed for a greater range of possible dietary nitrogen concentrations to occur. The function describing dietary nitrogen as a function of age produced a relatively constant value just under 0.5% from approximately fifty days of age onwards (figure 5.2b). The final two age pools were included to represent any possible carry over of pasture material from the previous growing seasons. On the 1st of December of each year, material in pool 11 was transferred to pool 12, and that in pool 12 to pool 13. Pool 13 became the terminal age pool.

Based on initial testing of the diet selection models, versions *I*, *II* and *III* were incorporated into the GRASP model as subroutines for further testing. Using optimisation software (PEST, Watermark Computing 1994), each model was tested against observed diet selection data. Parameters optimised in each model included:

- maximum nitrogen content (%) of new growth, and therefore the maximum possible nitrogen content of the diet;
- minimum nitrogen content of old dead pasture, and therefore the minimum possible nitrogen content of the diet;
- the value at which dry matter availability of each age pool had no restrictive effect on preference / intake of that pool;
- k value dictating the decline in diet preference of pools with increasing age, being -0.0286 in equation 5.1; and
- k value dictating the decline in dietary nitrogen content of pools with increasing age, being -0.1024 in equation 5.2.

After further work, modifications were made to the calculation of nitrogen concentration of the age pools. Initially, new growth had a set nitrogen concentration, and as it aged, the decline in nitrogen content was calculated as a linear function of a growth index (*GIX)*, with nitrogen decay occurring fastest under better growing conditions (Wilson 1982):

$$\text{rate of nitrogen decay} = a - b * GIX \tag{5.3}$$

$$Nit_t = (1.0 - \text{rate of nitrogen decay}) * Nit_{t-1} \tag{5.4}$$

where Nit_t is dietary nitrogen content of pool today, and

Nit_{t-1} is dietary nitrogen content of pool yesterday.

Comparison of the models, optimisation, and selection of the best set of parameters for each model was carried out against the dietary nitrogen data for Toorak collected by Lorimer (1976) and Pritchard *et al.* (1986) between 1970 and 1979. A total of 39 data points were available. *Diet Selection I* was able to account for 66.6% of the variation in observed dietary nitrogen concentration, *Diet Selection II* 80.4%, and *Diet Selection III* 77.9% (figure 5.3, see table 5.1 for parameter values). The optimised *k* value in *Diet Selection II* for the pool preference function was the lower boundary of the optimisation process (-1.0E-10) and represented a constant preference for all pools irrespective of the age of the pasture. However, in *Diet Selection II* preference calculations begin with the youngest age pool with 'sum of preferences' having a maximum value of 1.0, hence there is still a preference for younger pools.

Table 5.1. Parameter values for the Diet Selection II model for Mitchell (two stages of development) and mulga communities.

	Mitchell Grasslands		**Mulga**
Parameter / Variable	*Initial optimisation (Toorak data)*	*Final optimisation*	
Nitrogen concentration of new growth and maximum concentration possible in diet	2.74	2.39	2.18
Level of dry matter availability which no longer restricts preference or intake from individual age pools	225	261	11.9
k value for decline in diet preference with age	0	0	0
y intercept for rate of nitrogen decay function	0.0035	0.0041	0.0021
slope for rate of nitrogen decay function	0.019	0	0

A further ten data points were available from the Burenda grazing trial and eleven from the Biddenham experiment (table 4.3). Re-optimisation of the diet selection models (60 data points) resulted in *Diet Selection II* explaining the most variation (r^2=0.533) in dietary nitrogen across the three Mitchell grass sites. The parameters were not markedly changed. Predicted and observed dietary nitrogen values for Mitchell grass pastures are shown in

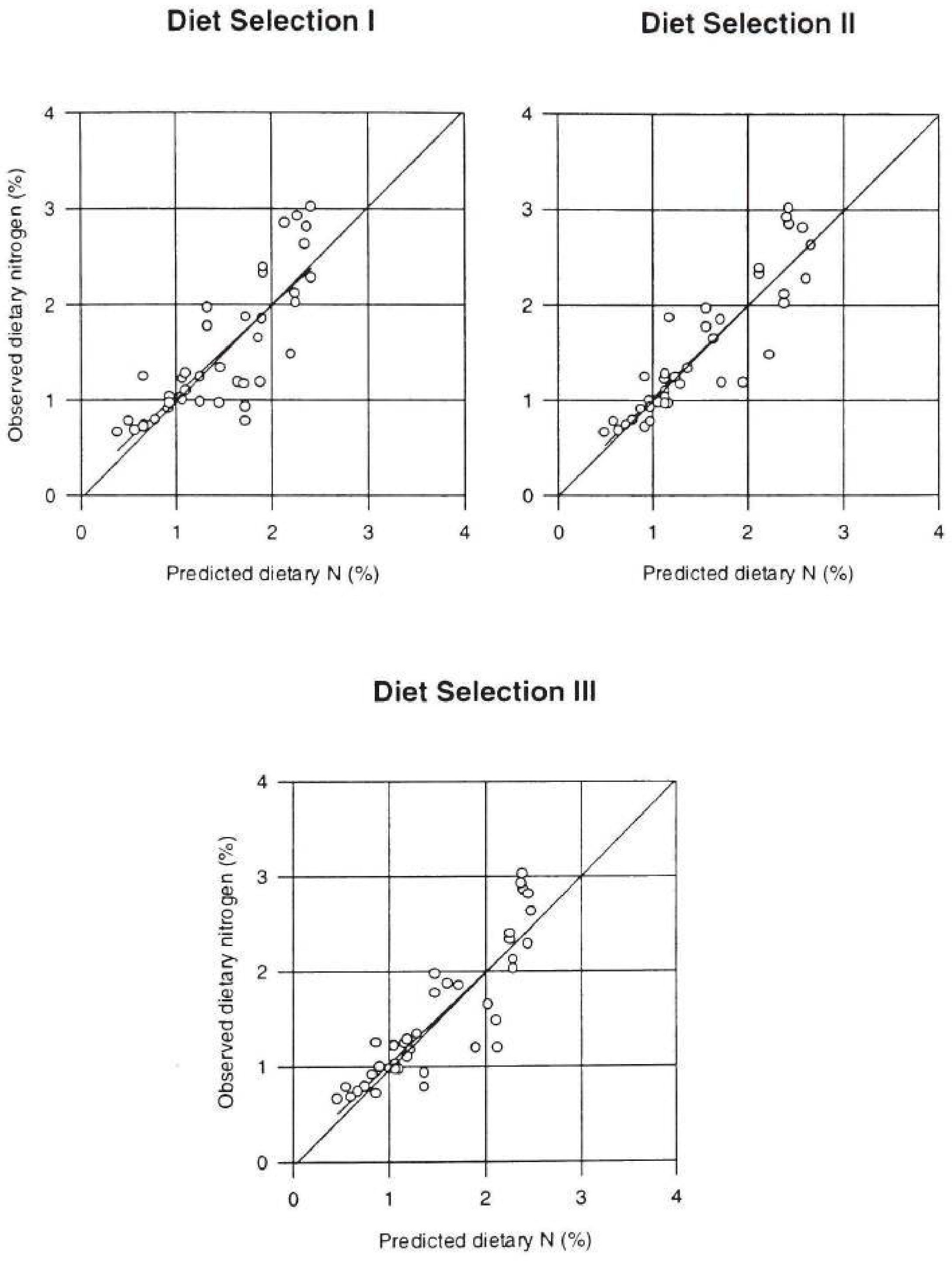

Figure 5.3. Predicted and observed dietary nitrogen concentrations of the three diet selection models using Toorak data and following optimisation.

figure 5.4. Extreme outliers may represent diets composed of a large proportion of forbs with high nitrogen contents. For example, Lorimer's (1976) dietary nitrogen contents greater than 2.5% all occurred when what was classified as 'other forbs', when measured (3 out of 5 observations), were the single largest component of the diet. Similarly, high dietary nitrogens (>2.5%) at Biddenham were associated with high forb content in the selected diet (Orr *et al.* 1988).

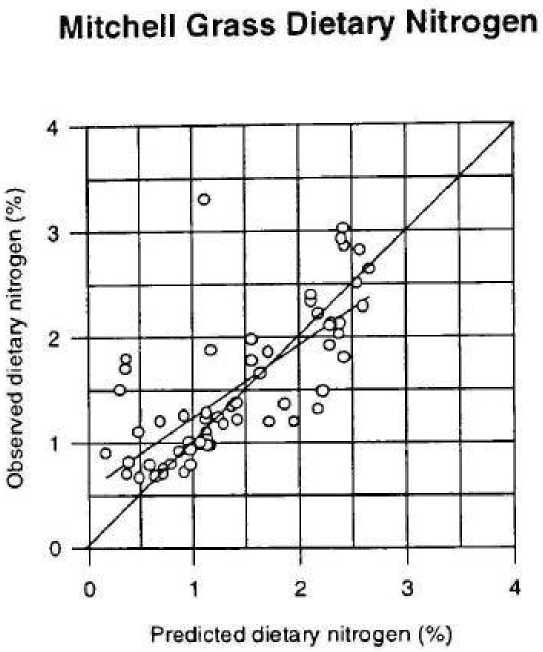

Figure 5.4. Predicted and observed dietary nitrogen concentrations of Diet Selection II model using Mitchell grass data and following optimisation.

Preliminary testing of the three versions of the diet selection model with dietary nitrogen data for the mulga grasslands failed to explain a significant amount of the observed variation. One of the major differences between Mitchell grass and mulga grassland associations is the presence of mulga leaves which serve as a source of nutrition, especially during dry periods.

5.2.2 *Proportion of green in diet*

The proportion of green in the diet influences GRASP via its effect on the green pool, and subsequent pasture growth response to available rainfall / soil water. The function in

GRASP relating the percentage green material in diet to percentage green material in pasture, is based on the work of Hendricksen *et al.* (1982) and Ash *et al.* (1982) with cattle:

$$\text{Modified Prop. GP} = (\text{ Proportion Green in pasture } - 0.1\ ) / 0.9 \qquad (5.5)$$

$$\%\ \text{Green in diet} = 19.0 * \text{Modified Prop. GP} / (\ 19.0 * \text{ Modified Prop. GP} + 1.0 - \text{Modified Prop. GP}\ ) \qquad (5.6)$$

where *Modified Prop. GP* is the modified proportion green in pasture.

The potential for greater feed selection by sheep required that this function be tested against available experimental data, and recalibrated if necessary. Lorimer (1976) recorded the percentage of green material in the diet of his *OF* sheep (figure 5.5) but did not record the proportion of green material in the pasture. GRASP was used to generate data on the percentage of green material in the pasture, and the data of Lorimer (1976) were then used to test the existing GRASP functions. Equation 5.5 was found to be unnecessary, the *Modified Prop. GP* variable in equation 5.6 being replaced with *Proportion Green in pasture*. Optimisation of the parameter (original value 19.0) within this function resulted in the value 313 giving the best fit (figure 5.6). Lorimer (1976) made 24 observations of which two outliers, in terms of predicted *vs.* observed values, were excluded from the analysis to ensure the best overall function resulted from the optimisation process. Figure 5.7 shows predicted and observed values using the original parameter and the optimised parameter, while figure 5.8 shows the predicted green proportion of the diet for sheep grazing at Toorak as a time series during the period when the Lorimer (1976), Pritchard *et al.* (1986) and Pritchard (1988) experiments were carried out. This shows the ability of sheep to be much more selective for green material than cattle and supports the findings of previous work (Arnold 1981, Hodgson 1982, Forbes and Hodgson 1985).

Following optimisation of the function describing the proportion of green in the diet, the diet selection models were re-optimised. The observation in the Biddenham data set,

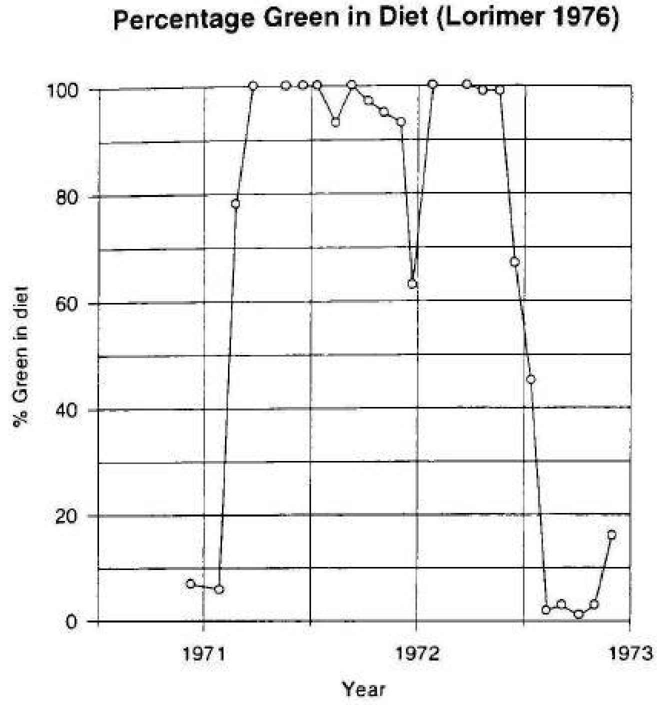

Figure 5.5. Percentage of green in the diet of Lorimer's (1976) sheep over time.

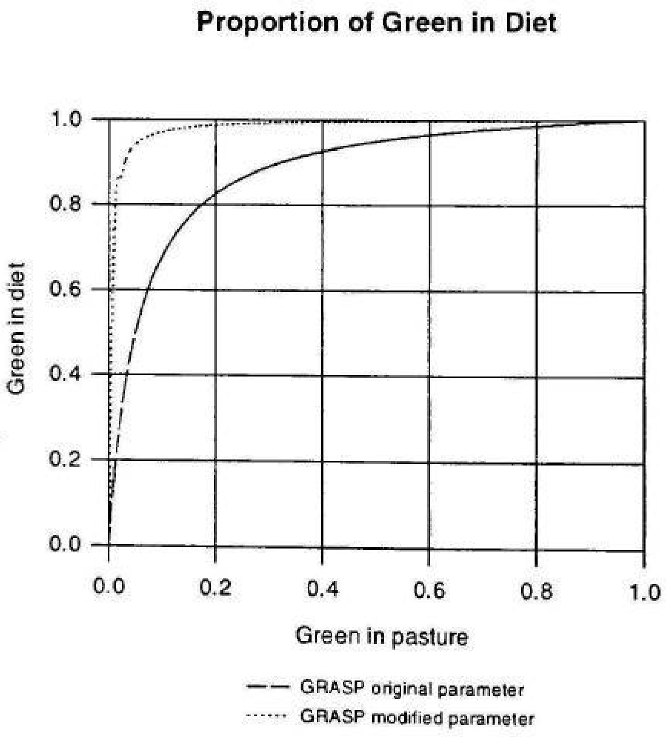

Figure 5.6. Proportion of green in the diet as calculated using the original GRASP parameter and the optimised parameter from Lorimer's (1976) data.

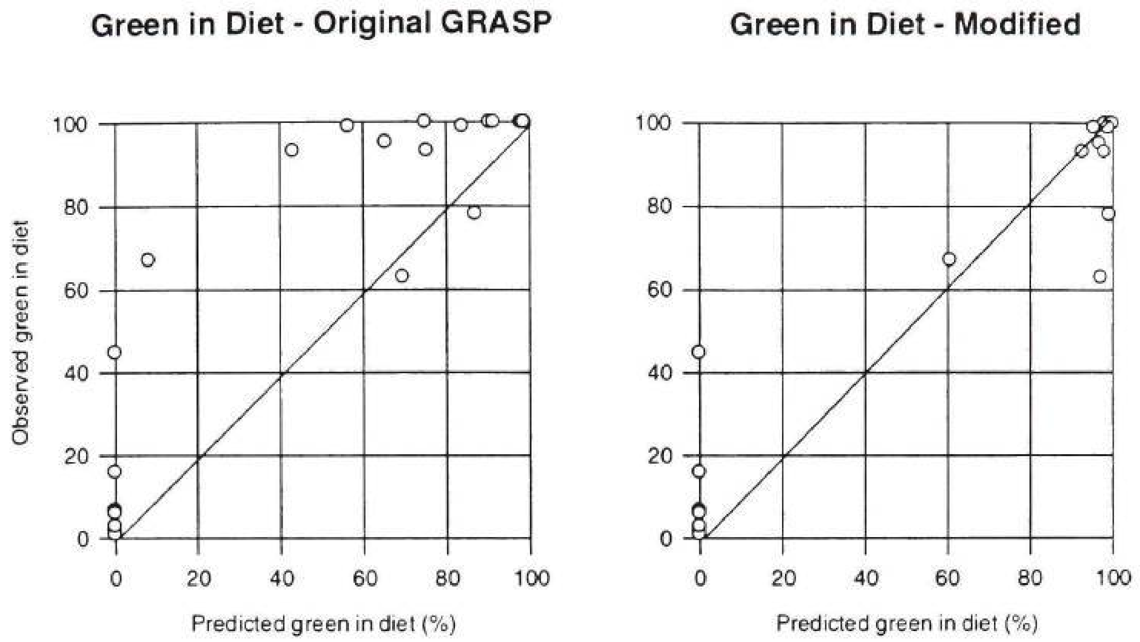

Figure 5.7. Predicted and observed values for green material present in the diet of Lorimer's (1976) sheep using the original GRASP and the optimised GRASP parameter.

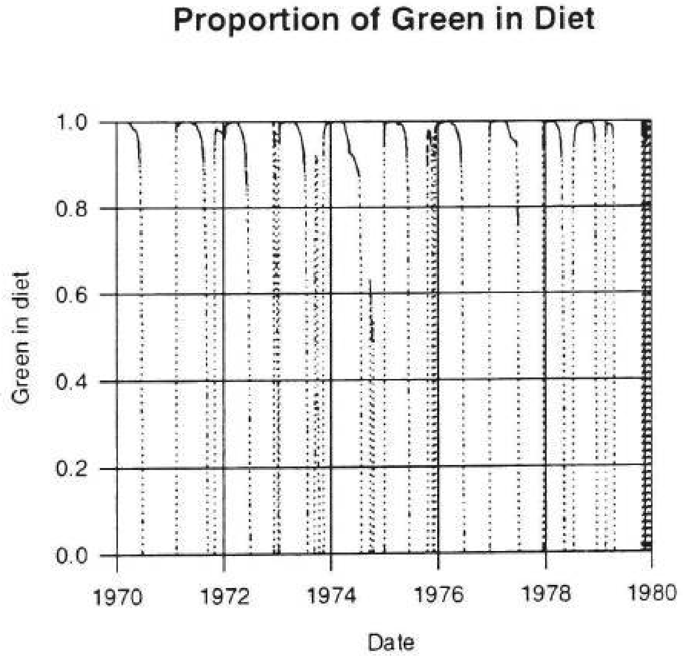

Figure 5.8. Predicted green proportion of the diet for sheep grazing at Toorak from 1970 to 1980 using the modified GRASP function.

where the observed nitrogen level was 3.3% (highest level of all data sets) and the predicted was only 1.27%, was excluded from the optimisation process as there was no supporting evidence for such a high quality diet (e.g. botanical composition of the diet was not available; yield, botanical composition and frequency of occurrence of species in the pasture were not available; no rain was reported to fall in the two months prior to dietary sampling; the equivalent observed dietary nitrogen content for a paddock modified in an attempt to increase the forb yield was 1.71%). As such, this particular diet observation cannot currently be explained in terms of climate or pasture modelling. The best results were obtained using the *Diet Selection II* model. The resultant parameters (table 5.1) were able to explain 58.1 % ($P<0.001$) of the variation (all 60 data points, figure 5.9) and 69.1% ($P<0.001$) of the variation (59 data points - outlier excluded) in dietary nitrogen concentration of the Mitchell grassland data. The optimised value in *Diet Selection II* for the slope of the rate of decay function was the lower boundary of the optimisation process (-1.0E-10) and represents a constant rate of decay irrespective of *GIX*.

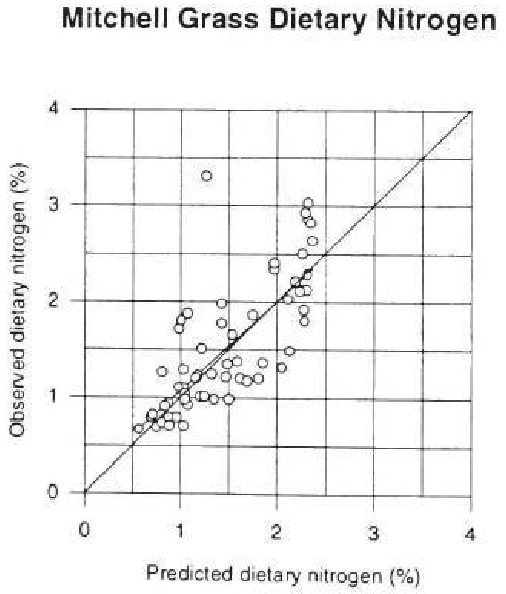

Figure 5.9. Predicted and observed dietary nitrogen levels for Mitchell grass data following optimisation for the percentage of green in the diet, and the Diet Selection II model.

5.2.3 Mulga grasslands

A much smaller data set existed for mulga grasslands in terms of diet selection, 16 observations of dietary nitrogen were available from the Halton experiment (Beale 1975) and the Arabella (McMeniman *et al.* 1986b) grazing trial. Additionally, the data collected at Halton (13 observations) required modification for reasons already discussed (table 4.3). This modification assumed mulga was 50% digestible. Figure 5.10 shows the predicted and observed dietary nitrogen concentrations resulting from the use of *Diet Selection II* and parameters for Mitchell grass. A consistent underprediction of dietary nitrogen content resulted.

The observation of Beale (1975) in which a dietary nitrogen concentration of 3.3% was observed (predicted value 1.1% using Mitchell grass parameters) was excluded from optimisation as this level of dietary quality was not supported by the observed nitrogen content for pasture forbs (1.7%), and the availability of forbs and overall pasture nitrogen content relative to other dietary sampling periods.

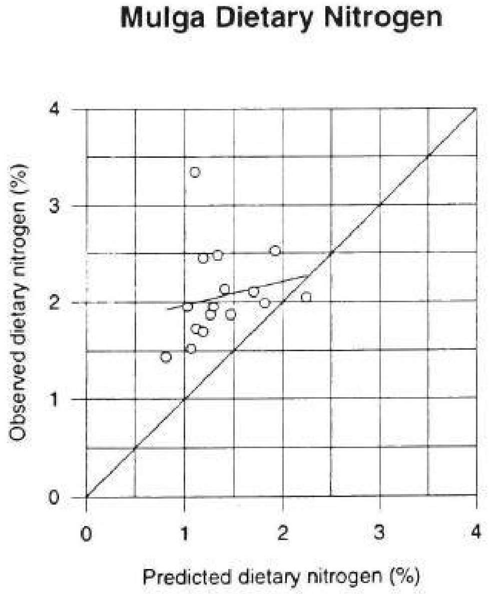

Figure 5.10. Predicted and observed mulga dietary nitrogen concentrations using Diet Selection II and the Mitchell grass parameters.

Optimisation of the *Diet Selection II* model resulted in 41.9% of the variation in mulga dietary nitrogen concentration being explained (figure 5.11), the parameters for the model are listed in table 5.1. With respect to the Mitchell grass model these parameters represent:

- lower nitrogen concentration of new growth and maximum concentration in diet;
- reduced rate of nitrogen decay; and
- lower level of dry matter of at which preference / intake of age pools is restricted.

Possible causes for the differences in parameters between the Mitchell and mulga models include:

- markedly reduced dry matter availability of mulga grassland associations compared with Mitchell grasslands; and
- mulga leaf on trees and litter were not considered in the predicted and observed dry matter yields.

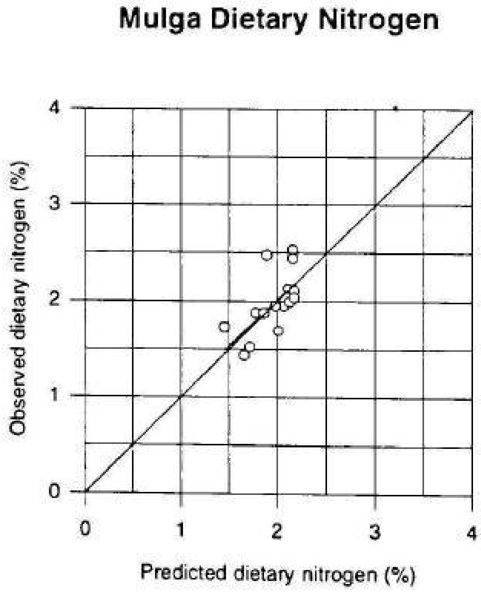

Figure 5.11. Predicted and observed mulga dietary nitrogen concentrations using Diet Selection II and the mulga parameters.

5.2.3 Buffel pastures

No data were available for Buffel pastures to enable a separate diet selection model to be calibrated. However, Mitchell grass parameters were used in an analysis of the Eastwood grazing trial (unpublished data, Chapter Six) which was carried out on buffel pastures.

5.2.4 Time series

The selected Mitchell and mulga diet selection models, developed from data pooled for their respective pasture types, were then used to examine how well individual trials were simulated (figure 5.12). A standard comparison of predicted and observed values is also shown in figure 5.13.

The Mitchell grass model was able to explain 75.3% ($P<0.001$) of the variation in the Toorak data although the higher observed dietary nitrogen levels were not well simulated. The Burenda data sets were obtained from different levels of utilisation with only five records per utilisation. The model simulated the general trend in observed values although the results were not significant ($P>0.05$). The Biddenham data were simulated well, 86.7% ($P<0.001$) of the variation was explained when the observation (3.3% dietary nitrogen) not used in the optimisation was excluded from the regression. When this single outlier was included, the variation accounted for was not significant ($r^2=0.35$, $P=0.547$) showing the potential difficulty of developing diet selection models when data includes variation that defies ecological explanation.

The mulga model was able to explain 51.3% ($P<0.01$) of the variation in the Halton data when the outlier (3.3% dietary nitrogen) was excluded, and 32.9% ($P<0.05$) when it was included. The time series plot shows the model failed to adequately predict the two higher levels of dietary nitrogen (one of which was excluded from the optimisation process), but in general did a satisfactory job. The Arabella data set has only three data points and the model ranked the three points correctly but was unable to simulate the higher dietary nitrogen concentrations.

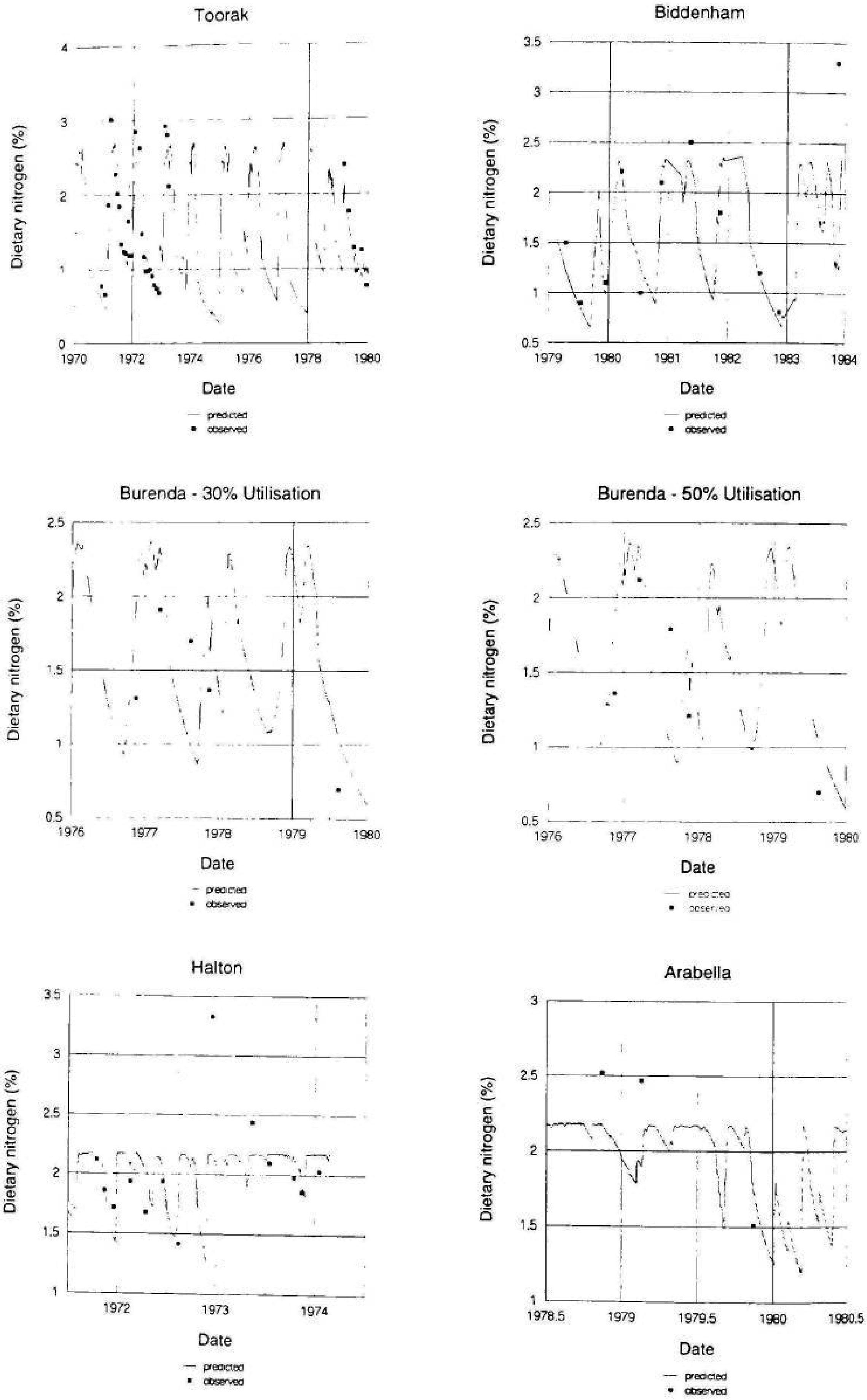

Figure 5.12. Time series comparison of predicted and observed dietary nitrogen concentrations for Toorak, Biddenham, Burenda (30 and 50%), Halton and Arabella using Diet Selection II and the appropriate parameters.

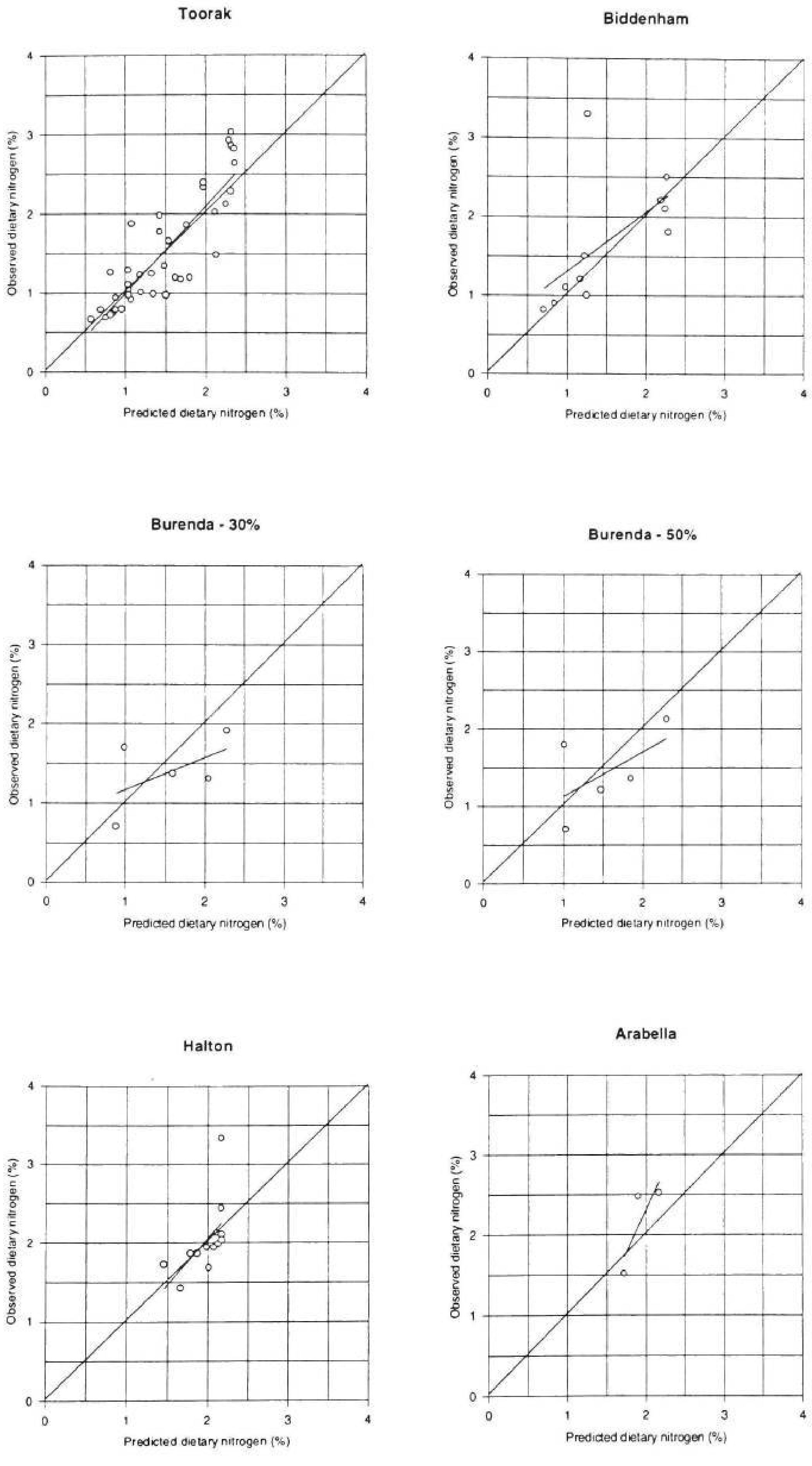

Figure 5.13. Predicted and observed dietary nitrogen concentrations for Toorak, Biddenham, Burenda (30 and 50%), Halton and Arabella using Diet Selection II and the appropriate parameters.

The diet selection models were able to account for a high proportion of variation in observed diets. The most likely source of outliers were very high nitrogen concentrations associated with forbs or new growth.

5.3 Dry matter intake - model development

Prediction of dry matter intake was examined by four different methods:

- multiple linear regressions using climatic, pasture and animal variables;
- function of dietary quality, pasture yield and climatic stress;
- the intake model in GRASP; and
- relevant intake equations in EPBTS.

Lorimer (1976) provided the best data set in terms of size (22 observations), frequency of sampling and reliability, to evaluate the above methods. Intake data were not corrected for liveweight (range 31.5 - 46.8 kg) as the same animals were used throughout the experiment.

5.3.1 Multiple linear regression

The use of climatic, pasture and animal variables was unable to explain the variation in Lorimer's (1976) observed dry matter intake. The most correlated (negative) variable was age of sheep ($r^2=0.333$, $P<0.05$). Other variables, such as total standing dry matter (*TSDM*), dietary digestibility and dietary nitrogen content, were not significantly ($P>0.05$) correlated.

5.3.2 Function of diet quality, pasture yield and climatic stress

The following equation was tested:

$$DMI = (a + b * \mathit{diet\ quality}) * (1.0 - \exp (-c * TSDM)) * (d + e * \max (0 , (THI - 80))) \tag{5.7}$$

where *DMI* is dry matter intake (kg DM / sheep / day), *diet quality* is either dietary nitrogen concentration or dietary digestibility,

TSDM is total standing dry matter (kg DM / ha),

THI is a temperature humidity index (King 1983), and

a, b, c, d and e are parameters able to be optimised.

Lake *et al.* (1996) have shown that *THI* (King 1983) can explain climatic stress effects on production in dairy cattle. Equation 5.7 was also tested without the climatic stress component. The inclusion of *THI* did not improve the proportion of variation explained.

The above two approaches were repeated using the combined Mitchell grass data set (32 observations) which included the work from Lorimer (1976) and Burenda (McMeniman *et al.* 1986b). The Biddenham data included feed intake observations but were for breeding ewes and therefore not included. The Pritchard (1988) data were not used because of marked variation in observed intakes compared with the earlier work of Lorimer (1976), discussed previously in Chapter Four. Pritchard's (1988) values were also substantially higher than estimated for equivalent animals using the Australian feeding standards (SCA 1990).

Use of the Mitchell grass data (32 observations) in the above two methods failed to explain any significant level of variation. However, a non-significant regression (P=0.054) which included maximum daily temperature, observed dietary nitrogen concentration and observed dietary digestibility, explained 75.6% of the variation in observed dry matter intake:

$$DMI = -0.469 + 0.013 * t_{max} + 2.765 * DMD - 0.023 * nitrogen \tag{5.8}$$

where t_{max} is maximum daily temperature,

DMD is dietary dry matter digestibility, and

nitrogen is dietary nitrogen content.

This was unexpected as nitrogen concentration and digestibility are correlated ($r^2 = 0.34$ - 0.79, see figures 4.3 and 4.4 and equations 5.15 to 5.21) and therefore unlikely to both be selected in a stepwise forward regression, although the coefficient for nitrogen content was negative.

The mulga data set (14 observations) and combined data sets were then tested using the above two methods with no significant results.

5.3.3 GRASP

GRASP simulates animal intake to remove pasture from pools, not to model animal production. The GRASP model assumed an intake of 400.0 kg DM / year / DSE after Beale (1985) without seasonal variation. This annual intake was used to calculate stocking rates (equation 6.1) in the pasture utilisation trials (see table 6.1), and in the calculations of property carrying capacity (Johnston *et al.* 1996). This intake was modified only by a *restriction factor* depending on total standing dry matter and the degree of pasture utilisation:

$$\mathit{restriction\ factor} = \max(\,0.0\,,\ \min(\,1.05 - 0.5 * \mathit{Util}\,),\ \mathit{TSDM} / 230\,,\ 1.0\,) \tag{5.9}$$

$$\mathit{DMI} = \mathit{restriction\ factor} * 400.0 / 365.0 * (\,\mathit{Wt}^{0.75} / 40^{0.75}\,) \tag{5.10}$$

where *Util* is the proportion of pasture growth since the 1st December consumed,
TSDM is the total standing dry matter (kg DM / ha),
DMI is dry matter intake / DSE (kg / day, DSE is a 40 kg sheep), and
Wt is liveweight of the sheep (kg).

A *restriction factor* of 1.0 allowed maximum feed intake. Figure 5.14 shows the relationship between GRASP predicted dry matter intakes and observed dry matter intakes ($r^2=0.095$ $P<0.05$ $n=46$) for the combined data set. Mean daily intakes for GRASP and observed data were 1.14 and 0.99 kg respectively.

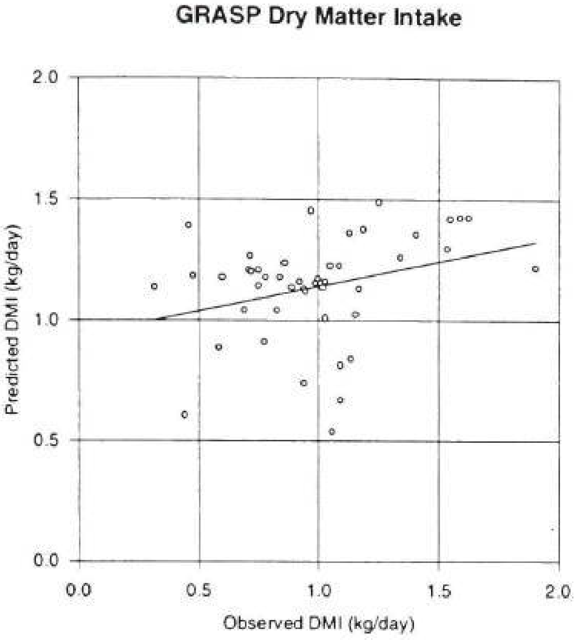

Figure 5.14. Predicted and observed Dry Matter Intakes using GRASP and the combined data set.

5.3.4 EPBTS

EPBTS required dietary digestibility as an input from which crude protein was calculated, while the diet selection subroutine within GRASP generated dietary nitrogen concentrations. Thus, it was originally planned that diet digestibility for the EPBTS subroutine would be calculated from GRASP generated dietary nitrogen. However, results of the multiple linear regression (equation 5.8), where both observed nitrogen and digestibility were selected in a forward stepwise regression (which explained a high percentage of the variation in Mitchell grass dry matter intake) resulted in an attempt to model the dietary digestibility of age pools in parallel with the nitrogen calculations.

Some of the variability in the relationship between digestibility and nitrogen concentration may have been influenced by maximum temperatures during the period of growth (Deinum *et al.* 1968, Wilson *et al.* 1991). Several functions were used in an attempt to model dry matter digestibility of new growth, and therefore, maximum digestibility:

$$Dry\ Matter\ Digestibility = 80.0 * (1.0 - a + b * t_{max}) \qquad (5.11)$$

$$Dry\ Matter\ Digestibility = 80.0 * (1.0 - a + b * max (0.0, t_{max} - c)) \quad (5.12)$$

$$Dry\ Matter\ Digestibility = max (d, 80.0 * (1.0 - a + b * max (0.0, t_{max} - c))) \quad (5.13)$$

$$Dry\ Matter\ Digestibility = max (d, 80.0 * (1.0 - a + b * t_{max}) \quad (5.14)$$

where t_{max} is the maximum daily temperature,

a and b are parameters,

c is a threshold temperature, and

d is the minimum digestibility.

The first equation assumed a maximum digestibility of 80%, this being reduced at the time of growth by the maximum daily temperature. The second equation reduces the digestibility at growth when maximum daily temperature exceeded a threshold temperature. The third and fourth regressions incorporated a minimum value for digestibility of growth. The above functions were optimised against observed digestibility data, initially using the same rate of decay as for crude protein, and then by a separate decay function which was also optimised. No satisfactory results were obtained, suggesting that temperature does not affect diet selection either directly or through effects on plant digestibility.

The conversion of calculated nitrogen concentration to digestibility was examined from three possibilities:

- Relationship operating within Grazfeed. The Grazfeed function was calculated by entering digestibilities (e.g. 40, 50%) into the commercial software and developing a relationship from the crude protein levels returned. The inverse of this relationship was used to calculate digestibility from crude protein:

$$Dry\ Matter\ Digestibility = 0.1865 + 1.2071 * Crude\ Protein^{0.5} \quad (5.15)$$

where *Dry Matter Digestibility* and *Crude Protein* expressed as proportions.

- Toorak Mitchell grass green leaf relationship (the green leaf relationship was very similar to the whole plant relationship but was used as this was thought to represent the green leaf selection capability of sheep, J. Carter unpublished data):

  *Dry Matter Digestibility = 0.3152 + 1.598 * Crude Protein*

  (r^2=0.55 P<0.001 n=16, 5.16)

  The data for the above regression were not standardised. Standardisation of the above *in vitro* samples using *in vivo* standards yielded the following regression:

  *Dry Matter Digestibility = 0.3760 + 1.317 * Crude Protein*

  (r^2=0.52 P<0.001 n=16, 5.17)

- Dietary relationship from *OF* sheep. The Lorimer (1976) data were the most comprehensive:

  *Dry Matter Digestibility = 0.3411 + 1.3531 * Crude Protein*

  (r^2=0.68 P<0.001 n=27, 5.18)

  The use of Mitchell grass data gave the following regression:

  *Dry Matter Digestibility = 0.4149 + 1.2915 * Crude Protein*

  (r^2=0.324 P<0.001 n=73, 5.19)

  The use of mulga grasslands data gave the following regression:

  *Dry Matter Digestibility = 0.3469 + 1.7010 * Crude Protein*

  (r^2=0.421 P<0.01 n=16, 5.20)

  The combined data gave the following regression:

  *Dry Matter Digestibility = 0.4131 + 1.2799 * Crude Protein*

  (r^2=0.330 P<0.001 n=89, 5.21)

The degree of correlation between digestibility and nitrogen are in agreement with the work of McIvor (1990). Using two accessions of *Urochloa* (different species), a linear relationship explained 49.3% of the variation. However, with these introduced grasses, and perhaps associated with increased soil nitrogen, the slope of the relationship was steeper (2.224) than the above relationships.

The digestibility of mulga, and dry matter intake in the *OF* work of Beale (1975), were modified assuming 50% digestibility when present in diet. The different regressions are shown in figure 5.15.

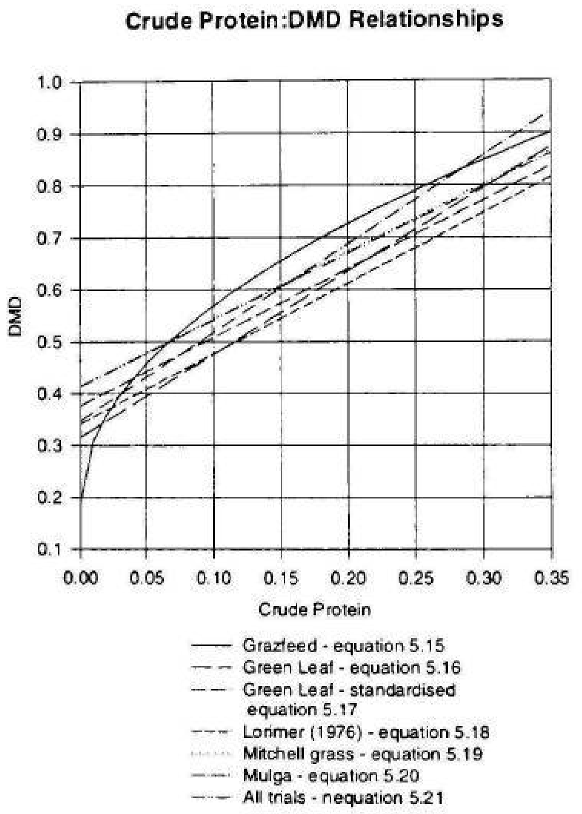

Figure 5.15. Different functions available to calculate Dry Matter Digestibility from Crude Protein content of the diet.

Apart from the Grazfeed and mulga functions, there were strong similarities between the regressions. The mulga regression was based on a small data set, the majority of which underwent some modification prior to use (see table 4.3). The all trial regression (equation 5.21) was selected for use in subsequent work. The correlation was low ($r^2=0.33$) but it was based on the most comprehensive data set, and was similar to the non-standardised and standardised green leaf regressions.

Optimisation and modifications were carried out on EPBTS parameters and functions used to predict dry matter intake. Simplification of equations calculating *rumen degradable protein required (RDPR)*, and reductions in *potential dry matter intake (PDMI)* for diets with inadequate protein levels, gave a slight improvement in dry matter intake calculations. Optimisations of these simplified equations were carried out with the Mitchell and mulga data sets initially, and then with the combined data set. The optimised parameter in the calculation of *RDPR* represented a microbial protein yield of 6.24 g / MJ *ME* (equation 5.41), a value slightly below the 8.4 g proposed by SCA (1990). The crude protein threshold at which *PDMI* is reduced, was 5.18% (equation 5.42), a value in line with the work of Minson and Milford (1967). Only 17.6% ($P<0.01$) of the variation in observed dry matter intakes was accounted for by this approach, but the mean values for both sets were very close (figure 5.16). Predicted feed intake values had a much lower range than the observed values.

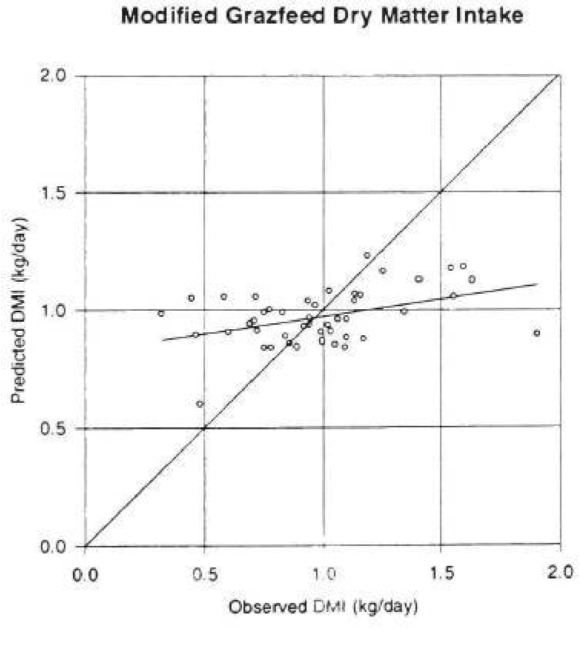

Figure 5.16. Predicted and observed Dry Matter Intake following modifications to the functions within EPBTS.

The modified EPBTS dry matter intake was calculated by the following method:

$$BthWt = 0.1 * SRW \tag{5.22}$$

$$N = SRW - (SRW - BthWt) * exp(-age * 0.015 / SRW^{0.27}) \tag{5.23}$$

where N is normal weight (kg), the weight of an animal when condition score is middle of the range,

SRW is the Standard Reference Weight (kg), the weight of an animal when it reaches mature skeletal size and has a condition score in the middle of the range (excluding fleece and conceptus),

$BthWt$ is standard birthweight (kg), and

age is age in days.

For immature sheep (≤ 24 months of age):

$$N = min (N, HighWt) \tag{5.24}$$

$$Z = N / SRW \tag{5.25}$$

$$BC = Wt / N \tag{5.26}$$

For mature sheep:

$$Z = N / SRW \tag{5.27}$$

$$BC = Wt / N \tag{5.28}$$

where $HighWt$ is the highest weight (kg) attained so far by the animal (fleece and conceptus free),

Z is relative size, and

BC is body condition.

$$\begin{aligned} &If\ t_{mean} > 25.0\ and\ t_{min} > 22.0\ then\ TF = 1.0 - 0.01 * (t_{mean} - 25.0) \\ &\qquad else\ TF = 1.0 \end{aligned} \tag{5.29}$$

where t_{mean} is the mean daily temperature (^{0}C),

t_{min} is the minimum daily temperature (^{0}C), and

TF is the temperature factor used to modify *potential dry matter intake*.

$$If\ BC < 1.0\ or\ immature\ animal\ PDMI = 0.04 * SRW * Z * (1.7 - Z) * TF$$
$$else\ \ PDMI = 0.04 * SRW * BC * (1.7 - BC) * TF \tag{5.30}$$

where *PDMI* is the *potential dry matter intake* (kg / day)

$$HF = max (1.0 ,30.0 / 3.0) \tag{5.31}$$

where *HF* is the height factor used to modify feed intake, height of tussock grasslands was assumed to be 10 - 30.0 cm per tonne of dry matter (G. McKeon pers. comm.).

$$Rate\ of\ Eating = 1.0 - exp (-0.002 * TSDM * HF * ZF) \tag{5.32}$$

$$Time\ Spent\ Eating = 1.0 + 0.6 * exp (-2.0 * (0.001 * TSDM * HF * ZF)^2) \tag{5.33}$$

$$Relative\ Availability = Rate\ of\ Eating * Time\ Spent\ Eating \tag{5.34}$$

$$Relative\ Ingestability = 1.0 - 1.0 * (0.8 - DMD) \tag{5.35}$$

$$DMI = PDMI * Relative\ Availability * Relative\ Ingestability \tag{5.36}$$

where *TSDM* is the total standing dry matter (tonne DM / ha),

DMD is dry matter digestibility of ingested feed, and

DMI is dry matter intake (kg DM / day).

$$MEf = 17.0 * DMD\ - 2.0 \tag{5.37}$$

$$MEI = MEf * DMI \tag{5.38}$$

$$Crude\ Protein\ Degradability = DMD + 0.1 \tag{5.39}$$

$$RDPI = DMI * Crude\ Protein * Crude\ Protein\ Degradability \tag{5.40}$$

$$RDPR = MEI * 0.00624 \tag{5.41}$$

$$if\ Crude\ Protein < 0.0518\ then\ PDMI = PDMI * RDPI / RDPR \tag{5.42}$$

and DMI functions recalculated

where MEf is metabolisable energy content of the forage (MJ / kg DM),
MEI is metabolisable energy intake,
$RDPI$ is *rumen degradable protein intake* (kg / day), and
$RDPR$ is *rumen degradable protein required* (kg / day).

The modified version of EPBTS was selected as the best method for calculating dry matter intakes.

5.3.4 Interaction between diet selection and feed intake

An iterative process was used to simulate dietary crude protein. The interaction between the relevant GRASP subroutines is shown in figure 4.14. Dry matter intake, as calculated by GRASP from the default intake level (1.096 kg DM / d) and pasture utilisation, was used in the diet selection subroutine to calculate a provisional dietary crude protein concentration. This was in turn used by the modified EPBTS subroutine to calculate the dry matter intake on a per sheep basis. The final dietary crude protein concentration was then calculated in the *DMI* subroutine using the new dry matter intake from EPBTS, stocking rate and availability of pasture in each age pool.

There were few differences in the provisional and final dietary crude protein / nitrogen concentrations indicating that the iterative procedure converged to dietary crude protein level. These differences arose when the provisional feed intake calculated by GRASP was greater than that of the modified EPBTS subroutine. The greater GRASP intake on these occasions resulted in the demand for feed from a specific pool exceeding that available, the difference being made up from older age pools, and hence, dilution of the dietary nitrogen concentration. Simulation of the Toorak utilisation trial resulted in differences between provisional and final dietary nitrogen concentration on only a small number of occasions in the 80% utilisation treatment, and none in the 50% utilisation treatment (figure 5.17).

Thus the above procedure for calculating diet selection and feed intake could be used to replace the assumed constant potential intake currently used in GRASP. However, only a small proportion of the variation in dry matter intake is explained.

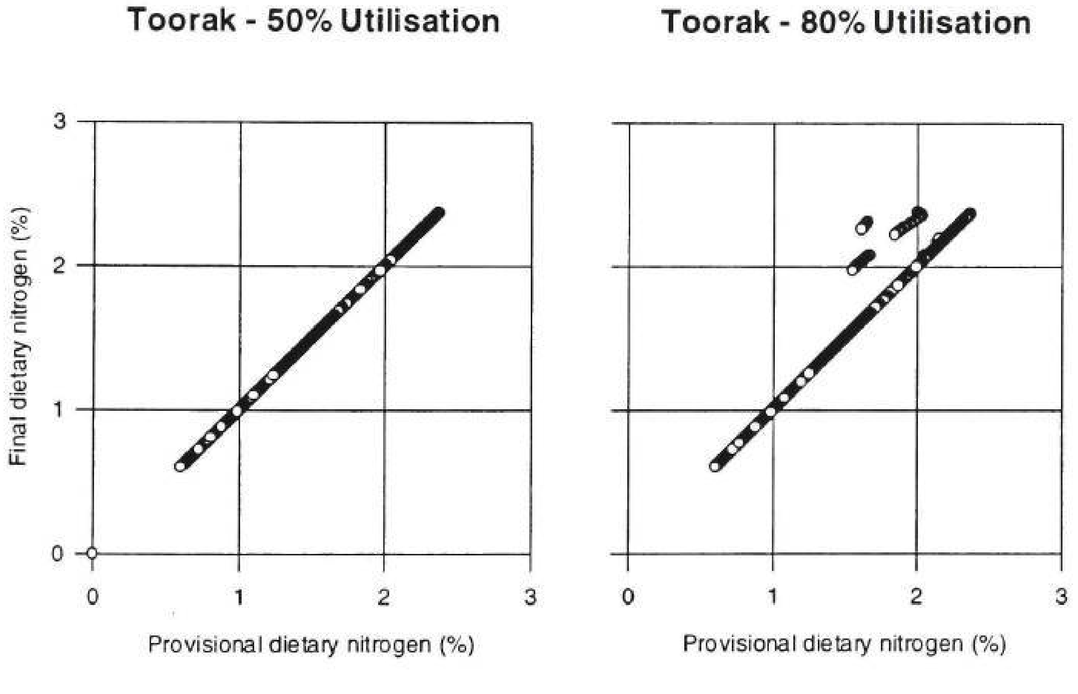

Figure 5.17. Relationship between provisional and final predicted dietary nitrogen concentration calculated using the modified EPBTS functions under two levels of high pasture utilisation.

5.4 Discussion

This chapter detailed work carried out to produce diet selection and feed intake models that would link with the GRASP model, producing dietary variables that would be used to explain the observed variation in grazing trial animal production (liveweight change and wool production).

The four theoretical diet selection models were initially based on equations 5.1 and 5.2 from the beef production model of Hendricksen *et al.* (1982), and a dry matter availability index. Equations 5.1 and 5.2 related the preference (scale 0 - 1) and nitrogen content of pasture to the age of that pasture, respectively. By using 11 age pools (figure 5.1) in which transfer of material occurred every fifth day, pasture ages at which the nitrogen content dropped from its maximum to minimum value (figure 5.2b) were adequately simulated allowing the selected dietary nitrogen to cover the range of available concentrations. Pool 12 was a weighted age pool and represented 'older' material from the current growing season with the minimum nitrogen concentration, while pool 13 represented carry over pasture from previous growing seasons. The nitrogen content of pasture (equation 5.2) was then replaced by equations 5.3 and 5.4. Equation 5.3 calculated the rate of nitrogen decay as a linear function of a growth index, *GIX* (table 6.2), occurring fastest under better growing conditions.

Initial optimisation of *Diet Selection II* produced a *k* value for equation 5.1 indicating the best predicted and observed values were obtained with a constant preference for all age pools. However, selection between the different age pools in *Diet Selection II* occurred because 'sum of preferences' had a maximum value of one, with preference calculated first from youngest to oldest pools. Preference for subsequent age pools was the minimum of '1 - sum of preferences' or, the preference calculated using equation 5.1.

Modification, and optimisation of the GRASP equations (from Hendricksen *et al.* 1982 and Ash *et al.* 1982) calculating the proportion of green in diet produced results consistent with generally accepted diet selection theories, i.e. the greater ability of sheep relative to cattle to selectively graze (Arnold 1981, Hodgson 1982, Forbes and Hodgson 1985). Re-optimisation of *Diet Selection II* produced parameters for equation 5.3 (rate of nitrogen decay) which represented a constant rate of decay irrespective of *GIX*. Thus while rapid growth may dilute nitrogen content of overall pasture, it does not affect the nitrogen content of the selected diet.

Differences between the parameters optimised for the Mitchell and mulga data sets represented lower nitrogen concentration from mulga new pasture growth, slower rate of mulga nitrogen decay and a very low level of mulga pasture at which preference for each pool is affected by the dry matter availability index. The marked differences in *Diet Selection II* parameters for Mitchell and mulga data sets (table 5.1) highlights the main difference in these two pasture communities. Mulga leaves, when available, are able to form a major component of grazing livestock diets, especially during periods of pasture shortage. The failure to measure / estimate the availability of mulga leaves in grazing experiments would appear to be a major problem in experiments conducted in mulga grasslands. The underlying assumption in this mulga dietary work is that the availability of mulga to grazing sheep is a constant resource, with no allowance for the dynamic nature and feedbacks operating within this ecosystem, e.g. the availability of mulga will increase with increasing tree basal area while pasture availability will decrease. The height of available mulga forage is also important, leaves above a certain level being unavailable to browsing sheep. As well, the mulga data set was limited in size with the majority of data requiring adjustment prior to being used. Overall, *Diet Selection II,* optimised for the Mitchell and mulga data sets did a reasonable job, although there was a failure to simulate some of the higher recorded dietary nitrogen concentrations which are likely to be associated with high forb content diets.

The level of feed intake is important because it influences subsequent pasture growth in GRASP as well as animal production. Multiple linear regressions (using climatic, pasture and animal variables), equation 5.7 and GRASP feed intake equations were unable to explain variation in observed feed intake. However, a forward stepwise regression selected both observed dietary nitrogen and dry matter digestibility, at a level which approached significance ($P=0.054$). Nitrogen and digestibility are both measures of pasture quality, being positively correlated with each other. It was expected that this correlation would prevent both variables from being selected in the same regression. This resulted in attempts to simulate dietary dry matter digestibility (equations 5.11, 5.12, 5.13 and 5.14) in parallel to the previously developed model simulating dietary nitrogen concentrations. However, these efforts were unsuccessful.

EPBTS explained 50% of the variation in grazing trial feed intakes in Chapter Four. EPBTS required dry matter digestibility, therefore, a number of functions relating dry matter digestibility to nitrogen / crude protein were examined (equations 5.15, 5.16, 5.17, 5.18, 5.19, 5.20 and 5.21). The relationships between the two variables were similar (figure 5.15) apart from the Grazfeed (equation 5.15) and mulga (equation 5.20) equations. Equation 5.21, based on the combined grazing trial data set, was selected for further work with EPBTS.

It was expected, based on the simulations in Chapter Four, that the EPBTS calculations of feed intake would respond to changes in diet quality. Initial simulations with EPBTS linked to the *Diet selection II* subroutine did not explain any of the observed variation in feed intake (results not presented). To have EPBTS better simulate feed intake, parameters and equations describing *RDPR* and the crude protein threshold at which feed intake was reduced, were modified and optimised as these were the most likely to change from temperate to tropical pastures. Although only 17.6% of the variation was explained, the mean predicted and observed values were similar, 0.970 and 0.986 kg respectively. The failure of simulated diet quality as a useful predictor of feed intake is consistent with the lack of significant correlation (r^2=0.187 P=0.08) between observed diet quality (*DMD*) and dry matter intake in the Lorimer (1976) data.

The preferred diet selection and feed intake model used *Diet Selection II*, with the appropriate modifications as detailed earlier, combined with the slightly modified EPBTS equations. These models are included as subroutines in GRASP (figure 4.14). Outputs from the combined GRASP model, including dietary quality and feed intake, were then available to investigate their relationships with wool production and liveweight change (Chapter Six).

Further development of GRASP to include forbs and other species is likely to improve the modelling of diet selection and feed intake. At this stage, all available predictors of feed intake have failed to adequately explain the observed variation. Future work should concentrate on the simulation of other possible predictors as indicated in the review on intake, e.g. water content of plant components (Appendix One, Part A).

CHAPTER SIX

Simulation of Wool Production and Liveweight Change

6.1 Introduction

This chapter reports work done using simple climatic, soil, pasture and dietary variables to explain the observed variation in annual wool production and liveweight change. As well, the relationship between wool growth rates and fibre diameter, and factors affecting clean wool yield were examined.

The aim of modelling wool growth is to predict the fleece weight that will be harvested at shearing. Fleece weight, animal numbers and wool price are the variables which determine the gross income of wool producing properties (Chapter Three). Fleece weight at shearing is a better measurement compared with estimations of wool growth over short time periods based on mid-side clipping and dye band techniques. For example, White (1978) reported marked differences in wool growth rates (mg / cm^2) were observed for sheep despite their having similar fleece weights at shearing. Thus, this chapter concentrates on the simulation of annual wool production.

Simulation of reproduction and mortality rates are also essential for a dynamic flock model. At this first stage of model development, the only functions available to predict reproduction and mortality required liveweight and body condition as inputs (Moore *et al.*

1995; see Appendix One, Parts D and E). Therefore, the ability to simulate liveweight change from simple GRASP generated variables was examined.

The modelling of both fleece weights and annual liveweight change followed the same approach used for modelling seasonal liveweight change in cattle (McCown 1980-81, McCown *et al.* 1981, Jones *et al.* 1990, McCaskill and McIvor 1993). McCown (1980-81) used a simple growth index derived from a moisture index (water balance model) and a temperature index to determine the start and cessation of the 'green' and 'dry' seasons. These seasons represented periods of liveweight gain and loss respectively. McCown *et al.* (1981) used the same model to examine quantitatively liveweight changes during the green and dry seasons, as well as annual liveweight change.

Similarly, McCaskill and McIvor (1993) used the water balance and pasture growth model of McCown (1980-81) and McCown *et al.* (1981) to predict 'green days'. The number of green days explained 78% of the annual variation in liveweight change for each pasture type and stocking rate combination they examined. Using pasture legume content, green days and percentage utilisation they were able to explain 58% of the variation in annual liveweight change across all treatments and years. Attempts to model variation in seasonal (early wet, late wet, dry season, transition season) liveweight change between years were unsuccessful, suggesting the use of annual green days to predict **annual** liveweight change would be more accurate than modelling liveweight change on smaller time scales.

Various workers have used simple climatic and pasture variables to explain variation in annual wool production (Hooper 1973, Reid and Thomas 1973, Easter 1975, White *et al.* 1979, Flavel *et al.* 1987, Shaw and Findlay 1990). This modelling has been carried out at regional, state and national levels.

Hooper (1973) developed a regression model to predict wool cut per head for each state based on a 'seasonal conditions variable' and a trend in time. The seasonal conditions variable was developed from rainfall for selected months in wool producing districts. The regression explained 72% of the variation in Queensland's wool cut per head from 1960-61 to 1971-72. However, statewide changes in numbers within different animal classes, e.g. number of lambs shorn, caused divergence in predicted and observed wool cut. No attempt was made to model regional variation in wool production.

Reid and Thomas (1973) showed that multiple regressions based on simulated monthly soil water explained more variation in regional wool production than rainfall for Queensland. Similarly, Flavel *et al.* (1987) found a broad based climatic measure of potential pasture growth (Fitzpatrick and Nix 1970) explained more of the variation in Australian average wool cuts than rainfall alone.

In the temperate zone, White *et al.* (1979) found dry matter availability and the digestibility of the feed on offer explained 49 - 74% of the variation in wool growth rates across three grazing trials. Using estimates of feed intake, 62 - 83% of the variation in wool growth was able to be explained. However, the relationship between monthly wool growth and feed intake varied throughout the year with negative relationships occurring in summer and early autumn. Shaw and Findlay (1990) used the model of Flavel *et al.* (1987), to produce a climatic index of potential pasture growth which predicted annual fleece weights for Victoria, after disaggregation to Australian Bureau of Statistics (ABS) regional levels. Potential pasture growth was dependent on rainfall, evaporation and, the calculated soil moisture, light and temperature. ABS data on sex and lamb / adult composition of sheep were also used.

Simulation of fibre diameter, and the yield of clean wool from the greasy fleece, are necessary because they affect the gross income derived from shearing. Fibre diameter is positively correlated with wool growth rates (Reis and Sahlu 1994), heavier fleeces having greater fibre diameter and usually receive a lower price per kilogram. Fibre diameter accounts for 50 - 75% of the variation in price of different wool types (Stott and Hanson 1993, Rogan 1995). Conversely, poor pasture conditions and / or overgrazing result in lighter fleeces with reduced fibre diameters which, in extreme conditions, have inadequate strength and are graded as tender (≤ 26 N / ktex), or part-tender (27 - 30 N / ktex, Baker *et al.* 1994). Tender fleeces suffer price penalties (Adams 1994, not modelled here).

6.2 Simulation of greasy fleece production

6.2.1 Methodology and field data

The aim of this work was to identify climatic, soil, pasture or dietary variables that were able to explain variation in observed fleece production at the paddock level. A number of grazing trials with the necessary observations have been carried out in Queensland (table 6.1). These trials covered a diverse range of pasture communities, soil types and climatic environments (see figure 4.1 for location of grazing trials).

For those trials where sheep numbers were changed on an annual basis to achieve a desired level of pasture utilisation, stocking rates were calculated using the following formula (Beale 1985, Phelps *et al.* 1994):

$$SR = TSDM / DMI * Util * ha \tag{6.1}$$

where *SR* is number of sheep to be placed in paddock,

TSDM is pasture yield in kg DM / ha at end of summer growth,

DMI is annual sheep dry matter intake, assumed to be 400 kg,

Util is desired level of utilisation, and

ha is paddock size in hectares.

6.2.1.1 Wool time trend

ABS data for (ABS[1] 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987b, 1988, 1989, 1990) were used to examine the pattern of greasy wool production per sheep in Queensland over an extended time period (figure 6.1). Total greasy wool production was the sum of individual shires shown in figure 1.1, this value was divided by the total number of sheep and lambs shorn to estimate production per head.

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[1] ABS data for the period 1951-52 to 1973-74 obtained directly from archival records of ABS, Brisbane office. Data for the period 1989-90 to 1991-92 were purchased directly from ABS in electronic format.

Table 6.1. Grazing trials used to develop regression models for annual fleece production and liveweight change.

Location and Source	Pasture Type	Observations - Type and Number	Comments
Eastwood (unpublished data) Located 32 km south of Blackall, central western Queensland. lat. $24^0$5' S, long. 145^0 5' E.	Originally gidgee (*Acacia cambagei*), planted to buffel grass (*Cenchrus ciliaris*) in 1961.	Greasy fleece weights were measured at the end of each grazing period, mid-side samples were taken at time of shearing for yield estimation allowing clean wool production to be calculated. Dye bands were applied to a number of sheep in each paddock approximately every two months. Clean wool production (mg / cm^2 / day) was calculated. Fibre diameter was also measured. Sheep liveweights were recorded approximately every four weeks following a fast of at least 10 hours.	Mean annual rainfall is 530 mm with 70% falling between October to March. The grazing trial began in 1967. Recording periods for the trial were 28-9-67 to 11-8-970, and 10-10-1970 to 8-8-1971. Four stocking rates were used with two replicates of 16 peppin weaner ewes replaced annually at each stocking rate: 0.1, 0.2, 0.4, 0.8 ha per sheep. Data were only available for the most heavily stocked paddocks for 1967-68 due to sheep receiving supplementation beyond this time. This paddock was restocked in February 1972 at the lighter stocking rate of 0.2 ha per sheep and ran till 8-8-1874. The lightest stocking rate (0.8) was continued from 27-4-72 till 23-8-77, while the other stocking rates (0.4 and 0.2) were continued from 27-4-1972 till 18.8-82.
Gilruth Plains (Roe and Allen 1945, Roe and Allen 1993) Located 22 km east of Cunnamulla, south-west Queensland. lat. $28^0$04' S, long. $145^0$41' E.	Mitchell grass.	Sheep were shorn prior to pasture sampling in October. Sheep liveweights were recorded approximately every four weeks.	This trial was split into two experiments of five years duration, 1941-45 and 1947-51. Merino wethers, 15 - 16 months old, were used at the start of each trial. Three different stocking rates were applied: 1, 2, 3 ha per sheep. The first trial period occurred during below average rainfall years and supplementation of sheep was required during the final two years. Supplementation was applied differentially to treatments.
Toorak (Phelps *et al.* 1994) Located south of Julia Creek, north-west Queensland. lat. 21^0S, long. 142^0 E.	Mitchell grass.	The Merino wethers were shorn each May. Following shearing and pasture yield estimation the sheep were reallocated or replaced with new sheep. Fleece weights, yield and fibre diameter were recorded. Sheep liveweights were recorded approximately every three months.	The trial began in May 1984 and is ongoing. Pasture stocking rates were calculated at the end of the summer growing season, usually late May, when 90% of the annual pasture production had occurred so as to achieve six levels of pasture utilisation over the next 12 months: 0, 10, 20, 30, 50, 80% pasture utilisation.
Burenda (McMeniman *et al.* 1986a, b, Beale *et al.* 1986, Orr 1986) Located north of Augathella, central western Queensland. lat. $25^0$47' S, long. $146^0$45' E.	Mitchell grass.	Fleece weights were measured at spring shearing up until 1978 after which shearing was carried out in autumn / early winter. Yield and fibre diameter were also measured. Dye bands measurements were made approximately every three months. Sheep liveweights were recorded approximately every four weeks.	The trial ran from 1975 to 1988. Pasture stocking rates were calculated at the end of the summer growing season (April) when 90% of the annual pasture production had occurred so as to achieve set levels of pasture utilisation over the next 12 months. Merino wethers were stocked so as to achieve the following levels of pasture utilisation: 10, 20, 30, 50, 80% pasture utilisation.
Arabella (McMeniman *et al.* 1986a, b, Orr *et al.* 1993) Located 20 km east of Charleville, south-west Queensland. lat. $26^0$26' S, long. $146^0$32' E.	mulga (*Acacia aneura*) grassland association.	Fleece weights were measured at shearing in autumn / early winter. Yield and fibre diameter were also measured. Dye bands measurements were made approximately every four weeks. Sheep liveweights were measured approximately every four weeks.	The trial ran from 1978 to 1984. Pasture stocking rates were calculated at the end of the summer growing season (April) when 90% of the annual pasture production had occurred so as to achieve four levels of pasture utilisation over the next 12 months. Merino wethers were stocked so as to achieve the following utilisation rates: 20 , 35, 50, 80% pasture utilisation. Following the completion of this trial, a second was begun in 1984 using breeding ewes and ran for two years. Three of the previous utilisation paddocks were used: 20% ---------> 20% pasture utilisation, 35% ---------> 50% pasture utilisation, and 50% ---------> 50% pasture utilisation. To allow for the nutritional demands of reproduction, the adult stocking rates were reduced by one third. This gave adult sheep utilisation rates of 14, 33 and 33%.

The following linear regression explained 67% of the variation in wool cut (P<0.001):

$$\textit{Greasy Wool Cut / head} = -47.426 + 0.0262 * \textit{Year} \qquad (r^2=0.670\ P<0.001,\ 6.2)$$

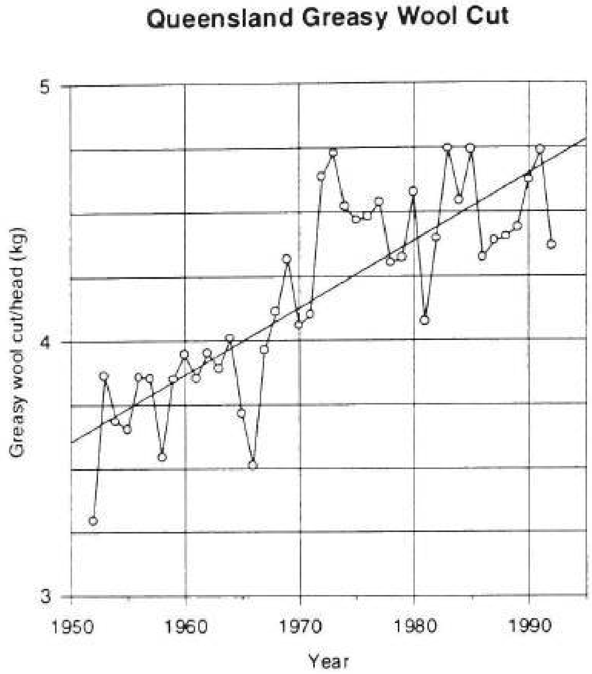


Figure 6.1. Mean Queensland greasy wool production per head for the period 1952 - 1992.

This equates to a gain of approximately 0.25 kg of greasy wool per sheep per decade. The above procedure was repeated for four major wool producing shires: McKinlay, Barcaldine, Murweh, Balonne. The results were similar to the trend in figure 6.1 indicating that a consistent increase in wool cut per head occurred throughout the state from 1952 - 1992. The individual shire regressions were:

- McKinlay

  $$\textit{Greasy Wool Cut / head} = -37.0 + 0.021 * \textit{Year} \qquad (r^2=0.433\ P<0.001,\ 6.3)$$

- Barcaldine

  $$\textit{Greasy Wool Cut / head} = -37.8 + 0.021 * \textit{Year} \qquad (r^2=0.429\ P<0.001,\ 6.4)$$

- Murweh

  $$\textit{Greasy Wool Cut / head} = -57.2 + 0.031 * \textit{Year} \qquad (r^2=0.517\ P<0.001,\ 6.5)$$

- Balonne

  $$\textit{Greasy Wool Cut / head} = -52.5 + 0.029 * \textit{Year} \qquad (r^2=0.617\ P<0.001,\ 6.6)$$

Possible reasons for this increase in wool production over time include superior genetics, improved disease control, improved management and husbandry, and possibly larger framed sheep. The ABS data lists 'sheep and lambs shorn' and does not differentiate between sheep type (wether, ewe, lamb). If there was an increase in the proportion of non-breeding to breeding stock over this period, a similar trend may have resulted but such a uniform response across individual shires is unlikely.

Analysis of grazing trials was done using the Queensland state regression (equation 6.2) to standardise wool cut to a common year, 1992. Gilruth Plains (Roe and Allen 1945, 1993) began in 1940 and concluded in 1952, and therefore, to a large extent lies outside the data on which the temporal trend was based. Analysis of data prior to 1952 was not carried out due to difficulty in obtaining data, together with alterations in regional boundaries. An extrapolation was therefore required to standardise the Gilruth Plains wool production data to the 1992 standard. This was a reasonable assumption given Gramshaw and Lloyd (1993) showed a consistent increase in Queensland fleece weights from the turn of the century to the present day.

Within the combined experimental data there was a reduction in greasy wool production with time ($r^2=0.386$ $P<0.001$ $n=173$). There are a number of reasons why the time trend in the state was in the opposite direction to the combined experimental data set. These include a markedly smaller number of records, most records being recorded in the last two decades, only one trial prior to the 1960's, and the possible interaction between various trial factors such as location, soil fertility, pasture type, seasonal quality and time. As will be shown, the early grazing trials, Gilruth Plains and Eastwood, were on more fertile or less climatically challenged landscapes than later and current trials (Burenda, Arabella, Toorak).

6.2.1.2 Effect of age

Within and between grazing trials the range of sheep ages was large. Brown *et al.* (1966) and Rose (1974) have shown how greasy wool production varies with age (see Appendix

One, Part C). The data of these authors were pooled and a function derived which described the variation in wool production of different aged sheep as a proportion of that produced by a sheep of approximately 50 months of age (figure 6.2). The oldest shearing age for the Rose (1974) data showed a marked divergence from the trend. For this reason, the Rose (1974) data for shearing age up to 114 months only were included in the non-linear regression analysis which accounted for 79.2% of the observed variation:

$$\begin{aligned} \mathit{Standardisation\ factor} = {} & 0.50414806 + 0.031237865 * age - 0.0011130916 * age^{2} + \\ & 0.00012788843 * age^{2.5} - 4.3988429E\text{-}06 * age^{3} \end{aligned} \tag{6.7}$$

Equation 6.7 appeared to be suitable for standardising fleece production for animals aged between 18 and 126 months of age at shearing. The standardisation factor represented the proportion of the recorded fleece weight to the maximal fleece that would have been produced by a 50 month old sheep under those conditions. The recorded greasy fleece weight was divided by the standardisation factor to give the standardised fleece weight,

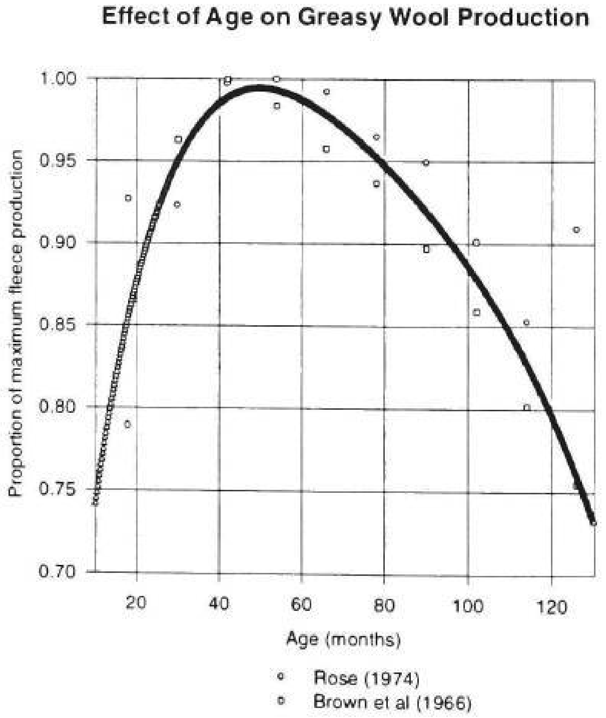


Figure 6.2. Relationship between age and maximum wool production based on the data of Brown et al. (1966) and Rose (1974).

after also taking into account the trend in time. The number of days between shearings was then used to calculate the standardised daily greasy wool growth rate (*Swool*). This allowed for the different time intervals between shearings. Thus, any resultant model would predict wool production for a standardised animal.

6.2.1.3 GRASP

The GRASP model was used to generate and accumulate the climatic, soil, pasture and dietary variables corresponding to the period in which the observed wool production occurred. To enable growth periods of varying length to be compared the variables were expressed on a daily or percentage basis. These variables were then used in forward stepwise regressions to identify functions best able to explain the observed wool production. Three approaches to model development were envisaged:

- general model for all wool growing regions of the state;
- models specific for major pasture communities; and
- models specific to pasture communities and location, e.g. northern Mitchell grasslands.

Results from the grazing trials were therefore analysed on an individual and pooled basis in order to identify the best approach.

6.2.1.4 Variables

A number of variables from GRASP were examined during model development and a brief explanation of these is presented in table 6.2. These output variables were chosen to represent the widest range of possible indicators of animal production.

6.2.2 Results

Results from the analysis of individual, and pooled grazing trials, using GRASP generated variables to explain observed variation in standardised daily greasy wool production (*Swool*), are shown in table 6.3. The best forward stepwise regression for each trial, and

Table 6.2. Variables used in the analysis of grazing trial wool production and liveweight change.

Variable	Description
Rain	Mean daily rainfall (mm / day).
Green leaf	Green leaf was accumulated in various classes during the running of all trial data. This included the percentage of days in which green leaf was below a set threshold, the threshold being set at a series of different values ranging from 1 - 100 kilograms of dry matter per hectare (kg DM / ha). For example, the variable *green leaf≤1* represented the percentage of days in which the green leaf pool was equal to or less than 1 kg DM / ha.
Avgrnlf	Mean daily green leaf pool (kg DM / ha).
Green pool	Total green pool was the sum of green leaf and green stem. Green pool was handled in a similar manner to green leaf (kg DM / ha).
Dead pool	Total dead pool was the sum of dead leaf and dead stem. Dead pool was handled in a similar manner to green leaf (kg DM / ha).
Avgrnpl	Mean daily green pool (kg DM / ha).
Soil water	This variable represented the percentage of days in which the soil water level was adequate for pasture growth to occur. If temperature was not limiting growth, this variable represented the length of the growing season for areas with a seasonal growth pattern.
THI	Temperature humidity index was calculated as for King (1983): *THI = maximum dry bulb temp. + 0.36 * dew-point temp. + 41.2* The effect of the *THI* on dairy cattle can be considered in terms of various thresholds (Lake *et al.* 1995): • < 72 - no stress, • 72 -78 - alert, • 79 - 87 - severe, and • > 87 - emergency. As no data were available for sheep, *THI* values greater than 80 were assumed to be significant. The number of *THI* units above 80 was accumulated for the period being analysed. Thus *THI* actually represents the mean daily value for max(0, *'THI - 80'*).
Util	Utilisation, represented total intake as a percentage of current season's growth. The season began on the 1st of December each year. This variable was able to exceed 100% due to consumption of carry over feed from the previous season.
Util2	Utilisation2, represented the percentage of carry over pasture present at 1st December, plus new season's growth, which was consumed by sheep, range 0 - 100%.
MCCD	This variable represented the percentage of days in which growth index is greater than 0.1. The soil water index component is calculated from a one layer water balance model after McCaskill and McIvor (1993).
Growth	Mean daily pasture growth (kg DM / ha).
Nit. intake	Dietary nitrogen intake was accumulated in various classes. This included the percentage of days in which dietary nitrogen intake was below a set threshold, the threshold being set at a series of different values. For example, the variable *nit. intake≤5* represented the percentage of days in which the dietary nitrogen intake was equal to or less than 5 g / d.
Avnitint	Mean daily nitrogen intake (g / d).
GIX	Growth index based on soil water availability and temperature, represented the percentage of days in which the growth index was at a level ensuring pasture growth would occur. This variable represented the length of the growing season for areas with a seasonal growth pattern.
Diet nitrogen	The dietary nitrogen concentration (%) was accumulated in various classes. This included the percentage of days in which dietary nitrogen was below a set threshold, the threshold being set at a series of different values. For example, the variable *diet nitrogen≤1.5* represented the percentage of days in which the dietary nitrogen was equal to or less than 1.5%.
Avdiet nitrogen	Mean daily dietary nitrogen concentration (%).
TSDM	Total standing dry matter on offer (kg DM / ha).

Table 6.3. Results from the analysis of individual, and pooled grazing trials, using GRASP generated variables to explain observed variation in standardised daily greasy wool production (Swool).

Grazing trial	Number of records	Most correlated variable	Variables selected in forward stepwise regression	Comments
Toorak	42	*green leaf≤30* r^2=0.718, $P<0.001$	[1]*green leaf≤30, MCCD* r^2=0.819, $P<0.001$ [2]*diet nitrogen≤1.5, Util*, and their interaction r^2=0.731, $P<0.001$	Toorak data suffered, as do most of the trials, from poor recording and / or storage of animal age records. Age of animals was based on written records where available and personnel communications from those with knowledge of the trial (D. Phelps, A. Barnes). Accurate ear tag recordings allowed those years when new sheep were introduced to the trial to be identified. The utilisation trials (Toorak, Burenda and Arabella) were designed to study the impact of set levels of grazing utilisation on pasture community stability and productivity, and accordingly, the major emphasis in terms of data collection was aimed at the pasture community. The 50 and 80% utilisation paddock fleece weights for 1989 were not available because sheep in these paddocks were replaced as bodyweights fell below 30 kg on humane grounds. Replacement of the sheep was carried out to maintain grazing pressure. Similarly, the 80% paddock fleece weight was not available for 1993. [1,2] In the first regression, the coefficient for *MCCD* was negative whereas its individual correlation with *Swool* was positive, although not at a significant level. The second regression was the best combination of variables where the signs of the variables were consistent with their individual relationships with *Swool*.
Burenda	48	*green pool≤2* r^2=0.505, $P<0.001$	*growth, nit. intake≤5*, and their interaction r^2=0.702, $P<0.001$	Fleece weight for all treatments for the years 1976 and 1980 were not available as a result of destocking following flooding and supplementary feeding respectively. The 50 and 80% utilisation paddocks were destocked in 1983, the 50% was restocked in 1984 providing another fleece weight for analysis. Age of sheep as they entered the trial was estimated based on data collected from various sources; project reports, original paperwork, published papers, ear tag numbers and diaries of staff (C. Evenson pers. comm.) involved in the trials.
Arabella	23	*green leaf≤6* r^2=0.883, $P<0.001$	*green leaf≤6, avgreen leaf* r^2=0.914, $P<0.001$	In 1985 and 1986, the wether sheep used previously in all treatments were replaced with breeding ewes. The nutritional drain on the ewes as a result of gestation and lactation would have affected their response to the available feed in terms of wool production. The 80% utilisation paddock was destocked in 1980, and therefore, a fleece weight in June 1981 was not available. Age of the sheep when first entering the trial was once again difficult to determine. For example, an undated report by Burrows *et al.* (197-) indicated that the Arabella trial was to be stocked with two tooth animals replaced annually; however, papers by McMeniman *et al.* (1986a, b) state that both Arabella and Burenda trials were stocked with 'adult Peppin Merino wethers' and 'mature (3 - 4 years old) Merino wethers' at the beginning of the experimental periods. Original paperwork, reports, published papers, diaries, ear tag numbers and personal communications with trial staff were used in order to best age the sheep.
Eastwood	40	*diet nitrogen≤0.7* r^2=0.320, $P<0.001$	*diet nitrogen≤0.7, Util* r^2=0.409, $P<0.001$	The standardisation of wool for age at shearing was based on the data of Brown *et al.* (1966) and Rose (1974) in which the youngest animals at shearing were 18 months of age. The Eastwood trial had a number of fleece records in which the age at shearing did not fall within the data on which the standardisation was based, these records were not used in the analysis. The ability of multiple regressions to explain the observed variation in *Swool* for the Eastwood trial was poor. The best regression in terms of correlation allowed a maximum value for *Swool* of only 15.45 g / d and failed to explain much of the variation in *Swool*.

Table 6.3 continued.

Grazing trial	Number of records	Most correlated variable	Variables selected in forward stepwise regression	Comments
Gilruth Plains	20	*nit. intake≤12* r^2=0.628, P<0.001	*nit. intake≤12, MCCD* r^2=0.869, P<0.001	A number of records from the original data set were of doubtful accuracy and were excluded from the analysis. Daily greasy wool growth rates for the years 1941 and 1947 were in the range 25.2 - 40.9 g / d (non-standardised). mean values for all other years were 13.53 g / d with a maximum of 17.27 g / d. This indicated that the sheep entering the trial at the beginning of each period (1940 - 1945 and 1947 - 1952) were not off shears. The fleece weights for the years 1941 and 1947 were therefore not included in the analysis. The high stocking rate for the 1944 fleece weights and all treatments in 1945 were excluded as supplementation occurred. In the multiple regression, the coefficient for *MCCD* was negative although its individual correlations with *Swool* was positive but not at a significant level.
All grazing trials	173	*green leaf≤4* r^2=0.413, P<0.001	*green leaf≤4, soil water* r^2=0.465, P<0.001	The relationships between *Swool* and *green leaf≤4* for the individual trials were: Toorak r^2=0.644 (P<0.001), Burenda r^2=0.422 (P<0.001), Arabella r^2=0.874 (P<0.001), Gilruth Plains r^2=0.151 (ns), Eastwood r^2=0.125 (P<0.05). The individual trial correlations with the multiple regression were: Toorak r^2=0.612 (P<0.001), Burenda r^2=0.635 (P<0.001), Arabella r^2=0.874 (P<0.001), Gilruth Plains r^2=0.069 (ns), Eastwood r^2=0.089 (ns). The model developed from the pooled data lacked the ability to accurately explain variation in observed *Swool* growth across all the trials. Those variables having the strongest correlations to the pooled data had highly variable relationships to individual trial data. The Gilruth Plains and Eastwood data sets appeared to be consistently different in terms of variable relationships compared with the Toorak, Burenda and Arabella data sets. No multiple regressions were found that explained a significant amount of the variation in *Swool* and whose variables had the same signs as did their individual relationships with *Swool*.
Mitchell grass trials (Toorak, Burenda, Gilruth Plains)	110	*green leaf≤1* r^2=0.482, P<0.001	*green leaf≤1, THI* r^2=0.561, P<0.001	Data from the Mitchell grass trials (Toorak, Burenda and Gilruth Plains) were pooled together and analysed in an attempt to develop a model that would explain variation in wool production across all Mitchell grass sites. The individual trial correlations with *green leaf≤1* were: Toorak r^2=0.596 (P<0.001), Burenda r^2=0.491 (P<0.001), Gilruth Plains r^2=0.090 (ns). The multiple linear regression when applied to the individual trials gave the following results: Toorak r^2=0.499 (P<0.001), Burenda r^2=0.475 (P<0.001), Gilruth Plains r^2=0.069 (ns).
Toorak and Burenda	90	*green leaf≤1* r^2=0.686, P<0.001	*green leaf≤1, growth,* and their interaction r^2=0.731, P<0.001	The individual trial correlations with *green leaf≤1* were: Toorak r^2=0.596 (P<0.001), Burenda r^2=0.491 (P<0.001). The multiple linear regression when applied to the individual trials gave the following results: Toorak r^2=0.600 (P<0.001), Burenda r^2=0.610 (P<0.001).
Toorak, Burenda and Arabella	113	*green leaf≤1* r^2=0.703, P<0.001	*green leaf≤1, growth,* and their interaction r^2=0.752, P<0.001	The individual trial correlations with *green leaf≤1* were: Toorak r^2=0.596 (P<0.001), Burenda r^2=0.491 (P<0.001), Arabella r^2=0.857 (P<0.001). The multiple linear regression when applied to the individual trials gave the following results: Toorak r^2=0.573 (P<0.001), Burenda r^2=0.605 (P<0.001), Arabella r^2=0.899 (P<0.001).

group of trials, is detailed in table 6.4, and predicted and observed values for these regressions shown in figure 6.3.

Results for the individual grazing trials, apart from Eastwood, were good, with 70 - 90% of the observed variation in *Swool* able to be explained by GRASP generated variables selected using forward stepwise regressions. Only 41% of the variation in Eastwood *Swool* was able to be explained. Similarly, pooling of all grazing trial data and analysis gave poor results (only 46% of *Swool* variation explained) with Eastwood and Gilruth Plains having no relationship with the regression when applied to their respective data sets (table 6.3).

Analysis of the pooled Mitchell grass grazing trial data highlighted the major divergence of the Gilruth Plains data from that of the Toorak and Burenda trials in terms of those

Table 6.4. Forward stepwise regressions explaining Swool selected for each grazing trial, and grouping of trials.

Grazing Trial	Regression	r^2 and P value	Equation number
Toorak	$^{1}Swool\ (g/d) = 23.144 - 0.144 * green\ leaf{\leq}30$ $- 0.099 * MCCD$ $^{2}Swool\ (g/d) = 21.045 - 0.152 * diet\ nitrogen{\leq}1.5$ $- 0.161 * Util$ $+ 0.002 * Util * diet\ nitrogen{\leq}1.5$	0.819, $P<0.001$ 0.731, $P<0.001$	6.8 6.9
Burenda	$Swool\ (g/d) = 13.251 + 0.607 * growth$ $- 0.634 * nit.\ intake{\leq}5$ $+ 0.168 * growth * nit.\ intake{\leq}5$	0.702, $P<0.001$	6.10
Arabella	$Swool\ (g/d) = 15.466 - 0.065 * green\ leaf{\leq}6$ $+ 0.021 * avgreen\ leaf$	0.914, $P<0.001$	6.11
Eastwood	$Swool\ (g/d) = 15.456 - 0.539 * diet\ nitrogen{\leq}0.7$ $- 0.018 * Util$	0.409, $P<0.001$	6.12
Gilruth Plains	$Swool\ (g/d) = 23.553 - 0.0935 * nit.\ intake{\leq}12$ $- 0.064 * MCCD$	0.869, $P<0.001$	6.13
All grazing trials	$Swool\ (g/d) = 14.286 - 0.056 * green\ leaf{\leq}4$ $+ 0.038 * soil\ water$	0.465, $P<0.001$	6.14
Mitchell grass trials (Toorak, Burenda, Gilruth Plains)	$Swool\ (g/d) = 17.617 - 0.0639 * green\ leaf{\leq}1$ $- 0.970 * THI$	0.561, $P<0.001$	6.15
Toorak and Burenda	$Swool\ (g/d) = 14.256 - 0.0617 * green\ leaf{\leq}1$ $+ 0.5028 * growth$ $- 0.0093 * green\ leaf{\leq}1 * growth$	0.731, $P<0.001$	6.16
Toorak, Burenda and Arabella	$Swool\ (g/d) = 14.897 - 0.071 * green\ leaf{\leq}1$ $+ 0.408 * growth$ $- 0.008 * green\ leaf{\leq}1 * growth$	0.752, $P<0.001$	6.17

[1,2] *In the first regression, the coefficient for MCCD was negative whereas its individual correlation with Swool was positive, although not at a significant level. The second regression was the best combination of variables where the signs of the variables were consistent with their individual relationships with Swool.*

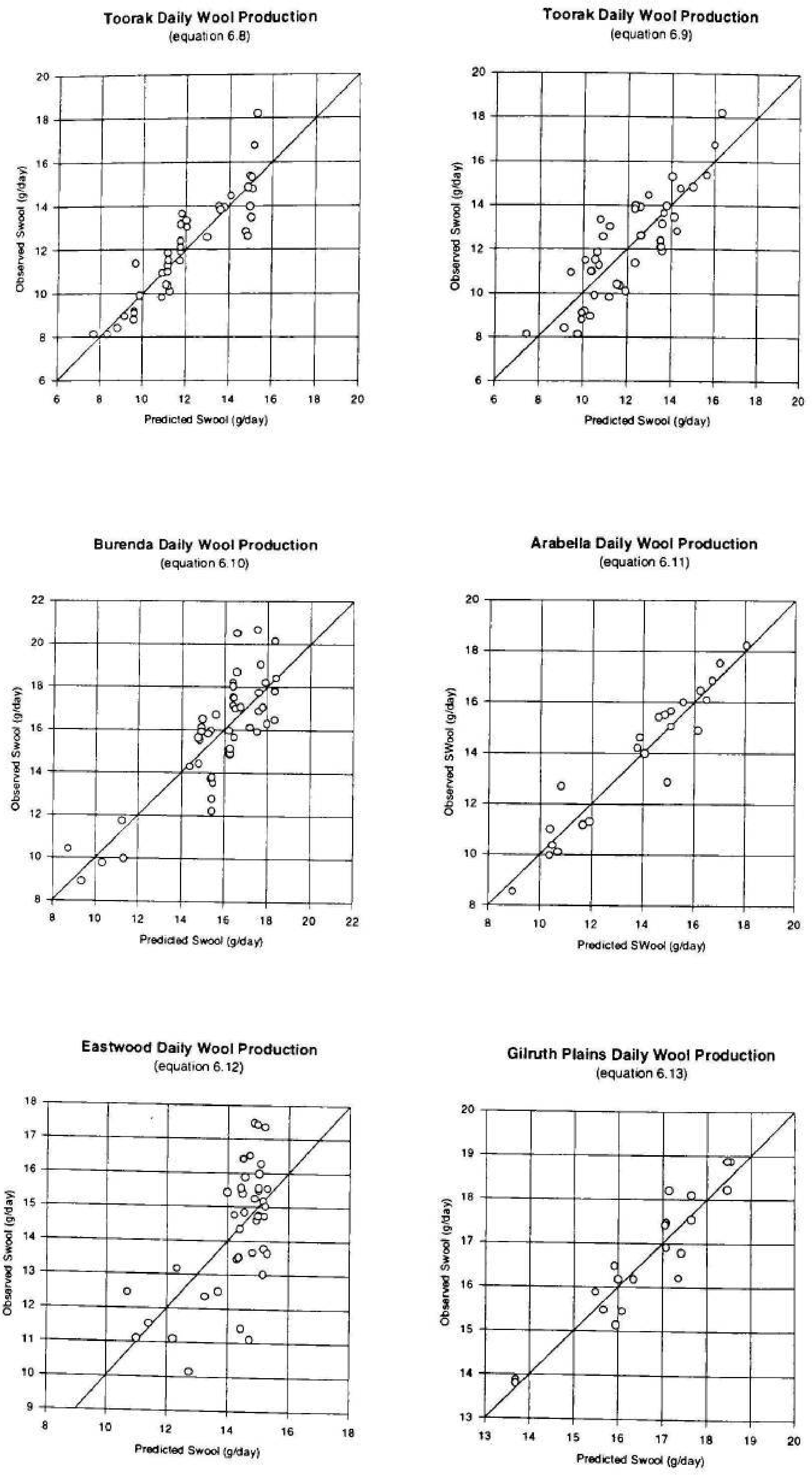
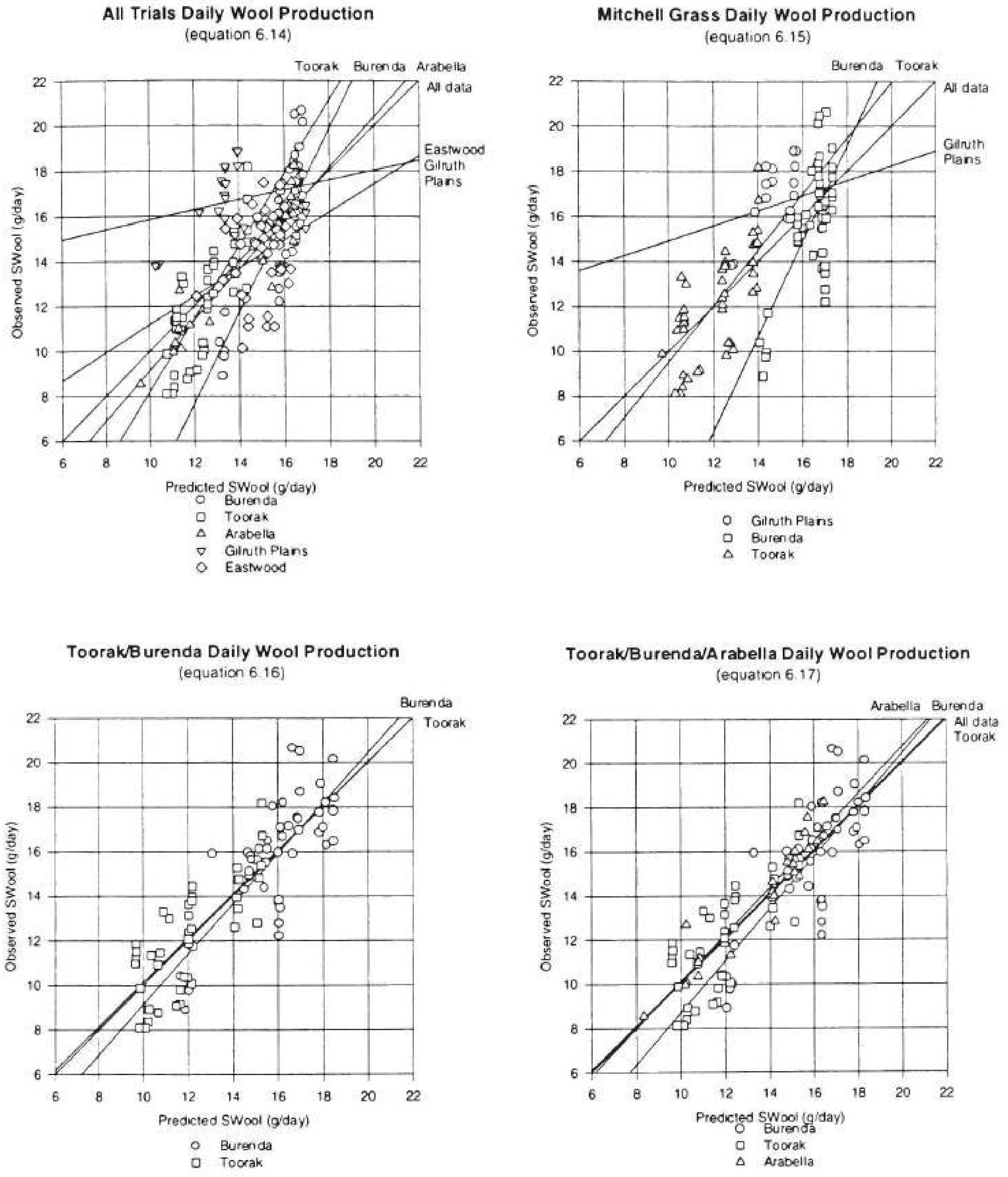


Figure 6.3. Predicted and observed standardised daily greasy wool growths (Swool) for individual, and pooled grazing trials, using the relevant regressions listed in table 6.4.



All Trials Daily Wool Production (equation 6.14)

Mitchell Grass Daily Wool Production (equation 6.15)

Toorak/Burenda Daily Wool Production (equation 6.16)

Toorak/Burenda/Arabella Daily Wool Production (equation 6.17)

Figure 6.3 continued.

variables which were highly correlated with *Swool*. In the Gilruth Plains data, 30 records of fleece production were recorded, six records were excluded because the sheep did not enter the trial off shears, and a further four records were excluded due to supplementary feeding. Records for the years 1950 and 1951 were also consistent outliers. These two years were very good in terms of rainfall and pasture production but only moderate fleece weights were recorded. The Gilruth Plains data were markedly different from the other trials, and from what was expected given our current understanding of the factors affecting wool production. Additionally, the trial began over 40 years ago and it was not possible to discuss possible causes with officers responsible for the trial. For these reasons the Gilruth Plains data were excluded from the Mitchell grass data and the analysis repeated using only the Toorak and Burenda records.

Pooling Toorak and Burenda data did not result in much loss of explanatory power when the multiple regression (equation 6.16) was applied to their individual data, compared with those values returned when each trial was analysed individually. The best correlation from Toorak explained 73% of the variation in *Swool*, while the pooled regression explained 60% of the variation. Similarly, for Burenda, the best correlation from the trial analysis explained 70% of the variation while the pooled data regression explained 61% of the variation in *Swool*. Addition of the Arabella data to Toorak and Burenda data similarly gave good results, 75% of variation in *Swool* being explained.

6.3 Use of selected wool models and long term climate data

6.3.1 Methodology

The grazing trials from which the wool production models were developed lasted for relatively short periods of time (6 - 14 years). As a result, only a small amount of the possible climatic variation may have been experienced. It was therefore decided to test the behaviour of selected wool models (table 6.4) using longer time series of climatic data (1957-1993). The predicted fleece weights were also compared with ABS shire level fleece weights testing for possible outliers. The assumptions and adjustments involved in this comparison are presented in Chapter Seven.

Shires examined were McKinlay, Tambo, Murweh, Boulia, Cloncurry, Flinders, Winton, Quilpie, Longreach, Blackall, Paroo, Waggamba, Bungil, Millmerran, Inglewood and Balonne. The wool production model selected for each shire was based on the predominant pasture community (Weston *et al.* 1981), and climatic data were generated for a representative location within each shire (N. Flood pers. comm.). The model was run for two years to stabilise before wool production was first estimated in 1960 or 1961, depending on the selected month of shearing. Detailed results for a number of shires will now be presented.

6.3.2 Results

Predicted and observed fleece values for McKinlay, Tambo and Murweh shires are shown in figures A4.1, A4.2 and A4.3 of Appendix Four respectively. The results presented here will also concentrate on these three shires but note will be made of extreme outliers occurring in the other shires.

For McKinlay shire (northern Mitchell grass), Toorak equation 6.8 was unable to account for any significant amount of variation in the ABS data while equations 6.9, 6.16 and 6.17 explained 22.6 ($P<0.01$), 32.3 and 30.6% ($P<0.001$) of the variation in observed data respectively. The lower proportion of variation explained, compared with the grazing trials, was to be expected given the year-to-year variation in shire wool is less than that in the grazing trials from which the regressions were developed (Chapter Three).

For Tambo shire (southern Mitchell grass), equation 6.10 produced two marked outliers, a negative fleece and a fleece of approximately 10 kg, and was therefore deemed unsuitable for further use. These outliers arose because GRASP was producing combinations of variables which did not occur during the limited number of years and climatic variability of the Burenda grazing trial. A second Burenda regression model using *green pool*$\leq$*2* and *soil water* ($r^2=0.680$ $P<0.001$, not shown) was also tested. This equation, along with equations 6.16 and 6.17 overpredicted fleece weight, accounting for 28.8 ($P<0.01$), 30.0 and 31.3% ($P<0.001$) of the variation respectively. Use of Burenda equation 6.10 in Winton, Longreach, Blackall, Paroo, Waggamba, Bungil and Balonne shires produced values representing extremely small or negative fleeces. Use of the alternative Burenda wool production model in Winton, Longreach, Paroo and Balonne shires also gave values representing extremely small or negative fleeces.

Equations 6.16 and 6.17 predicted almost constant fleece weights for Tambo shire throughout the period 1960 - 1993, apart from a slight increase associated with the trend in time. The reason for this was the lack of variation in annual pasture growth estimated by GRASP for the Tambo shire (figure 6.4). This plateau effect occurred despite marked variation in annual rainfall. The GRASP model used a constant level of nitrogen availability, with the result that nitrogen depletion occurred preventing any further pasture growth. Nevertheless, GRASP simulated considerable variability in those variables representing the length of the growing season, e.g. *soil water* (figure 6.4), suggesting that within season climate variability is a major source of variation in the quality of animal nutrition. The results for Tambo emphasis the major developments that should occur in GRASP in the future, as supported by the evaluation of Day *et al.* (1996). Of particular relevance in this case are:

- modeling variable nitrogen supply, e.g. effect of drought on subsequent years; and
- variable species requirements of nitrogen for growth, e.g. perennial grasses can dilute down to low nitrogen levels whilst forbs are likely to stop growth at higher nitrogen concentrations.

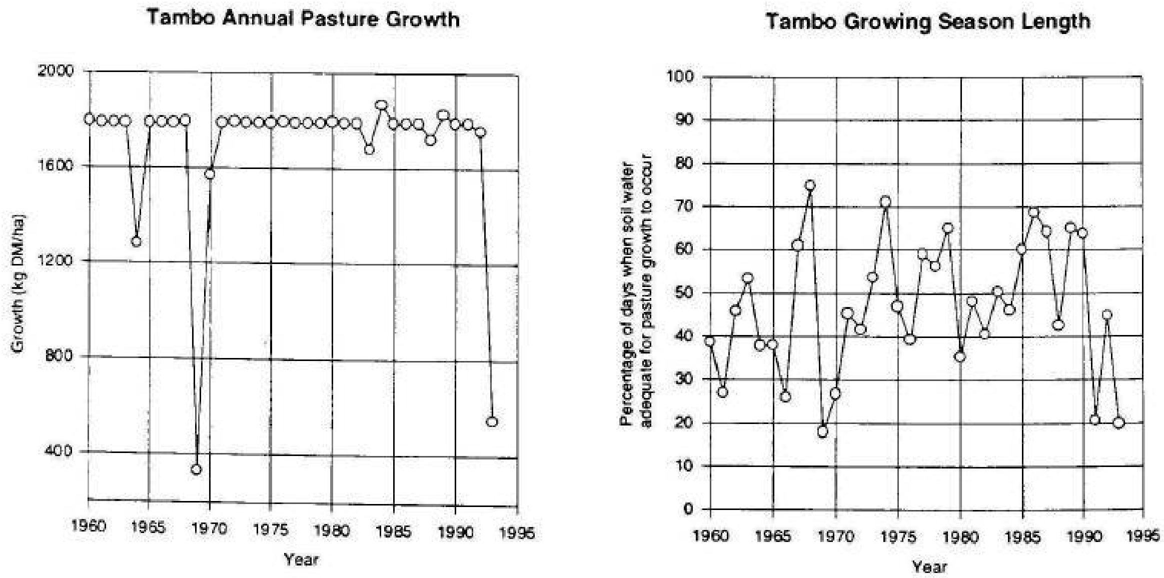


Figure 6.4. Annual pasture growth and length of the growing season (estimated by the soil water variable) for the Tambo shire

The inclusion of these effects in GRASP will result in simulation of greater variability in pasture production and animal nutrition, and hence, provision of output variables that may explain a greater proportion of observed variation in animal production.

For Murweh shire (mulga grassland), neither equations 6.11 or 6.17 were able to account for any significant amount of variation in the observed fleece weights.

6.4 Simulation of fibre diameter

6.4.1 Methodology

The relationships between fibre diameter and wool production were examined. Fibre diameter was measured in the Toorak, Burenda and Arabella grazing trials and data from these trials were pooled. As the intervals between shearings varied, fibre diameter was examined as a function of mean daily wool growth rates.

Wool growth rates, as recorded and adjusted for age of the sheep, were used in the analysis given the shorter time period over which these trials were conducted (1975 - 1995), and the strong relationship between wool production and fibre diameter (see Appendix One, Part C for the discussion on fibre length growth rate / fibre diameter relationship). Use of *Swool* values, rather than recorded values, in this analysis would have assumed there was no trend over time for fibre diameter as there was shown to be for fleece weights and thus, uncoupling of the fibre length growth rate / fibre diameter relationship. The wool production values were therefore standardised for age of the sheep only ($Swool_{age}$) using a relationship based on the data of Brown *et al.* (1966) and Rose (1982, figure 6.5):

$$Proportion\ max.\ fibre\ diameter = 0.9228 + 0.0765 / (1.0 + ((age_{year} - 6.4238) / 4.7169)^2) \qquad (r^2=0.794\ n=19,\ 6.18)$$

This function was then used to standardise the reported fibre diameter to that which the standard sheep at approximately 50 months of age would have produced (*Smicron*).

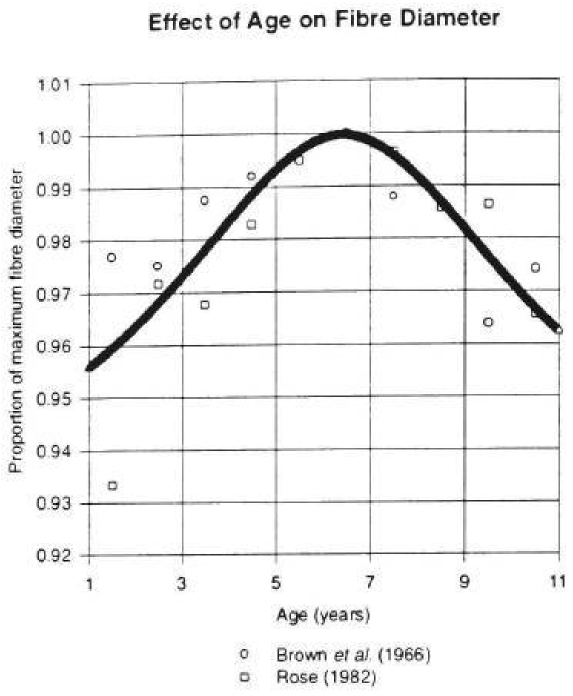


Figure 6.5. Relationship between fibre diameter and age of sheep based on the data of Brown et al. (1966) and Rose (1982) and equation 6.18.

Toorak fibre diameters recorded for 1986 and 1987 appeared unrealistic and could not be confirmed (D. Phelps pers. comm.), and hence, were not used in this analysis.

Also, wool production data (wool growth rates and fibre diameter), available on a more frequent sampling basis (approximately every eight weeks) from the Eastwood grazing trial were similarly analysed.

6.4.2 Results

$Swool_{age}$ was found to explain 54% ($P<0.001$ $n=104$) of the variation in pooled *Smicron* but with a marked outlier from the Arabella trial present. The outlier (16.0μ and 12.0 g / d) was from the 50% utilisation treatment in 1983, whereas the other three treatments for this year recorded markedly greater fibre diameters despite having lower greasy wool growth rates (20% - 19.2μ and 10.4 g / d, 35% - 21μ and 9.4 g / d, 80% - 19.6μ and 9.2 g / d). Unfortunately, the individual animal data from the Arabella trial were not available for examination. Removal of this outlier gave the following regression (figure 6.6):

$$Smicron = 16.5 + 0.409 * Swool_{age} \qquad (r^2=0.582\ P<0.001\ n=103,\ 6.19)$$

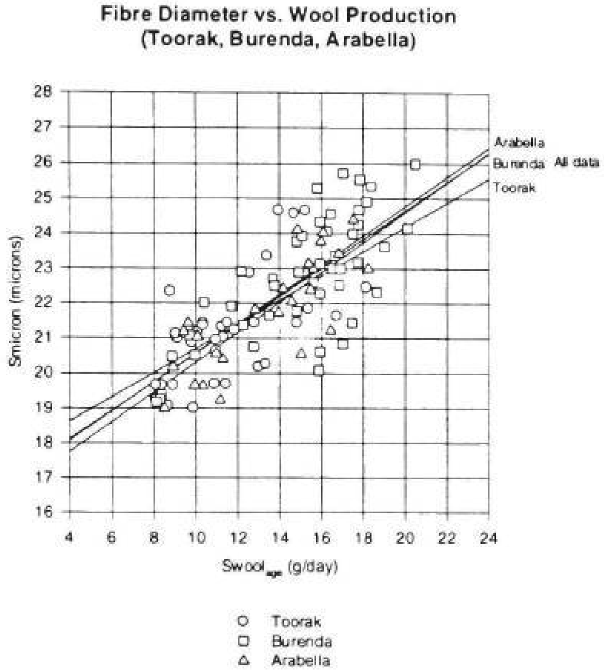


Figure 6.6. Relationship between mean annual fibre diameter adjusted for age (Smicron) and daily greasy wool growth rates adjusted for age ($Swool_{age}$) for the pooled data set (Toorak, Burenda and Arabella grazing trials) and equation 6.19.

The individual trial correlations between *Smicron* and $Swool_{age}$ were:

- Toorak, $r^2 = 0.362$ $P<0.001$ n=32;
- Burenda, $r^2 = 0.569$ $P<0.001$ n=46; and
- Arabella, $r^2 = 0.644$ $P<0.001$ n=25.

Analysis of the more frequently measured wool production data from Eastwood revealed no significant relationship between wool growth rates and fibre diameter.

6.5 Simulation of clean wool yield

The yield of clean wool from greasy wool is reduced during pregnancy and lactation, greater in rams compared to ewes, and rises, then falls with increasing age (see Appendix One, Part C for more details).

6.5.1 Methodology

Clean wool yields (clean wool / greasy wool) were reported for the Toorak, Burenda and Arabella grazing trials. These values were adjusted for the age of the sheep using a function based on the data of Brown *et al.* (1966) and Rose (1982, figure 6.7):

$$\textit{Proportion max. clean yield} = 0.8598 + 0.1259 * age_{year} - 0.0448 * age^2 + 0.0078 * age^3 - 0.0006 * age^4 + 2.0606 * 10^{-5} * age^5 \quad (r^2=0.789\ n=20,\ 6.20)$$

This function was used to standardise the reported clean wool yields to that of a standard sheep at 50 months of age.

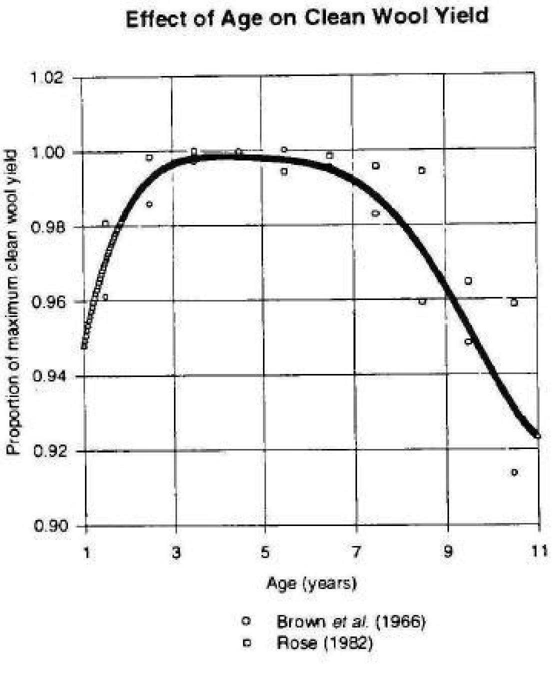


Figure 6.7. Relationship between clean wool yield and age of sheep based on the data of Brown et al. (1966) and Rose (1982) and equation 6.20.

Observed clean wool yields were examined for relationships with observed greasy wool growth rates, growth rates adjusted for age and time trend (*Swool*), and growth rates adjusted for age only ($Swool_{age}$). Forward stepwise regressions using GRASP generated climatic, soil, pasture and dietary variables (table 6.2) were carried out to identify variables, or combinations of variables, which were able to explain the observed variation in clean wool yield.

6.5.2 Results

The actual effect of age on clean wool yields, as adjusted by the standardisation factor (equation 6.20), was very small, the correlation between reported yields and standardised yields being 1.0 ($P<0.001$).

No significant relationships were found between clean wool yield and reported greasy wool growth rates, *Swool*, or $Swool_{age}$ for the pooled Toorak, Burenda and Arabella data, in line with the findings of White and McConchie (1976). Using the Toorak data only, wool growth rates explained 40.2% ($P<0.001$) of the variation in clean wool yield, upon removal of an outlier. However, since this relationship was not supported by Burenda and Arabella data it was considered unreliable. No significant relationships were found between the pooled clean yield data and GRASP generated variables.

The Toorak data contained a reported yield of 90%, a value of questionable accuracy. Removal of this value from the pooled Toorak / Burenda / Arabella data gave a mean value of 70.1% (±5.3 SD) with a range of 58.3 - 80.0%. Given no relationship was found between clean wool yield and the variables examined, a constant clean yield of 70% was considered appropriate for the model.

6.6 Simulation of liveweight change

6.6.1 Methodology and field data

6.6.1.1 Annual liveweight change

Modelling of annual *fleece free liveweight* change was approached using a similar method as adopted with fleece production. Toorak, Burenda, Arabella, Gilruth Plains and Eastwood grazing trials provided the liveweight observations. The annual liveweight change was the difference between the final *fleece free liveweight* (recorded or calculated), and the initial *fleece free liveweight* when the sheep were introduced to the paddocks for each grazing period. Mean daily liveweight change was calculated as this value divided by the number of days in the grazing period. Use of mean daily, rather than annual values, was necessary as the grazing periods varied in duration. Due to apparent errors within the data the number of records available for liveweight change analysis did not always match that number used in the wool production analysis (tables 6.3 and 6.5). Given the findings of the wool modelling work it seemed highly unlikely that a single model would adequately describe liveweight change across all five sites. However, this possibility was examined with the data being analysed on both a pooled and individual basis.

Compensatory growth and the changing energy value of gain as animals approach their 'maximal' liveweight may result in differential liveweight change in response to similar pasture conditions. Compensatory growth, the increased rate of liveweight gain following a period of feed restriction, results from a combination of increased feed intake, reduced maintenance costs and increased efficiency of use of energy (see Appendix One, Part B). Wool growth, unlike liveweight change, does not exhibit compensatory growth (see Appendix One, Part C).

The relationship between annual liveweight change and annual wool growth was examined for each field trial. The previous analysis of wool growth indicated that multiple regressions with climatic derived variables explained a high proportion (> 80%) of annual variation for four out of five trials (table 6.4). When all paired annual liveweight change and wool growth data were examined (figure 6.8), there was little relationship between these biological production variables ($r^2=0.171$ $P<0.001$). Similarly, when individual trials were examined, relationships only explained a small proportion of the variation: Burenda $r^2=0.365$ ($P<0.001$), Toorak $r^2=0.186$ ($P<0.01$), Arabella $r^2=0.324$ ($P<0.01$), Gilruth Plains $r^2=0.05$ (ns), Eastwood $r^2=0.230$ ($P<0.01$).

Unfortunately, the liveweight change data from the five grazing trials appeared to be less reliable than the wool production data (table 6.5). Marked variation in the manner of measuring sheep liveweights appeared to exist. In many cases, liveweights were not measured both before and after shearing. Additionally, where one weight was recorded, it was often not obvious whether this weight was with or without fleece. Handling of

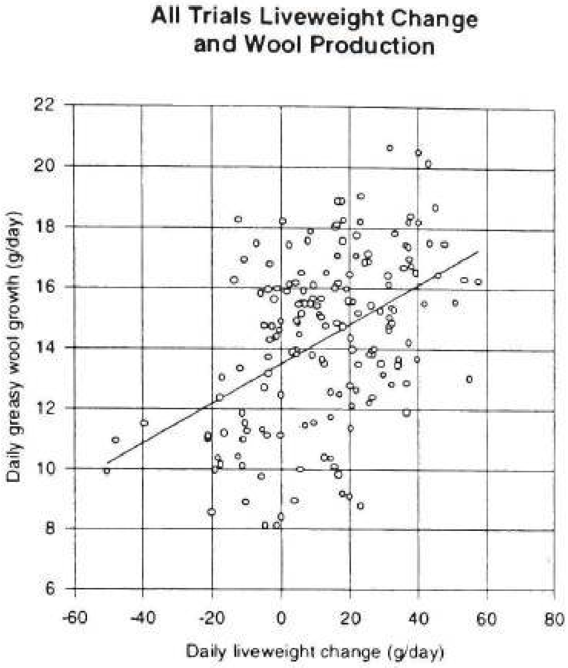


Figure 6.8. Relationship between daily liveweight change and daily greasy wool growth rates for all grazing trials (r^2=0.171 P<0.001, n=170).

animals prior to weighing could have markedly affected the weights that were recorded, e.g. in some of the trials it was not recorded whether there was a standard withholding period from feed and / or water. To the contrary, there appeared to be instances where highly variable handling methods were adopted.

Furthermore, there were variable approaches to the annual re-allocation of sheep to each treatment. For example, in Gilruth Plains sheep were grazed on the same treatment resulting in accumulating effects of differential grazing pressure on liveweight and body size (Roe and Allen 1945, 1993). However, Toorak sheep were re-randomised each year, when not replaced, so that effects of heavy grazing on liveweight were not accumulated on any one stocking rate treatment. After several years the different grazing treatments (stocking rate or utilisation) resulted in variable pasture composition and yield (Roe and Allen 1945, 1993, Beale 1985). Thus, not only were animal histories different but after several years the pastures supplied different quality diets (McMeniman *et al.* 1986a, b). When the liveweight and wool growth data for the first year of each trial were examined, significant linear relationships were found between annual wool growth and annual liveweight change (figure 6.9): Burenda r^2=0.465 (ns), Toorak r^2=0.949 (P<0.01) Arabella r^2=0.906 (P<0.05), Eastwood r^2=0.990 (P<0.01). Gilruth Plains was not included as sheep

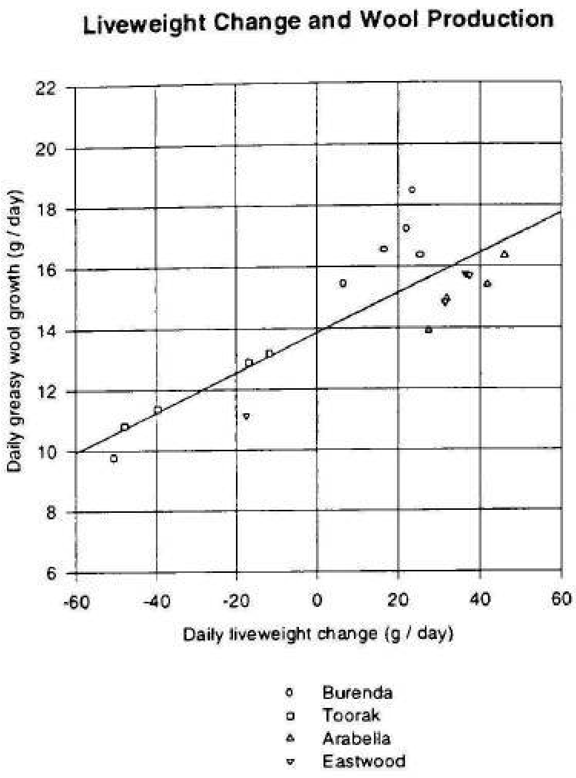


Figure 6.9. Relationship between daily liveweight change and daily greasy wool growth rates for the first year of Burenda, Toorak, Arabella and Eastwood grazing trials (r^2=0.718, P<0.001, n=18).

in the first year of each trial appeared not to have been shorn prior to entry (table 6.3). The first year of each grazing trial represents the ideal case where pre-existing differences between animals have been randomised across treatments, and paddocks of similar composition and yield were likely to have been selected as part of trial design.

The above analysis suggests that two approaches could be investigated in modelling liveweight change:

- 'typical' liveweight change could be related to modelled wool production, excluding liveweights incorporating compensatory gain. Adjustments would be made to this relationship when compensatory liveweight gain was expected; and
- development of regressions for liveweight change independently of those for wool growth, but using the same climate derived variables.

Since the liveweight data are not of sufficient quality to identify periods of likely compensatory gain, in some cases animals were supplemented, the second approach was adopted in this thesis.

6.6.1.2 More frequent liveweight measurements

The Toorak, Burenda and Arabella data were examined further using liveweights measured at shorter time intervals during each grazing period, e.g. weights for the Arabella trial were measured approximately every four weeks giving 149 records. These *with fleece weights* were modified by trial-specific wool production models to give *fleece free liveweight*. As with annual liveweight change, the change in *fleece free liveweight* between weighings was divided by the number of days in the interval to give an estimated mean daily liveweight change.

For every estimated liveweight change, a suite of climatic, soil, pasture and dietary variables were generated and tested for their ability to explain the observed liveweight change. Several models based on equation 6.29 (derived from Arabella annual liveweight change work) and operating on a daily time step were tested to explain the variation in mean daily liveweight change. These models were:

- $if\ (green\ pool < x)$

  $Daily\ liveweight\ change\ (g / d) = a + b * THI + c * dead\ pool / SR$

  $else$

  $Daily\ liveweight\ change\ (g / d) = d + e * THI + f * green\ pool / SR$ (6.21)

- $if\ (\%\ green\ in\ pasture < x)$

  $Daily\ liveweight\ change\ (g / d) = a + b * THI + c * dead\ pool / SR$

  $else$

  $Daily\ liveweight\ change\ (g / d) = d + e * THI + f * green\ pool / SR$ (6.22)

- $if\ (green\ pool < x)$

  $Daily\ liveweight\ change\ (g / d) = a + b * THI + c * dead\ pool$

  $else$

  $Daily\ liveweight\ change\ (g / d) = d + e * THI + f * green\ pool$ (6.23)

- $if\ (\%\ green\ in\ pasture < x)$

$$Daily\ liveweight\ change\ (g/d) = a + b * THI + c * dead\ pool$$

else

$$Daily\ liveweight\ change\ (g/d) = d + e * THI + f * green\ pool \quad (6.24)$$

- $if\ (\%\ green\ in\ pasture < x)$

$$Daily\ liveweight\ change\ (g/d) = a + b * THI + c * exp(-d * dead\ pool / SR)$$

else

$$Daily\ liveweight\ change\ (g/d) = e + f * THI + g * exp(-h * green\ pool / SR) \quad (6.25)$$

where a, b, c, d, e, f, g, h and x are all coefficients.

The PEST optimisation software (Watermark Computing 1994) was also used to optimise the parameters in each of the models against the available data sets.

6.6.2 Results

6.6.2.1 Annual liveweight change

Results from the analysis of individual, and pooled grazing trials, using GRASP generated variables to explain observed variation in annual liveweight change are shown in table 6.5. The best forward stepwise regression for each trial, and group of trials, is detailed in table 6.6, and predicted and observed values shown in figure 6.11.

Results from the individual grazing trials, apart from Eastwood, were good, with 80 - 97% of the observed variation in mean daily liveweight change explained by GRASP generated variables selected using forward stepwise regressions. Fifty-two percent of the variation in Eastwood mean daily liveweight change was explained. The Eastwood forward stepwise regression included *TSDM* with a negative coefficient. Individually, *TSDM* was negatively correlated with Eastwood mean daily liveweight change but at a non-significant level.

Table 6.5. Results from the analysis of individual, and pooled grazing trials, using GRASP generated variables to explain observed variation in mean daily liveweight change.

Grazing trial	Number of records	Most correlated variable	Variables selected in forward stepwise regression	Comments
Toorak	37	*soil water* $r^2=0.848$, $P<0.001$	*soil water, Util* $r^2=0.927$, $P<0.001$	The 50 and 80% utilisation treatment records for 1989 were not available because sheep in these paddocks were replaced as bodyweights fell below 30 kg to avoid mortalities. Similarly, the data for the 80% treatment were not available for 1993. The liveweight records for 1988 were of doubtful reliability. In the 80% utilisation paddock, a large proportion of the sheep were removed as their weight fell below 30 kg but were not replaced. The mean weight at the end of the grazing period (shearing) would have therefore been an overestimation of the true mean weight for the treatment. The removal of lighter weight sheep was considered to have a lesser impact on the mean fleece weight, therefore this record was not removed from the earlier wool analysis. The mean *fleece free liveweight*, plus the mean *fleece weight*, was greater than the recorded mean *with fleece liveweight* for the 10, 20 and 50% utilisation paddocks. This error was not due to a few individual sheep records being markedly wrong, but was consistently recorded for most of the sheep, and was the opposite of the trend seen in all other years. Such a situation could have occurred if the *with fleece liveweights* were recorded following a period of fasting / yarding, whereas the *fleece free liveweights* were recorded without fasting / yarding. However, this would seem impractical and unlikely. Rather, a systematic error during recording of one of the liveweights was more likely to be the cause. Because of these problems, all records for 1988 were excluded from the liveweight analysis.
Burenda	42	*avgrnpl* $r^2=0.606$, $P<0.001$	*avgrnpl, rain* and their interaction $r^2=0.878$, $P<0.001$	Liveweight change records for all treatments for the years 1976 and 1980 were not available as a result of destocking following flooding and supplementary feeding respectively. The 50 and 80% utilisation paddocks were destocked in 1983, the 50% only was restocked in 1984. The liveweight records for 1979 were considered of doubtful reliability and excluded from the analysis for the following reasons: • final liveweights for this year came from a separate piece of paper found during a search of original trial records held at Charleville DPI and were not recorded elsewhere on any of the numerous liveweight summaries; • for the 10% utilisation treatment only, another piece of paper was found with a different final mean weight; and • this was a short grazing period as the shearing was changed from spring to autumn. The remaining records in the Burenda data set for annual liveweight change also required some interpretation. The weights were collated from a number of sources and a decision was generally needed regarding whether the final recorded liveweights were *with fleece* or *fleece free*, this information was seldom recorded.
Gilruth Plains	26	[1]*rain* $r^2=0.271$, $P<0.01$	*rain, MCCD* and their interaction $r^2=0.881$, $P<0.001$	The high stocking rate for 1944 and all treatments in 1945 were excluded from the analysis due to supplementation. Unlike the wool production analysis, the liveweight change records for the first year of each trial, 1940 and 1947, were eligible for analysis. [1] Correlation coefficient was negative. The three data points which heavily influenced this relationship were all from 1941.

Table 6.5 continued.

Grazing trial	Number of records	Most correlated variable	Variables selected in forward stepwise regression	Comments
Arabella	22	[2]*diet nitrogen≤1.8* $r^2=0.692$, $P<0.001$	*avnitint, green pool≤6* and their interaction $r^2=0.818$, $P<0.001$	Records for the years 1985 and 1986 dealt with breeding ewes and were therefore excluded because of the impact of gestation and lactation on liveweight change. The 80% utilisation treatment was destocked in 1980 and so no record was available. [2,3]The relationship between daily greasy wool production and daily liveweight change for the Arabella data set were approximately linear with the exception of the some of the 1984 records (figure 6.10). It was expected that those conditions favouring liveweight change are also those that would give high levels of wool production. Variation in this biological coupling could occur due to compensatory increases in liveweight change following poor seasons. No compensatory increase in wool production occurs (Butler-Hogg 1984). The 1984 20% utilisation treatment was a distinct outlier, the sheep averaged a liveweight loss of 12.13 g / d during the year but were able to produce 18.07 g / d of greasy wool for the same period, the highest level of wool production recorded. The remaining 1984 treatment records were also suspect giving rise to the possibility of a systematic error in liveweight measuring / recording. Therefore, the Arabella data were examined twice: • 22 records (no ewe or 1984 20% utilisation records); and • 19 records (no ewe or 1984 records).
	19	[3]*soil water* $r^2=0.835$, $P<0.001$	*THI, green leaf≤4* and their interaction $r^2=0.967$, $P<0.001$	
Eastwood	38	*avnitint* $r^2=0.259$, $P<0.01$	*green leaf≤15, TSDM* $r^2=0.523$, $P<0.001$	The weight change for a number of years in the heavy stocking rate (0.1 ha / sheep) were not recorded.
All grazing trials	165	*Util* $r^2=0.259$, $P<0.001$	*Util, nit. intake≤12* $r^2=0.397$, $P<0.001$	Twenty-two records from the Arabella trial were included. The individual trial correlations with the multiple regression were: Toorak $r^2=0.548$ ($P<0.001$); Burenda $r^2=0.820$ ($P<0.001$); Arabella $r^2=0.636$ ($P<0.001$); Gilruth Plains $r^2=0.007$ (ns); Eastwood $r^2=0.226$ ($P<0.01$).
Mitchell grass trials (Toorak, Burenda, Gilruth Plains)	105	*avgrnpl* $r^2=0.344$, $P<0.001$	*avgrnpl, TSDM* $r^2=0.487$, $P<0.001$	Poor results from this pooled data set were similar to the analysis of Mitchell grass wool production. The individual trial correlations with the multiple regression were: Toorak $r^2=0.699$ ($P<0.001$); Burenda $r^2=0.629$ ($P<0.001$); Gilruth Plains $r^2=0.154$ ($P<0.05$).
Toorak and Burenda	79	*avgrnpl* $r^2=0.534$, $P<0.001$	*avdiet nitrogen, Util* $r^2=0.672$, $P<0.001$	Individual trial correlations between observed and predicted mean daily liveweight change values using the multiple regression were: Toorak $r^2=0.868$ ($P<0.001$); Burenda $r^2=0.495$ ($P<0.001$).
Toorak, Burenda and Arabella	101	*Util* $r^2=0.460$, $P<0.001$	*avgrnpl, avdiet nitrogen* and their interaction $r^2=0.630$, $P<0.001$	Twenty-two records from the Arabella trial were included. Individual trial correlations between observed and predicted mean daily liveweight change values using the multiple regression were: Toorak $r^2=0.637$ ($P<0.001$); Burenda $r^2=0.629$ ($P<0.001$); Arabella $r^2=0.604$ ($P<0.001$).

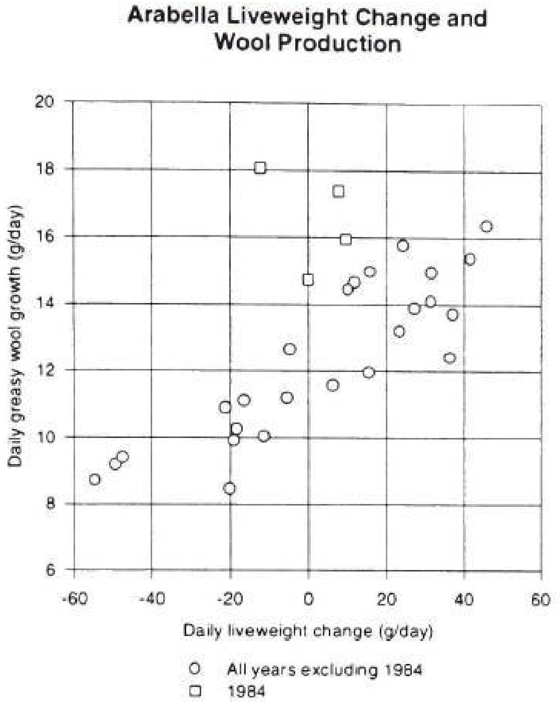


Figure 6.10. Relationship between greasy wool production and liveweight change for the Arabella utilisation trial.

In line with the findings for wool growth rate, pooling all data gave poor results, 40% of the variation being explained. Eastwood was poorly related (r^2=0.226 P<0.01), and Gilruth Plains had no significant relationship when the pooled regression was applied to their data.

In contrast to wool growth rate, the regression for the pooled Mitchell grass liveweight data had significant correlations when applied to the individual trial data, although not strongly, and at a low level of significance for Gilruth Plains (r^2=0.154 P<0.05). However, *TSDM* was included in the regression with a negative coefficient.

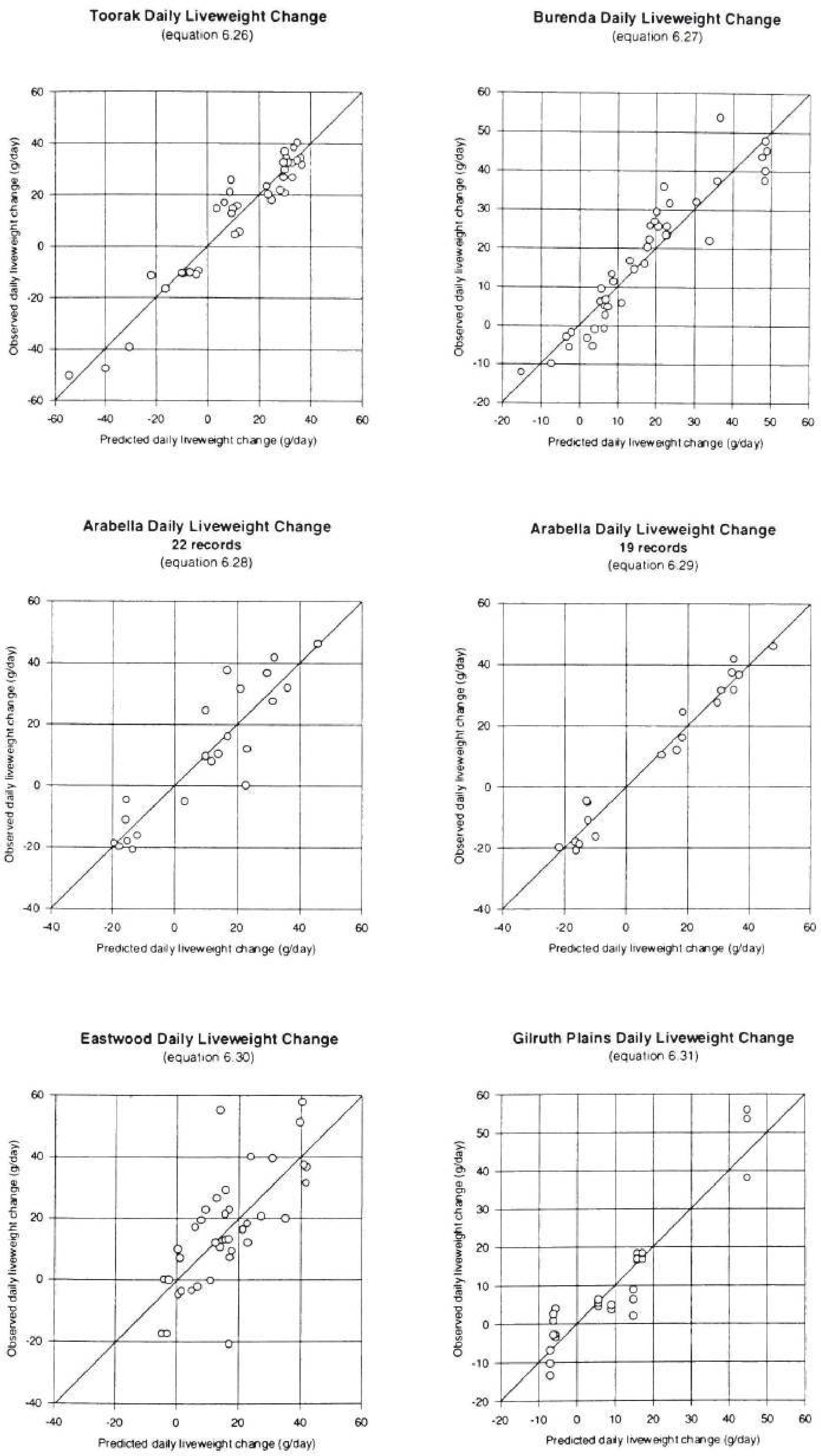
Analysis of Burenda and Toorak grazing trials, with or without Arabella data, gave regressions which explained 65% of the variation in observed mean daily liveweight change. For the Toorak and Burenda data, pooling resulted in no loss of explanatory power for Toorak, but a large loss for Burenda, as indicated by their r^2 values when the regression (equation 6.34) was applied to their individual trial data, compared with the r^2 when each trial was analysed individually. The best regression for Toorak explained 93% of the variation in mean daily liveweight change, while the pooled regression explained

Table 6.6. Forward stepwise regressions explaining mean daily liveweight change selected for each grazing trial, and grouping of trials.

Grazing Trial	Regression	r^2 and P value	Equation number
Toorak	$\text{Daily liveweight change } (g/d) = -43.460$ $+ 2.654 * \text{soil water}$ $- 0.314 * \text{Util}$	0.927, P<0.001	6.26
Burenda	$\text{Daily liveweight change } (g/d) = -182.156$ $+ 0.921 * \text{avgrnpl}$ $+ 105.357 * \text{rain}$ $- 0.497 * \text{avgrnpl} * \text{rain}$	0.878, P<0.001	6.27
Arabella	[1]$\text{Daily liveweight change } (g/d) = -80.862$ $+ 6398.575 * \text{avnitint}$ $+ 0.785 * \text{green pool} \leq 6$ $- 81.464 * \text{avnitint} * \text{green pool} \leq 6$	0.818 P<0.001	6.28
	[2]$\text{Daily liveweight change } (g/d) = 133.012$ $- 133.191 * \text{THI}$ $- 1.828 * \text{green leaf} \leq 4$ $+ 1.607 * \text{THI} * \text{green leaf} \leq 4$	0.967 P<0.001	6.29
Eastwood	$\text{Daily liveweight change } (g/d) = 48.437$ $- 0.855 * \text{green leaf} \leq 15$ $- 0.005 * \text{TSDM}$	0.523, P<0.001	6.30
Gilruth Plains	$\text{Daily liveweight change } (g/d) = 9.942$ $- 44.136 * \text{rain}$ $+ 2.377 * \text{MCCD}$ $- 0.489 * \text{rain} * \text{MCCD}$	0.881, P<0.001	6.31
All grazing trials	$\text{Daily liveweight change } (g/d) = 33.529$ $- 0.361 * \text{nit. intake} \leq 12$ $- 0.257 * \text{Util}$	0.397, P<0.001	6.32
Mitchell grass trials (Toorak, Burenda, Gilruth Plains)	$\text{Daily liveweight change } (g/d) = 3.537$ $+ 0.150 * \text{avgrnpl}$ $- 0.019 * \text{TSDM}$	0.487, P<0.001	6.33
Toorak and Burenda	[1]$\text{Daily liveweight change } (g/d) = -67.893$ $+ 56.764 * \text{avdiet nitrogen}$ $- 0.326 * \text{Util}$	0.672, P<0.001	6.34
Toorak, Burenda and Arabella	[1]$\text{Daily liveweight change } (g/d) = -111.488$ $+ 0.321 * \text{avgrnpl}$ $+ 64.099 * \text{avdiet nitrogen}$ $- 0.138 * \text{avgrnpl} * \text{avdiet nitrogen}$	0.630, P<0.001	6.35

[1] *Arabella grazing trial - 22 records.* [2] *Arabella grazing trial - 19 records.*

87% of the variation. However, for Burenda, the best regression explained 88% of the variation while the pooled data regression explained only 50% of the observed variation. Inclusion of Arabella data resulted in a regression with similar explanatory power for pooled data, and also when applied to the individual grazing trials, approximately 60%.



Toorak Daily Liveweight Change
(equation 6.26)

Burenda Daily Liveweight Change
(equation 6.27)

Arabella Daily Liveweight Change
22 records
(equation 6.28)

Arabella Daily Liveweight Change
19 records
(equation 6.29)

Eastwood Daily Liveweight Change
(equation 6.30)

Gilruth Plains Daily Liveweight Change
(equation 6.31)

Figure 6.11. Predicted and observed mean daily liveweight change for individual, and pooled grazing trials, using the relevant regressions listed in table 6.6.

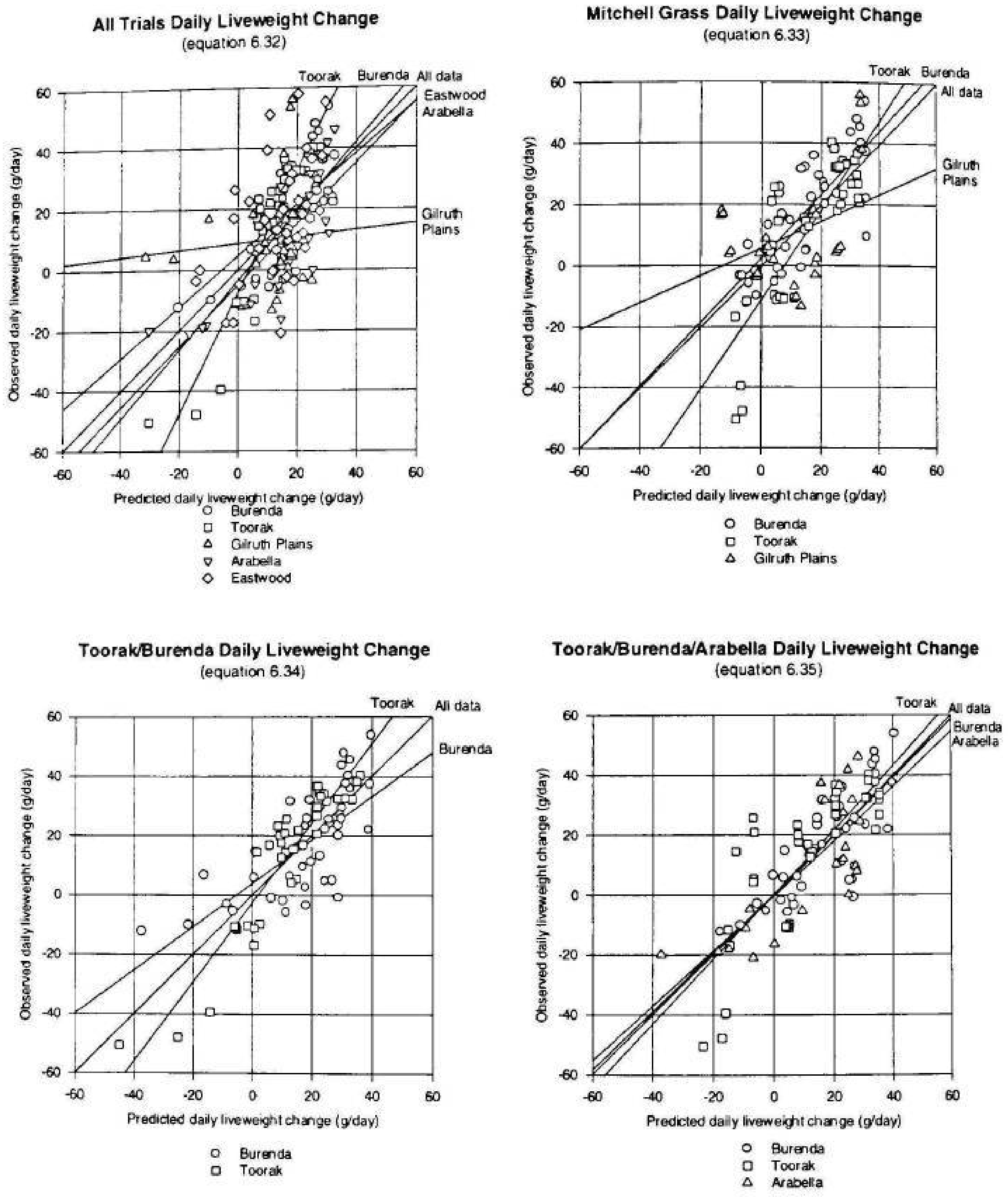


Figure 6.11 continued.

6.6.2.2 More frequent liveweight measurements

The Toorak data had 233 records available for analysis. Results of the forward stepwise regression analysis using the model generated variables were poor. The percentage of days when the intake of nitrogen was less than or equal to 20 g (*nit. intake≤20*) was the most correlated variable (r^2=0.410 P<0.001), followed by *avgrnpl* (r^2=0.355 P<0.001). The best combinations of two variables was *nit. intake≤20* and *THI* (r^2=0.481 P<0.001). Other combinations of two variables included:

- *avnitint, Util* and their interaction (r^2=0.403 P<0.001); and
- *avgrnpl, THI* and their interaction (r^2=0.398 P<0.001).

The optimisation approach using PEST software was unable to optimise any of the test models (equations 6.21 - 6.25) using the Toorak observed liveweight change.

The Burenda data set had 386 records of frequently measured liveweights available for analysis. Results of the regression analysis were very poor; the best single variable only explained 5.5% of the observed liveweight change variation (*avnitint* P<0.001), while the best combination only explained 13.6% of the variation (*avnitint* and *rain* P<0.001). Optimisation of equations 6.21 - 6.25 using the more frequent liveweight measurements resulted in only 16 - 20% of variation in liveweight change being explained.

The Arabella data set had 149 records of frequently measured liveweights available for analysis. Results of the forward stepwise regression analysis using the model generated variables were poor. *Avnitint* was the most correlated variable (r^2=0.276 P<0.001), and the best combination of two variables was *avnitint* and *TSDM* (r^2=0.350 P<0.001). Equation 6.23 was slightly better than the other models tested but only explained 34% of the observed variation in liveweight change.

6.7 Discussion

6.7.1 Wool production

In this section, the biological basis for a general model of wool production for use in western Queensland is reviewed. The above regression analyses show that a general model incorporating all grazing trials could **not** be derived from the wide range of climate, soil, pasture and dietary variables examined, especially with respect to Eastwood and Gilruth Plains. Analysis of grazing trials on an individual basis produced good results except in the case of Eastwood (r^2=0.409 P<0.001). Toorak (r^2=0.819 P<0.001and r^2=0.731 P<0.001), Burenda (r^2=0.702 P<0.001), Arabella (r^2=0.914 P<0.001) and Gilruth Plains (r^2=0.869 P<0.001) all had regressions with very good explanatory power. The use of regression models also requires particular attention to extrapolation outside the range of conditions experienced during the field trials. Hence, there is a need to re-examine the above analyses from this perspective.

The quantity and quality of absorbed amino acids (sulphur) generally limits the ability of sheep to grow wool to their genetic potential (see Appendix One, Part C for further discussion). Amino acids available for absorption in the intestines are of three types (in ascending order of importance): endogenous, rumen non-degradable dietary material, microbial (Appendix One, Part B). Rumen microbial activity is dependent on adequate energy being supplied in the diet, which is a function of digestibility of the diet, and critical levels of nitrogen / protein for microbial usage (e.g. 6.25% crude protein). Thus, the major climatic, pasture and management effects on energy supply would be expected to be the main causes of variation in wool growth. Energy supply can be limited by pasture yield and / or pasture quality.

6.7.1.1 Critical pasture yields

Grazing trials in rangelands have shown that sheep can obtain adequate nutrition at low levels of pasture availability (50 - 500 kg DM / ha). For example, Holm *et al.* (1991) found that in a stocking rate trial on chenopod shrublands, annual wool production was not greatly reduced until the average of three monthly herbaceous yields declined below 50 and 150 kg DM / ha for high and low shrub densities respectively. Of the trials in western Queensland, only Gilruth Plains and Eastwood trials had pasture yields measured frequently enough to examine such relationships (figure 6.12). Comparison with minimum observed pasture yield during each period of wool growth shows that yields greater than 500 kg DM / ha allowed adequate wool production.

Similarly, models of daily dry matter intake of sheep in rangeland pastures (Leigh and Mulham 1966, Wilson *et al.* 1969, Noble 1975, White 1978, Short 1985, Grazfeed) do not generally reduce dry matter intake until yields decline below 250 - 500 kg DM / ha (figure 6.13). Leigh and Mulham (1966), Wilson *et al.* 1969 and Short (1985) were cited in the work of Short (1987).

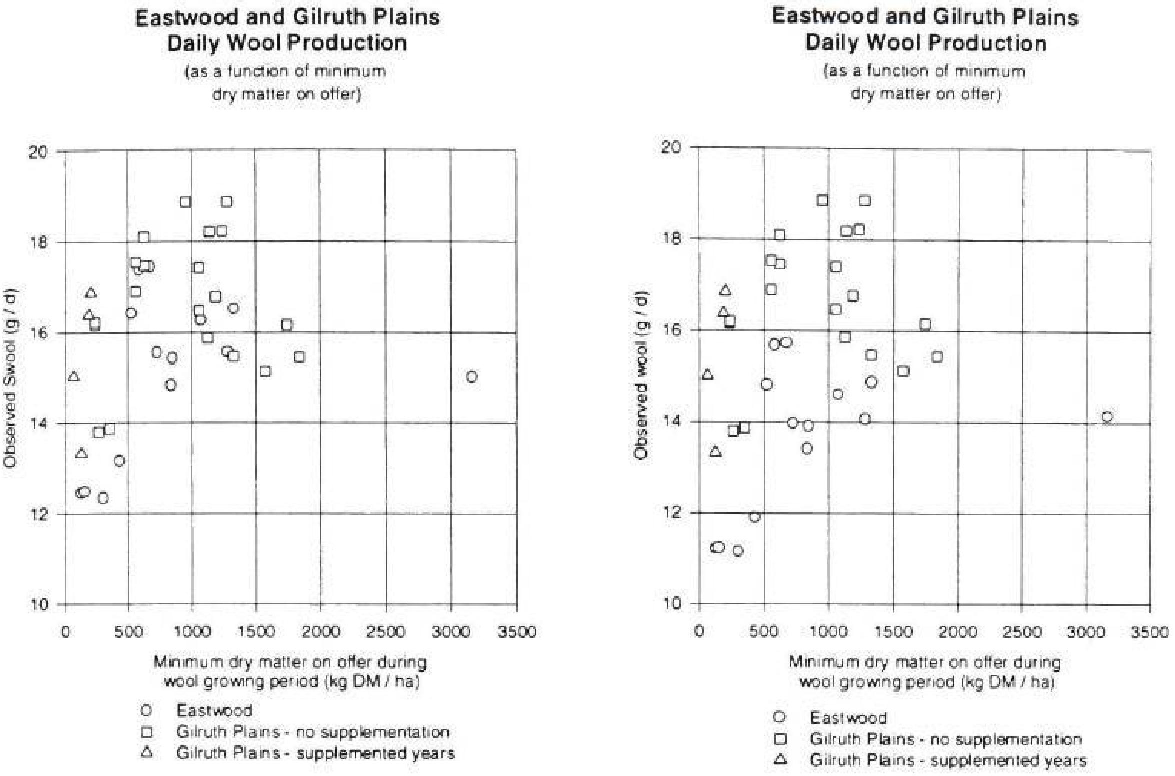


Figure 6.12. Relationship between the minimum recorded TSDM and the associated wool growth rates, as reported and standardised (Swool), for Gilruth Plains and Eastwood grazing trials.

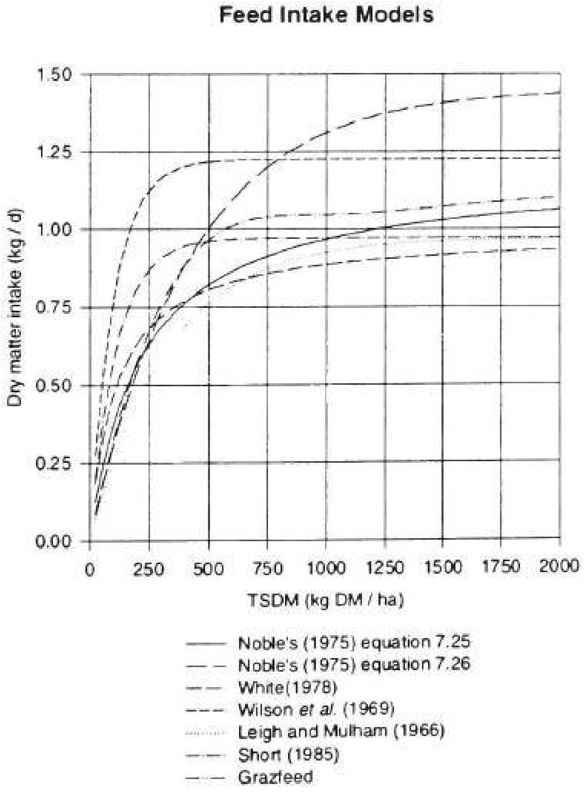


Figure 6.13. Predictions of feed intake as a function of TSDM. The original equations (7.25 and 7.26) of Noble (1975) were adjusted assuming 63% of grazing loss of pasture was due to ingestion. Other model calculations were done for a 40 kg sheep.

The decisions to destock or supplementary feed in the grazing trials were examined to evaluate the possible influence of critical pasture yields at the time of stock changeover. Pasture yield was found to have little direct role in these management decisions. This is likely because sheep can select a high quality diet even at very low pasture yields, and hence these decisions were made on animal or pasture condition rather than pasture yield. Thus it is not unexpected that the *TSDM* variable was not selected by multiple regression analyses.

6.7.1.2 Pasture quality

Lack of importance of pasture yields, or critical yields, emphasises the importance of pasture quality relationships in determining wool growth. Digestibility and protein content of standing pasture declines with age (Wilson and Mannetje 1978) although the rate of decline can be delayed at the onset of water stress (Wilson 1982). In rangelands where growth conditions are infrequent, pastures are often senescent or dead. Under such conditions, measurements of pasture quality (digestibility and protein) were too low (Beale 1975, McMeniman *et al.* 1986a, Carter unpublished data) to supply adequate energy and protein for maximum liveweight gain and wool production.

Sheep have the capability to select higher quality diets than the pasture on offer (Chapter Five and Appendix One, Part A). Even under dry conditions, opportunities for selection of high quality diets exist; on mulga pastures Beale (1975) measured high levels of mulga (34 - 67%) in dried pastures providing high protein levels. Similarly, McMeniman *et al.* (1986a) reported mulga content in the diet at 35% when grass was dry.

McMeniman *et al.* (1986a) found that the apparent preference for forbs on both mulga and Mitchell grass pastures had beneficial effects on nutrient status, and hence there is potential for managed or natural variation in forbs to increase animal production. Under drought conditions the opportunity for such selection declines. Similarly, Lorimer (1976) on Mitchell grasslands measured a high preference for forbs and Flinders grass early in the season and then a decline as the season continued and conditions deteriorated, Mitchell grass quickly becoming the predominant dietary component. Weston and Moir (1969) measured by direct observation the preference of sheep for plant species and plant components in north-west Queensland. After seasonal rain, sheep selected heavily for forbs and annual grasses, then progressed to seed-heads of curly Mitchell grass (*Astrebla lappacea*) with some leaf of bull Mitchell grass (*Astrebla squarrosa*), Flinders grass, and other remaining or late-germinating annuals. After this, sheep selected leaves of curly Mitchell grass, with some leaves and pods of mimosa bush (*Acacia farnesiana*), and finally the stems of curly Mitchell grass. Given this ability of selection it is surprising that a high proportion of variation in fleece production can be explained by climate derived variables (table 6.4).

Furthermore, the analysis of 'worst' years in the grazing trials is difficult as supplementation or removal of stock occurred, and hence the data used in the regression analysis may not fully reflect the frequency or effect of these drought conditions. Supplementation and destocking are real world management options, destocking being achieved by agistment or sale. There are variable 'trigger points' at which management intervention is likely to occur, these are more likely to be influenced by animal condition and the quality of the pasture, rather than pasture yield. The practical rules will have to be derived from the analysis of property records.

Chapter Five highlighted the problems of developing a diet quality index from a single species sward model such as GRASP. Accounting for age distribution in the pasture was able to explain 69 and 42% of variation in measured diet quality on Mitchell and mulga grasslands respectively. Further development of GRASP to incorporate different species or plant groups, e.g. perennials, annuals, forbs, and their differential response to rainfall, should enable an improved estimation of pasture quality, and therefore diet quality.

The studies of Weston and Moir (1969), Beale (1975), Lorimer (1976) and McMeniman *et al.* (1986a) tabled the following sources of variation in diet selection:

- availability of green feed;
- possible variation in diet selection between green grass and green forbs; and
- possible selection for mulga, seeds etc.

Despite the above complexities, the high correlations found in this thesis reflects the dominating effect of the presence of green material on pasture quality. Thus, threshold variable such as the percentage of days when green leaf was less than or equal to 1 kg DM / ha (*green leaf ≤1*), or in practical terms, the percentage of days when there was no green material available for selection, explain a high proportion of wool growth. Lorimer (1976) found that the quality of green dietary material declined with pasture age. However, the diet selection model (Chapter Five), which included the effect of age was not able to explain substantially more variation in wool growth (table 6.7).

Table 6.7. Correlations (r^2) between Swool and key pasture and dietary variables for the grazing trials.

Grazing trial	*green leaf≤1*	*avnitint*	*avdiet nitrogen*	*nit. intake≤12*	*diet nitrogen≤1.2*
Eastwood	0.109 P<0.05	0.186 P<0.01	0.038 ns	0.072 ns	0.111 P<0.05
Gilruth Plains	0.090 ns	0.439 P<0.01	0.397 P<0.01	0.585 P<0.001	0.628 P<0.001
Toorak	0.596 P<0.001	0.327 P<0.001	0.467 P<0.001	0.302 P<0.001	0.426 P<0.001
Burenda	0.491 P<0.001	0.108 P<0.05	0.336 P<0.001	0.388 P<0.001	0.173 P<0.01
Arabella	0.857 P<0.001	0.255 P<0.05	0.809 P<0.001	0.614 P<0.001	0.377 P<0.001

ns - not significant, P>0.05.

This analysis showed the importance of simulating the green and dead material, and in particular the length of time that no green material is present. Lorimer's (1976) study confirms the rapidity with which the proportion of green in the diet changes. GRASP has several functions which affect death rate of green material including the effects of age, low soil moisture and frost. The parameters for these functions have been derived from GUNSYND exclosures (Day *et al.* 1996) based on observations of green **cover** for 160 site * year data sets. Validation of the green yield simulation was only available for two sites, Eastwood and Brian Pastures (Ash *et al.* 1982, McKeon *et al.* 1982, K. Rickert unpublished data). In future development of GRASP, more attention should be given to parameterisation of death functions, accurate available water ranges and species differences given the importance for simulating animal production.

Equations for wool growth developed from the pooled data explained a low proportion of the variation for Eastwood and Gilruth Plains grazing trials. The Eastwood grazing trial was carried out on improved pastures (buffel sown on recently cleared gidgee country). *Diet nitrogen≤7* was the most correlated variable, however, the diet selection model used on this pasture was developed and calibrated with data from Mitchell grass pastures (Chapter Five). The regression developed from the combined grazing trial data had no significant correlation when applied separately to the Eastwood trial, indicating fundamental differences existed between this trial and the Toorak, Burenda and Arabella trials. Eastwood is an anomalous situation in terms of high nitrogen availability (40 kg N / ha) compared to native pastures (10 - 20 kg N / ha, Day *et al.* 1996). Therefore, the relationship between nitrogen and digestibility / energy is likely to be different for sown pastures. Modelling liveweight change in cattle on newly established pastures in eastern Queensland has had similar difficulty (McKeon *et al.* 1980). The sensitivity of liveweight change to climatic variability increased as the sown pasture ran down in nitrogen availability. At this stage in GRASP's development, no attempt has been made to model changes in nitrogen availability following clearing. Incorporation of a better nitrogen model is one approach for re-examining the Eastwood data. Given buffel pastures only account for 2.3 - 4.0% of Queensland rangelands concerned with wool production (Cavaye 1991), the development of a wool production model for buffel is currently less important than that for the other pasture communities. However, as the area of naturalised buffel grass continues to expand (T. Hall pers. comm.), then models will have to be developed. The approach developed above should be applicable to new trials, e.g. the buffel grazing trials conducted by QDPI in the Roma district (T. Hall pers. comm.).

Gilruth Plains diverged greatly from the other two Mitchell grass grazing trials. Relationships which were strong across the remaining Mitchell grass trials, and the sole mulga trial, were generally not significant at this site. Although on a different soil type this would not be expected to completely account for the marked differences found as the ability of GRASP to simulate pasture production at this site was quite good (Day *et al.* 1996). However, prior to the beginning of the trial there was a protracted dry period (Roe 1941), and combined with the predominance of short lived annual forbs at Gilruth Plains (D. Orr pers. comm.), the resultant changes in pasture botanical composition during the course of the experiment (Roe and Allen 1945, 1993) may account for some of the problems encountered in this work. This fact, in combination with the extended time period since the trial was carried out, led to the decision to exclude the Gilruth Plains data from further work.

In all of the shire comparisons (figures A4.1, A4.2, A4.3 of Appendix Four), the predicted wool production was generated using a point climatic file, whereas the ABS shire data encompasses the whole spectrum of climatic variability experienced within that shire for a specific 12 month period. The parameters used within GRASP will also vary throughout a region in line with changing soil type, pasture community and tree density. Additionally, the timing of management and husbandry events will vary markedly compared with the necessarily simplistic approach adopted here and detailed in Chapter Seven. The most important finding was that both the Burenda wool growth models were regarded as unsuitable for further use because of unsatisfactory extrapolation when applied to conditions outside the range used in their development. At some locations the simulation of pasture growth by GRASP showed little year-to-year variation when nitrogen was the major limitation to pasture growth (figure 6.4). Hence those wool growth models using pasture growth as a variable simulated little variation.

Two possible wool production models were therefore still available:

- general model based on *green leaf≤1* and *growth* for all wool growing regions of the state developed from the Toorak, Burenda and Arabella grazing trials (equation 6.17 in table 6.4); and
- models specific for major pasture communities; Mitchell grass (non-mulga) developed from either Toorak or Toorak and Burenda data (equations 6.8, 6.9 and 6.16 in table 6.4), and mulga developed from Arabella data (equation 6.11 in table 6.4).

Further work presented in Chapter Seven at the shire level using ABS data will dictate which will be the final wool growth model / s chosen.

A relationship was developed allowing fibre diameter to be estimated from wool growth rates. This was necessary in order to allow for variation in the value of each kilogram of clean wool produced to be calculated. The wool models simulate greasy wool growth, and clean wool is calculated in the completed bio-economic model by assuming a yield of 70% as in other models such as Grazfeed (Freer *et al.* submitted). A constant percentage yield was selected given that the observed variation (58 - 80%) was unable to be accounted by differences in wool growth rates or GRASP generated variables, and the limited published information on factors affecting clean wool yield (Appendix One, Part C).

6.7.2 Liveweight change

The use of simple climatic, pasture and dietary variables failed to explain adequate levels of variation in annual liveweight change when data from the five grazing trials were combined, as was the case in the wool production analysis. However, the results on an individual trial basis were generally much better. Toorak (r^2=0.927 $P<0.001$), Burenda (r^2=0.878 $P<0.001$), Arabella (19 records - r^2=0.967 $P<0.001$, 22 records - r^2=0.818 $P<0.001$) and Gilruth Plains (r^2=0.881 $P<0.001$) all had multiple regressions with very good explanatory power. The resultant regressions for estimation of liveweight change were different to those for estimations of wool production (tables 6.4 and 6.6). Application of wool regressions to liveweight change data, and vice versa, produced unsatisfactory results (not shown) as would be expected given the poor relationship between these two animal variables (figure 6.8).

As with the analysis of wool growth, analysis of Eastwood grazing trial explained only 52.3% ($P<0.001$) of variation in annual liveweight change, and with *TSDM* included in the forward stepwise regression with a negative coefficient. The regression developed for Gilruth Plains explained 88.1% ($P<0.001$) of variation in annual liveweight change, but the coefficient for rain was negative. The three data points which heavily influenced this relationship were all from 1941. This relationship implies that as rainfall increases sheep will lose more weight, highlighting the potential limitation of extrapolation with multiple regressions. Nevertheless, heavy rains over a short period of time may result in loss of production and even mortalities due to sheep drowning and bogging, and inability to graze due to flooding. The grazing trial data were not adequate to develop predictive equations of these effects of rainfall and, in future, property data should be sought to determine the effects on mortality.

The results of the regression analysis carried out using pooled annual liveweight change were very similar to those of the annual fleece production analysis, especially in terms of the correlations between predicted and observed values when regressions were applied to individual grazing trials. Application of the liveweight change regression developed from the combined trial data set to Eastwood and Gilruth Plains resulted in a weak (r^2=0.226, P<0.001) and no correlation, respectively. Application of the Mitchell grass regression to Gilruth Plains resulted in a low correlation (r^2=0.154, P<0.001). The consistency in findings for Eastwood and Gilruth Plains in both wool and liveweight change pooled data highlights that there are fundamental factors differentiating these two grazing trials from the other three trials. As well, the consistency of analyses indicates that the adjustment for time trend applied to Gilruth Plains wool production values (1941 - 1951), and Eastwood (1968 - 1982), were not responsible for the poor results in the pooled wool grazing trial analysis.

As for wool production, pooling of Toorak and Burenda, with or without Arabella liveweight change data, produced satisfactory results. Although not used subsequently in this thesis, the regressions developed from these trials provide a simple method of predicting annual liveweight change.

Results using more frequent liveweight measurements from the Toorak, Burenda and Arabella trials were very poor. This finding is similar to that of McCaskill and McIvor (1993) who also found the ability to predict seasonal (4 seasons / year) liveweight change of cattle using model generated variables was much reduced compared with annual liveweight change predictions. Thus liveweight change on an annual basis was regarded as the only suitable time period that could be modelled using this regression approach.

CHAPTER SEVEN

Selection of the Wool Production Model

and

Integration of the Bio-economic Model

7.1 Introduction

Annual wool production models were described in Chapter Six based on data from the Arabella grazing trial (mulga grassland), Burenda grazing trial (Mitchell grass), Toorak grazing trial (Mitchell grass) and combinations of these trials. Presented in this chapter is the comparison of Australian Bureau of Statistics (ABS[1] 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987b, 1988, 1989, 1990) shire and state level wool data, and outputs from selected wool production models. This comparison was conducted in order to select the most suitable wool production model, as well as examine shire flock population dynamics. The necessary assumptions and adjustments required for the comparison to be completed, and mentioned previously in Chapter Six, will be detailed.

The data sources and steps taken to construct the completed bio-economic model, in terms of economic and physical inputs, are also presented here. The outputs of the bio-economic model are presented in Chapter Eight.

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[1] ABS data for the period 1951-52 to 1973-74 obtained directly from archival records of ABS, Brisbane office. Data for the period 1989-90 to 1994-95 were purchased directly from ABS in electronic format.

7.2 Selection of wool production model/s

7.2.1 Methodology

Up until this point, all work done with GRASP, including the shire fleece comparison reported in Chapter Six and shown in figures A4.1, A4.2 and A4.3 of Appendix Four, were done with the 'point' version of GRASP. Each simulation was conducted with the 'point' being a specific paddock in one of the grazing trials. Use of simulated fleece production from the point version of GRASP, in the comparison with ABS shire level fleece data, required that each shire was assumed to be a single homogenous paddock enabling a single parameter set to be used. Although simplistic, the comparison was conducted mainly to observe the behaviour of the wool production models when exposed to a greater range of climate variability, and as such, identified the models developed from the Burenda grazing trial as being unsuitable for further use.

At this point in time it became possible to make use of the 'spatial' version of GRASP. The two versions, point and spatial, are similar in terms of calculations performed. However, the point version includes developments since 1993 which will not be included in the spatial version until refereed by the peer group of modellers. The point version can be operated from a personal computer while the spatial version, which repeats all calculations for each 25 km^2 pixel throughout Queensland, is run on a super computer. This means that when using spatial GRASP to calculate shire level fleece production, the calculations are repeated a number of times for each shire, depending on the number of pixels within its boundaries, and the predicted shire mean fleece is weighted for stocking rates. For every pixel within each shire, the most suitable parameter sets for soil type, pasture community and tree density are used. As a result, the spatial GRASP predictions for mean shire fleece weights should be more realistic and better suited for comparison with ABS shire level fleece weights. All reference from herein to GRASP, unless specifically stated, will refer to the spatial version.

The comparison of shire level wool production presented here was conducted to select the most suitable wool production model/s for the wool producing regions of Queensland.

GRASP was run for the period 1955 to 1993. The first two years (1955 - 1956) were 'spin up' years, and used actual rainfall but mean long term temperature, humidity etc., which was not available prior to 1957. Unfortunately, the diet selection and feed intake subroutines, described in Chapter Five, whose output were used in some of the wool production models, were unable to be incorporated in the spatial version due to computing limitations. Therefore, the comparison was restricted to wool production models not using dietary variables: equation 6.8 from Toorak, equation 6.11 from Arabella, equation 6.16 from Toorak / Burenda, equation 6.17 from Toorak / Burenda / Arabella.

The wool production models estimated per head production in terms of '1992' sheep at 50 months of age. When comparing the predicted wool production with the recorded shire production, allowance needed to be made for the year and flock structure. The effect of gestation and lactation on the wool production of breeding ewes, as well as the preferred time of shearing and joining for each shire, also needed to be taken into account. The assumptions, and adjustments made, to the predicted wool production values will now be detailed.

7.2.1.1 Time trend

The predicted annual fleece was corrected for trend over time using the inverse of the previously described statewide regression (equation 6.2).

7.2.1.2 Age structure of the flock

Allowance for the flock structure in terms of age was estimated using age specific mortality rates based on the data of Turner *et al.* (1959), Moule (1966) and Rose (1972). No single function was able to adequately describe the combined data which were subsequently broken into two age groups, 0.75 - 2.0 years and 2.0 - 13.0 years, and appropriate functions fitted (figure 7.1). These functions explained 99.4 and 86.3% of the variation respectively.

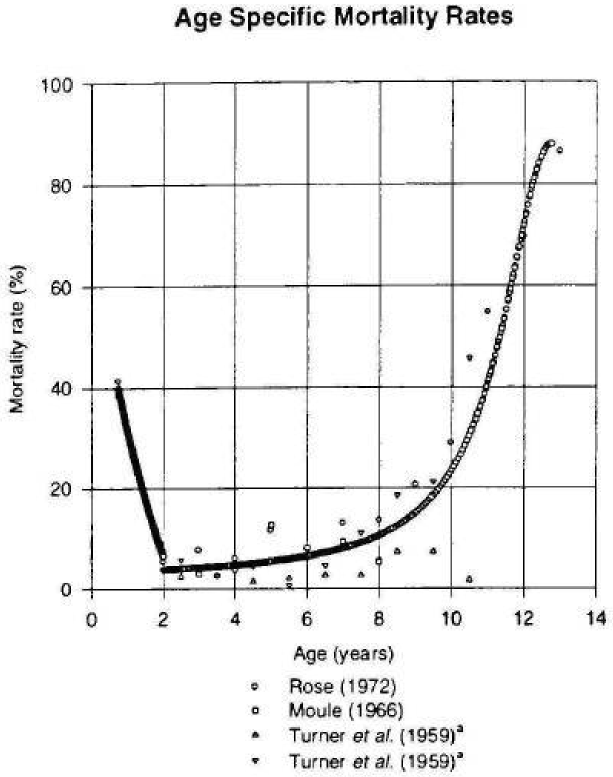


Figure 7.1. Functions describing age specific mortality rates from the data of Turner et al. (1959), Moule (1966) and Rose (1972). a Turner et al. (1959) presented their data for two different periods, for average-good years of 1951 - 57 and the drought year of 1957 - 58.

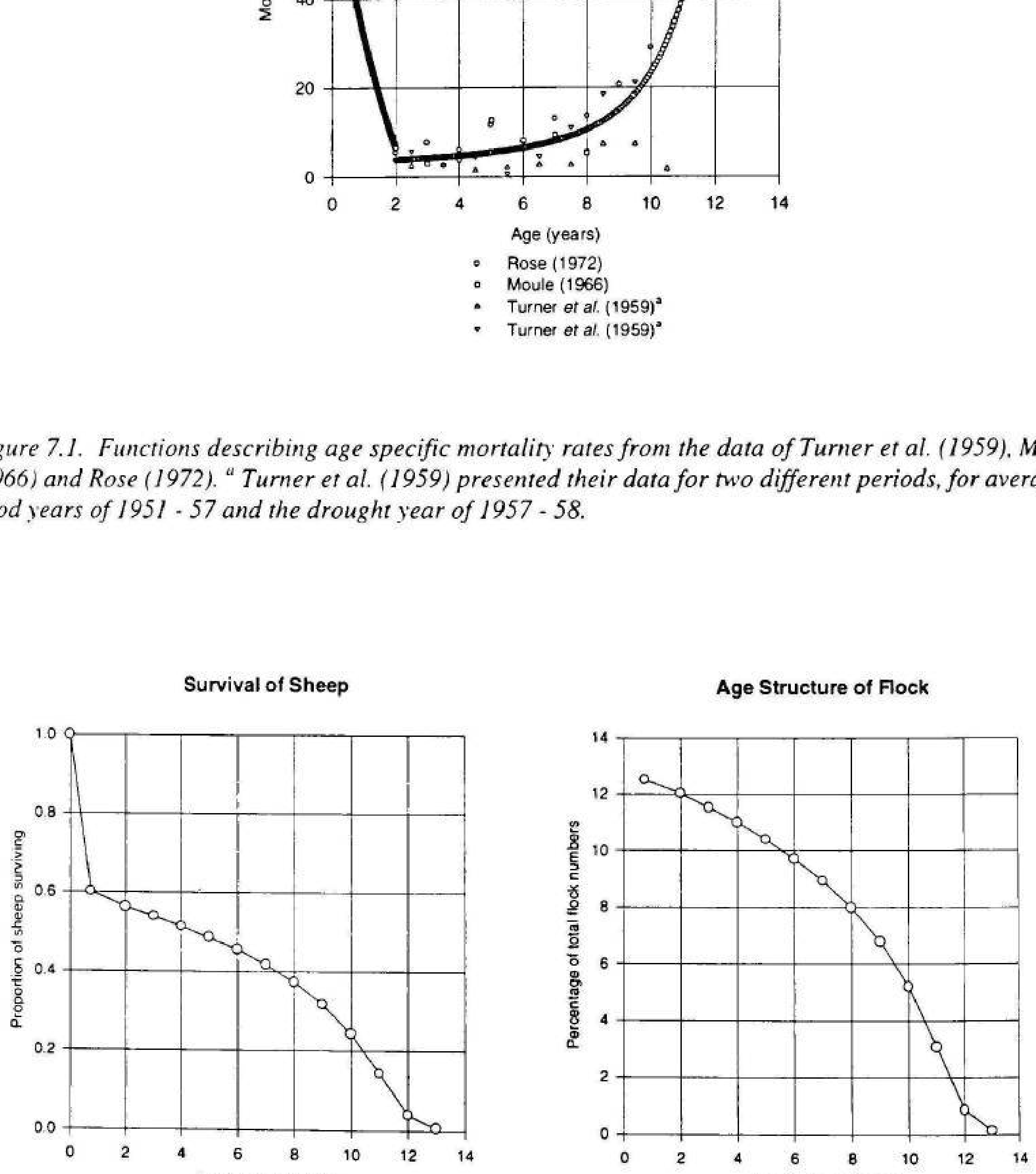


Figure 7.2. Survivability of sheep and the age structure of a flock using the calculated age specific mortality rates.

The age specific mortality rates were used to calculate the percentage of sheep surviving to 13 years of age and the age composition of the flock (figure 7.2). These calculations assumed that all lambs / weaners entered the flock and no sales / purchases and classing occurred. The age specific mortality rates were the means for many years and the flock composition represents the mean or typical composition under the stated management assumptions. Variation in climate and season may affect the mortality rates of different aged sheep by a varying degree, as was seen in the data of Turner *et al.* (1959).

Although very simplified, the mean flock structure, in conjunction with the equation describing wool production as a function of age (equation 6.7), provided some ability to make allowances for the effect of age of sheep within the shire flock. In practical terms, predicted wool production per head was reduced by approximately 10% relative to a flock in which all sheep were 50 months of age.

7.2.1.3 Effect of gestation and lactation

The effect of gestation and lactation on wool production is discussed in Appendix One, Part C, and estimates from various workers and reviewers listed in table A1.2. The values of Rose (1974) were chosen for use in the calculations allowing for the costs for gestation and lactation.

ABS records supply the number of ewes mated to produce the lamb drop for a specific year. Pregnancy rates for the north-west of the state are generally in the order of 85 - 90%, increasing on a north - south gradient (table A1.3 of Appendix One). For this work, all sheep mated were assumed to be pregnant, and therefore experienced the associated reduction in wool production.

As most lamb marking losses occur in the first few days (see Appendix One, Part D), those sheep not marking lambs were assumed to have experienced no reduction in wool production associated with lactation. Ewes were assumed to give birth to single lambs only.

7.2.1.4 Time of shearing

Time of shearing is important as it represents the point within each model run when the accumulated variables, based on the previous 12 months simulation, were used to estimate the annual fleece production. The shearing month for each shire (table 7.1) was estimated from the following data sources: ABS (1976, 1983, 1988), Pearse (1990), Wool International wool sales data (1987-88 to 1992-93 seasons), Thompson (1993), Buxton *et al.* (1995a, b), R. Armstrong (unpublished data).

Wool sales information was purchased from Wool International for the 1987-88 to 1992-93 selling seasons and was used to help select the preferred time of shearing for each shire. The data included greasy weight for individual sale lots and the associated wool statistical area. A lag of 4 weeks was assumed between time of shearing and sale of wool (D. Cobon and N. O'Dempsey pers. comm.). Sale of wool did not occur all year round with breaks at Easter and Christmas. As well, sales were suspended in 1991 from February 4th to February 24th due to collapse of the reserve price scheme. Adjustments to the monthly sales totals occurred to take into account those periods when sale breaks occurred. The data were analysed using four different approaches: all selling seasons pooled, individual selling seasons, 1987-88 and 1988-89 selling seasons pooled, 1987-88 selling season. The third and fourth approaches were preferred due to the effect price instability may have had on producers deciding when to market their wool, i.e. the lag period between time of shearing and sale of wool may have been more variable in those analyses which included the period in which the reserve price scheme collapsed. It should be noted that price instability, in terms of floor price paid by wool buyers, first occurred in June 1989. This analysis of sales data provided useful support for other sources when selecting the preferred shire times of shearing, but was potentially flawed in the following areas:

- property to which sale was attributed was not necessarily the property at which production occurred;
- assumed lag period between time of shearing and sale may not be suitable; and
- the method of handling sale breaks may not have been suitable.

Table 7.1. Timing of management and husbandry operations for each wool producing shire.

Shire	Division	Shearing	Joining
Aramac	Central West	15th August	15th October
Barcaldine	Central West	15th August	15th October
Barcoo	Central West	15th August	15th October
Blackall	Central West	15th August	15th April
Boulia	Central West	15th August	15th October
Ilfracombe	Central West	15th August	15th October
Isisford	Central West	15th August	15th April
Longreach	Central West	15th August	15th October
Tambo	Central West	15th August	15th April
Winton	Central West	15th August	15th October
Allora	Darling Downs	15th September	15th April
Cambooya	Darling Downs	15th September	15th April
Chinchilla	Darling Downs	15th September	15th April
Clifton	Darling Downs	15th September	15th April
Crows Nest	Darling Downs	15th September	15th April
Glengallan	Darling Downs	15th September	15th April
Inglewood	Darling Downs	15th September	15th April
Jondaryan	Darling Downs	15th September	15th April
Millmerran	Darling Downs	15th September	15th April
Murilla	Darling Downs	15th September	15th April
Pittsworth	Darling Downs	15th September	15th April
Rosalie	Darling Downs	15th September	15th April
Rosenthal	Darling Downs	15th September	15th April
Stanthorpe	Darling Downs	15th September	15th April
Tara	Darling Downs	15th September	15th April
Taroom	Darling Downs	15th September	15th April
Waggamba	Darling Downs	15th August	15th April
Wambo	Darling Downs	15th September	15th April
Banana	Fitzroy	15th September	15th April
Bauhinia	Fitzroy	15th September	15th April
Jericho	Fitzroy	15th August	15th October
Peak Downs	Fitzroy	15th September	15th October
Cloncurry	North West	15th September	15th October
Flinders	North West	15th September	15th October
McKinlay	North West	15th September	15th October
Richmond	North West	15th September	15th October
Balonne	South West	1st March	15th April
Bendemere	South West	15th August	15th April
Booringa	South West	15th August	15th April
Bulloo	South West	15th March	15th April
Bungil	South West	15th August	15th April
Murweh	South West	15th August	15th April
Paroo	South West	15th March	15th April
Quilpie	South West	15th March	15th April
Warroo	South West	15th August	15th April

7.2.1.5 Time of joining and lambing / lamb marking

Timing of joining and lambing / lamb marking (table 7.1) was important as this dictated whether the gestation and lactation costs of lambs that were marked in a certain year, influenced wool production for that same year. Times chosen were based on information from a number of sources: Moule (1954), Entwistle (1970, 1972), Payne (1978), McMeniman (1985), Jordan *et al.* (1989), Jordan and Le Feuvre (1989), Thompson (1993), Pearse (1990), N. O'Dempsey (pers. comm.), P. Johnston (pers. comm.). To highlight the interaction of selected shearing and joining / lambing times, two shires (McKinlay, Tambo) will be discussed.

McKinlay shearing was estimated to occur in September and lambing in March. The significance of these dates is that wool production collected by ABS in March of year 't', actually referred to wool shorn in September of 't-1'. The *number of lambs marked,* collected by ABS in year 't', also referred to lambs marked in late autumn / early winter of year 't-1'. It should be noted that ABS reports the *number of ewes mated,* to give the *number of lambs marked.* In the case of McKinlay, this meant the *number of ewes mated,* collected in March of year 't' and which referred to lambs marked in year 't-1', were the ewes actually joined in year 't-2'. Therefore, data collected by ABS in March of year 't' were used to calculate the gestation and lactation costs appropriate to wool shorn in September of 't-1'.

Tambo shearing was estimated to occur in August and lambing in September. ABS wool production data collected in March of year 't' referred to that shorn in August of 't-1', while the gestation and lactation costs for this shearing would be calculated using data collected by ABS in March of 't-1'. No attempt was made to split the gestation costs, instead it was assumed that the drain on the ewe associated with foetal requirements was greatest near term as shown by Oddy (1985).

7.2.1.6 Stocking rate

Total grazing pressure in terms of DSE were estimated based on ABS sheep and cattle numbers, as well as age and physiological status. Stocking rate was reset annually on the 31st of March in line with the ABS census. ABS shire stock numbers were distributed throughout each shire based on the mean pasture growth for each pixel (25 km^2), resulting in more productive areas having higher stocking rates (Carter *et al.* 1996). National parks were excluded from both sheep and cattle distributions while pasture communities, such as black spear grass and spinifex, and dingo fences, were used to restrict the distribution of sheep. Macropods were also taken into account although little reliable information was available.

7.2.1.7 Number of sheep shorn

The number of sheep shorn per unit area is essential to calculate the wool production per unit area (ha, property, shire etc.). The number of sheep shorn in any year is a function of the number of animals in the previous year, reproduction and mortalities, and management responses to the current and perceived future physical and economic environments. Given that a dynamic flock population neither existed, nor could be developed in the time available, an analysis was carried out on the relationship between ABS shire sheep numbers at the beginning of each census year (end of previous census year), and the number of sheep shorn in that year. If an adequate relationship existed, this would provide a simple method of calculating the number of sheep shorn per unit area, and therefore wool production per unit area.

In certain situations, it may be considered worthwhile to estimate future wool production in conjunction with analogue climate data predictions (Stone and Auliciems 1992). For this reason, the relationship between ABS sheep numbers reported in March of year 't' and the number of sheep shorn as reported in March of year 't+2' was examined.

Both analyses of the number of sheep shorn were conducted over two time periods, 1953 to 1994 and 1975 to 1994 (1980 to 1994 in the latter examination of number of sheep shorn). This was done to ensure any positive correlation present was due to a relationship between the two variables, and not due to possible long term trends in enterprise mix, as was noted previously in Chapter Three (see figure 3.11).

7.2.1.8 Within models comparison

The four remaining wool production models (equations 6.8, 6.11, 6.16 and 6.17) were first compared with each other in terms of mean shire fleece production for all Queensland wool producing shires over the period 1957 to 1993. This within models comparison was repeated using shires considered more homogenous for pasture communities based on the pasture map of Weston *et al.* (1981). Quilpie was selected as having the greatest proportion of mulga, with Bulloo and Murweh also considered 'mulga' shires, but to a lesser extent. Ilfracombe was considered almost exclusively Mitchell grass, with McKinlay, Flinders, Richmond, Barcaldine, Bungil, Warroo, Waggamba and Balonne selected as having a high proportion of Mitchell grass / non-mulga pasture communities.

7.2.1.9 Comparison with ABS data

Using the two groups of shires (mulga, Mitchell grass / non-mulga) described above, the predictions of the appropriate wool production models were then compared with the ABS shire level fleece data.

Total shire wool production as predicted using equations 6.8 (Toorak), 6.11 (Arabella) and 6.17 (Toorak / Burenda / Arabella), for appropriate shires based on pasture homogeneity, were also compared with ABS data over the period 1957 - 1993. Number of sheep shorn was taken to be the current stocking rate for each shire at the time of their designated shearing month. The wool model developed from the combined Toorak and Burenda data (equation 6.16) was not examined at this stage because of its relative similarity to the Toorak / Burenda / Arabella model (tables 7.4 and 7.5). Total Queensland greasy wool production (1957-1993) as reported by ABS was then compared with that predicted by equation 6.17 (Toorak / Burenda / Arabella).

7.2.1.10 Sheep sales

Some initial work was carried out into dynamic modelling of the shire flock using McKinlay, Tambo and Murweh as test shires. Annual sheep sale numbers, as reported by ABS, were examined to identify if climatic and pasture variables, stocking rate, and wool price were able to explain the variation, thus allowing for more dynamic modelling of the number of sheep shorn. Unfortunately, sheep sale figures were only reported from 1975 onwards. Both the absolute number and percentage sold were examined. The market indicator price, available from the 1976-77 selling season on a weekly basis, was adjusted for inflation using the consumer price index (Commodity statistical bulletin 1994). The GRASP generated variables were from the point version of GRASP using Julia Creek, Tambo and Charleville climatic data for the McKinlay, Tambo and Murweh shires respectively.

7.2.2 Results

7.2.2.1 Number of sheep shorn

The number of sheep and lambs shorn, as reported by ABS, was found to be highly correlated with the total number of sheep reported at the end of the previous census year for most shires (table 7.2). Those shires where there were no significant relationships have only small sheep populations as indicated by the mean ABS values for 1990-1994, and are of minor importance in terms of commercial wool production, e.g. Cambooya - 600 head, Crows Nest - 230 head, Rosalie - 1860 head. Therefore, the use of the shire sheep numbers for the year 't' provided a convenient method of calculating the number of sheep shorn in year 't + 1'.

The results were not so good when ABS sheep numbers collected at the end of census year 't' were examined for their relationship with the number of sheep shorn in the census year 't + 2', especially over the more recent period (1980 - 1994, table 7.3). The change in sheep numbers includes the impact of climate on reproduction and mortality and management responses.

Table 7.2. Correlation (r^2) between sheep at beginning of census year (end of previous census year), and number of sheep shorn in that year.

Shire	1953-1994	P value	1975-1994	P value
Allora[a]	0.806	<0.001	0.413	<0.01
Aramac	0.885	<0.001	0.587	<0.001
Balonne	0.835	<0.001	0.913	<0.001
Banana	0.962	<0.001	0.982	<0.001
Barcaldine	0.750	<0.001	0.626	<0.001
Barcoo	0.637	<0.001	0.853	<0.001
Bauhinia	0.972	<0.001	0.956	<0.001
Bendemere	0.918	<0.001	0.576	<0.001
Blackall	0.746	<0.001	0.419	<0.01
Booringa	0.844	<0.001	0.825	<0.001
Boulia	0.857	<0.001	0.817	<0.001
Bulloo	0.535	<0.001	0.770	<0.001
Bungil	0.970	<0.001	0.604	<0.001
Cambooya[a]	0.776	<0.001	--	ns
Chinchilla	0.916	<0.001	0.495	<0.001
Clifton	0.904	<0.001	0.504	<0.001
Cloncurry	0.954	<0.001	0.908	<0.001
Crows Nest[a]	0.506	<0.001	--	ns
Flinders	0.921	<0.001	0.846	<0.001
Glengallan	0.904	<0.001	0.642	<0.001
Ilfracombe	0.832	<0.001	0.439	<0.01
Inglewood	0.848	<0.001	0.950	<0.001
Isisford	0.797	<0.001	0.637	<0.001
Jericho	0.931	<0.001	0.759	<0.001
Jondaryan	0.958	<0.001	0.545	<0.001
Longreach	0.801	<0.001	0.790	<0.001
McKinlay	0.927	<0.001	0.748	<0.001
Millmerran	0.968	<0.001	0.864	<0.001
Murilla	0.954	<0.001	0.694	<0.001
Murweh	0.828	<0.001	0.868	<0.001
Paroo	0.733	<0.001	0.744	<0.001
Peak Downs	0.949	<0.001	0.931	<0.001
Pittsworth	0.923	<0.001	0.605	<0.001
Quilpie	0.682	<0.001	0.889	<0.001
Richmond	0.946	<0.001	0.830	<0.001
Roesenthal	0.863	<0.001	0.853	<0.001
Rosalie[a]	0.906	<0.001	--	ns
Stanthorpe	0.837	<0.001	0.833	<0.001
Tambo	0.817	<0.001	0.673	<0.001
Tara	0.938	<0.001	0.855	<0.001
Taroom	0.954	<0.001	0.960	<0.001
Waggamba	0.929	<0.001	0.833	<0.001
Wambo	0.941	<0.001	0.666	<0.001
Warroo	0.910	<0.001	0.831	<0.001
Winton	0.841	<0.001	0.894	<0.001

ns - not significant. [a] *for these shires the respective years are 1958-1994 and 1980-1994*

Table 7.3. Correlation (r^2) between sheep at end of previous census year 't' and number of sheep reported shorn in census year 't+2'.

Shire	1953-1994	P value	1980-1994	P value
Allora[a]	0.414	<0.01	--	ns
Aramac	0.572	<0.01	--	ns
Balonne	0.914	<0.001	0.461	<0.01
Banana	0.820	<0.001	0.746	<0.001
Barcaldine	0.622	<0.001	--	ns
Barcoo	0.617	<0.001	0.282	<0.05
Bauhinia	0.659	<0.001	0.675	<0.001
Bendemere	0.613	<0.05	--	ns
Blackall	0.433	<0.01	--	ns
Booringa	0.797	<0.001	0.297	<0.05
Boulia	0.779	<0.001	0.549	<0.01
Bulloo	0.779	<0.001	0.294	<0.05
Bungil	0.635	<0.001	--	ns
Cambooya[a]	--	ns	--	ns
Chinchilla	0.487	<0.01	--	ns
Clifton	0.467	<0.01	--	ns
Cloncurry	0.986	<0.001	0.876	<0.001
Crows Nest[a]	--	ns	--	ns
Flinders	0.776	<0.001	--	ns
Glengallan	0.615	<0.001	0.489	<0.01
Ilfracombe	0.402	<0.05	--	ns
Inglewood	0.933	<0.001	0.758	<0.001
Isisford	0.613	<0.001	--	ns
Jericho	0.322	<0.05	--	ns
Jondaryan	0.520	<0.01	--	ns
Longreach	0.814	<0.001	--	ns
McKinlay	0.661	<0.001	--	ns
Millmerran	0.738	<0.001	0.484	<0.01
Murilla	0.546	<0.01	--	ns
Murweh	0.857	<0.001	0.351	<0.05
Paroo	0.762	<0.001	--	ns
Peak Downs	0.923	<0.001	0.603	<0.001
Pittsworth	--	ns	--	ns
Quilpie	0.883	<0.001	0.437	<0.01
Richmond	0.721	<0.001	--	ns
Roesenthal	0.698	<0.001	0.396	<0.05
Rosalie[a]	--	ns	--	ns
Stanthorpe	0.750	<0.001	0.408	<0.05
Tambo	0.680	<0.001	--	ns
Tara	0.854	<0.001	--	ns
Taroom	0.912	<0.001	0.719	<0.001
Waggamba	0.844	<0.001	--	ns
Wambo	0.637	<0.01	--	ns
Warroo	0.818	<0.001	0.437	<0.01
Winton	0.865	<0.001	0.477	<0.001

ns - not significant. [a] for these shires the respective years are 1958-1994 and 1980-1994.

7.2.2.2 *Within models comparison*

The four wool production models were, as expected, positively correlated, especially the Toorak / Burenda (equation 6.16, TB) and Toorak / Burenda / Arabella models (equation 6.17, TBA) when compared for all Queensland wool producing shires (table 7.4).

Table 7.4. Correlation matrix (r^2) for the Toorak (equation 6.8), Arabella (equation 6.11), Toorak / Burenda (TB, equation 6.16) and Toorak / Burenda / Arabella (TBA, equation 6.17) wool models in terms of mean shire fleece production for all Queensland wool producing shires over the period 1957 to 1993.

	TBA	**TB**	**Toorak**	**Arabella**
TBA	1.0			
TB	0.99	1.0		
Toorak	0.65	0.65	1.0	
Arabella	0.77	0.83	0.66	1.0

The Arabella and TBA wool models were compared using those shires previously designated as 'mulga' shires. For the years 1957 to 1993, the correlation (r^2) for the two models for Quilpie shire only, and Quilpie, Bulloo and Murweh shires combined, were 0.89 and 0.88 respectively, values greater than when the models were compared across all Queensland shires (table 7.4). At fleece weights less than 4 kg the TBA wool model estimated greater weights than the Arabella model (not shown). At fleece weights greater than 4 kg the reverse situation occurred. For all Queensland shires, comparison of the TB and TBA models showed a similar relationship but with the change occurring at 3 kg compared with 4 kg (not shown).

The Toorak, TB and TBA wool models were used with the Mitchell grass / non-mulga shires (table 7.5). The TB and TBA wool models were very similar with a slope approaching 1.0, and y intercept approaching 0.0, for Ilfracombe, combined Mitchell grass / non-mulga shires, and all Queensland shires. The TBA and TB models predicted heavier fleeces than the Toorak model for all Queensland and Mitchell grass shires, the difference being greatest at low fleece weights (not shown).

Table 7.5. Correlation matrix (r^2) for the Toorak (equation 6.8), Toorak / Burenda (TB, equation 6.16) and Toorak / Burenda / Arabella (TBA, equation 6.17) wool models in terms of mean shire fleece production for selected Mitchell grass / non-mulga shires over the period 1957 to 1993. Values in italics are for the model comparison using Ilfracombe shire only.

	TBA	TB	Toorak
TBA	1.0		
TB	0.99 *0.99*	1.0 *1.0*	
Toorak	0.61 *0.65*	0.60 *0.63*	1.0 *1.0*

7.2.2.3 Comparison with ABS data

Graphs of the comparison of mulga, and Mitchell grass / non-mulga model predicted shire fleece weights with ABS data, for the appropriate shires, are shown in figures A4.4 and A4.5 of Appendix Four respectively. The level of variation in shire fleece weights (CV approximately 10%) was previously shown to be less than that experienced at the paddock and property level (CV range generally 15 - 20%, table 3.9). Therefore, the wool production model which was developed from the small paddock scale grazing trials would be expected to have a higher year-to-year variation than occurs in shire fleece weights.

The Toorak / Burenda / Arabella wool model appeared better able to simulate the fleece production of the mulga shires (Quilpie, Murweh, Bulloo), explaining 43.3, 40.2 ($P<0.001$) and 26.6% ($P<0.01$) of the respective variation. The Arabella wool model explained 39.1, 31.4 ($P<0.001$) and 15.9% ($P<0.05$) of the respective variation.

For the Mitchell grass / non-mulga shires, the TB and TBA wool models performed better than the Toorak model in seven and six of the nine shires respectively. The correlations (r^2) for each model for all nine shires are shown in table 7.6. The results for total shire wool production (figures A4.6 and A4.7 of Appendix Four) were quite promising for most shires and reinforced the general suitability of the TBA model over the Arabella and Toorak wool models.

Based on these findings the Toorak / Burenda / Arabella wool model was selected as being the most suitable for both mulga and Mitchell grass / non-mulga pastures in the bio-economic model. This model was able to explain 57% ($P<0.001$) of the variation in

Queensland mean fleece weights and, on the use of sheep stocking rates, 78% ($P<0.001$) of the variation in annual Queensland greasy wool production (figures A4.8 and A4.9 of Appendix Four).

Table 7.6. Correlations (r^2) for predicted and observed (ABS) shire fleece weights using the Toorak (equation 6.8), Toorak / Burenda (equation 6.16, TB) and Toorak / Burenda / Arabella (equation 6.17, TBA) wool models for nine Mitchell grass / non-mulga shires.

Shire	Toorak - equation 6.8	TB - equation 6.16	TBA - equation 6.17
Balonne	0.387 ($P<0.001$)	0.400 ($P<0.001$)	0.387 ($P<0.001$)
Barcaldine	-- ns	0.247 ($P<0.01$)	0.251 ($P<0.01$)
Bungil	0.381 ($P<0.001$)	0.514 ($P<0.001$)	0.491 ($P<0.001$)
Flinders	0.266 ($P<0.01$)	0.350 ($P<0.001$)	0.335 ($P<0.001$)
Ilfracombe	0.135 ($P<0.05$)	0.245 ($P<0.01$)	0.235 ($P<0.01$)
McKinlay	0.329 ($P<0.001$)	0.240 ($P<0.01$)	0.256 ($P<0.01$)
Richmond	0.139 ($P<0.05$)	0.143 ($P<0.05$)	0.112 ($P<0.05$)
Waggamba	0.417 ($P<0.001$)	0.370 ($P<0.001$)	0.332 ($P<0.001$)
Warroo	0.349 ($P<0.001$)	0.426 ($P<0.001$)	0.388 ($P<0.001$)

7.2.2.4 Sheep sales

Significant results from the analysis of ABS sheep sales data using climatic and pasture variables generated from the point version of GRASP, and wool price variables are shown in table 7.7. These results should be interpreted with caution, as variables generated from the point version of GRASP were compared with shire level data. Rainfall, soil type, pasture community and tree density may differ markedly within a single shire. There were several significant relationships found, but none which was applicable across all three shires.

7.3 Integration of the bio-economic model

This section details the additional data sources and assumptions made in order to complete the bio-economic mode.

7.3.1 Price indices

Price indices were required to convert nominal prices received and paid by producers to real dollars, or a common base to facilitate comparisons. Two annual indices were

Table 7.7. Relationships of sheep sold with climatic, pasture and price variables.

Shire	Dependent variable	Climatic/Pasture variable	Correlation (r)	P value
McKinlay	number of sheep sold	mean annual standing dry matter	-0.253	<0.05
		standing dry matter at beginning of May in previous year	-0.336	<0.01
		pasture utilisation[b] in May of previous year	0.463	<0.01
	percentage of sheep sold	mean annual standing dry matter	-0.316	<0.05
		standing dry matter at beginning of May in previous year	-0.399	<0.01
		annual pasture utilisation[c]	0.210	<0.05
		pasture utilisation[b] in May of previous year	0.484	<0.001
Tambo	percentage of sheep sold	standing dry matter at beginning of April in previous year	-0.258	<.0.05
	number of sheep sold	flock numbers at beginning of year	0.433	<0.01
		standing dry matter at beginning of April in previous year and flock numbers at beginning of year	0.579	<0.05
		flock numbers at beginning of year and mean annual indicator price[a]	0.670	<0.05
Murweh	percentage of sheep sold	mean annual indicator price[a]	0.569	<0.001
	number of sheep sold	flock numbers at beginning of year	0.354	<0.01
		mean annual indicator price[a]	0.496	<0.01
		mean annual indicator price[a] and flock numbers at beginning of year	0.783	<0.001

[a] *The mean wool annual price represents the mean price for April - March for the ABS year under examination. The coefficient for the wool price variable was positive indicating that as wool prices rise more sheep are sold. The possibility that higher wool prices resulted in greater sheep numbers and therefore greater turn off was examined using the Murweh data. No significant relationship existed between flock numbers at the beginning of the year and wool prices.*

[b] *Pasture utilisation calculated as intake / growth.*

[c] *Pasture utilisation calculated as intake / (growth + standing dry matter at beginning of period).*

available, the *Consumer Price Index* (CPI, Commodity statistical bulletin 1994) and the *index of prices paid by Queensland farmers* (ABARE pers. comm.). The indices were closely correlated ($r^2=0.99$ $P<0.001$, figure 7.3) but are calculated using different 'baskets of goods and services' to measure changes in prices and may move independently of each other. The CPI basket of goods and services is based on the buying behaviour of employees of metropolitan Australia (ABS 1987a) while the farmers prices paid index basket of goods and services is based on those of importance to Queensland farmers (Indexes of prices received and paid by farmers: December quarter 1995 (1996)). When examining time series of prices received and paid by Queensland wool producers, the *index of prices paid by Queensland farmers* was therefore the most appropriate index series.

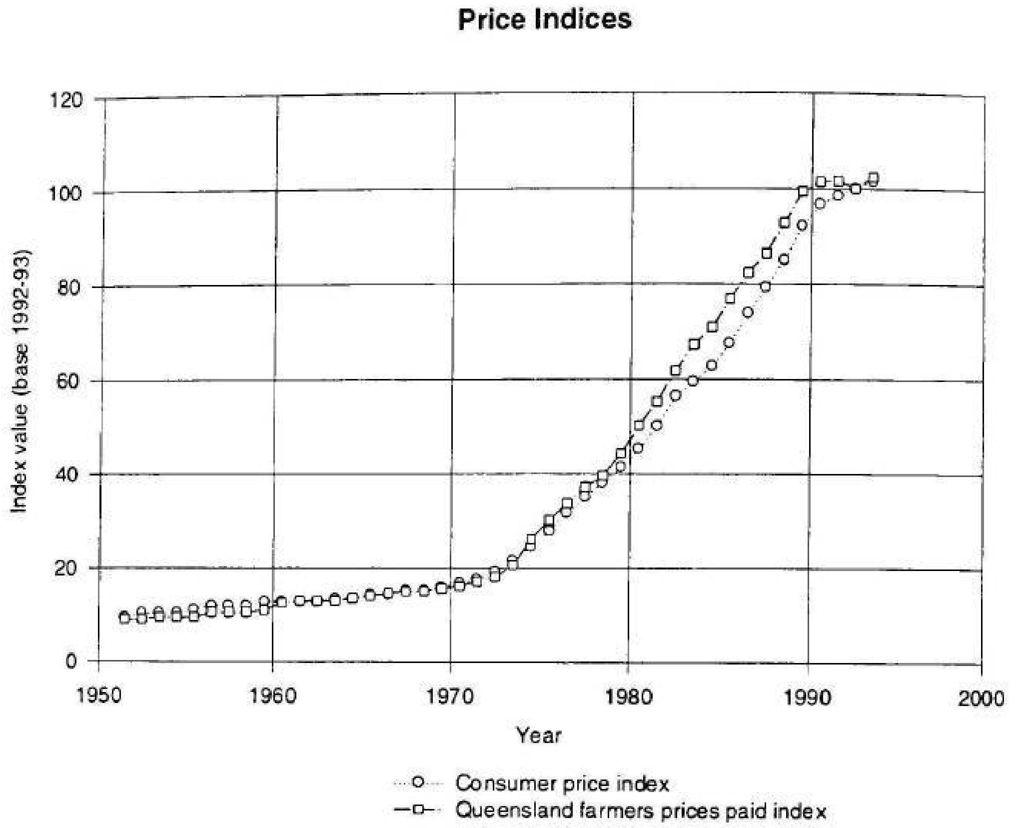


Figure 7.3. Relationship between Consumer Price Index and index of prices paid by Queensland farmers for the period 1951-52 to 1993-94 (base 1992-93).

7.3.2 Wool prices

Detailed wool prices (c / kg clean) were available for the selling seasons 1973-74 to the present from Wool International, formerly the Australian Wool Corporation (AWC 1974, 1975, 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, Wool International 1994, 1995, 1996). These were indicator prices covering a number of wool types based on closing auction quotations for a range of microns (19 - 27μ). Prior to the 1994-95 season, the indicators were based on all Australian sales, whereas from this time on, indicators were based on prices from eastern sale centres only.

Unfortunately, no detailed wool price data were available for the period prior to 1973-74. However, two time series of wool prices going back to 1952-53 were obtained. The first was mean greasy auction prices (Commodity statistical bulletin 1993), and the second, mean annual clean wool prices (National Council of Wool Selling Brokers supplied by

Wool International). The two wool price time series were closely correlated (r^2=0.99 P<0.001, figure 7.4) with the slope of the linear relationship between the two representing a yield of 67%.

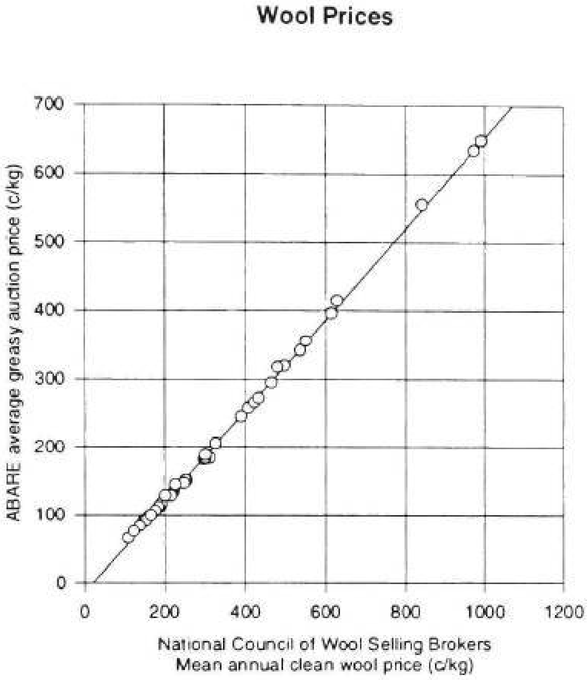


Figure 7.4. Relationship between mean greasy auction prices (Commodity statistical bulletin 1993) and mean annual clean wool prices (National Council of Wool Selling Brokers supplied by Wool International) for 1951-52 to 1992-93.

The wool price time series from the National Council of Wool Selling Brokers (NCWSB) was then used to investigate possible relationships between it and mean annual micron specific wool prices from 1973-74 to 1994-95, in both nominal and real dollar terms (figures 7.5 and 7.6). These two figures highlight the need to have time series of wool prices in real dollars instead of nominal dollars. Figure 7.5 implies small premiums were paid for finer fibre diameter wools prior to 1979-80, but figure 7.6 shows fine wool premiums existed prior to 1979, and were of a similar magnitude to later years except for the late '80's and early '90's. In real dollars (base 1992-93), the NCWSB clean price was strongly correlated with all micron groups:

- 19 micron, r^2=0.643 P<0.001 n=22;
- 20 micron, r^2=0.822 P<0.001 n=22;
- 21 micron, r^2=0.968 P<0.001 n=22;
- 22 micron, r^2=0.980 P<0.001 n=22;
- 23 micron, r^2=0.947 P<0.001 n=22;
- 24 micron, r^2=0.891 P<0.001 n=22;
- 25 micron, r^2=0.853 P<0.001 n=22;
- 26 micron, r^2=0.874 P<0.001 n=12;
- 27 micron, r^2=0.830 P<0.001 n=22.

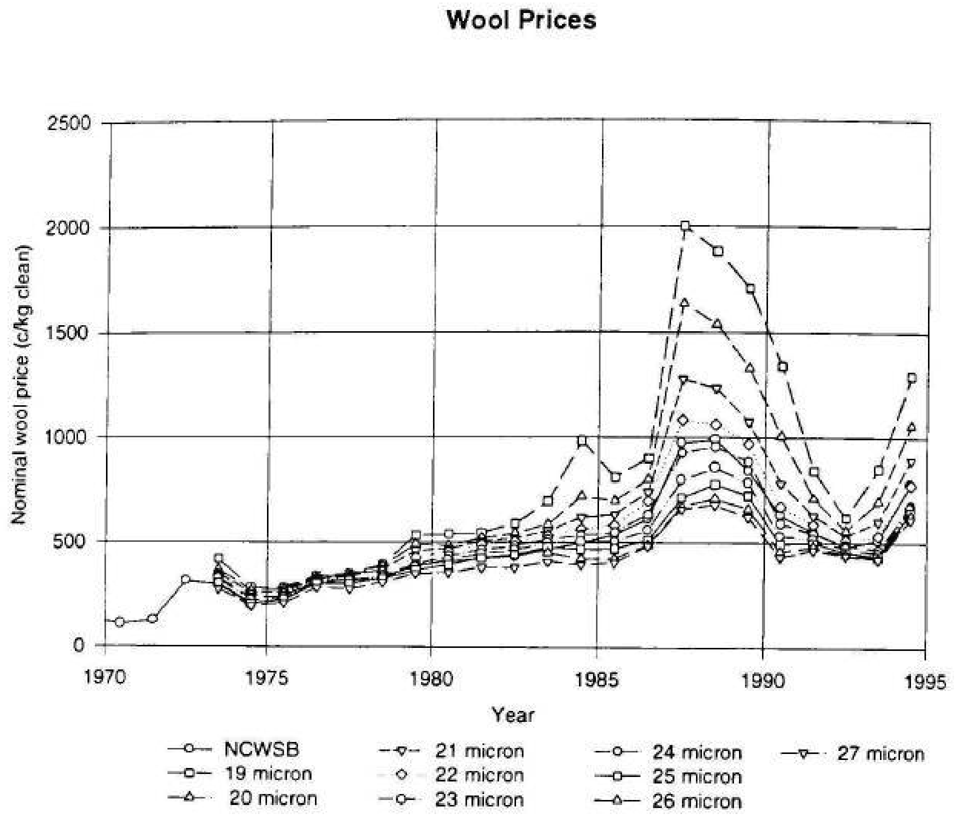


Figure 7.5. Mean annual micron specific nominal wool prices (Wool International) and NCWSB mean annual nominal wool prices for 1973-74 to 1994-95.

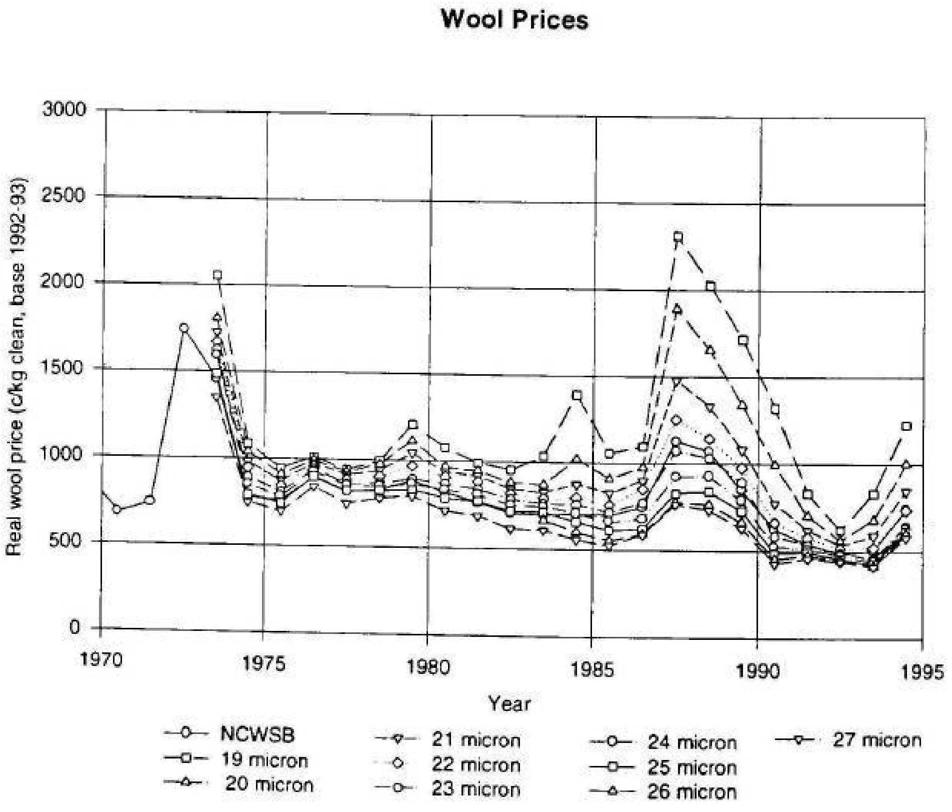


Figure 7.6. Mean annual micron specific real wool prices (Wool International) and NCWSB mean annual real wool prices for 1973-74 to 1994-95 (base 1992-93).

The ratios of mean annual micron specific prices to the NCWSB price from 1973-74 to 1994-95 in real dollars (base 1992-93) were then used to produce mean annual micron specific prices from 1956-57 to 1972-73 where no detailed price data were available. These ratios were:

- 19 micron - 1.528;
- 20 micron - 1.324;
- 21 micron - 1.191;
- 22 micron - 1.107;
- 23 micron - 1.035;
- 24 micron - 0.978;
- 25 micron - 0.923;
- 26 micron - 0.735;
- 27 micron - 0.840.

The 26 micron price ratio was outside the general trend because prices for this class were reported from 1983-84 only, giving 12 mean annual values compared with 22 for the other classes. The 26 micron ratio was, therefore, estimated as the mean of the 25 and 27 micron ratios, 0.882, and was used to calculate the mean annual 26 micron wool price from 1956-57 to 1972-73. For the period 1973-74 to 1982-83, the mean annual 26 micron price was estimated as the mean of the 25 and 27 micron mean annual wool prices. Using these processes, a time series of mean annual micron specific wool prices in real terms was available for the spatial model to enable returns from wool sales to be calculated.

7.3.3 Variable costs

The physical and financial information collected by ABARE in their Australian agricultural grazing industry survey was used in Chapter Three to examine the temporal variability in costs of production for an average Queensland sheep farm. The same survey information subsequently became available in more detail, via a spreadsheet computer package called ASPIRE (Farm surveys report 1994) for the years 1977-78, and was expressed in real dollars (base 1992-93) using the index of prices paid by Queensland farmers. From 1956-57 to 1976-77, when no data were available to estimate variable costs, the mean from 1977-78 to 1994-95 was used. Farm variable costs included fodder, freight, handling and marketing expenses, livestock materials, purchase of livestock, shearing and crutching. This data set is limited in regional and temporal variation prior to 1977-78. Currently, ABARE regional survey data for Queensland are being processed by QDPI but was not available at the time this work was completed. Unfortunately, the author is unaware of any time series of economic data which would allow variable costs prior to 1977-78 to be better estimated, despite extensive enquiries.

7.3.4 Gross margin

Fibre diameter dictates the price for clean wool, and a constant yield of 70% (see Chapter Six) is applied to results from the wool production model to enable wool returns per sheep to be calculated. Combined with the stocking rate data, wool returns per ha, and variable costs per ha, can also be estimated. Gross margin per sheep and per ha are then calculated as wool returns less variable costs. This analysis ignores sale of culled / cast sheep. However, ABARE survey data indicates that sheep sales accounted for only 9.3% of cash receipts for an average property from 1982-83 to 1993-94.

7.3.5 Property size

Information from ABS on the area of rural holdings, and number of rural landholdings, allowed mean shire property size to be estimated. Area of rural holdings was available from 1956-57 to 1994-95, but the number of rural landholders was only available for 1974-75 to 1994-95. For the period 1956-57 to 1973-74, the number of rural land holders for each shire was taken to be the 1974-75 value. Knowledge of mean shire property size allowed the calculation of total greasy wool production per property, total wool returns per property, and total gross margin per property. Graphic output of these calculations are presented in the following chapter.

7.4 Discussion

ABS wool production data for shires were used to examine the suitability of wool growth models which were developed from grazing trials conducted in small paddocks (Chapter Six). The regression from the pooled Toorak, Burenda and Arabella data (equation 6.17) was the basis of a bio-economic model for all wool producing regions of the state. The bio-economic model gave a reasonably accurate prediction of wool production for the wool producing shires after making assumptions to standardise the historical records. The wool production models predict greasy wool growth rates (g / day) for a standardised sheep, i.e. a 50 month old non-breeding animal in 1992. Limitations of the model were due to it not being a dynamic flock model, and lack of spatial variation in the estimated variable costs.

It was originally intended to have a fully dynamic sheep population model operating in each pixel throughout the state which would simulate lamb marking, mortality, sales and purchases, in line with the model of White (1978). However, early work with the B. J. White model highlighted the importance of decision rules, the basis for these rules for individual shires or regions simply does not exist in the literature. This is not surprising given the 'human factor' which is more difficult to simulate than biological or economic processes (Hansen and Jones 1996). Further, most wool producers may run both sheep and cattle. Thus, the size of the flock is dependent on not only the carrying capacity of the property and the season, but also the economic environments of both the wool and beef industries. This is further complicated in regions where cropping is possible. The initial implementation of a statewide spatial model required a simple but versatile approach that could accommodate the enterprise mixes, as described in Chapter Eight.

CHAPTER EIGHT

Demonstration of Output from the Bio-economic Model

8.1 Introduction

Chapter Seven detailed the data sources, and their integration into the bio-economic model. This chapter provides examples of the output from the model, and options available for presentation and interpretation of this information. The Climate Impacts and Spatial Systems group of the Queensland Department of Natural Resources uses thematic maps to present spatial rainfall data, and other associated information, to interested parties. Thematic maps condense a large amount of information into a format for easy comprehension and are used in this chapter to present selected output from the bio-economic model. Whilst provision of detailed information for individual pixels or regions is possible, the main role of this model was as a tool for rapidly assessing the physical and financial condition of the Queensland wool industry, a role best suited to thematic map presentation.

8.2 Methodology

8.2.1 Bio-economic model calculations and outputs

The bio-economic model uses pasture variables generated from the GRASP pasture production model to estimate wool production for a standardised sheep (50 months in 1992) using regression equations developed from grazing trials in Chapter Six. The GRASP model requires data on climate, soil, pasture community, trees and stock as inputs. All inputs to GRASP, and outputs such as percentage of days when green leaf was less than or equal to 1 kg DM / ha (*green leaf≤1*), as used in the Toorak / Burenda / Arabella wool production model (equation 6.17), are able to be presented as thematic maps. The estimated wool growth rate is then converted to an annual fleece weight adjusted for age structure of the flock, gestation, and lactation, as detailed in Chapter Seven. This fleece weight is the annual wool production per DSE. Fibre diameter is calculated from the simulated wool growth rates (equation 6.19), then wool price is calculated from fibre diameter.

Fleece production is combined with stocking rate at the selected month of shearing (table 7.1) to estimate wool production per ha. There are two options for this calculation, firstly, a *sheep only stocking rate* may be used which assumes all other livestock (cattle, horses and other herbivores) are evenly distributed throughout each shire in line with the distribution of sheep numbers, i.e. enterprise mix is assumed to be constant for all properties in a shire. Alternatively, all livestock are converted to dry sheep equivalents (*potential sheep stocking rate*), and therefore, the 'potential' wool production per ha is estimated. Potential production is that which would occur if all properties within the wool producing regions of Queensland were solely dedicated to wool production. The latter approach was adopted for the reasons outlined below.

- When making economic comparisons or appraisals of farm performance, different enterprises (beef, wool etc.) are analysed separately in order to ascertain the relative profitability of each. Thus, enterprise productivity per unit area is expressed relative to the area from which the production arises, not total farm area. Gross margin, which is the major financial measure used in this model, is also strictly an enterprise variable.
- Comparison of regional differences of production on a per ha basis using *sheep only stocking rates* (shire total sheep / shire area) does not include the effect of the presence of other grazing animals on pasture attributes. Differences between regions would not only reflect the relative productivity of the land and season (stocking rate and wool production per DSE), but also the mix of sheep and cattle which may be influenced by many factors including farmer preference.
- Following on from the above point, use of *sheep only stocking rates* resulted in regions of inherently productive country (Darling Downs, Central Highlands)

having low rates of wool production per ha where beef production and / or cropping were of major importance (not shown). This problem was accentuated in the Central Highlands district because of low sheep numbers and the limited information available to estimate their distribution and therefore stocking rates of the wool enterprise component.

- Changes in enterprise mix over time would prevent sensible examination of percentile maps of variables expressed on a per ha basis if *sheep only stocking rates* were used. For example, a percentile map of gross margins per ha calculated using *sheep only stocking rates* would be affected by changing enterprise mix over time, and therefore sheep stocking rates, independent of climatic and economic environmental effects.

However, the use of *potential sheep stocking rates* is not without problems; there may be confusion when interpreting maps, especially in those shires where sheep numbers are low relative to cattle numbers. It is therefore essential to ensure that the maps are clearly defined, and the user made aware, that *potential sheep stocking rate*, and not *sheep only stocking rates*, have been used in the model calculations.

By using *potential sheep stocking rate* and ABARE variable costs, potential greasy wool production per ha, potential wool returns per ha (assuming a clean wool yield of 70%), potential variable costs per ha, and potential gross margin per ha are able to be calculated.

Shire mean property size is then used to estimate variables such as potential greasy wool production per property and potential gross margin per property. These 'per property' maps must also be interpreted with care, especially in shires where property size is reported to be larger than 25 km^2 (pixel size). For these large properties, the 'per property' value is the mean of all pixels contained within the property boundary.

The above physical and financial outputs can be presented as thematic maps for any year between 1957 and 1995, the latter year being chosen in this chapter to demonstrate selected outputs. Maps were constructed using software developed by N. Flood of the Department of Natural Resources.

8.2.2 Percentile maps

Using the time series (1957 - 1995) of physical and financial outputs it is possible to compare the performance of each pixel for a specified year relative to all other years using percentile maps. For example, greasy wool production per ha for 1995 may be ranked against values in all previous years, for each pixel. This approach provides an analysis, similar to that of rainfall and drought mapping, where rainfall and pasture yield percentiles are used to indicate relative severity of drought.

8.2.3 Predictions for 1996

At the time the work presented in this thesis was completed, actual climate data were available up until the end of April. Therefore, to predict performance of the wool industry for 1996 required climate information for the remainder of the year, or at least until the last shearing date. This was done using analogue years selected for positive SOI (Southern Oscillation Index) values in March - April (Stone and Auliciems 1992). The selected years were 1959, 1960, 1963, 1971, 1974 and 1975, all of which were run from the 1st of May in conjunction with the recorded data for the first third of the year. The mean of all GRASP model runs was then used to estimate wool production, thereby providing a near-real time analysis of productivity in the Queensland wool industry.

A number of assumptions are required to allow the model to be run into the future. Wool prices were calculated as the mean of the micron specific market indicators as reported up until the week ending 29th March. Other variables such as stocking rate were assumed to be the same as for the previous year, 1995. These assumptions are of course able to be modified using the best estimates of future management responses and economic variables.

All physical and financial measures calculated for 1995 (and earlier years) can also be presented as predictions for the 1996 calendar year.

8.2.4 Map smoothing

Map smoothing is currently performed on all spatial thematic map products provided by the Climate Impacts and Spatial Systems Group to persons outside the research group itself. This is done to avoid over-interpretation of the model outputs given the differing scale and accuracy of inputs, e.g. splined rainfall, numbers and distribution of stock, and variable costs. The smoothed value for each pixel is the mean value of itself and a specified number of pixels in all directions from it. The degree of smoothing performed has been arrived at based on expert opinion (J. Carter pers. comm.) and the scale at which the maps are expected to be interpreted, e.g. the part-shire level (see Discussion). For the smoothed thematic map presented in this chapter, smoothing was carried out for each pixel using two pixels in all directions, or in other words, each smoothed pixel value represents the mean value for 25 pixels (25 km * 25 km).

8.3 Results

Selected physical and financial variables form the bio-economic model for 1995 are presented as thematic maps.

- Figure 8.1 is percentage of days when green leaf less than or equal to 1 kg DM / ha (*green leaf≤1*) during the 12 months prior to the 1995 shearing. This output variable from GRASP was used in equation 6.17 of the bio-economic model to estimate wool growth rates. Output is shown for all pixels in shires where wool production occurs.
- Figure 8.2 is simulated greasy fleece production (kg / DSE), using the Toorak / Burenda / Arabella wool production model (equation 6.17), with adjustments for age structure of the flock, time trend, gestation and lactation costs. Output is shown for this variable, and others related to wool production, for only those pixels where sheep are present.
- Figure 8.3 is fibre diameter (μ) calculated using simulated wool growth rates and equation 6.19.
- Figure 8.4 is wool price received (c / kg clean), based on fibre diameter.

- Figure 8.5 is potential greasy wool production / ha, calculated using *potential sheep stocking rates.*
- Figure 8.6 is potential wool returns / ha, calculated from potential greasy wool production / ha, wool price received and a clean wool yield of 70%.
- Figure 8.7 is potential variable costs / ha, calculated from ABARE variable costs and *potential sheep stocking rates.*
- Figure 8.8 is potential gross margin / ha, calculated as potential wool returns / ha less potential variable costs / ha.
- Figure 8.9 is mean property size (ha) for each shire, from ABS data.
- Figure 8.10 is potential gross margin / property, calculated from potential gross margin / ha and mean shire property size.
- Figure 8.11 is percentile map of potential gross margin / ha for 1995 relative to values calculated for 1957 - 1994.
- Figure 8.12 is smoothed thematic map of potential gross margin per ha (see figure 8.8 showing output prior to smoothing).

8.4 Discussion

This chapter aimed to provide examples of the type of output available from the bio-economic model, as well as some of the options available for data presentation. Taken together the maps provide a vivid picture of the variation across the state in key components of production and finance. A more detailed interpretation follows, and the advantages and limitations of the model are discussed.

8.4.1 The 1995 shearing season - results

Output for the 1995 shearing, the month of which may vary from shire to shire (table 7.1), show the northern wool producing regions to have generally experienced better pasture conditions (as measured by *green leaf≤1*, figure 8.1), and therefore higher fleece weights (figure 8.2), larger fibre diameters (figure 8.3), and reduced clean wool price (figure 8.4), relative to the rest of the state. A pattern of increased productivity associated with the Mitchell grasslands is noticeable. However, inclusion of stocking rates and calculation of variables on a per ha basis provides a different interpretation. Figures 8.5, 8.6 and 8.8 show a general trend for the Darling Downs, Central Highlands and Maranoa to be the most productive regions, followed by the northern and central districts with productivity declining markedly in the more western parts of the state. These trends are even more obvious with the smoothed presentation of potential gross margin per ha (figure 8.12).

Potential gross margin per property (figure 8.10) relies on ABS mean shire property sizes (figure 8.9) and assumes a homogenous nature to property area within each shire; an obvious simplification of the real world. However, this is the only available information on property size that can be used in conjunction with spatial GRASP. Use of a digital cadastral database detailing individual properties boundaries will be discussed below. As stated earlier, maps of output on a per property basis must be interpreted carefully, especially where larger properties may include a number of productivity levels within their boundaries. In such situations, the correct value would be the weighted mean of all values within the property boundaries.

Percentile maps such as figure 8.11, allow output, in this case potential gross margin per ha for 1995, to be ranked for each pixel or region relative to historical values. In this case, gross margin per ha for nearly all wool producing regions of the state is within the lower 20 percentiles. Examination of other percentile maps (not shown) indicates that this is largely due to the effect of wool prices received during 1995 relative to previous years.

8.4.2 Model resolution and interpretation

The resolution of the spatial model may best be considered in terms of the requirements of the user who operate at four geographic scales: property, shire, ABARE statistical division, industry. Given the different resolution of inputs to the bio-economic model and the different resolution of user requirements, it is appropriate to examine the matching of 'needs' and scale of modelling.

For an individual property, the model is best calibrated to the specific soil and pasture descriptions (Johnston *et al.* 1996), and animal production data (Buxton *et al.* 1995a, b).

Stafford Smith *et al.* (1995) have linked GRASP output to Herd-Econ, using multiple regressions similar to those in Chapter Six to examine 'what if' management options for properties. Future development of the spatial model may include overlaying of a digital cadastral database which would enable the calculation of actual physical and financial measures where property size is greater than 25 km^2. If individual managers were prepared to collaborate, this would provide an opportunity for model validation and calibration in real time.

At a shire or regional level, such as ABARE statistical divisions, the bio-economic model allows regional outlooks to be made, which might trigger appropriate action to developing situations. These activities occur already, usually in response to stressful conditions rather than in anticipation of financial stress.

At an industry level, information from the model can be used to indicate both the likely impact of recent climate variation (e.g. drought), and estimations of future variation on output. Both shire and industry wool production predictions are presented in Appendix Four (figures A4.4, A4.5, A4.6, A4.7, A4.8, A4.9).

Thus the model caters for a wide range of geographic scales and the level of resolution is dependent on the nature of the application.

8.4.3 Using the model as a predictive tool

Although no predictive output from the bio-economic model was presented here (due to space restrictions), the model is able to be run into the future using the assumptions detailed in 'methodology'. Climate prediction, a science of variable accuracy, is not the only area requiring more attention before the predictive output from the bio-economic model can be considered robust. Stocking rate and number of sheep shorn are important variables in terms of model accuracy. Loss of accuracy of simulations is to be expected as the period since last census data availability increases as was shown in Chapter Seven for the relationships between sheep at end of previous census year 't', and number of sheep reported shorn in census years 't+1' (table 7.2) and 't+2' (table 7.3). Extremes of climate are likely to increase this loss of accuracy through management responses (agistment, sales) and mortalities. However, inputs such as these are able to be modified in accordance with available information, e.g. reports from stock inspectors.

The sensitivity to stocking rate cannot be assessed until models incorporate reproduction and mortality. In White's (1978) analysis, the sensitivity to stocking rate can be assessed by the change in sheep numbers following changes in decision rules. For example, a reduction in the ceiling stocking rate at which culling commences resulted in an increase in mean sheep numbers over a 29 year period from 8 780 to 8 900, an increase of 1.4%. This increase in sheep numbers was accompanied by an increase in the mean return on equity from 2.99 to 3.10%, a 3.67% increase (0.11/2.99). Models of reproduction and mortality are being developed in a parallel project, e.g. Moore *et al.* (1995) and Pepper *et al.* (1996). They showed 81 - 87% and 63 - 78% of variation in lamb marking and mortality, respectively, could be accounted for using variables derived from GRASP. These relationships are yet to be fully implemented and tested as has been done for wool growth in Chapter Seven. However, even if reproduction and mortality could be forecast, management responses are yet to be modelled. For 40 cattle properties in north eastern Queensland, the relative annual change in herd numbers could be related to proportional pasture utilisation calculated for each property in each of the years studied (Scanlan *et al.* 1994). However, Johnston (submitted) repeated a similar analysis for 40 properties in the mulga zone but found little variation in flock numbers and little effect of pasture utilisation. Thus, modelling management responses at a property level in the sheep zone to differing physical and economic environments requires further research.

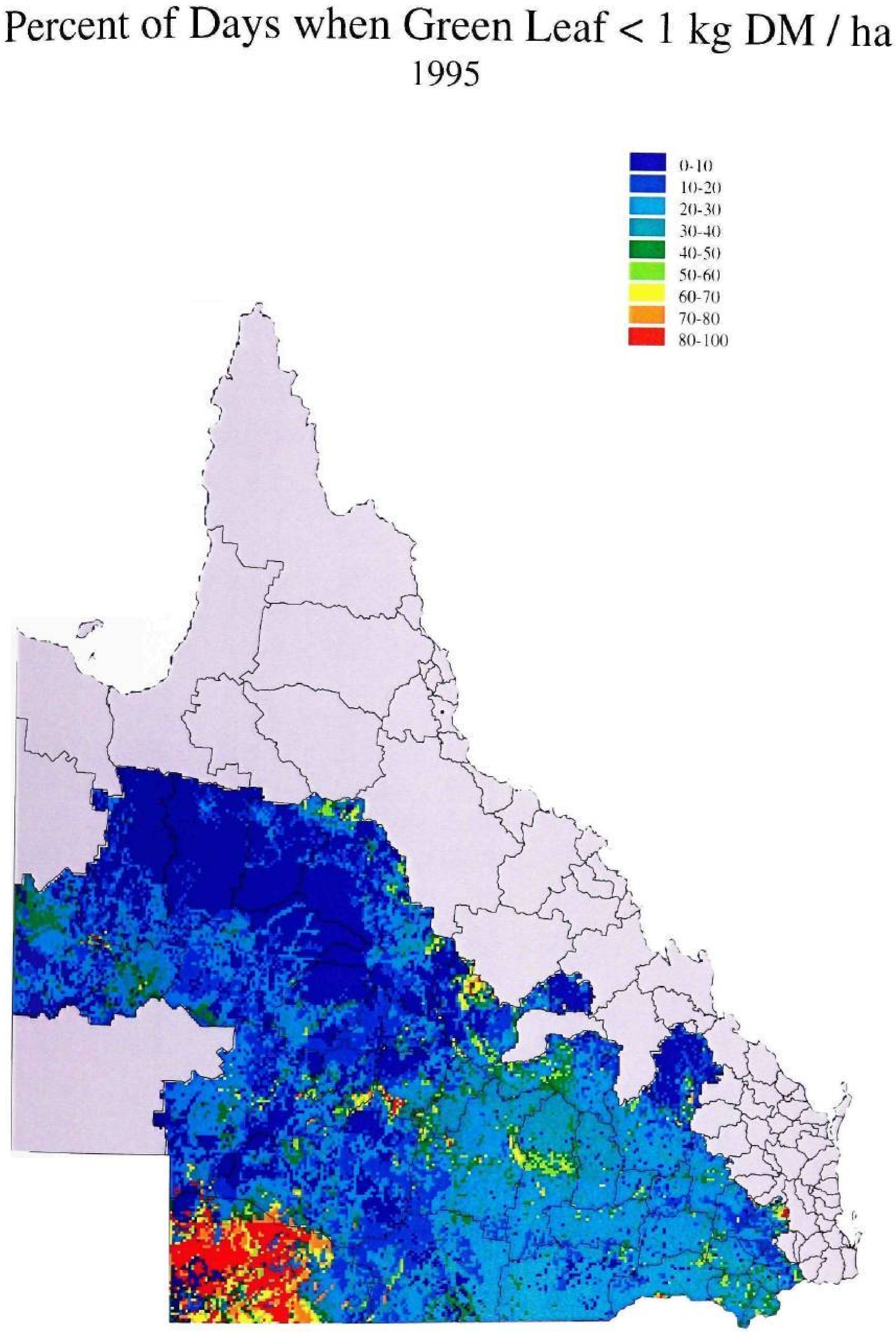


Figure 8.1. Percentage of days when green leaf less than 1 kg DM / ha for the 12 months prior to the 1995 shearing.

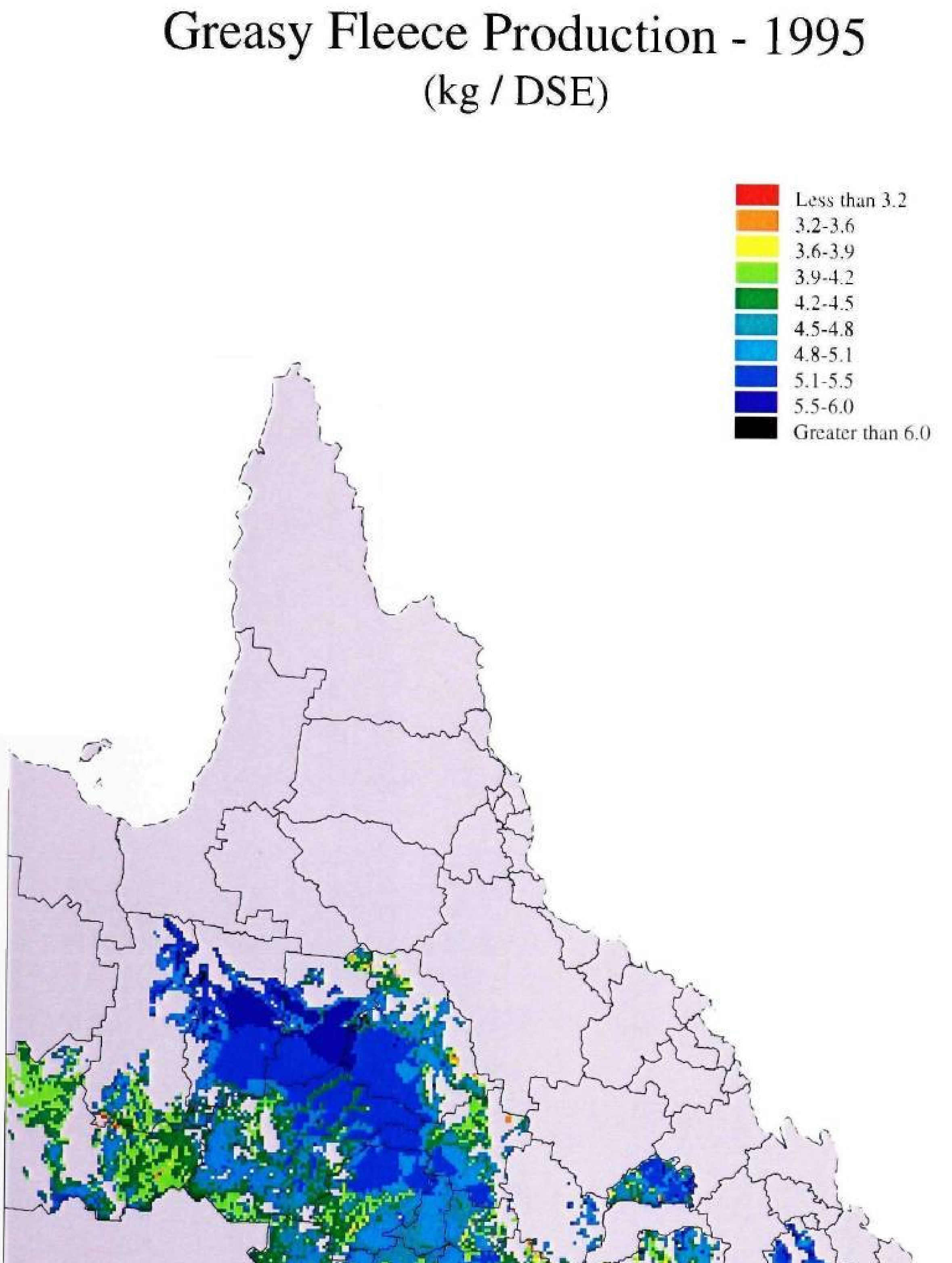


Figure 8.2. Greasy wool production / DSE simulated for the 1995 shearing.

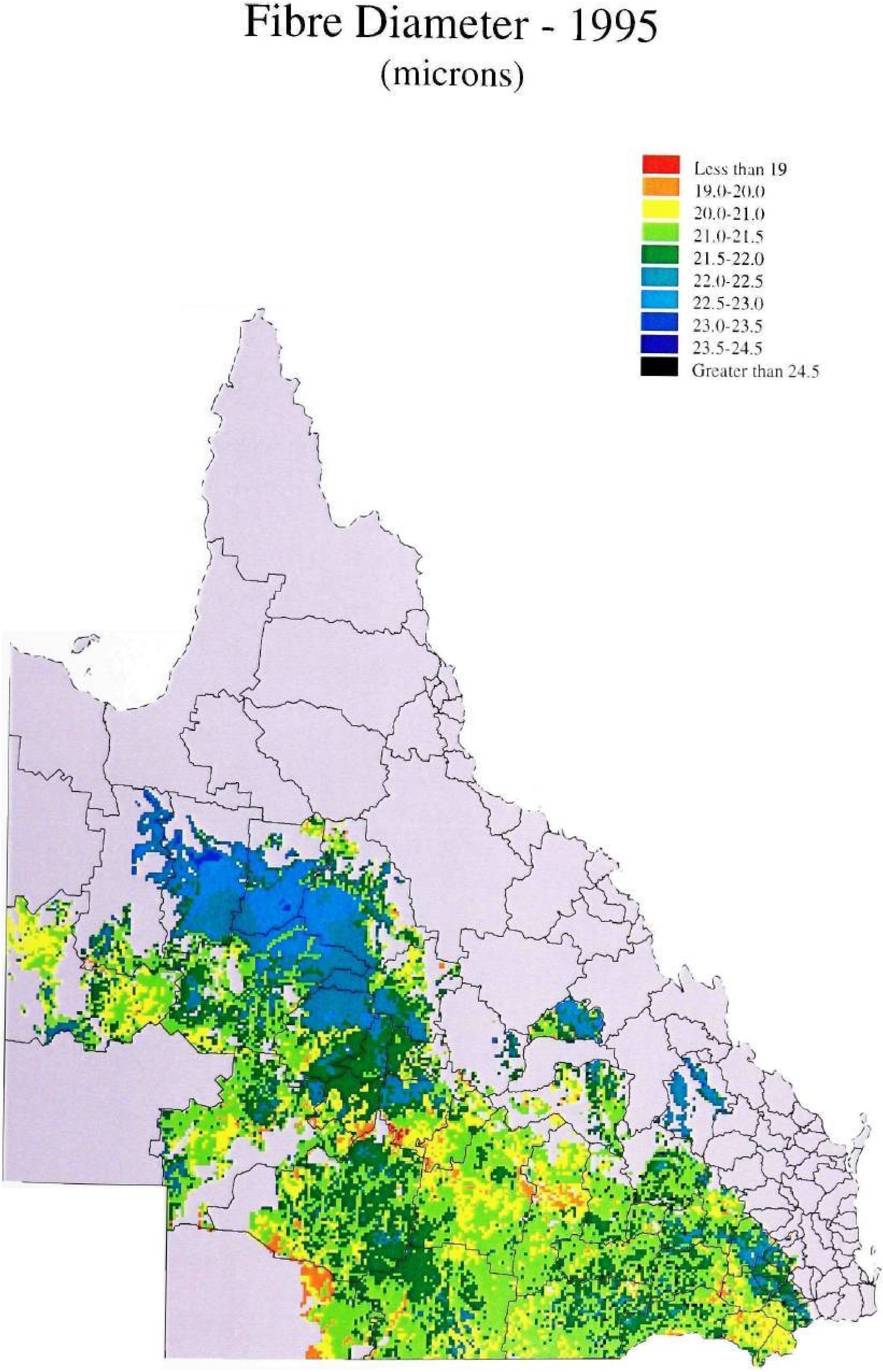
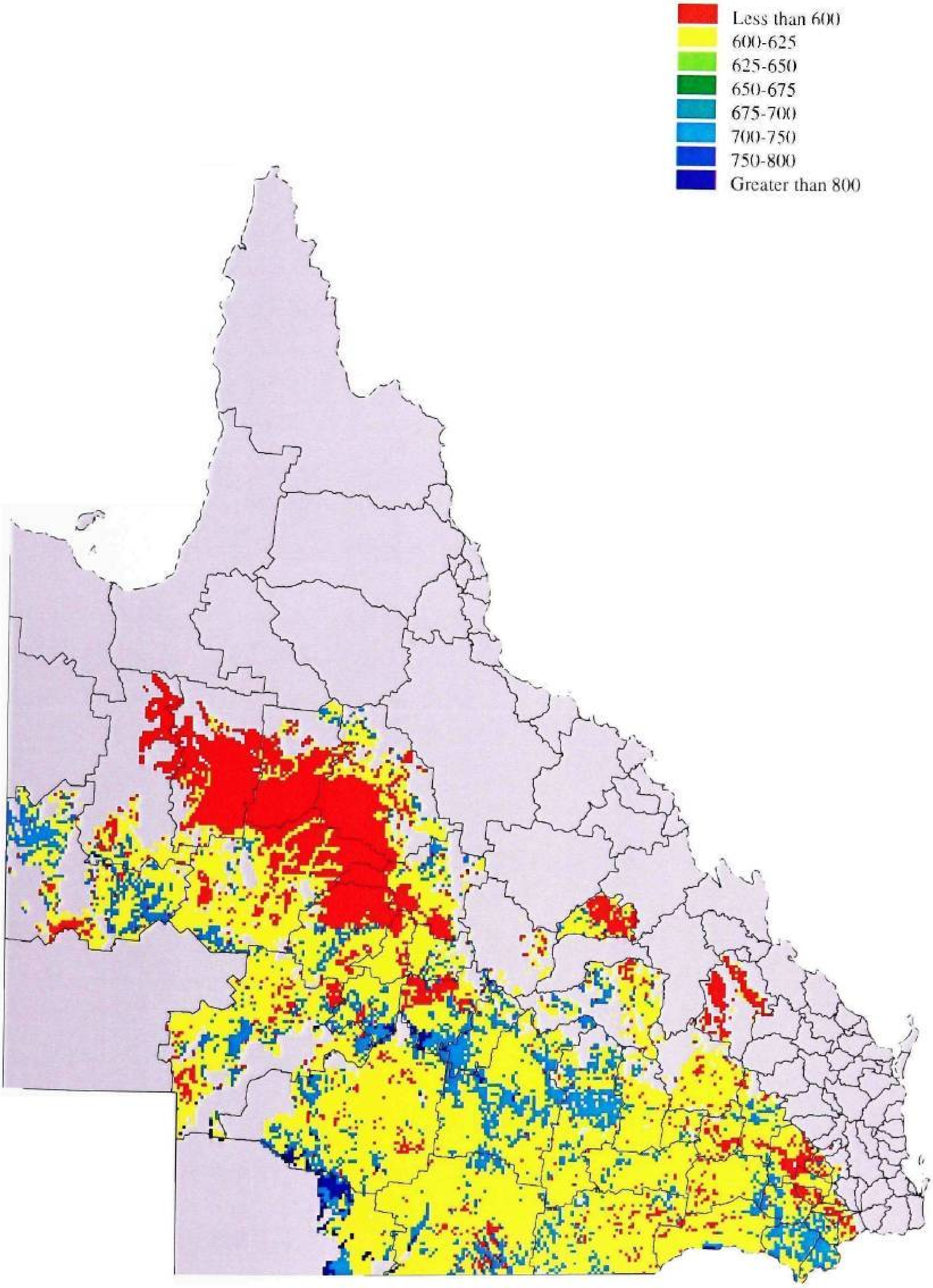


Figure 8.3. Mean fibre diameter for the 1995 shearing.



Wool Price Received - 1995

(c / kg clean, Base 1992-93)

Figure 8.4. Price received for clean wool shorn in 1995.

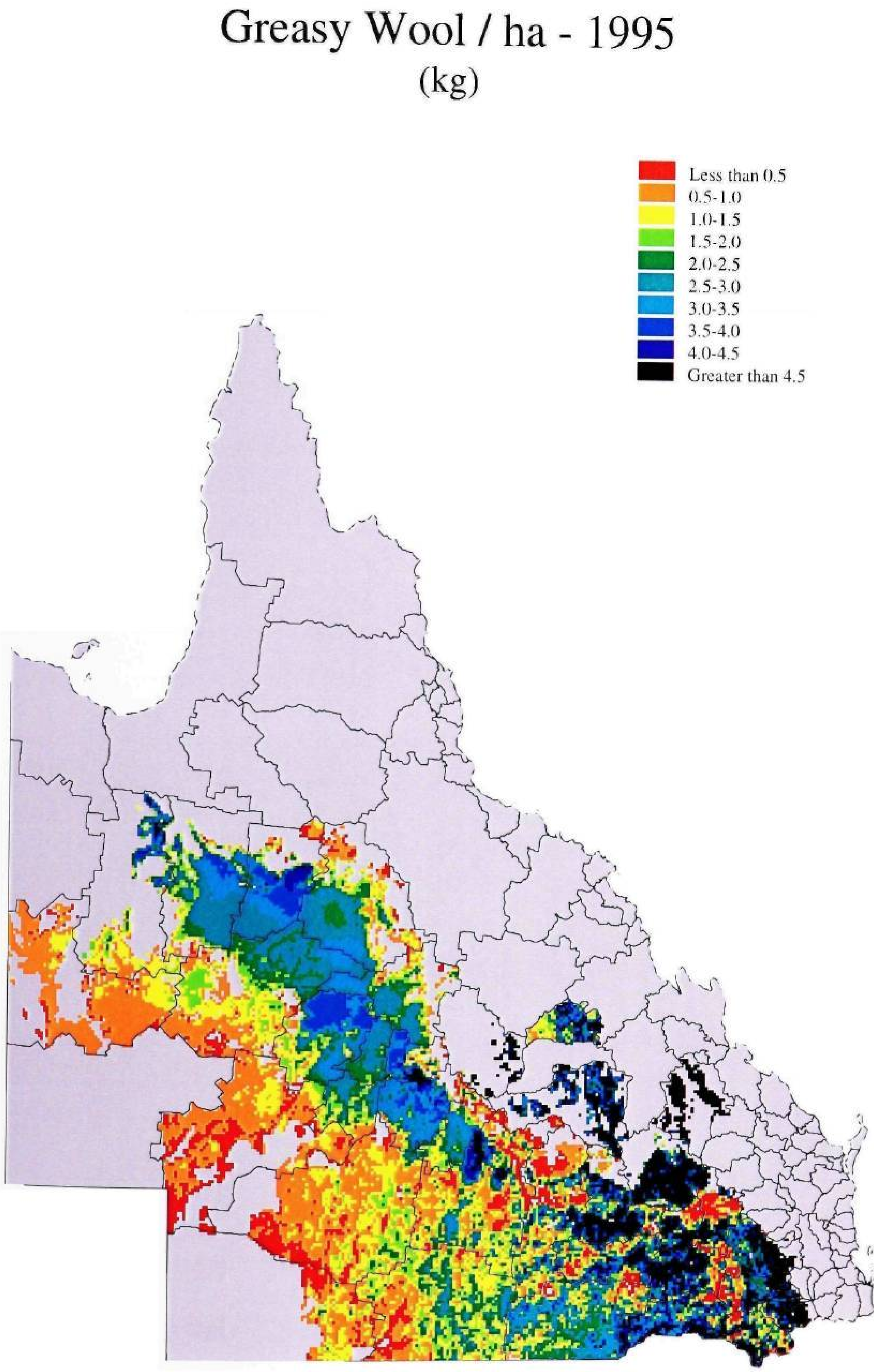


Figure 8.5. Potential greasy wool production (kg / ha) for the 1995 shearing.

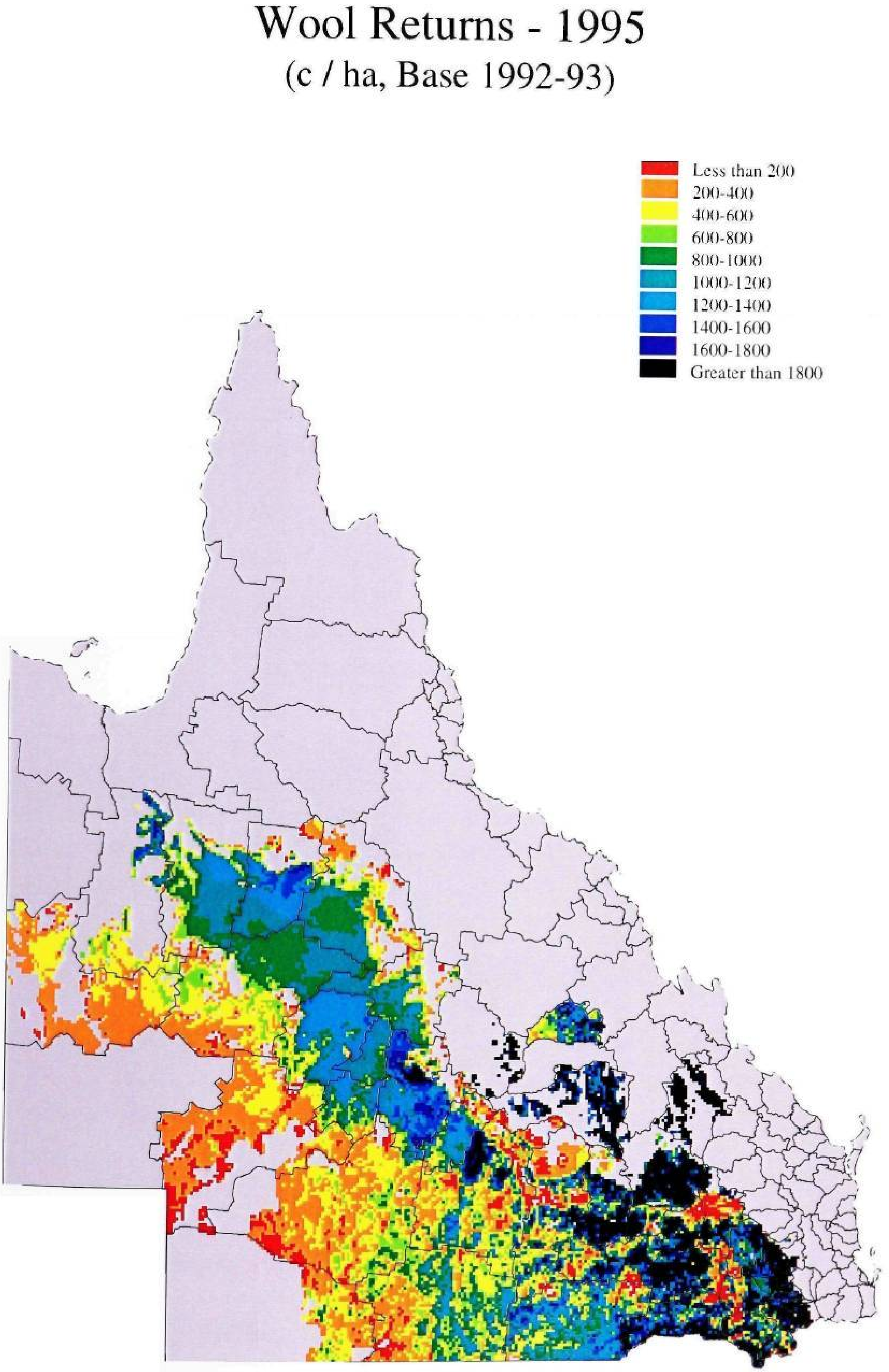
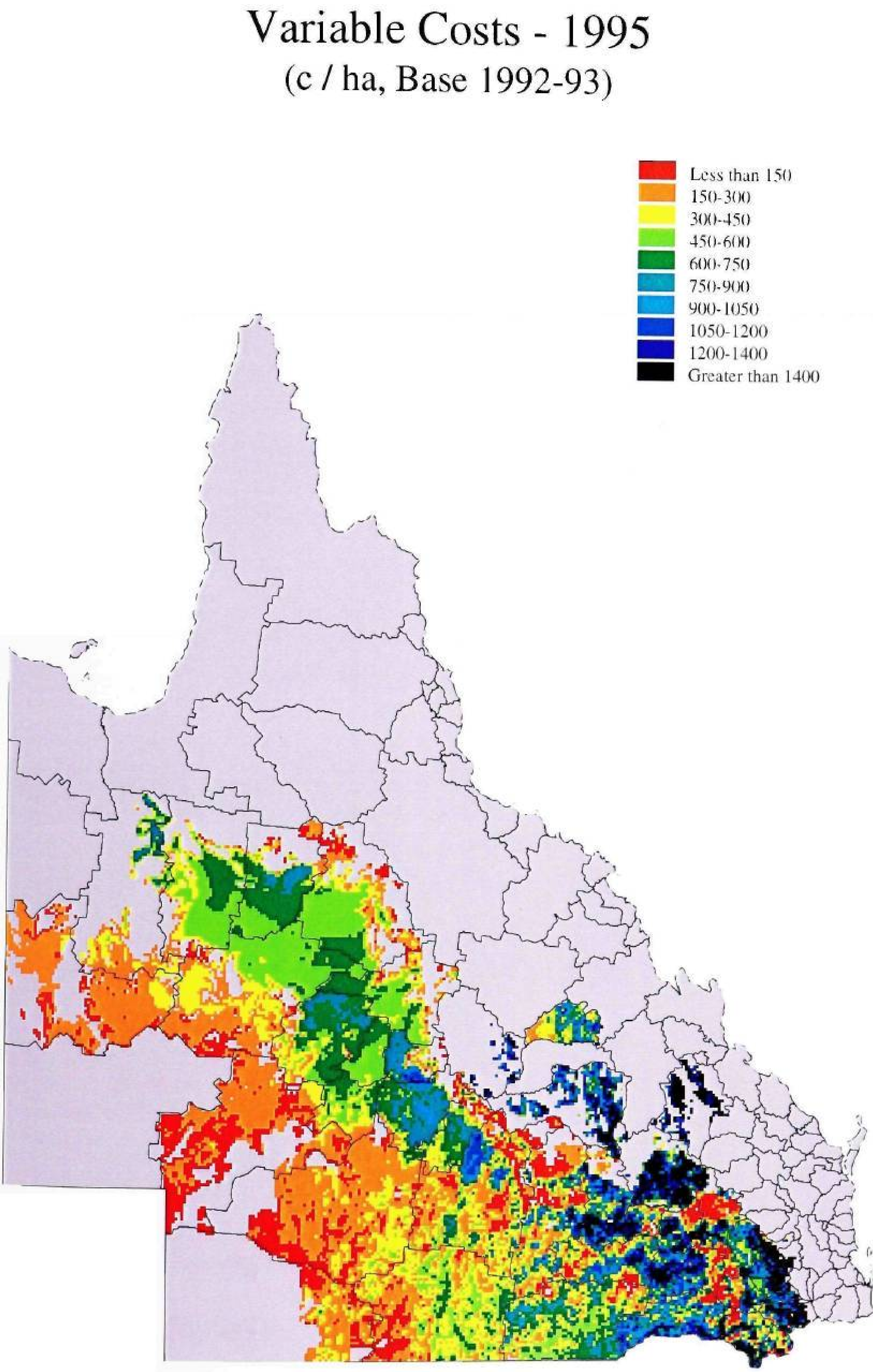


Figure 8.6. Potential wool returns / ha for the 1995 shearing.



Variable Costs - 1995

(c / ha, Base 1992-93)

Figure 8.7. Potential variable costs / ha for the 1995 shearing.

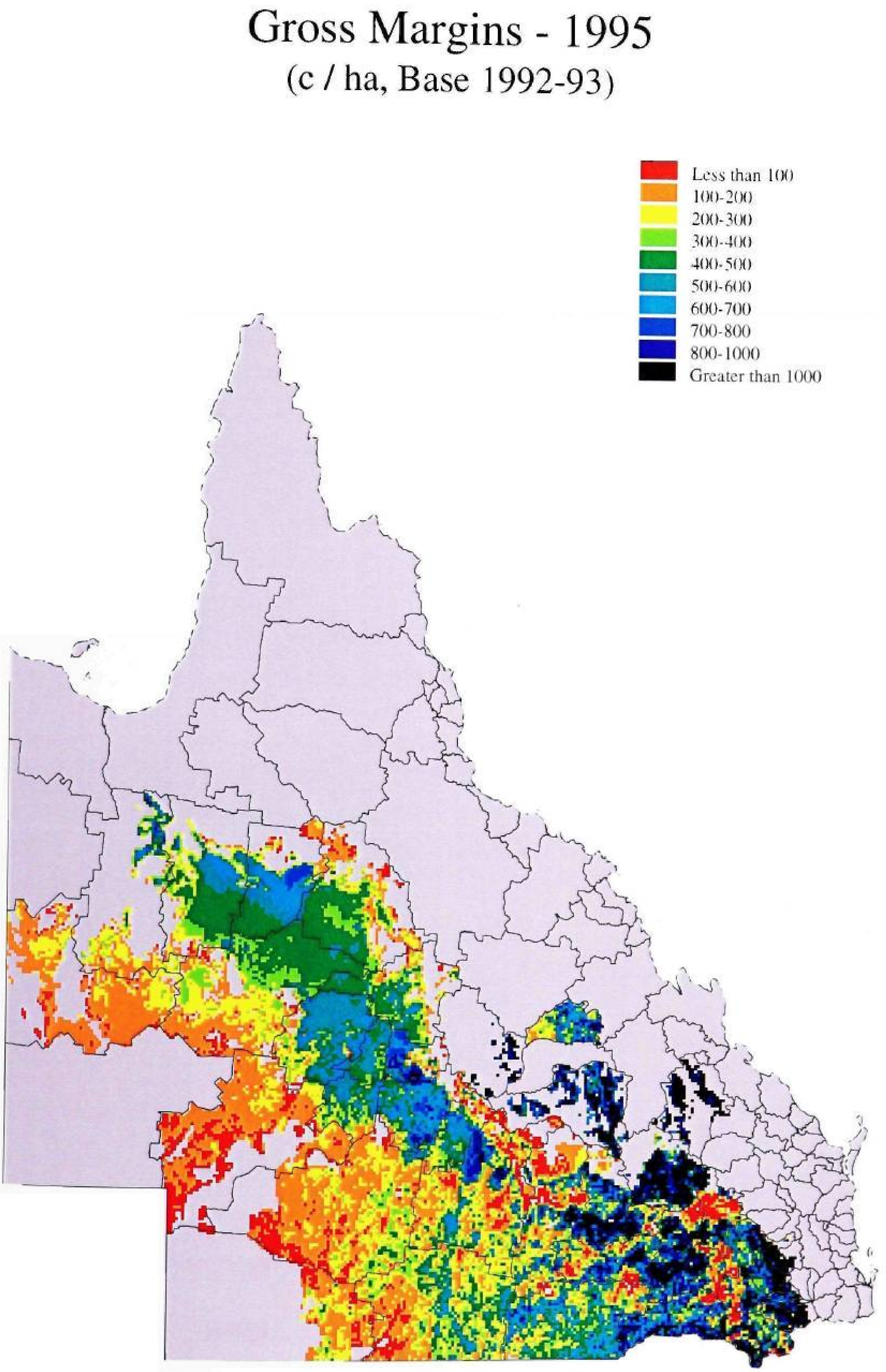


Figure 8.8. Potential gross margin / ha for the 1995 shearing.

Shire Mean Property Size - 1995
(ha)

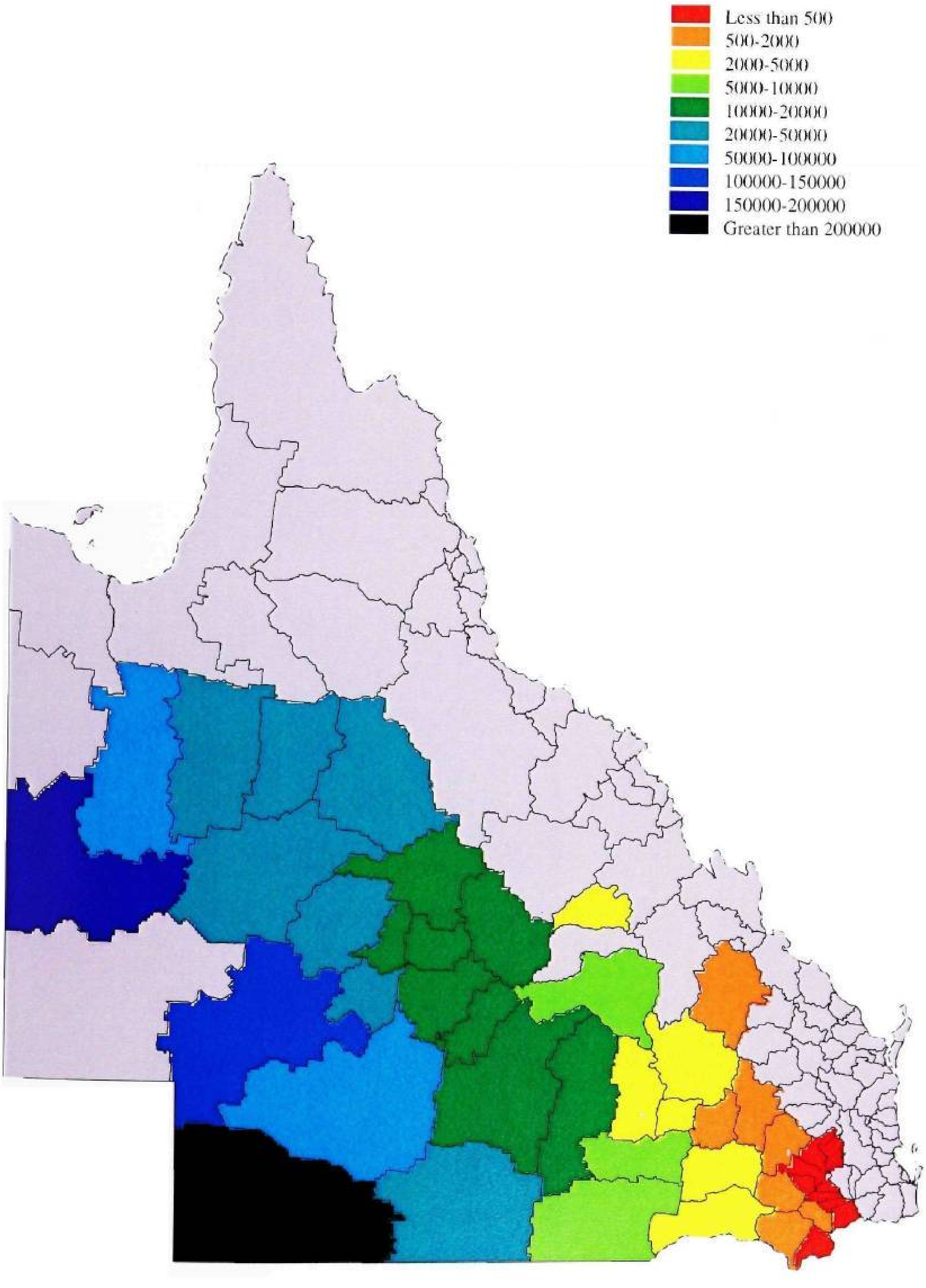
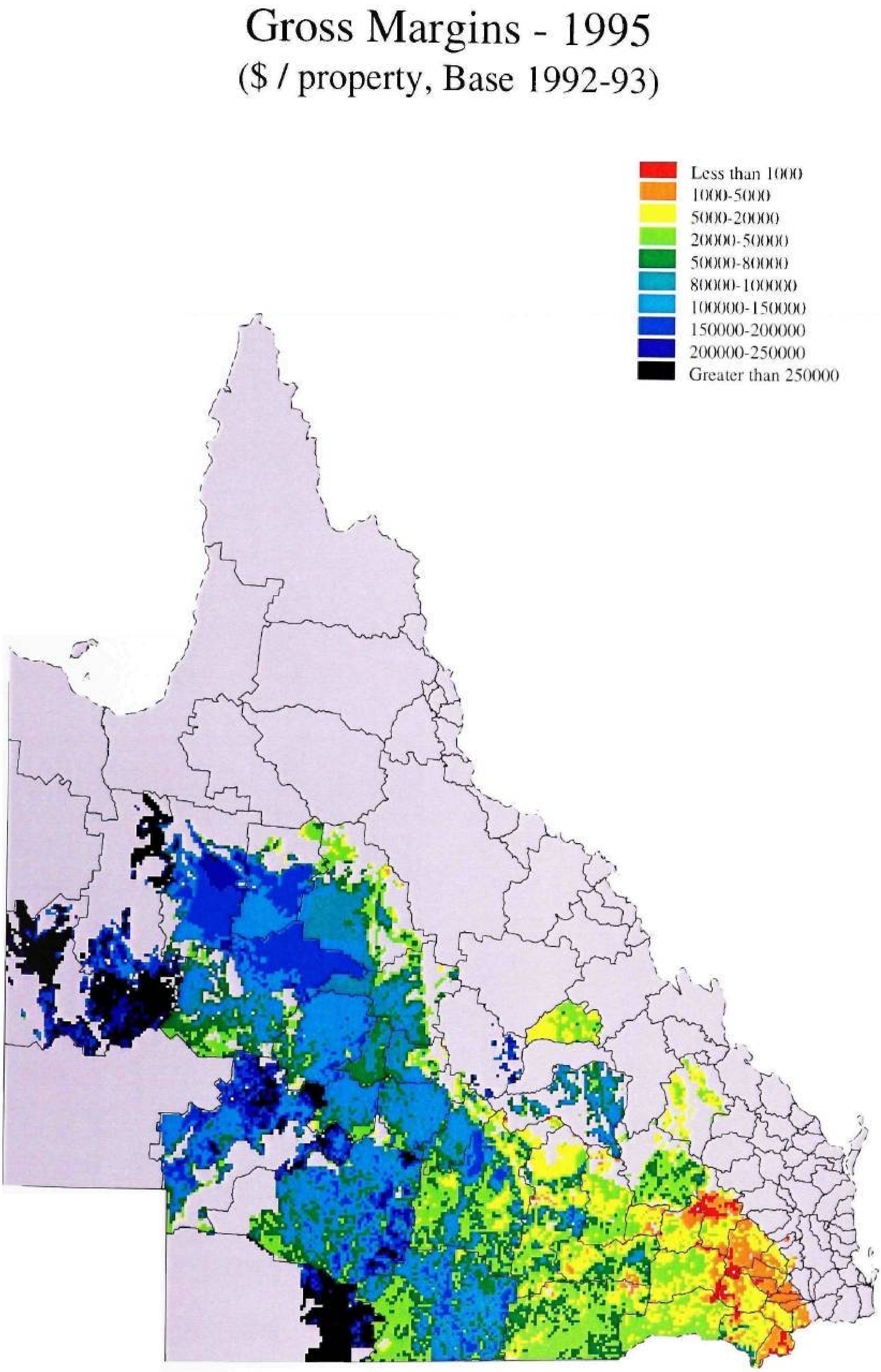


Figure 8.9. Shire mean property size for 1995.



Gross Margins - 1995
($ / property, Base 1992-93)

Figure 8.10. Potential gross margin / property for the 1995 shearing.

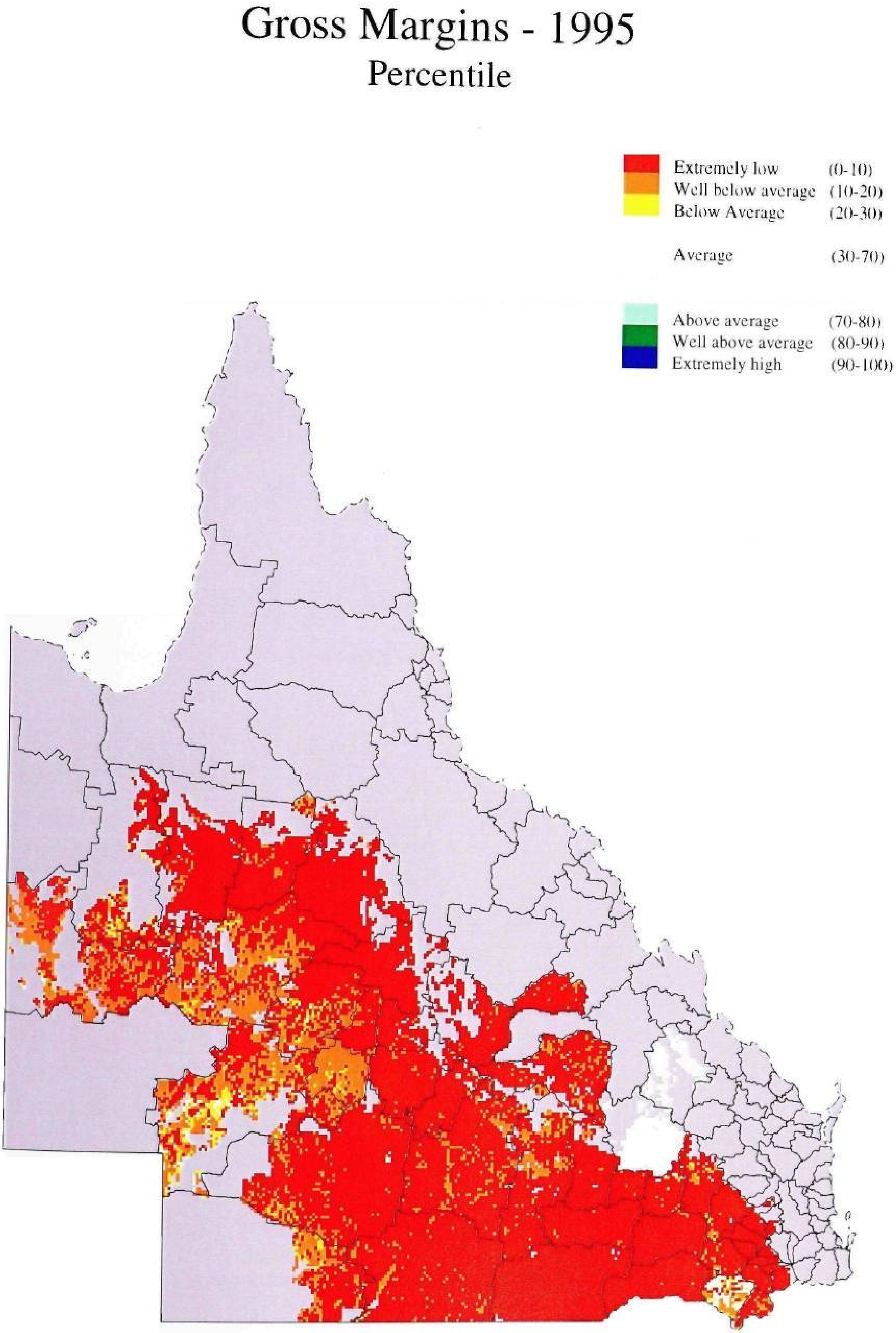
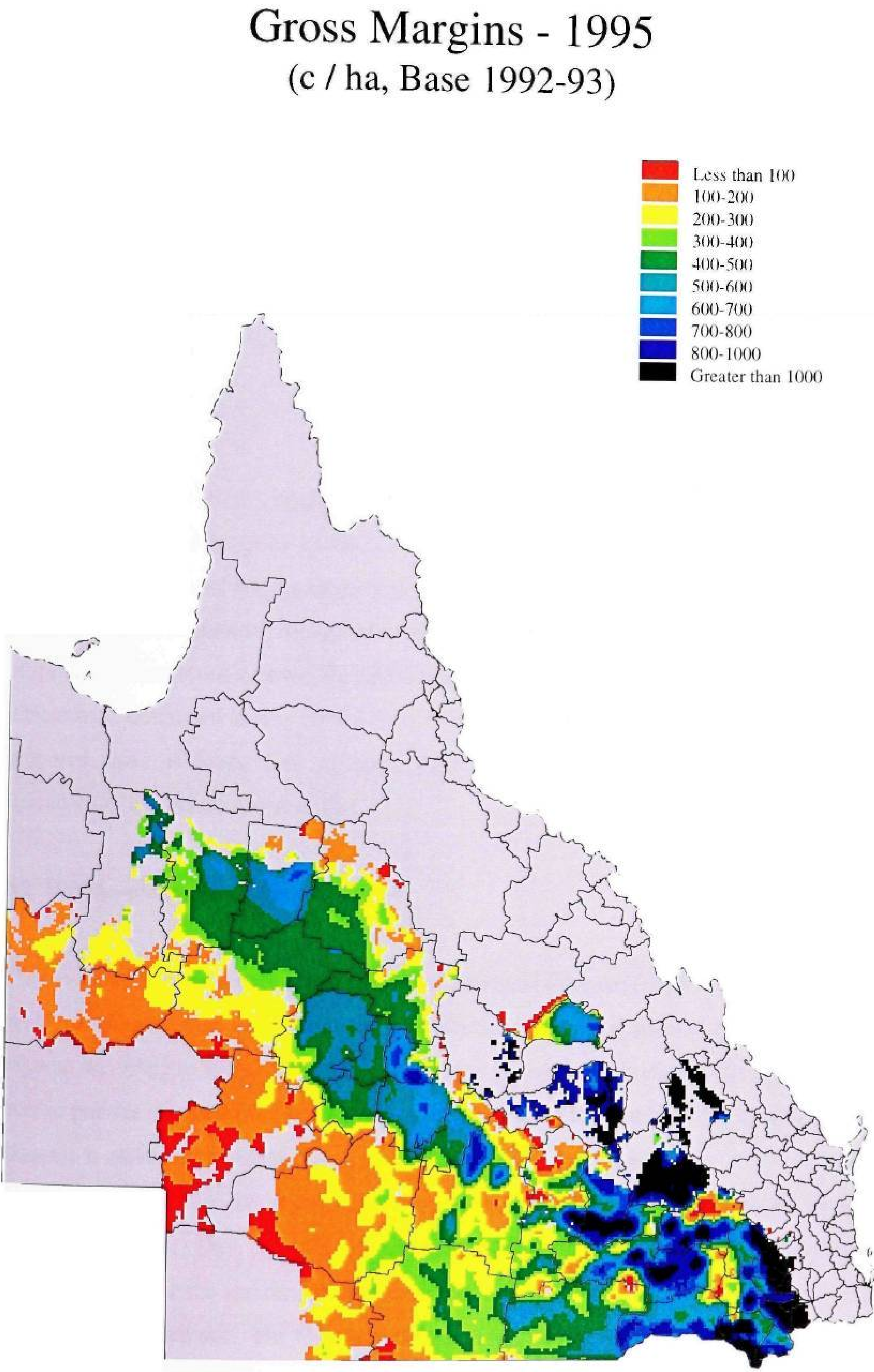


Figure 8.11. Potential gross margin / ha for 1995 relative to historical values.



Gross Margins - 1995
(c / ha, Base 1992-93)

Figure 8.12. Smoothed potential gross margin / ha for the 1995 shearing.

CHAPTER NINE

General Discussion and Conclusions

9.1 Introduction

This discussion will cover a range of important issues which were identified during this work. Firstly, an overall description of the bio-economic model will be reviewed. This will be followed by discussions relating to the process of modelling adopted in this work and how the model provides a framework for further model development. Findings of the sensitivity analysis of the Queensland wool industry, the application of Grazfeed to Queensland grazing trials, and difficulties encountered during model development are also discussed. This then leads into proposed areas of future field research, future GRASP development, and alternatives in operations of the bio-economic model.

9.2 The bio-economic model - summary

The bio-economic model uses pasture variables generated from the GRASP pasture production model to estimate wool production for a standardised sheep (50 months in 1992), which is adjusted according to age structure of the flock, and gestation or lactation status. ABS data are used to provide stocking rates to the model, and to estimate the number of sheep shorn. Fibre diameter is estimated from the wool production and this in turn enables wool to be valued. Wool prices used are the reported micron specific indicator prices where available, or extrapolated prices. Data from the ABARE Australian agricultural grazing industries survey are used to estimate the variable costs on a per head basis. This enables a simple gross margin analysis to be carried out. The Queensland farmers index of prices paid is used to express all monetary values to a common base, 1992-93. Physical and financial data from the model are presented as thematic maps allowing easy comparison between regions. Comparison of regional data relative to historical performance are presented as percentile maps.

9.3 The bio-economic model - the process of modelling and a framework for future development

The wool production and annual liveweight change model, which was not used in the completed bio-economic model, were empirical expressions derived from field data. They increase our understanding of the processes involved in wool growth as they identify key climate derived variables which explain the variation in annual fleece production for grazing trials. However, they do not provide insight into the differing roles of energy and protein, physiological status and impact of pasture composition. It is important to re-emphasise the aims for the model development, i.e. to provide an objective measurement of the physical and financial performance of the wool industry on a regional basis, as an aid to policy makers. This reasoning is probably best encapsulated by Poppi (1996), 'the quick and dirty method of associative relationships, while lacking the elegance of mechanistic models, will always win out in the game of expedience'.

Application of multiple regression models outside the limited environment from which they are developed may lead to errors. However, this lack of robustness can be reduced by ensuring the variables in regressions are biologically sound, and that the magnitude and direction of their coefficients are in line with known biological relationships. Testing of the response surface of multiple regression models by use of extended series of climatic data will also help to identify limits to the model. This was done in Chapter Six where two regressions developed from the Burenda grazing trial were found to produce unrealistic values. Whilst never being able to guarantee the behaviour of multiple regression models outside the environment from which they were developed, the use of sensible variables and coefficients, and extensive testing outside of their developmental environment, allows a model builder to have confidence in their ability to behave in a realistic manner.

Simulation models generally continue to undergo development and refinement, at least until time and / or funding shortages force such activities to cease (Dillon 1971). Given the possibility of a model builder becoming 'bogged down' in specific areas of model development, and subsequently unable to adequately address all areas of concern due to time or funding limitations, it has been argued that a 'crash through' approach to modelling is best (White 1978). By ensuring that the proposed end-point is reached, a framework is available for further model development, as well as providing the model builder with a better knowledge of the limitations and requirements of the model.

This analysis provides the basis for simulation studies on wool enterprises, e.g. impact of climate change and use of safe stocking rates. Those components of the model which are inaccurate or fail to mimic the variability in the real world should receive further attention.

9.4 Sensitivity analysis of the Queensland wool industry using three bio-economic models

The sensitivity analysis of the Breedewe, Herd-Econ and B. J. White models highlighted the importance of modelling annual fleece production accurately as this, along with wool price received, had the greatest impact on farm enterprise gross margin. These three models varied greatly in their operations and input requirements. The Breedewe and Herd-Econ models required the user to provide the biological rates (lamb marking, mortality and wool production) whereas the B. J. White model calculated these variables within the model itself. The models were also sensitive, but to a lesser extent, to variable costs.

Code for the B. J. White and EPBTS models had to be written and revision of existing models requires considerable time and effort (Trapp and Walker 1986). Anderson (1974) considered such revisions often necessitated 'an input comparable to that of the original modeller'; this was certainly felt to be the case in this study. The B. J. White model was used in the sensitivity analysis, but perhaps more importantly, it gave the author a grounding in programming, an awareness of the complexity and interactions in systems models and, the importance of accurate definition and quantification of decision rules. In the author's view, the B. J. White model is suited to north western Mitchell grasslands, and the new code ensures that the model can be used by other scientists.

Variability in wool prices, fleece production and variable costs were also examined (Chapter Three). The national market indicator price had a coefficient of variation of 25% following adjustment for rate of inflation. ABS data for shire fleece production had a coefficient of variation of approximately 10%, but variability in shire level wool production is probably 'damped' because it incorporates a range of soil and pasture types, climatic variability, genotypes and management options. The number of sheep shorn for selected shires was found to be more variable, especially for McKinlay shire (44%). This was heavily influenced by the change in sheep numbers relative to cattle, i.e. the enterprise mix. Factors such as the level of wool and cattle prices relative to historical values, and to each other, no doubt influence the choice of enterprise mix. Variable costs of production also had a high coefficient of variation per sheep and lamb shorn, 35%.

The price received for wool, and variable costs of production were direct inputs to the model. Price received for wool was calculated from the mean micron specific indicator price for each calendar year, as reported by AWC and Wool International, or as extrapolated from the mean National Council of Wool Selling Brokers price in the appropriate years (Chapter Seven). Variable costs of production were calculated from the ABARE Australian agricultural grazing industries survey. Handling these two economic components in this manner avoided the requirement to simulate their variability over time. The high variability in the number of sheep shorn highlights the need for further research into a dynamic flock population model. This will be discussed in more detail later.

As stated in Chapter Three, the B. J. White model was seen, initially, as a base model upon which the final model could be developed, because wool production, lamb marking, mortality and decision rules were all simulated within the model which required only climatic and economic inputs. The energy balance operating within the B. J. White model was based on Vickery and Hedges (1972), while the energy and protein balance equations tested in Chapter Four represented a contemporary version of these early energy balance models. Unfortunately, EPBTS was unsuitable given the available test data. The B. J. White model decision rules were based on the author's and expert opinion of the decision making process as carried out by wool producers on the north-west Mitchell grasslands. However, during the extensive review of literature dealing with the Queensland wool production system, no information was found which would enable decision rules to be quantified for a specific, let alone all wool producing regions.

9.5 Application of EPBTS to Queensland grazing trials

The EPBTS version of Grazfeed appeared to be a faithful representation of the relevant code. Using trial data in which the organic matter or dry matter digestibility were known, resulted in good agreement between observed and predicted dry matter intakes for most trials. Unfortunately, EPBTS was unable to simulate the liveweight changes observed in most of the trials, generally underestimating liveweight gain and overestimating liveweight loss.

Predictions for the Burenda and Arabella trials were not consistent with the general trend. In these two trials the observed feed intake was greater than that predicted, and when used to predict liveweight change gave values in good agreement with the observed liveweight values.

Given the available test data, it was necessary to conclude that EPBTS was unsuitable to form the biological basis for the bio-economic model. However, this should not be taken to imply that EPBTS and the theory underlying it are incorrect. Rather, the data used in the testing of EPBTS were probably not suitable, this will be discussed further in the next section.

9.6 Problems encountered during model development

The compilation of data for the grazing trials used in testing of EPBTS, and the development of the wool growth and liveweight change regressions, was a time consuming task, far greater than was originally envisaged. Most trials presented problems in terms of both incomplete records and lack of information detailing the conditions under which the observations were made. The trials were conducted to examine plant population dynamics and pasture stability under various stocking rate or utilisation treatments, with sheep liveweight and fleece production being of lesser importance. These trials were conducted over a large time span (1940's → present), and include a number of soil and pasture types, as well as different climate patterns.

At the time these trials were implemented, simulation modelling was either non-existent or in its infancy. As a result, the data were collected without regard to computer models. Long term grazing trials also suffer from the problem of lack of 'ownership' and staff turnover. It appears essential for a person to 'own' the trial in order to ensure consistent trial methodology and most importantly, record keeping.

The necessity for the cataloguing and preservation of both sheep and cattle grazing trial information has been recognised by many people. Recently, work has begun on development of a database for sheep, dairy and beef cattle grazing trial information (K. Rickert pers. comm.). This database will not only store relevant historical information and make it available to interested parties, but will also act a repository for current and future research data. The field data collected in this thesis will provide the first contribution to this database ensuring access for future interested persons.

The work with EPBTS and the relevant Queensland grazing trials highlighted the lack of suitable data sets for the testing of this daily time step model. Lorimer (1976) collected the only suitable time series of pasture, dietary and animal information. Greater confidence was placed in this data set because it was assumed that repeated sampling would ensure a consistent and accurate methodology. However, even this data set had a suspicious observation of dry matter intake / dry matter digestibility. The ability of an incorrect measurement to influence findings was highlighted in the time series analysis of Lorimer's (1976) data where the suspicious data point resulted in markedly different results for Lorimer's (1976) time series and daily data sets (Chapter Four). The impact of this point was marked because of the time intervals between measurements, approximately every 4 - 6 weeks. Had the time interval been shorter the impact would have been less. Similarly, in the development of the diet selection model (Chapter Five), data outliers had a major impact on model development.

Two grazing trials, Arabella (Beale 1975) and Toorak (Pritchard *et al.* 1986, Pritchard 1988) appeared to have systematic errors in their experimental procedure. The errors and possible reasons were discussed in Chapter Four. The Arabella data were modified using assumptions detailed by the author and the modified data used in the analysis of EPBTS.

The Gilruth Plains and Eastwood grazing trials were eliminated from the final data sets used to develop the annual fleece and liveweight change equations (Chapter Six). The reasons listed were: inappropriate or lack of correlation with model variables, time period since the Gilruth Plains trial was completed, difficulty in locating original records, depletion of soil nitrogen during the course of the Eastwood trial, lack of data to parameterise the diet selection model. Also, the author lacked confidence in the two data sets gained from close scrutiny of all available sources of information as well as communications with persons involved in the experimental work.

The model was validated indirectly as no independent data exists to properly carry out validation. This lack of suitable data increased the importance of model verification, as discussed by Noble (1975, Chapter Two). In this study ABS shire level wool production data were used to select the most appropriate wool model from those developed in Chapter Six using the grazing trials. Given the scale of the model inputs and operations, and therefore its precision, the best indication of validity was the comparison with total shire and Queensland wool production (Chapter Seven; figures A4.6, A4.7, A4.8 and A4.9 in Appendix Four).

The timing of management operations was assumed constant across all years for which the model is able to run (1957 → present). However, it is possible that time of shearing and joining / lambing may have varied over the past 40 years. Evidence of this was seen in the data sources from which the shire specific shearing months were selected.

9.7 Areas for further field research

The work conducted with EPBTS has highlighted the lack of reliable information on diet selection and feed intake of grazing sheep in Queensland. Additionally, there is limited information on energy and protein digestion and metabolism under these conditions. Further research is needed into diet selection and feed intake on a frequent sampling basis (preferably weekly), especially when pasture quality, and therefore, the potential diets of grazing animals are changing rapidly. Until more detailed information is available, it is impossible to conclude whether or not the functions present in EPBTS are representative of the real world.

In order to simulate dynamic flock populations, it is essential to understand the factors affecting the decisions made by producers. It is likely that this type of information will only be adequately collected by in-depth surveys, similar to the approach of Johnston (submitted) and Buxton *et al.* (1995a, b).

9.8 Areas for further model development

A dynamic sheep population model needs to be developed, and should include normal farm operations such as lamb marking, mortality and the trading (sales and purchases of sheep) of different age classes. This development will improve the accuracy of modelling wool production and its economics. As lamb marking and mortality functions exist (Appendix One, Parts D and E), the greatest task lies in quantification of the decision rules. This will require an understanding of those factors, climatic, physical and economic (see figure 1.2) which influence both the tactical and strategic decisions made by farmers. The enormity of this task cannot be understated. For example, work was carried out, but not presented here, on the ability to simulate changes in liability using anonymous property physical and financial records for the north-west of the state (P. Newman unpublished data). The previous year's physical and financial records, plus the current year's physical records were analysed in order to predict changes in short term liabilities. The only variable correlated with the current year's short term liabilities was the previous year's short term liabilities.

The water balance, pasture growth and other subroutines within GRASP continue to be improved. Because the wool production model is a multiple regression equation, changes in the operations of GRASP may necessitate reanalysis of the relevant grazing trial data. The procedure to do this is highly automated and would not require an excessive time period. Those areas within GRASP requiring further analysis include modelling of the green pool, botanical composition of the sward and its changes, the interaction of woody weeds, the user friendly nature of GRASP, and implications of modelling at the point and spatial levels.

The wool production models detailed in Chapter Six identified the green pool, including green leaf, as being strongly related to wool production. Therefore, it is essential that further work be conducted in this area to ensure the model simulations of the green pool across different pasture communities are as accurate as possible.

GRASP currently simulates pasture as a homogenous pool of pasture species with no allowance for changes in botanical composition due to grazing pressure or weather patterns. Goodall (1971) suggested that management of a pastoral property is concerned with managing one or more ecosystems, and that an ecosystem model which ignores the floristic composition of the vegetation is unlikely to be very successful as a predictive tool. Similarly, Hirata *et al.* (1993) found failure of their grazing model to accommodate changes in botanical composition over time led to incorrect predictions of cattle liveweight change. During the course of this work, and other projects (G. McKeon pers. comm.), the ability of GRASP to adequately simulate animal production has been lacking in periods with high forb content in the pasture and diet. As such, the requirement for GRASP to model the major pasture species, or groups of species (perennials, annuals, forbs), has been recognised but awaits further work. The GUNSYND project (Day *et al.* 1996) is the first attempt to simulate species differences using GRASP, but the prediction of species change is yet to be developed. Similarly, the dynamic nature of woody weed populations and their impact on pasture productivity is yet to be fully simulated. Browse plants, such as mulga, are incorporated in GRASP through their contribution to tree basal area, but no allowance is made for their contribution to the amount and quality of dry matter that is available for selection by sheep, either as standing plants or as litter on the ground.

When modelling at a scale greater than the small grazing trial paddock or point level, it becomes difficult to make allowances for the interactions between different land units. For example, sheep graze areas of paddocks differently, those areas closest to watering points receiving the greatest grazing pressure. However, within a paddock there are also areas that receive 'run-on' from areas of land producing 'run-off'. This interaction may, under certain rainfall events, result in a large impact on animal nutrition through the availability of fresh green feed, whereas the impact on overall pasture yield may be quite small.

At a larger scale again, the distribution of total animal numbers throughout each shire requires better definition. The underlying assumption in the spatial GRASP model is that potentially more productive areas have proportionally higher stocking rates. This assumption implies that land degradation would occur across the whole shire if animal numbers were sufficiently high. Therefore, modifications to the distribution of grazing pressure are necessary before the potential effects of high stocking rates and land degradation on the physical and financial performance of wool production can be simulated.

9.9 Alternatives in model operations

There are several components of the bio-economic model in which assumptions or operations may be modified.

Currently, a shearing date has been selected for each shire (Chapter Seven) and the variables for the wool production model collected for the preceding 12 months. Therefore, the model output for 1995, or any other year, represents slightly different production periods for different shires. An alternative approach would be to collect the appropriate GRASP outputs over the same 12 month period for all shires, i.e. to simulate wool production for a specified calendar year (assuming all sheep shorn on 31st December), financial year (assuming all sheep shorn on 31st July) or any specific 12 month period. A more complex alternative is to calculate the probability of shearing occurring in each month for each wool producing shire. Thus, the final output for the 1995 calendar year, for example, would be the weighted mean of the results for each month. This latter approach would also make better use of the weekly micron specific price indicators (aggregated to monthly means) for the years they are available.

The value of simulated wool production is based on the calculated fibre diameter from which the price received is determined. Mean annual micron specific wool prices, rather than mean monthly values based on time of shearing (and a suitable shearing to sale lag period), are currently used for a number of reasons. Firstly, the peak time of shearing, although based on a number of sources, is open to interpretation, especially in southern shires where a more even monthly distribution was noted. The lag period between shearing and wool sales may also vary with geography (distance to sale center), infrastructure (availability of rail and road transport services), and the economic environment (e.g. wool prices), thereby influencing the price received for wool shorn in a specific month. As stated earlier, the possibility of changes in the timing of shearing since 1957 would need further investigation and quantification before monthly micron specific prices were used in the production of percentile maps of financial performance.

The Agricultural Property Systems group of the QDPI is currently developing a digital cadastral database (DCDB) of information relevant to the Queensland grazing industries at the individual property level. This database, in the future, may provide a better method of estimating property size. This may be in terms of a probability distribution of property sizes within a specific shire, or even use of the DCDB as a layer in the bio-economic model so that actual property sizes are used in the production of maps showing 'per property' outputs.

9.10 SWOT analysis

Table 9.1 provides a summarised analysis of the *strengths*, *weaknesses*, *opportunities* and *threats* (SWOT analysis, Dillon 1988) of the work presented in this thesis.

Table 9.1. SWOT analysis of work presented in this thesis.

Attribute	Description
Strengths	• produced a useable model which provides a base for further research and application; • first comprehensive analysis of all available data relating to Queensland wool production; • conducted within an existing modelling framework (GRASP), therefore, can contribute to further developments; • examined the modelling of sheep production over levels ranging from a detailed physiological approach based on Australian feeding standards and Grazfeed, to the use of multiple regression models.
Weaknesses	• physiological approach did not work successfully and therefore the model had to use multiple regressions in order to deliver a suitable end-product; • failure to simulate sheep production from buffel pastures; • no flock population dynamics model incorporating decision rules; • nitrogen cycling in buffel pastures on cleared land not simulated, time since clearing of land and effect on nitrogen not simulated.
Opportunities	• direct field and model research into areas identified as requiring more work; • at the property level, 'what if' management options can be examined; • at the shire / regional level, allows for better use of limited human resources; • assessment of climate variability on industry output; • assessment of climate and economic variability on industry financial well-being.
Threats	• the model may not have the level of accuracy required for decision making but, as with other models, an evaluation of this issue requires the model to be widely used.

9.11 Summary

The need for objective physical and financial information relating to wool production, as well as other areas of primary production, is highlighted by the recent work of West and Smith (1996). These workers analysed 100 years of media articles, parliamentary speeches and popular reports (books, cartoons, films, poems) relating to drought and found each was considered unprecedented in terms of its destructive powers. Other circumstances such as time of the year, economic recession and poor commodity prices were often used to reinforce the scenario of 'worst ever drought'. Drought was also linked to a 'litany of indicators of wider moral anomie and structural collapse: the end of the "Australian way of life", farm bankruptcy, rural suicide, rural-urban migration, divorce and family breakdown, rural murder, domestic violence, massive stock depletion, rural juvenile crime etc'. Objective assessments of rural industries, and communities, are required if this phenomenon is to be avoided in the future.

Bennett and Macpherson (1985) considered usefulness to be the main measure of success of a modelling activity and most models were unsuccessful. Similarly, Trapp and Walker (1986) and Seligman (1993) reported few models are used for any long period of time, few had significant effect on rangeland science or the management of rangelands. The bio-economic model in this thesis is very simple and attaches to an existing pasture production model which is actively used by a dedicated group of researchers. As well, a user friendly Windows version of GRASP is being developed (J. Clewett pers. comm.). This version should act as a catalyst for further model refinement. Current applications of bio-economic modelling in rangelands (Buxton *et al.* 1995a, b, Johnston *et al.* 1996) suggest that modelling is being more widely accepted by industry.

The usefulness of the wool bio-economic model is yet to be evaluated. This may not be done until the next major industry crisis (e.g. drought) occurs. To ensure the model is ready for this event, it is essential in the intervening period that institutional support in terms of data acquisition, model maintenance and development is provided (Seligman 1993). The immediate future of the bio-economic model will probably involve internal use in the QDPI and Department of Natural Resources. This will allow for appraisal and feedback of the accuracy and usefulness of models outputs. Future developments may also include coupling with a beef bio-economic model under development (D. Mayer pers. comm.) to provide whole property (mixed enterprise) physical and financial information, extension of modelling work to include other states, and provision of information to interested persons using technology transfer options such as the World Wide Web.

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Finally, I would like to thank my family and friends for their support and understanding.

Appendix One

Review of the Biology of Sheep and Wool

Part A

Diet Selection and Feed Intake

A1.1 Plant animal interface

Modelling of the interaction which occurs at the plant animal interface has been identified as a major challenge to the successful modelling of grazing animal production systems (White *et al.* 1979, Black *et al.* 1982, Kenney and Black 1984, Ketelaars 1986, Ungar and Noy-Meir 1986, Denham and Spreen 1986). De Waal (1990) in his review, noted that a greater understanding of the nutritive value of native pastures and the interface between these pastures and grazing animals was needed. Thus, lack of data on diet selection and the ruminant digestive processes is a problem when describing the regulation of feed intake, especially for tropical pastures (Hogan *et al.* 1987).

A1.2 Diet selection

Diet selection is an important aspect of extensive grazing systems due to the wide variety of plant species that make up rangeland pastures and temporal variation in quantity and quality between and within species (Weston and Moir 1969, Lorimer 1976).

Often the terms *selection, preference* and *palatability* overlap in meaning. Noble (1975) proposed the following definitions:

- *selection* is a measure of what sheep actually consume while grazing;

- *preference* is a relative term and is usually estimated by ranking the selections of species after taking into account their availabilities; and
- *palatability* is a property of a species, or more correctly, the individuals of a species and is often inferred from the physical and chemical properties of the plant and its degree of selection.

Much of the research on diet selection has been carried out using penned sheep and cattle under controlled conditions. Generally, a limited number of feeds is used and only one or two factors affecting diet selection are examined at one time. Extrapolation of such results to the grazing environment should be done with caution.

Grazing sheep have been shown to select leaf in preference to stem, and young green material in preference to older dry material (Weston and Moir 1969, Lorimer 1976, Arnold 1981, Forbes and Hodgson 1985). Therefore, the herbage ingested is generally of a higher nitrogen (*N*) concentration, fibre and metabolisable energy (*ME*) content than the bulk feed on offer (Weston and Moir 1969, McMeniman *et al.* 1986a, Jung *et al.* 1989). Reasons for diet selection, as well as additional factors affecting diet selection, are described below.

A1.2.1 Leaf versus stem

Hogan *et al.* (1987) considered the selection of leaf over stem (Arnold 1981) was due to the relative ease of prehension and chewing rather than chemical factors. Hendrickson and Minson (1980) found the shear load (resistance to defoliation) of mature stem to be 5 - 10 times greater than leaf of tropical legumes. The preferential intake of leaf over stem can change both the structure and composition of the sward. At lower stocking rates animals 'patch' graze whereby they graze certain areas more frequently which will be shorter in height while the remainder of the pasture grows taller (Forbes 1988).

A1.2.2 Size of feed particles and rate of feed intake

The size of feed particles on offer affects diet selection. Kenney and Black (1984) found reducing the length of wheaten straw from 30 mm to 10 mm resulted in an absolute preference for the shorter forage. Similarly, Kenney *et al.* (1984) found shorter forage particles were preferred. This preference for shorter particles over longer identical particles was thought to occur because they were able to be ingested at a faster rate with less time spent chewing.

Discrimination between forages with different potential intake rates is reduced when feed intake rate is high, as in the case of hungry animals, or when particle size of forages is reduced (Kenney and Black 1984, Edwards *et al.* 1994).

Other factors, apart from particle size, which affect rate of intake will also affect preference. Black and Kenney (1984) reported penned sheep did not spend equal time eating two different artificial pastures on offer, but spent greater amounts of time eating those with sward characteristics which could be ingested faster.

A1.2.3 Fasted or non-fasted

Edwards *et al.* (1994) found sheep that were fasted showed less discrimination between cereal and straw pellets of varying length compared with non-fasted sheep.

A1.2.4 Distribution of plants

Work by Edwards *et al.* (1994) suggested that the spatial distribution of plant species in swards may affect selection, since where a preferred plant species was equally represented in two swards, greatest selection would occur in that sward where the preferred species was clumped together rather than evenly distributed throughout the sward.

A1.2.5 Age and breed

Arnold *et al.* (1981), grazing a flock of mixed age and breed on pastures of *Phalaris tuberosa* and *Trifolium subterraneum*, found no effect of age of sheep on botanical composition selected. However, sheep up to 12 months of age tended to select forage of a higher nutritional level. There was also evidence that breeds may differ in their preferences for certain species or strains of forage, but no evidence to suggest that one breed were consistently more or less selective than another breed.

A1.2.6 Dry matter content

Kenney *et al.* (1984) found the intake rate of wet matter fell (60 → 14 g / min) as dry matter content of the feed on offer increased from 15 to 94%. The intake rate of dry matter rose (9 → 14 g / min) as the dry matter content of feed increased to 40% at which point it plateaued. When wet and dry forages were both offered to sheep, more wet feed was ingested and dried forage was eaten more slowly but the amount of dry matter from both forages was similar, indicating that the preference for a forage is little affected by water content. However, Black *et al.* (1987) cited unpublished data of P. Kenney *et al.* for barley grass of identical characteristics, where sheep strongly selected grass with a lower water content.

A1.2.7 Pasture quality

The degree of selection practiced by sheep depends on the quality of pasture available (Jung and Sahlu 1986). When pasture *in vitro* dry matter digestibility (*DMD*) was high, there was little selection within the available pasture, but as the *DMD* declined to 55%, the degree of selection increased. Thereafter the selection dropped off sharply.

Hamilton *et al.* (1973) reported a good correlation between the amount of green herbage on offer and the proportion of green feed in sheep's diet using four different temperate grass species. In contrast, Lorimer (1976) found grazing sheep were able to select almost exclusively for green diets until the proportion of green in the pasture fell to very low levels.

A1.2.8 Rumen conditions

Short term alterations in diet selection probably occur in response to changes in the rumen environment in order to sustain optimal rumen conditions (Cooper *et al.* 1995).

A1.2.9 Theories of diet selection

Provenza (1995) outlined four models of ruminant diet selection:

- euphagia - based on the ability of animals to smell and taste specific nutrients and toxins in forages;
- hedyphagia - based on the belief that nutritious materials taste good and toxic materials taste bad. The taste component of this model occurs through the immediate 'pleasing' of olfactory, gustatory and tactile senses;
- body morphophysiology and size - based on the belief that ruminant species, through their evolutionary development, differ in their ability to ingest forages based on their physical and chemical characteristics; and
- learning through foraging consequences - includes aspects from the above three models. Diet selection is an ongoing learned behaviour, mediated through positive and negative feedback mechanisms.

Provenza (1995) believed there was increasing evidence to suggest nutritional wisdom, or the ability to select a high quality diet and avoidance of toxic materials, arises because 'neurally mediated interactions between the senses (i.e. taste and smell) and the viscera enable ruminants to sense the consequences of food ingestion, and these interactions operate in subtle but profound ways to affect food selection and intake, as well as the hedonic value of food'. Forages that contain toxins, or fail to supply nutritional requirements, are considered to cause 'unpleasant feelings of physical discomfort', and avoided relative to other forages.

Hogan *et al.* (1987) considered the ease with which plant parts could be chewed and swallowed gave rise to diet selection. Kenney and Black (1984) hypothesised deliberate selection for plants and their components does not occur, and the different proportion of plants and their components in the diet result from sheep spending an equal time grazing pasture components that were eaten at different rates. They further suggested that the intake rate of any component depends on three factors:

- the potential rate at which it can be eaten;
- its accessibility; and
- its relative 'acceptability'.

Kenney and Black (1984) and Colebrook *et al.* (1985) have shown that sensory factors such as taste, odour and texture affect selection of forages.

A1.2.10 Predicting diet selection

In vitro digestibility and gross chemical composition are of limited value in predicting forage preference of sheep (Arnold 1981, Kenney and Black 1984). Kenney and Black (1984) found the mean preference for a forage was more strongly correlated with the intake rate of forages (r^2=0.87) than with *in vitro* digestibility of organic matter (r^2=0.30). However, over the range of potential intake rates of 11 - 21 grams / minute for six native grasses and two clovers, sensory factors had a greater effect on preference than did intake rates (Colebrook *et al.* 1985).

A1.3 Dry matter intake

A1.3.1 Control of feed intake

The mechanisms by which feed intake is regulated, as shown in figure A1.1 (from Hogan *et al.* 1987), are complex and not yet fully understood (Weston 1979, Freer 1981, Ingvartsen 1994).

A1.3.1.1 CNS control

Central nervous system (CNS) control of eating behaviour and feed intake of herbivores is largely through the hypothalamus. Input to the hypothalamus comes from higher centres of the brain, the gastrointestinal tract, pancreas, liver and those components forming the circulating energy pool (Weston and Hogan 1973, Weston 1979, Weston and Poppi 1987). Feed intake control is often classified as short term or meal eating regulation, and long term or average daily intake regulation (Poppi *et al.* 1994, Dynes 1996, Weston 1996). Weston and Poppi (1987) and Weston (1996) defined the latter as the regulation of feed intake occurring over a period of greater than two to three days.

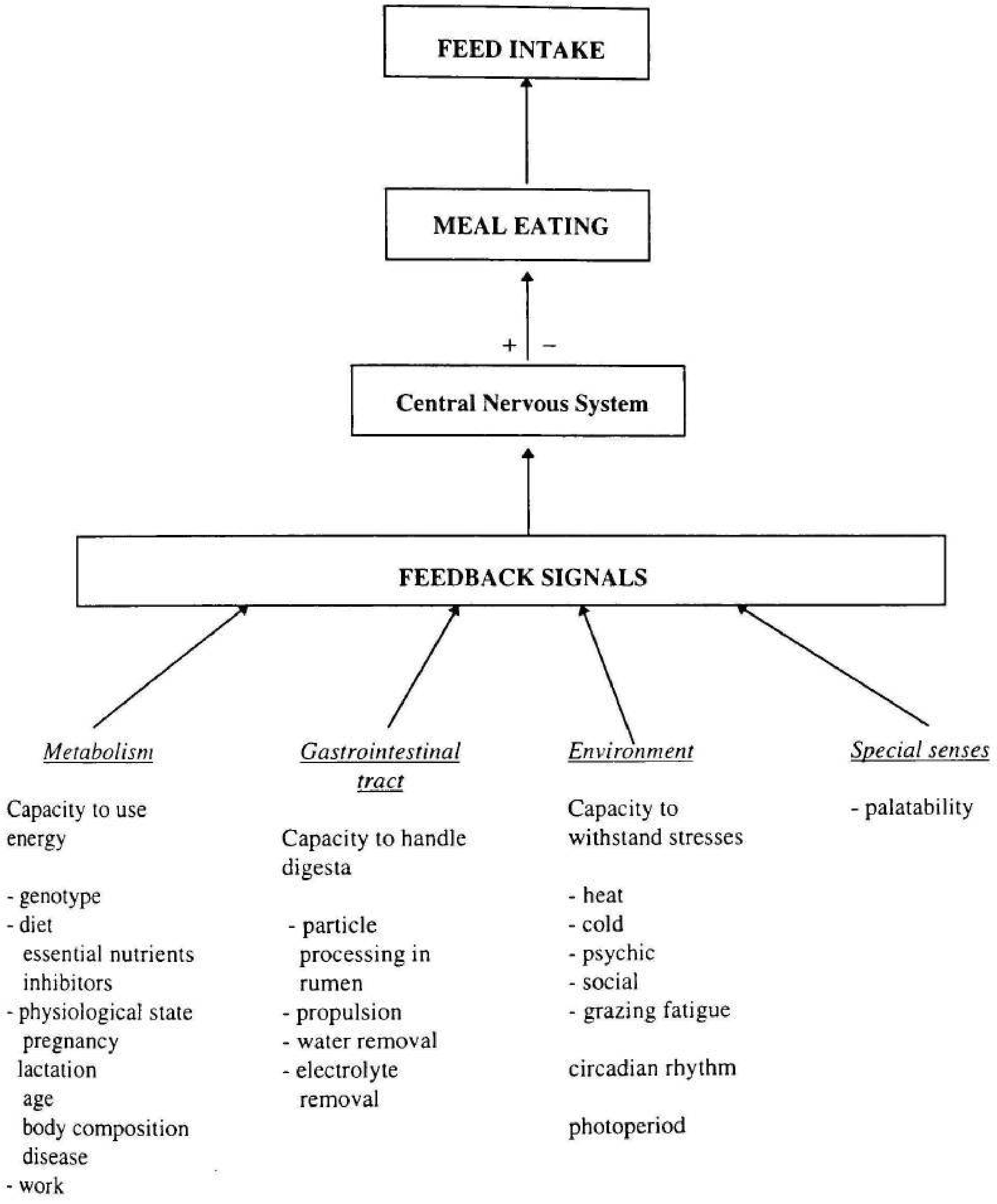

Figure A1.1. Factors associated with the regulation of feed intake (taken from Hogan et al. 1987).

A1.3.1.2 Short term control

Meal eating regulation occurs in the hypothalamus due to neural and humoral feedback mechanisms resulting from changes within tissues, organs and body systems (Weston and

Poppi 1987, Poppi *et al.* 1994). Freer (1981) reported the following factors were probably involved in the short term control of feed intake:

- stretch receptors located in the gastrointestinal tract;
- changes in body temperature;
- intestinal or circulating hormones; and
- plasma metabolite concentration.

Weston and Poppi (1987) reviewed meal eating regulation under optimal conditions. They considered the tissues, organs and pathways involved in the regulation and concluded 'that a wide range of signals may be concerned with meal eating regulation in herbivores under optimal conditions' and that 'no clear picture in the regulation has emerged, with no single metabolite or receptor system being predominantly implicated'. The inability of different meal eating patterns to alter feed intake suggested that systems which appear to control meal eating 'may form part of a network of signals designed mainly to protect the internal milieu from disturbance and the gastrointestinal tract from overload; in this context they may not be necessary for feed intake regulation'. Subsequently, Poppi *et al.* (1994) reported there was no consensus on how meal control relates to daily intake although many of the factors which influence short and long term intake have been identified, some of which appear to be operating simultaneously.

A1.3.1.3 Long term control

Long term feed intake control is usually described by a two component feed intake model, physiologically determined / physically restricted (Weston 1984). The physiological component of control is seen with diets of high quality where feed intake is determined by the energy requirements of the animal. As feed quality falls, the physical component becomes active and feed intake is then dictated by the rate at which indigestible feed moves from the reticulo-rumen. The factors affecting long term feed intake are discussed under three headings although marked interaction exists between these areas:

- nutritive requirements of the animal;
- physical and chemical composition of the forage; and
- forage availability.

A1.3.2 Nutritive requirements of the animal

Feed intake regulation under optimal conditions is largely determined by energy needs although the exact mechanisms remain unknown (Weston and Hogan 1973, Freer 1981, Weston 1985, Weston and Poppi 1987, Forbes 1988). The amount of energy an animal requires for maintenance, plus its genetic potential for production, sets the upper physiological limit to intake. This maximum physiological intake is only achievable under favourable climatic conditions, and where the feed is palatable, readily available and of high quality (Weston and Hogan 1973, Weston and Poppi 1987, Weston 1996). Under optimal feed conditions, ruminants alter their feed intake so as to maintain both constant digestible energy intake and production levels. Dinius and Baumgardt (1970) showed feed intake compensation occurred in sheep over a dietary digestible energy range of 10.3 - 14.6 MJ / kg DM. However, the nutrient demands of ruminants is modified by factors such as age, physiological status and the environment.

Few grazing animals on native pastures have diets that allow potential production to be attained. Animals on less than optimal diets attempt to satisfy their energy demands until restricted by negative feedback to the central nervous system, as a result of fatigue or the overloading of the digestive or metabolic systems (Hogan *et al.* 1987). The capacity of the digestive tract is affected by both animal and plant factors.

A1.3.2.1 Tissue metabolite buildup

Hogan *et al.* (1987) considered that, following removal of digesta from the rumen, the next most limiting factor on feed intake was build up of metabolites within the tissues. This control mechanism would only be active with immature forages, and is typified by lactic acidosis following carbohydrate engorgement, ammonia toxicity, nitrate poisoning and pregnancy toxaemia.

A1.3.2.2 Physiological status

The effects of pregnancy on feed intake are unexpected given the changing energy demands (Weston and Poppi 1987). There is no increase in feed intake during the first two trimesters, often a decline in the final trimester with a marked decrease in the final few days of pregnancy. During lactation intake increases but this increase is less than the increase in energy demands due to lactation, with the disparity more obvious in better conditioned animals. As lactation begins to decline feed intake also falls but at a slower rate. Marked hormonal changes occur during late pregnancy and lactation affecting adipose metabolism; lipogenesis is reduced and lipolysis increased which results in high levels of circulating energy metabolites. These changes may help explain why feed intake falls, and why animals in better condition (more fat) have a relatively greater decline.

In contrast, Arnold (1981) reported the grazing time of late pregnant sheep was unchanged while the rate of eating increased (27%) resulting in increased feed intake. Sheep in early lactation had higher intake due to a 2 - 12% increase in grazing time and a 20% increase in rate of eating. Similarly, Weston and Cantle (1982) and Weston (1988) reported lactating ewes to have greater feed intakes (25 and 26% respectively).

The mechanism by which ruminants experiencing increased energy demands due to growth or lactation are able to increase their feed intake, despite no change in diet quality, remains to be explained. Weston and Hogan (1973) suggested animals retain more digesta in the rumen and larger particles exit the reticulo-rumen. Weston and Cantle (1982) reported weaner lambs had feed intakes and rumen digesta loads (gut fill) 21 and 32 - 35% greater than adult animals respectively. Also, lactating ewes had increased digesta loads of 18 - 20%. Similarly, Weston (1988) found lactating ewes had higher digesta loads in the rumen (21%), reticulum (10%), omasum (25%) and abomasum (24%) although the reticulum and abomasum increases were not significant ($P>0.05$). Rate of particle removal from the reticulo-rumen was also increased due to three possible mechanisms, firstly, the digesta load led to more substrate being digested per unit time, secondly, greater rumination leading to increased digestion and outflow, thirdly, increased propulsion to the omasum.

Increased feed intake is also a feature of compensatory weight gain of sheep and cattle. More information on compensatory growth is presented in Part B of this appendix.

A1.3.2.3 Age

Younger animals have a higher intake per unit bodyweight, and an associated higher digesta load (Weston 1985).

A1.3.2.4 Climatic effects

Young (1987) reported that photoperiod, environmental temperature, solar radiation and humidity may all modify feeding behaviour. Longer periods of light increase intake while high temperatures, high intensity solar radiation and high humidity may all combine to increase the heat load on animals and lower feed intake. Arnold (1981) also considered humidity played an important but unknown influence on feed intake.

There is generally an inverse relationship between food intake and ambient temperature, which is affected by an animal's thermal susceptibility, acclimatisation and diet. Most ruminants have low susceptibility to thermal stress due to a large body mass, effective thermal insulation and body cooling by respiratory evaporation (Young 1987).

Bell *et al.* (1987) found no difference in feed intake for pregnant ewes exposed to a diurnal pattern of heat stress (38 - 40^{0}C for 9 hours, 30 - 32^{0}C for 15 hours daily, relative humidity 40 - 50%), compared with control ewes which was in line with the findings of Alexander *et al.* (1987). Arnold (1981) reported sheep modified their diurnal grazing behaviour as daily maximum temperatures increased above 25^{0}C, night grazing increased up to 70% of total grazing time. Young (1987) reported reduced feed intake from heat stress usually arises from sudden changes in the animals or their environment.

The type of diet may also affect the heat load. Thermally stressful conditions may reduce feed intakes further if the protein to energy ratio of the diet is low. Such forages are utilised inefficiently with an increased heat increment of feeding, which, when combined with the climatic heat stress, reduces feed intake (Leng 1989, 1990, 1991).

Shearing during moderate cold stress increases feed intake due to increased maintenance requirements (Wheeler *et al.* 1963, Weston 1983, Dabiri *et al.* 1995), increases greatest with low fibre forages (up to 70%) and least with high fibre forages (up to 15%; Weston and Hogan 1973). In contrast, severe cold stress may reduce feed intake (Young 1987).

The effect of thermal stress on feed intake is due to short term thermal stress which challenges the homeothermy of susceptible animals, and changes to metabolic and digestive functioning as the animal becomes acclimatised (Young 1987). Also, animals acclimatised to cold environments have higher resting metabolic rates while those acclimatised to hot environments have lower resting metabolic rates. Animals in cold environments also have higher feed intake levels, presumably as a result of increased flow of digesta from the rumen and higher levels of dietary protein reaching the intestines. Thwaites (1985) considered both feed intake and the rate of thyroid secretion to be 'chronically depressed' in the tropics.

A1.3.2.5 Animal health

The health of an animal influences feed intake; infectious, metabolic and parasitic diseases all depress feed intake.

A1.3.3 Physical and chemical composition of the forage

The physical and chemical properties of forage determine its nutritive intake. Generally plant constituents are either cell contents or the cell wall.

A1.3.3.1 Cell contents

Cell contents of plants include protein, water soluble carbohydrates, lipids, organic acids, vitamins, non-protein nitrogenous compounds, pigments and minerals (Jones and Wilson

1987). The water soluble or non-structural carbohydrates can be further divided into sugars and storage polysaccharides. Sugars include glucose, fructose and sucrose while the polysaccharides are mainly starches and fructans (Armstrong 1982). Smith (1973) reported that fructosans are the predominant non-structural polysaccharide in temperate grasses while starches predominate in legumes and tropical grasses. The cell contents are in general rapidly and completely digested within the digestive tract (Weston and Hogan 1973).

A1.3.3.2 Cell wall constituents

Cell wall constituents make up 30 - 85% of the forage (Weston and Hogan 1973). Cell wall components include cellulose, hemicellulose, pectin, lignin, silica and cuticle (Jones and Wilson 1987). Cellulose is the most common polysaccharide and is made up of large numbers of glucose molecules bound together (Weston and Hogan 1973, Bailey 1973). Cell wall lignin, silica and cuticle are indigestible, pectin is potentially completely digestible while the potential digestibility of cellulose and hemicellulose varies with its degree of lignification (Jones and Wilson 1987). Li *et al.* (1994) reported 16 - 18% of lignin was digested in two annual legumes.

Harkin (1973) reported lignin levels for temperate grasses (whole plant dry weight basis) of 3 - 5% in leaves and 6 - 7% in stems, increasing to 5 - 6% and 11 - 14% during maturation. Overall, values for legumes and tropical grasses were 2.3 - 14.5% and 2.5 - 15.5% respectively, the tropical grasses having potentially higher levels than legumes and temperate grasses. Lignin, through its contribution to the structural strength of plants also affects the resistance of forages to physical degradation during mastication and rumination (Weston and Hogan 1973).

A1.3.3.3 Physical resistance

In contrast to the situation with high quality diets, ruminants on poor quality diets are unable to increase feed intake to maintain digestible energy intake. In fact, feed intake and digestible energy intake decrease with falling feed quality since the rate of digestion decreases (Weston 1985, Weston and Poppi 1987).

A1.3.3.4 Physical resistance - mastication and rumination

With poor quality forages the need to be extensively chewed before swallowing may restrict feed intake (Weston 1985, Weston and Poppi 1987, Poppi *et al.* 1994). Weston (1984) reported chewing and ruminating time both increased as feed quality declined, while Laredo and Minson (1973, 1975b) showed different energy requirements for mechanical breakdown of plant components with similar digestibility were associated with differences in feed intake. In contrast, Weston and Hogan (1973) considered mastication to be a non-limiting factor in particle breakdown.

Hogan *et al.* (1987) cited Reid *et al.* (1962) and unpublished data of J. Hogan who found cattle grazing red clover had 60% of cell contents released and sheep grazing clover / ryegrass had 65% (range 33 - 88%) of cell contents released respectively by mastication and subsequent cell wall rupture. Mastication during ingestion and rumination becomes more important as a means of reducing particle size as forages mature and decline in quality (Hogan *et al.* 1987). Similarly, anatomical differences between temperate (C3) and tropical (C4) grasses result in leaves of C3 grasses being more easily fragmented during chewing (and digestion) than leaves of C4 grasses (Wilson and Kennedy 1996). The production of saliva is considered to be a non-limiting factor (Hogan *et al.* 1987).

Rumination consists of triple contractions of the rumen leading to regurgitation of a bolus of digesta, a period of chewing resulting in further cell disruption and particle fragmentation followed by return of the digesta to the rumen (Balch 1971). Rumination is stimulated by dietary fibre affecting mechanoreceptors in the cranial portions of the reticulo-rumen (Campion and Leek 1996). Hogan *et al.* (1987) questioned whether ruminants on poor quality pasture with extended grazing periods may have insufficient time for rumination.

A1.3.3.5 Physical resistance - rumen digesta outflow

Rumen capacity and the rate of removal of feed from the reticulo-rumen are the most important factors limiting feed intake on sub-optimal feeds (Blaxter *et al.* 1961, Weston and Hogan 1973, Weston 1979, Freer 1981, Weston 1985, Hogan *et al.* 1987, Weston and Poppi 1987, Dado and Allen 1995).

Weston and Hogan (1973) considered the rumen an organ of limited volume. Poppi *et al.* (1994) reviewed the work of several workers and also found a similar maximum volume for animals of similar physiological status across a range of diets although there were exceptions. Given the rumen is of limited volume, the rate of feed intake can not exceed its rate of removal from the rumen (Weston and Hogan 1973, Weston 1979). Removal of rumen contents occurs by eructation, absorption, or passage to the remainder of the gastrointestinal tract (Weston and Poppi 1987, Poppi *et al.* 1994). Blaxter *et al.* (1961) showed the rate of feed intake is positively related to digestibility, which is in turn positively related to the rate of passage of feed particles through the rumen.

Although the rumen may be of limited volume, the actual amount of material (digesta load) held in the reticulo-rumen of non-pregnant non-lactating sheep and cattle may vary by 300% (Weston 1985), the digesta load generally increases as digestibility of diet decreases and the deficit between energy intake and energy requirements increases (Weston and Cantle 1982, Weston 1984, Hogan *et al.* 1987, Weston 1988, Kennedy 1995a). Weston (1996) proposed that for non-optimal forages where the upper physiological load limit was not reached, hunger signals were proportional to the energy deficit (net energy of forage and physiological status) and satiety signals proportional to the rumen load (resistance to removal of material from the rumen). The interplay between these two factors determines the level of feed intake.

As well as age and physiological state of the animal, digesta load is also influenced by palatability and presence of essential nutrients in the feed through their effects on feed intake (Weston and Cantle 1982, Weston 1985). Weston and Davis (1986) suggested that low palatability reduces feed intake in certain situations although rumen capacity is not limiting. This effect may also explain trial results where digesta load is not increased with diets of lower digestibility and avoid the incorrect conclusion that load limit is determining forage intake (Weston 1996). Weston (1984) and Weston and Poppi (1987) postulated the ability of the rumen to accept a greater digesta load may promote rumination and microbial function and therefore increase rumen outflow.

Vagal nerve stimulation of the reticulum results in a biphasic contraction of the reticulo-rumen followed by contractions in the omasum at a rate of approximately one per minute, these contractions allowing for the passage of digesta from the reticulo-rumen (Hogan *et al.* 1987). The reticulo-omasal orifice is a muscular sphincter. Reid *et al.* (1991) cited Ohga *et al.* (1965) who reported the reticulo-omasal orifice opened immediately prior to the first phase contraction of the reticulum and was at a maximum during the second phase of the contraction. Closure of the reticulo-omasal orifice occurred followed by a second short period of opening.

The upper physiological capability of ruminants to propel fluid digesta from the rumen is unknown but Weston and Poppi (1987) considered it unlikely to be a factor limiting feed intake. Similarly Hogan *et al.* (1987) considered the capacity of the rumen to eructate gases to be a non-limiting factor. Therefore, removal of forage solids from the rumen, which varies with forage type, is the rate limiting step affecting feed intake.

Weston and Cantle (1984) showed increased rumen fill and slow particle clearance from the rumen are associated with both increased omasal fill and decreased rate of emptying of digesta from the body of the omasum indicating a possible role of the omasum in controlling rumen outflow.

A1.3.3.6 Digesta particle size and specific gravity

Less than 40% of food particles entering the rumen after mastication are small enough to pass to the omasum (Weston and Kennedy 1984). Poppi *et al.* (1980, 1985) found that most feed particles greater than 1.18 mm in size cannot leave the rumen through the reticulo-omasal orifice. These larger particles are reduced in size by rumination and fermentation (Minson 1982, Hogan *et al.* 1987). Poppi *et al.* (1981) reported that approximately 72% of particles present in the rumen were classed as small (≤1.18 mm). Although retention time of large particles (>1.18 mm) was an important influence on total rumen digesta retention time, the retention of small particles was more important, and probably the rate limiting process.

Rumen digesta can be envisaged as a series of pools of digesta of varying size, movement from one pool to the next requiring time but increasing the possibility of passage from the reticulo-rumen (Poppi *et al.* 1985). Van Soest *et al.* (1988) proposed that the particle size limiting passage from the reticulo-rumen is not constant but varies with feeding conditions such as level of intake and grinding of feedstuffs. Particles passing through the reticulo-omasal orifice are mainly comprised of lignin (Dulphy and Demarquilly 1983).

Sutherland (1988) cited the following hypotheses for the differential clearance of particles from the reticulo-rumen:

- entrapment in the fibrous mat of the rumen (Welch and Smith 1978);
- entrapment and channelling by the walls of the honeycomb cells of the reticulum (Reid 1984); and
- filtration by the unguliform papillae at the reticulo-omasal orifice (Ehrlein 1980).

Sutherland (1988) proposed that in sheep the dorsal rumen raft was an effective first stage separator, holding intermediate sized particles that have been reduced sufficiently in size to have specific gravities below that of the liquid medium in preference to those particles of smaller sizes. A second stage separation was proposed to occur in the reticulum whereby light, larger particles in the ventral fluid are able to rise out of the bottom reticular layer and escape passage. McBride *et al.* (1984) demonstrated that fluid in the omasum can flow in both directions, and this may allow any larger particles escaping the reticulo-rumen to be returned for further digestion (Sutherland 1988).

Pasha *et al.* (1994) suggested their results using nylon particles of different specific gravity given to sheep, and the work of Neel *et al.* (1993), with steers indicated that the mean specific gravity of rumen digesta may be an important variable influencing the retention of particles within the rumen. In contrast, Kennedy (1995b) and Neel *et al.* (1995) reported factors other than particle buoyancy influenced the passage of particles from the reticulo-rumen of cattle and swamp buffalo, although the former author did not rule it out as a contributing factor.

McBride *et al.* (1984), using a fibre-optic endoscope, demonstrated that large rumen particles up to 10 mm in length were able to exit the reticulo-omasal orifice. They suggested that no active filtration occurs at the orifice, rather those particles passing from the reticulo-rumen do so because they are in the right position, ventrally in the cranial sac, at the right time. Position within the rumen was related to whether particles were trapped within the rumen mat or not, and particle buoyancy.

A1.3.3.7 Digesta fermentation

The nutrient requirements of rumen microbes for optimal activity and subsequent microbial yields are detailed in Part B of this appendix.

A1.3.3.8 Leaf versus stem

Pen feeding trials have shown the preferential intake of leaf fractions over stem. Laredo and Minson (1973) reported a mean difference of 46% for five tropical grasses and Laredo and Minson (1975a) a 34% difference for three tropical grasses. The difference in intake between the two fractions occurred despite similar *in vitro* dry matter digestibilities. Similar work on perennial ryegrass found higher intake levels of the leaf fraction over the stem fraction at similar *in vitro* digestibilities, although the difference in intakes was lower at 20% (Laredo and Minson 1975b). Laredo and Minson (1973, 1975a) showed the difference in intake rates of leaf and stem fractions of tropical grasses was associated with a shorter rumen retention time for leaf, the larger surface area allowing for greater microbial degradation and a faster rate of passage through the rumen. Laredo and Minson (1975b) suggested a three fold difference in surface area of tropical leaf and stem fractions compared, to a two fold difference with perennial ryegrass, to be responsible for the greater difference in intake rates of the tropical fractions. Chemical differences between leaf and stem fractions were considered unimportant because pelleting increased intake of tropical stems, indicating physical factors rather than nutrient deficiency to be the limiting factor (Laredo and Minson 1975a).

A1.3.3.9 Plant maturity

Forage maturity influences plant composition as cell contents decline and cell wall constituents increase proportionally as a plant ages (Laredo and Minson 1973). Also the leaf stem ratio usually decreases (Weston and Hogan 1973), with leaf generally having greater cell content levels than stem, as indicated by protein levels (Laredo and Minson 1973). Stem components also accumulate more lignin than leaf during maturation (Harkin 1973), thereby reducing rate of digestion. Dulphy and Demarquilly (1983) cited the work of Andrieu *et al.* (1981) who examined the relationship of feed intake to plant age for 1432 green forages and found them to be 'close, linear or slightly curvilinear, with the slope and origin varying according to species'.

Also, low protein levels in mature forages may prevent the proper functioning of microbes in the reticulo-rumen, resulting in reduced digestion and feed intake (Allden 1981, see Appendix One, Part B).

A1.3.3.10 Palatability

The palatability of plants, as indicated by the senses of sight, smell, taste and touch (texture), may influence feed intake (Dulphy and Demarquilly 1983, Weston 1985). The effect of palatability on feed intake is probably minimal following a period of adaptation, although some plants are not eaten even in periods of feed shortage (Weston and Hogan 1973). Weston and Davis (1986) also linked resistance to mastication with physical palatability through the presence of awns, spines or hairs (Dulphy and Demarquilly 1983, Hogan *et al.* 1987). The effect of palatability on digesta load and feed intake (Weston and Davis 1986) has been described above. Variation in palatability probably allows animals to discriminate between feeds of various nutritional value or toxic plants (Ketelaars and Tolkamp 1992a).

A1.3.3.11 Water content

Another dietary aspect which may limit feed intake is the water content of the forage. Davies (1962) reported lowered dry matter intakes when the dry matter content of capeweed (*Arctotheca calendula*) dominant pastures fell below 16%. Infusion of water via a rumen fistula had no effect on feed intake while a water filled balloon did reduce feed intake. Similarly, Pethick and Chapman (1991) found capeweed with high water content (88 - 90%) reduced feed intake due to intact cells occupying rumen volume since water present in the cells was not absorbed until the cells were ruptured.

Lorimer (1976) reported lower than expected intakes for sheep on Mitchell grass pastures in north-west Queensland at a time when forage was of high digestibility, one to two weeks after heavy rains. He suggested the sheep were unable to ingest sufficient dry matter because of the high plant water content. Minimum and maximum moisture content of common grazing species in western Queensland vary markedly (Wood *et al.* 1996): *Astrebla* spp. (Mitchell grass) 0.0 - 79.5%, *Iseilema* spp. (Flinders grass) 4.2 - 83.7%, *Cenchrus ciliaris* (buffel grass) 0.0 - 82.9%, *Monachather paradoxa* (mulga oats) 1.4 - 50.0%, *Thyridolepis mitchelliana* (mulga Mitchell) 0.0 - 76.2%, forbs 0.0 - 82.9%.

In contrast, Weston and Hogan (1973) in an early review concluded that there was insufficient evidence that water content of plants was able to limit feed intake. They noted that conditions favouring the high water content in plants also favour changes in the levels of minor chemical constituents which may affect feed intake. Hogan *et al.* (1987) also considered that these alterations in plant composition, as shown by Deinum *et al.* (1968), and possibly the accumulation of secondary metabolites, may reduce feed intake given the large capacity of fluid to be moved across the rumen wall. Pasha *et al.* (1994) in more recent work suggested that possible high rumen ammonia levels may result in reduced rates of feed intake on high moisture diets (22% DM). Weston (1996) also questioned why no data on rumen water load of animals ingesting forages with high water content were available to examine the proposal that water content of forage, and physical occupation of rumen space, reduced feed intake.

A1.3.3.12 Climatic effects

Season and environmental conditions may also affect plant composition as previously stated. Water soluble carbohydrate and nitrogen concentrations of perennial ryegrasses are negatively correlated throughout the year due to divergent seasonal changes in the concentration of these components (Radojevic *et al.* 1994). Plants growing under warmer temperatures are also more lignified and therefore less digestible (Deinum *et al.* 1968, Wilson *et al.* 1991).

A1.3.3.13 Toxic substances

Campling and Lean (1983) reported the presence of toxic substances or appetite depressants in forages may decrease feed intake.

A1.3.3.14 Legumes

Intake of tropical legumes is greater than tropical grasses of the same digestibility (Thornton and Minson 1973). This is thought to be due to a reduced rumen retention time and higher rumen packing density of legumes.

A1.3.3.15 Grinding and pelleting of forages

Minson (1982) reported grinding and pelleting of feed generally increased feed intake and the response was greatest for feeds with the lowest original intake. The rise in feed intake was associated with lower digestibility but higher rate of passage through the rumen. However, Minson (1967) found a smaller response to grinding and pelleting for low quality forages, compared with good quality forages, where the crude protein content was below that necessary for proper rumen microbial activity.

Laredo and Minson (1975a) found that for tropical grass leaf and stem fractions, pelleting caused a proportionally greater increase in intake of the leaf fraction which had a higher intake originally. They concluded that the greater overall surface area of both leaf and stem due to grinding (following rapid pellet breakdown in the rumen) led to more rapid digestion and passage from the reticulo-rumen; the surface area of the leaf fraction was still greater than that of the stem fraction following grinding. Minson (1982) suggested the different intake and digestibility relationships for chopped and pelleted forages is associated with less need for forage to be broken down by rumination, and consequently, the faster passage through the rumen. Balch (1971) showed that animals fed ground forage or concentrate diets ruminate very little. Weston (1996) considered the increased intakes associated with grinding and pelleting of lower quality forages could, in part, also be associated with the correction of a palatability constraint, e.g. a physical property such as toughness acting as an intake constraint. However, Faichney (1983a) reported that although grinding and pelleting of forages results in a decrease in rumen digestion which is usually explained by decreased rumen retention time, direct measurements made by Balch (1950), Weston and Hogan (1967) and Faichney (1983b) reveal increased rumen mean retention times for ground forages.

A1.3.4 Forage availability

Weston and Hogan (1973) concluded pasture density, pasture length, proportion of pasture in upright or prostate form and uniformity of plant distribution, all influence the availability of forage and therefore feed intake

A1.3.4.1 Yield

An asymptotic relationship exists between feed intake or animal production and herbage yield in some reports (Willoughby 1959, Allden 1962, Arnold 1963, Arnold and Dudzinski 1967, Allden and Whittaker 1970), while others did not find a relationship (Carter *et al.* 1960, Wheeler *et al.* 1963, Lorimer 1976). Where a relationship existed there was variation in the asymptote, i.e. the herbage yield not influencing feed intake or animal production. Willoughby (1959) found green pasture yields above 1572 kg DM / ha to be non-limiting for liveweight gain. The yield of dry pasture was not related to animal production when green pasture was present. Allden (1962) and Allden and Whittaker

(1970) cited Scott Young (1960) who was unable to find any influence on animal performance of green herbage yields above 673 kg DM / ha. Allden (1962) and Arnold (1963) estimated pasture yields of approximately 2245 kg DM / ha while Allden and Whittaker (1970) found yields of approximately 1800 kg DM / ha to be the point at which the rate of feed intake was not limited by herbage availability. Black and Kenney (1984) using artificial grass pastures found maximum intake rate was attained at 1000 kg DM / ha.

Willoughby (1959), Allden (1962) and Weston and Hogan (1973) considered variation in the level of herbage giving maximum animal production was to be expected because of the complexity of the relationship and differences in age and weight of animals, pasture type, botanical composition, plant spacing and previous nutritional history. Allden and Whittaker (1970) argued that much of the variation in the literature arose because herbage yield per unit area was a poor indicator of herbage availability. Instead, they found pasture height as estimated by tiller length was more closely related to availability.

A1.3.4.2 Plant height

Arnold (1963) showed increasing plant heights reduced grazing time while Allden and Whittaker (1970) found plant height, as estimated from tiller lengths, to be much more closely related to availability and rate of herbage consumption than pasture yield. There was a rapid increase in the rate of herbage consumption as tiller lengths increased up to 7.7 cm, after which there was little response to further increase. Associated with the changes in rate of feed intake, Allden and Whittaker (1970) reported an almost linear increase in bite size with increased tiller length from 3.7 to 36.7 cm. Rate of biting was generally the reverse, the number of bites per minute decreased as tiller length increased. These experiments calculated rate of herbage consumption over a one hour period using hungry sheep and reflect potential intake rather than actual grazing behaviour.

Black and Kenney (1984), with artificial pastures of identical tiller density, found rate of herbage intake increased with sward height, while for pastures with identical sward height, rate of pasture intake was related to bulk density. Herbage mass per unit area best described intake rate, but for pastures of less than 1000 kg DM / ha, intake rate was several fold greater when sheep grazed tall, sparse pastures compared with short, dense pastures.

A1.3.4.3 Leaf to stem ratio

Bite size and total intake of tropical legume pasture by cattle increased as the ratio of leaf to stem increased (Hendrickson and Minson 1980). Other workers also found bite size of cattle to be more closely related to the leaf stem ratio (or leaf density) than plant height (Stobbs 1973a, 1973b, 1975, Chacon and Stobbs 1976). Stobbs (1973b) suggested the reason why bite size of cattle decreased with increasing height of some tropical plants to be the fall in leaf density at the sward surface. Forbes (1988) also reported that bite size of cattle was more related to leaf stem ratio in swards with a tall flower canopy, while in swards without a tall flower canopy, bite size was more closely related to sward leaf height.

A1.3.4.4 Calculation of feed intake

The herbage intake of a grazing animal can be calculated from the following equation (Allden and Whittaker 1970, Forbes 1988):

$$I = R * T$$

where I is herbage intake, R is rate of eating, and T is time spent grazing.

Rate of eating can be calculated as:

$$R = S * B$$

where S is size of bite, and B is rate of biting.

Time spent grazing, rate of biting and bite size are not independent variables. However, bite size is the most important determinant of feed intake while the other two are compensatory variables (Hogan *et al.* 1987, Forbes 1988).

A1.3.4.5 Bite size

The best predictor of rate of pasture intake is the herbage mass effectively covered by one bite (Black and Kenney 1984). Both size of bite and rate of biting are functions of the animal and the sward being grazed (Allden and Whittaker 1970, Ferrer Cazcarra *et al.* 1995). Bite size can be limited by the area which a sheep's mouth can cover, but not necessarily by the depth of the mouth since long grasses may be removed at their base and drawn into the mouth (Hogan *et al.* 1987).

Bite size may vary greatly depending on the type of pasture being grazed and the stage of growth of that pasture (Forbes 1988). Bite size is generally greater with temperate swards of increased height / tiller length and increased bulk density, and tropical swards with increased leaf stem ratios and increased leaf density at the sward surface (Black and Kenney 1984, Allden and Whittaker 1970, Stobbs 1973a, 1973b, 1975, Chacon and Stobbs 1976, Forbes 1988, Morris *et al.* 1993, Ferrer Cazcarra and Petit 1995, Ferrer Cazcarra *et al.* 1995).

A1.3.4.6 Rate of biting

As bite size declines with sward structure, rate of biting and / or grazing time increases in an effort to maintain intake (Black and Kenney 1984, Forbes 1988, Morris *et al.* 1993, Ferrer Cazcarra and Petit 1995, Ferrer Cazcarra *et al.* 1995). Black and Kenney (1984) found prehending bite rate doubled as intake per bite declined 20 fold. However, the rate of total jaw movements during grazing was virtually unaffected by sward characteristics; prehending bites accounted for 20% of jaw movements where intake per bite was high (200 mg) and increased to 80% of jaw movements as intake per bite declined. The increase in rate of biting may however be inadequate to maintain the rate of feed intake (Hodgson 1982, Black and Kenney 1984). The rate of biting depends on the rate animal's masticate the feed, moisten it with saliva, form a bolus and swallow it (Hogan *et al.* 1987). These processes may limit intake of poor quality feeds (Weston 1985, Weston and Poppi 1987, Poppi *et al.* 1994). Forbes (1988) cited earlier work of his (Forbes 1982) which showed a general increase in rate of biting with time of day for sheep and cattle.

A1.3.4.7 Rate of eating

As bite size decreases, rate of biting will increase wherever possible so as to maintain ingestion rate. Both physical and chemical characteristics of a forage influence its rate of ingestion. The rate of ingestion will increase with forages that allow optimal bite size and rate of biting.

Factors such as smaller feed particles, reduced fibre and cell wall levels, reduced comminution energy requirements, cold stress and hunger will all increase the rate of feed intake (Weston and Hogan 1973, Laredo and Minson 1973, Dulphy *et al.* 1980, Weston 1983, Kenney *et al.* 1984, Kenney and Black 1984, Edwards *et al.* 1994). In the grazing situation, rate of feed intake is also affected by the resistance of herbage to harvesting, grasses being more resistant due to a higher tensile strength and a smaller ratio of leaf mass to cross sectional area of stem than clover (Hogan *et al.* 1987). Kenney *et al.* (1984) also found that for decreasing levels of dry matter content in forage, rate of intake would increase to compensate for the reduction in dry matter content. However, for forages below 40% dry matter the rate of intake was insufficient to compensate for the dry matter reduction and dry matter intake fell.

Allden and Whittaker (1970) found sheep grazing pastures of 1800 kg / ha or greater were not limited by pasture availability and attained a maximum intake rate of about 6 g DM / min. Black and Kenney (1984) showed the rate of intake increased as the height and density of the sward increased, and that sheep generally preferred pastures that could be eaten at a faster rate. Using artificially constructed kikuyu pastures they observed a maximum rate of intake of 6.9 g DM / min at 1000 kg DM / ha. The same authors later (Kenney and Black 1986) using artificial subterranean clover swards observed a much higher maximum intake rate of 20 g DM / min at >2000 kg DM / ha, presumably as a result of the greater ease of prehension and mastication, and the increased sward density at the top of the clover sward.

A1.3.4.8 Time spent grazing

Allden and Whittaker (1970) found that as the amount of available herbage declined below the point at which availability restricts the rate of herbage consumption, there was a compensatory increase in the time spent grazing. As herbage availability further declined a point is reached at which increased grazing time is unable to compensate for the reduction in rate of herbage consumption and herbage intake declines.

Arnold (1963) reported daily grazing times of more than 11 hours for lactating ewes over a whole range of pasture yields, to less than seven hours for dry ewes on abundant pasture (> 2245 kg DM / ha). Similarly, Arnold (1981) gave the maximum daily grazing time as 12 - 13 hours for sheep, this time being influenced by the nutritional requirements of the animal, availability and distribution of feed, and the rate at which the animal is able to eat, while Young and Corbett (1972a) reported grazing time increased from 8.2 to 12.3 hours as pasture availability declined from 2800 to 370 kg DM / ha. Weston and Poppi (1987) considered that upper values for grazing times were not necessarily maximas, and that grazing time capability in many situations does not limit feed intake.

A1.3.5 The theory of Tolkamp and Ketelaars

These two workers recently (Ketelaars and Tolkamp 1992a, 1992b, Tolkamp and Ketelaars 1992) disputed the commonly held beliefs regarding the two component model of feed intake (physiologically determined / physically restricted). Their views are summarised below.

Tolkamp and Ketelaars reviewed 831 roughage feeding trials and failed to find the expected plateauing of digestible organic matter intake for forages of 65 - 70% organic matter digestibility and over. Also, intake of indigestible material fell with feed digestibilities over 70% while the intake of organic matter and digestible organic matter continued to rise. This led them to question whether the real advantage of a higher feed digestibility is due to a lower degree of rumen fill or to other factors. They also suggested the work by Dinius and Baumgardt (1970) and Conrad *et al.* (1964), and the theoretical base of the two component model of feed intake regulation, is biased in experimental design and analysis.

In their review, both organic matter digestibility and protein content are positively correlated with feed intake. For a given level of digestibility, intake increased with protein content; the levels of protein were such that the results could not have arisen from microbial response to a previous protein deficiency. They suggested that the effects of dietary protein could be related to changes in ruminal fermentation products or changes in the protein energy ratio of absorbed nutrients, both metabolic factors.

Ketelaars and Tolkamp (1992a) concluded that the available evidence does 'not allow any conclusion to cause and effect: is a higher intake cause of a shorter retention time or the consequence of it ?'. They proposed a new theory in which feed intake regulation was the optimisation of costs and benefits of feed consumption. Intake of net energy was considered to be the benefit, and oxygen consumption the cost. Optimum feed intake gave the maximum net energy intakes per unit of oxygen. Underlying this theory are the concepts that the total amount of oxygen an animal consumes during its potential lifespan is fixed, and that animals try to maximise the efficiency of oxygen utilisation. This maximisation results from natural selection, population survival being dependent on the reproductive success of a small group of females reaching a longer life span. Oxygen, though necessary for life, produces by-products causing cellular damage which accumulates over time resulting in ageing and eventually death. Therefore the amount of oxygen consumed can be considered the cost of feed consumption. They further hypothesised that net energy intake and oxygen consumption were not the parameters animals monitored in order to adjust the intensity of feeding. Instead, they viewed intracellular pH as the likely parameter controlling feed intake.

Part B

Energy / Protein Digestion and Metabolism in Sheep

B1.1 Introduction

A unique advantage of ruminants is their ability to extract energy from complex plant polysaccharides due to the digestive processes of bacteria, protozoa and fungi in the rumen (Weston and Hogan 1973, Bird 1985, Bauchop 1985, Jones and Wilson 1987, Russell 1988).

Reticulo-rumen, omasal, abomasal and intestinal digestive processes are complex, as is the fate of nutrients following absorption across the gastrointestinal wall. It is impossible to consider protein digestion / metabolism and energy digestion / metabolism in isolation because of the interaction that occurs in these processes (Leng 1985, 1989, 1990, 1991, Poppi and McLennan 1995). However, in this short review, each will be considered separately but their interactions will be noted. Special mention will also be made of the findings and recommendations of the Standing Committee on Agriculture (SCA 1990).

B1.2 Protein Digestion

Protein in forage is usually expressed as crude protein (6.25 * nitrogen) which includes true protein (75 - 85%), free amino acids, low molecular weight peptides, nucleic acids and other nitrogenous compounds such as alkaloids and inorganic nitrogen (Lyttleton 1973).

B1.2.1 Degradation in the rumen

The fate of both nitrogen and energy sources, entering the rumen varies (Hogan 1982, Wallace 1988). Some passes through unfermented to the abomasum and intestines; some undergoes microbial fermentation, releasing volatile fatty acids, or ammonia which is absorbed across the rumen wall in the case of protein. Alternatively, some products of fermentation are incorporated into microbes which may pass to the abomasum and intestines, or may undergo degradation in the rumen.

The fate of nutrients is influenced by the type and number of microbes present, the accessibility and degradability of protein and energy substrates, and time spent in the rumen (Hogan 1982).

McAllister *et al.* (1994) reported that most rumen fermentation is carried out by microbes attached to the inner surfaces of food particles since the cuticle of forages prevents microbes attaching to the plant surface, and hence digestion. The acts of prehension, mastication and rumination physically disrupt this barrier releasing cell contents and allowing access to the inner surfaces. Microbial attachment to these particles allows for the apposition of microbial digestive enzymes directly to the surface of the food particle and concentration of digestion at this point.

Lack of available energy, or poorly synchronised release of energy, may prevent microbes from incorporating amino acids and ammonia into microbial protein (Hogan 1982, Wallace 1988, Sinclair *et al.* 1995). Dietary protein that escapes degradation in the rumen passes to the abomasum and intestines where it may undergo digestion and absorption (Armstrong 1982).

The degree of degradation of feed protein depends on the potential degradability of the protein, while actual protein degradation is influenced by factors such as physiological status, feed composition, environmental factors and level of feeding via altered fractional outflow rates (Faichney 1983a, Corbett 1987, Faichney and White 1988).

The potential degradation of protein decreases with decreasing feed quality, as indicated by lower crude protein and digestibility (Wilson and Strachan 1981, Webster *et al.* 1982, McMeniman *et al.* 1986b). Corbett *et al.* (1987) reported pastures of grasses with C4 photosynthetic pathways may have as little as 50% of ingested crude protein degraded in the rumen. McMeniman *et al.* (1986b) found intake of tropical pastures with digestible organic matter levels of 53 and 48% had 58 and 37% of nitrogen apparently digested in the rumen.

For predictive purposes, SCA (1990) related forage protein degradability to forage crude protein and crude fibre (or modified acid detergent fibre) content:

*rumen degradability of protein = (crude protein - 0.125 * crude fibre) / crude protein*

*rumen degradability of protein = (crude protein - 0.1 * modified acid detergent fibre) / crude protein*

B1.2.2 Microbial yield

Under optimal conditions, microbial yield may theoretically reach 30.0 grams dry cells per mole of ATP (Leng 1991). The amount of microbial protein formed in the rumen and reaching the intestines, as a ratio of the volatile fatty acids, depends on the following factors (Faichney 1983a, Van Soest *et al.* 1988, SCA 1990, Leng 1990, 1991):

- feed substrate;
- composition and number of microbes;
- the supply of energy, surplus to maintenance, as provided by high energy phosphates (ATP) released during the fermentation of dietary, endogenous and microbial material to *VFA*s;
- amino acid and ammonia nitrogen;
- dilution or fractional outflow rate; and
- supply of other essential elements (sulphur, phosphorous, magnesium, cobalt).

Protein, peptides, amino acids and ammonia nitrogen are supplied from the degradation of dietary, microbial and endogenous protein; ammonia nitrogen may be further supplied from the diet as non-protein nitrogen, or as urea in saliva and directly from the blood across the rumen wall (Hogan 1982, Faichney 1983a, Lewis and Hill 1983). Some rumen microbes require nitrogen in the form of both ammonia and amino acid so that microbial activity may be reduced even when total nitrogen appears adequate (Maeng and Baldwin 1976, Leng 1990).

Allden (1981) reviewed the literature dealing with the necessary forage protein / nitrogen level for optimal microbial functioning and reported values ranging from 5 - 10% crude protein (0.8-1.6% nitrogen), with 6.25% crude protein (1.0% nitrogen) being the most common. Lyttleton (1973) reported tropical grasses as having crude protein levels typically in the range of 5 - 10%, the level rising above 10% only for very young grasses and often falling below 5% for mature grasses. Typical crude protein values for temperate grasses were reported as 10 - 20% with higher values often measured, legumes were in the range of 15 - 25%.

Satter and Slyter (1974) showed rumen ammonia nitrogen levels of 50 mg / litre to be a suitable non-limiting environment for microbial activity. However, Leng (1991) considered ruminants on poor quality forages required rumen ammonia nitrogen levels of at least 200 mg / litre to optimise forage utilisation. He reported ammonia nitrogen levels of 80 - 100 mg / litre allowed maximum forage digestibility, but further increases in ammonia nitrogen increased feed intake and therefore forage utilisation. Where protein supplements provide rumen escape protein, 100 mg rumen ammonia N / litre optimised forage utilisation.

Endogenous nitrogen entering the intestines arises from salivary protein and urea, sloughed rumen epithelial cells, urea crossing the rumen wall from the blood and sloughed abomasal cells and secretions (Harrop 1974, Hogan 1982, Faichney 1983a). Faichney (1983a) reported endogenous protein nitrogen of sheep entering the intestines ranged from 6 - 11 g / day under various feed and climatic conditions. Dove and Milne (1994) estimated the flow of endogenous nitrogen into the intestines was 6.21 g / day based on the work of Corbett *et al.* (1982), McMeniman *et al.* (1986b) and their own data. Harrop (1974) found 0.46 - 2.6 grams N / day was added to the digesta from the fundic region of the abomasum and 0.05 - 0.37 grams N / day from the pyloric region. The majority of this nitrogen was in the form of protein (65 - 91%) with lesser amounts as mucin (2 - 24%) and urea / ammonia (2.8 - 13.4%). Endogenous nitrogen is also added distal to the rumen / abomasum in the form of pancreatic enzymes, sloughed epithelial cells, mucous secretions and bile pigments (SCA 1990). The net microbial yield and efficiency of feed utilisation may be reduced by degradation of microbial cells and fermentation of cell contents within the rumen (intraruminal nitrogen recycling), mostly by rumen protozoa, and to a lesser extent, bacteriophage-mediated lysis of rumen bacteria (Leng 1991, Morrison and Mackie 1996).

Corbett (1987) cited data of Hogan (1982) which indicated the level of crude protein leaving the stomach will be approximately equal to the dietary crude protein intake (net protein transfer) where forage crude protein is 230 - 310 g / kg digestible organic matter (*DOM*). For forages above this range there will be a net loss of nitrogen with ammonia absorbed across the rumen wall and converted to urea. This urea may be recycled via saliva or directly across the rumen wall, or be excreted in urine. Forages with crude proteins below the range will have a net gain in terms of nitrogen leaving the rumen, provided adequate nitrogen is supplied to the rumen via the recycling processes. Forages within the range, but with easily degraded crude protein will also suffer a net loss of nitrogen as protein will be degraded and ammonia released at a rate faster then it can be synthesised into microbial protein due to lack of energy. However, Poppi and McLennan (1995), using temperate data collated from a number of sources, found the transfer of protein from the rumen to intestines became negative at a much lower level of digestible organic matter, 210 g *CP* / kg *DOM*. For pastures of 50.0% organic matter digestibility, losses in net transfer will occur when crude protein of the feed exceeds 9.4%. A similar value exists for tropical pastures (Higgins *et al.* 1992)

Microbial nitrogen yields vary markedly, and are often expressed as different units. Dove and Milne (1994) reported microbial nitrogen flows of 21.7 and 11.5 g / kg organic matter intake (*OMI*) for spring / summer and autumn temperate pastures respectively. Corbett and Pickering (1983) presented work by Pickering *et al.* (1982) and revised data of Corbett *et al.* (1982) and reported a mean microbial nitrogen flow of 25.8 ± 1.3 g / kg (±

standard error) digestible organic matter intake (*DOMI*, range 20.3 - 32.0) for sheep grazing temperate grass and legume pastures. This was equivalent to a microbial nitrogen flow of 37.6 ± 2.2 g / kg organic matter apparently digested in the rumen (*OMADR*, range 30.4 - 46.7). The results of Dove and Milne (1994) in terms of *OMADR* were 40.75 ± 4.9 and 18.6 ± 1.7 g microbial nitrogen for spring / summer and autumn pastures respectively. SCA (1990) cited an unpublished review of 32 sheep digestion trials by E. Furnival in which the microbial nitrogen yield was 35.8 ± 1.9 g / kg *OMADR*. McMeniman *et al.* (1986b) reported microbial nitrogen yields of 42.1, 52.2 and 19.7 g / kg *OMADR* for sheep grazing Mitchell grass pastures, and 35.3, 47.6 and 37.7 g / kg *OMADR* for mulga grasslands. The low value for the Mitchell grass pastures occurred at a time when the nitrogen content of the dietary organic matter was at its lowest, 0.7%. Hogan *et al.* (1989) reported microbial nitrogen yields of 28.9 ± 3.3 and 36.5 ± 5.1 g / kg *OMADR* for two tropical grasses, and 47.0 ± 1.6 and 34.0 ± 1.6 for a temperate grass and legume respectively.

Corbett and Pickering (1983) compared results of Pickering *et al.* (1982) with revised data of Corbett *et al.* (1982) and reported a consistently greater microbial nitrogen yield for early growths of a number of temperate pastures compared with later growths, 40 - 47 and 30 - 33 g / kg *OMADR* respectively. Similarly, Dove and Milne (1994) found differences in efficiency of microbial protein synthesis for sheep on temperate pastures in spring / summer and autumn, and attributed this to differences in forage water soluble carbohydrate (*WSC*) content, and altered fermentation patterns. Corbett (1987) suggested that acetate to propionate ratios above three indicated *WSC* levels were low enough to limit the supply of energy for microbial protein synthesis.

SCA (1990) preferred to report microbial yields as a function of digestible organic matter intake or its equivalent, *ME* intake, in order to avoid two assumptions made by ARC (1984). These assumptions were a constant proportion of digestible organic matter intake apparently digested in the rumen (0.65), and a constant microbial protein yield per unit o organic matter apparently digested in the rumen (200 g / kg). Given a constant *ME* value for organic matter digested in the rumen (15.58 MJ / kg), *OMD* > 0.7, and no nutritiona limitations to microbial activity, SCA (1990) recommended microbial protein production should be 11.0 g / MJ *ME* (170 g / kg *DOMI*) for first growths of temperate grasses / legumes and forages such as oats. The microbial protein production for most forages (other than silages), including those less than 0.7, was 8.4 g / MJ *ME* (130 g / kg *DOMI*). This differentiation in microbial protein production accounted for seasonal variation observed by Corbett and Pickering (1983) and other workers cited by SCA (1990).

B1.2.3 Amino acid absorption

Protein reaching the intestines is from one of three sources: undegraded dietary protein, microbial protein, endogenous protein. Undegraded dietary protein is made up of undegradable dietary protein plus that portion of rumen degradable protein which leaves the rumen without being degraded (Faichney 1983a). Additionally, ammonia resulting from rumen microbial fermentation but not utilised for microbial growth nor absorbed is also present (Lindsay and Armstrong 1982). The proportion of total nitrogen in the form of non-ammonia nitrogen (crude protein leaving the stomach = $NAN * 6.25$; SCA 1990) entering the intestines has been reported between 92 - 96% (Hogan *et al.* 1989). The proportion of crude protein which is true protein entering the intestines is generally taken to be 0.8, the remainder being mainly nucleic acids (Smith 1975, SCA 1990). The amino acid composition of protein leaving the stomach is relatively constant because the majority is of microbial origin (Lindsay and Armstrong 1982, Hogan *et al.* 1989, Oosting *et al.* 1995), which itself is of fairly constant composition (Ørskov 1982). However, there may be greater variability in levels of lysine, threonine and the sulphur containing amino acids, methionine and cystine (Hogan and Weston 1981). The supply of sulphur amino acids are important determinants of wool growth rates (see Appendix One, Part C).

Protein entering the intestines is extensively degraded by abomasal and pancreatic enzymes prior to uptake of amino acids, and ammonia passing from the rumen, across the intestinal wall (Lewis and Hill 1983). Most protein evaluation systems reviewed by Faichney (1983a) used average values for apparent or true digestibility of true protein to calculate the net or true metabolisable protein supply; use of true digestibility required endogenous secretion to be included in the estimation of the requirements of the animal. SCA (1990) considered there was more reliable data pertaining to apparent digestibility and preferred this option to the use of true digestibility.

Armstrong and Hutton (1975) gave a range of 0.31 - 0.90 for the amount of individual amino acids entering the small intestine and being absorbed. Lindsay *et al.* (1980) reported 52 - 86% of individual amino acids were truly digested in the small intestine. Oosting *et al.* (1995) reported somewhat higher values for true digestibility, 67 - 91%. In both articles, cystine was digested markedly less than the other amino acids at 52 and 67% respectively. The microbial crude protein component of protein leaving the stomach will have a fairly constant rate of digestion and absorption (0.7 for microbial true protein, SCA 1990), whereas the undegraded dietary protein leaving the rumen will be digested to a variable extent, older forages being less digestible (Corbett 1987).

Lindsay *et al.* (1980) and Oosting *et al.* (1995) took endogenous protein into account and reported 73 and 86% absorption for true protein entering the intestines respectively. Hogan *et al.* (1989) reported 70 and 71% of non-ammonia nitrogen (crude protein leaving the stomach) for two tropical grasses was truly digested in the intestines. This equated to 153 ± 12 and 167 ± 17 g *NAN* being truly digested / kg *DOMI* (± standard error). The unpublished review of E. Furnival, cited by SCA (1990), found the apparent digestibility of non-ammonia nitrogen was 0.57 ± 0.04 in the duodenum and ilium, and 0.15 ± 0.09 in the large intestine.

Armstrong (1982) listed values ranging from 7.72 - 13.81 grams of amino acid absorbed in the small intestine per MJ of *ME* consumed for a range of temperate grasses and legumes. Generally, the protein *ME* contribution of grasses, in terms of total *ME* absorbed, was lower than for legumes. Similarly, Corbett (1987) gave values of 8.6 - 15.2 grams of amino acid absorbed per MJ of *ME* consumed (three trials were similar in both reviews). McMeniman *et al.* (1986b) reported lower values for Mitchell grass and mulga grasslands, 2.90 - 9.66 grams of amino acid absorbed per MJ of *ME* (mean 6.44). No allowance for amino acids of endogenous origin were included in the above values.

SCA (1990) assumed the true protein component of microbial protein leaving the stomach to be 0.8, and that 0.7 of this will be apparently digested. This represented 6.1 g of apparently digestible *MCP* leaving the stomach / MJ *ME* (95 g / kg *DOMI*) for first growth pastures etc., and 4.7 g of apparently digestible *MCP* / MJ *ME* (73 g / kg *DOMI*) for other forages. SCA (1990) followed ARC (1980, 1984) in assuming the digestibility of undegraded dietary protein of feeds other than forages is equivalent to the digestibility of microbial true protein, 0.7. For forages, they used the equations by Webster *et al.* (1982) which reduced the digestibility of undegraded dietary protein in line with the crude protein content of the forage:

$$\textit{digestibility of undegraded protein} = (\, 0.455 * \textit{crude protein} - 14.65 \,) / 100$$

This review of protein absorption has assumed none occurs proximal to the small intestines. However, recent findings suggest significant amounts of peptides may be absorbed in the omasum, highlighting the need for further research into the function of this organ (Webb *et al.* 1992, 1993 cited by Faichney 1996; unpublished data of H. Tagari and G. J. Faichney cited by Faichney 1996).

Amino acids not absorbed in the small intestine pass through to the large intestine where they are deaminated with ammonia and absorbed across the caecal wall (McDonald 1948 cited by Elliot and Little 1977, Hogan 1982, Lindsay and Armstrong 1982). Microbial fermentation in the caecum and colon results in microbial crude protein production which is not absorbed (Elliott and Little 1977).

B1.3 Protein metabolism

Absorbed amino acids (essential and non-essential) and ammonia are mainly used to produce protein in the liver and peripheral tissues. Essential amino acids are those that the animal is unable to synthesise from ammonium ions and energy (Weston and Hogan 1973). Many non-essential amino acids are metabolised as they pass through the wall of the small intestine and are resynthesised as necessary from carbon skeletons and ammonia (Hogan 1982). Amino acids are also important precursors of gluconeogenesis (Lindsay 1980).

B1.3.1 Maintenance protein requirements

SCA (1990) calculated net protein requirements for the various maintenance activities, then used an efficiency factor to calculate the requirements for *apparently digestible protein leaving the stomach* (*ADPLS*). The protein maintenance requirement is that amount required to replace protein lost through synthesis and catabolism (protein turnover). Protein for maintenance consists of endogenous faecal protein, endogenous urinary protein, and dermal protein losses (sweat, scurf, hair, wool, hooves, horn).

Endogenous faecal protein (*EFP*) represents the amino acids which enter the gut in secretions and sloughed mucosal cells and are not digested and absorbed. *EFP* losses for both sheep and cattle increase as the dry matter intake of the diet increases, 15.2 g being lost for every kg of dry matter consumed (SCA 1990). Corbett *et al.* (1987) stated 'the need to allow for *EFP* is not eliminated simply by using values for the apparent digestibility of protein in the intestines because the endogenous faecal nitrogen has originated from a larger quantity of *ADPLS* previously absorbed and metabolised'.

Endogenous urinary protein (*EUP*) loss is calculated for sheep as a minimum of 3.375 g / day with an additional loss of 0.147 g / day for every kilogram of bodyweight (ARC 1980 adopted by SCA 1990).

The minimum dermal protein loss for sheep is 0.25 g / $kg^{0.75}$ (Corbett *et al.* 1987). The maintenance costs of dermal protein of sheep represent a continual irreversible loss of protein as wool irrespective of their body condition or nutritional status. Protein requirements for wool growth will be discussed in more detail later.

Hogan (1982) gave the protein maintenance requirements of an adult sheep at 12 - 13 g / day but ignored dermal maintenance requirements.

B1.3.2 Protein requirements of gain

The net requirement of protein for liveweight gain is dependent on the protein content of that gain. The actual protein (and fat) content of varies with age (liveweight), sex and rate of liveweight gain (SCA 1990).

SCA (1990) used liveweight as a proportion of the animal's *SRW* (see below) to predict the proportion of fat and protein in each unit of empty bodyweight gain. This value is modified for the rate of gain, via the ratio of net energy available for gain to net energy requirements for maintenance. The efficiency of *ADPLS* for liveweight gain is the same as that for maintenance.

B1.3.3 Wool protein requirements

The protein required for wool growth is equivalent to clean wool growth which is entirely protein (SCA 1990). SCA (1990) related clean wool growth to *MEI*, but at a constant rate which was specific for each genotype of sheep, via a standard reference weight (*SRW*) and standard fleece weight (*SFW*). *SRW* is the liveweight of an animal when skeletal development is complete and the empty body contains 250 g fat / kg, and SFW of a non-pregnant, non-lactating, adult sheep (2 years or older) of given type (breed, strain, sex) is the annual greasy fleece production (kg). *SFW* declines exponentially for animals less than two years of age.

B1.3.4 Protein requirements for pregnancy and lactation

This topic is not reviewed here as this study deals with wethers and non-breeding ewes. The reader should refer to reviews by Corbett (1987) and SCA (1990) for more information.

B1.3.5 Efficiency of protein use

Poppi and McLennan (1995) reported that the efficiency of protein deposition was dependent on two factors, availability of non-protein energy yielding substrates, and availability of essential amino acids.

SCA (1990) stated the efficiency of use of all amino acids is reduced if one particular amino acid is lacking, or where amino acids levels are excess to requirement. They applied an efficiency of 0.7 to *ADPLS* for calculations involving endogenous faecal protein, endogenous urinary protein and growth.

B1.3.6 Efficiency of wool production

Hogan *et al.* (1979) reviewed the efficiency with which wool is grown and reported the following values: 0.93 - 1.73 g clean dry wool / 100 g organic matter intake, 1.17 - 2.20 g / 100 g digestible organic matter intake, 8.3 - 15.1 g / 100 g of absorbed amino acids. Corbett (1987) reported that low conversion rates arose because of the specific requirements of wool growth for sulphur containing amino acids, the low prevalence of these amino acids in total absorbed amino acids and, therefore, wastage of the non-limiting non-sulphur containing amino acids. SCA (1990) reported an efficiency factor of 0.6 for *ADPLS*.

B1.4 Energy digestion and metabolism

Plant carbohydrates undergo extensive microbial fermentation within the rumen releasing volatile fatty acids which are absorbed across the rumen wall (Corbett 1987), and to a lesser extent, across the omasum and abomasum (Moir 1984). Methane and carbon dioxide are also produced (Weston and Hogan 1973, Armstrong 1982) and removed by eructation. Water soluble carbohydrates are readily accessible to microbial digestive enzymes while the insoluble cell wall polymers require the diffusion of enzymes within their structure before digestion can occur (Smith 1973, Weston and Hogan 1973).

Volatile fatty acids constitute 50 - 75% of the digestible energy ingested by ruminants (Lewis and Hill 1983). Acetic acid is the most common volatile fatty acid producec followed, in declining order, by propionic, butyric and valeric / isovaleric acids (Soeparnc *et al.* 1984, Soeparno and Davies 1987, McMeniman *et al.* 1989, Dijkstra 1994, Oostin *et al.* 1995). Their relative production ratios (fermentation pattern) are affected by forage composition (Dove and Milne 1994).

Propionic acid is especially important as it enters the liver and undergoes gluconeogenesis, providing 50 - 75% of ruminant glucose (Bergman 1990). Leng (1985) cited Cridland (1984) who reported propionate supplied 80 - 90% of glucose produced by maintenance-fed animals. Leng (1985) also highlighted evidence suggesting propionate production from forages, and therefore glucose production, influenced the efficiency of metabolisable energy utilisation.

Although forages generally contain low levels of lipids (Hawke 1973), those present undergo hydrolysis in the rumen and release fatty acids, glycerol and sugars (Weston and Hogan 1973, Lewis and Hill 1983). This is followed by biohydrogenation of the unsaturated fatty acids, and fermentation of the glycerol and sugars, to produce *VFA*s. Rumen microbes also produce lipids which flow to the abomasum and intestines and undergo digestion and absorption (Lewis and Hill 1983).

Gross energy values for carbohydrates, protein and fats are approximately 17.6, 24.0 and 39.0 MJ / kg respectively, and the gross energy of forages is assumed to be 18.4 MJ / kg DM (SCA 1990). The gross energy of digestible food is termed digestible energy, the difference between gross energy of intake and gross energy of faeces.

The loss of energy as methane and nitrogen in urine is a loss of digestible energy, leaving metabolisable energy. Reported values for digestible energy losses in methane include 11 - 13%, 10% and 11.5% (Graham 1967, Corbett 1987, Oosting *et al.* 1993), while values for digestible energy losses in urine include 6 - 12% and 8.9% (Graham 1967, Oosting *et al.* 1993). Digestible energy losses in urine occur because certain products of digestion require conjugation to energetically useful substances before they can be excreted (Weston and Hogan 1973). Total digestible energy losses (methane and urine) for forages have been reported at 18.0 and 20.4% (Graham 1967, Oosting *et al.* 1993). SCA (1990) used the generally accepted conversion factor of 0.81 to convert digestible energy to metabolisable energy.

Although the level of forage digestibility varies with level of feeding (Graham and Searle 1972, Smuts *et al.* 1995), and therefore, potentially the metabolisabe energy available to the body, SCA (1990) did not make allowance for this. Instead, they considered the increased costs of maintenance as level of feeding increased (9% of *MEI*), compensated for any decrease in digestibility and metabolisable energy.

Plant fibre escaping fermentation in the rumen and digestion in the intestines may ferment in the caecum and colon. Armstrong (1982) reported 0.04 - 0.28 of digestible energy disappeared by fermentation in the caecum and colon. This represented 0.00 - 0.30 of digestible cellulose and 0.05 - 0.41 of digestible hemicellulose. Similarly, McMeniman *et al.* (1986b) reported 0.65 (range 0.48 - 0.78), 0.23 (0.10 - 0.39) and 0.13 (0.05 - 0.23) of apparently digested organic matter was apparently digested in the rumen, small intestines and large intestines respectively. Corbett (1987), cited Ulyatt *et al.* (1975) who reported 0.08 - 0.17 of total volatile fatty acid production arose from the caecum and colon.

B1.5 Energy metabolism

The efficiency factor converting net energy (actual energy used for maintenance, growth etc.) to metabolisable energy represents the loss of heat from using metabolisable energy, and to a lesser extent, the heat released during rumen fermentation. Webster (1980) reported heat lost in fermentation was 6 - 8% of digestible energy.

Wallach *et al.* (1984, 1986) reviewed the manner in which sheep grazing models calculate maintenance energy requirements and weight gain.

B1.5.1 Maintenance energy requirements (ME_{maint})

SCA (1990) gives the following definition for maintenance: *'At the maintenance level of feeding, the requirements of the animal for nutrients for the continuity of vital processes within the body, including the replacement of obligatory losses in faeces and urine and skin, are exactly met so that the net gain or loss of nutrients and other tissue substances by the* *animal as a whole is zero. Maintenance is not synonymous with zero change in weight.'* In practice maintenance often means zero gain or loss of energy, other nutrients being ignored. Because of the difficulty in accurately measuring energy balance, constant liveweight is generally used as a proxy for maintenance. However, this assumption may be erroneous because of changes in gut fill and body composition (Young and Corbett 1972a).

Young and Corbett (1972a) considered the energy for wool growth to be only 2.6% of the energy for maintenance. The following regression equation described the maintenance energy requirements (MJ *ME* / day) of Merino sheep grazing pasture at various liveweights and various stages of fleece growth:

$$ME_{maint} = 188.7 * Wt + 1071$$

Other workers have estimated maintenance energy to be 9.5 - 11.4 MJ *ME* / day (Coop and Hill 1962), 3.6 - 5.9 MJ *ME* / day (Lambourne and Reardon 1963), and 7.13 MJ *ME* / day (Langlands *et al.* 1963b).

Maintenance energy, as calculated by SCA (1990), is the sum of resting metabolic rate, and energy costs associated with feed intake, grazing and cold stress. Cold stress was ignored in this study as it is unlikely to be of concern in Queensland. Both the resting metabolic rate and grazing costs are calculated in terms of net energy (*NE*) and converted to *ME* by a common efficiency factor (k_m). The resting metabolic rate in net energy terms is 0.26 MJ / $kg^{0.75}$, this is increased for entire males (15%) and decreased for ages up to six years.

The resting metabolic rate includes the energy associated with standing, eating and ruminating. The feeding cost of a prepared ration for penned sheep was 2 - 3% of total maintenance costs (Young 1966). Osuji (1974) reported the energy cost of ruminating to be small at 0.125 kJ / kg / hour while Graham (1964a) found rumination needed 1.0 kJ / kg / hour (range 0.33 - 2.17) and was unaffected by rate of feed intake. Resting metabolism costs have been reported as 5.73 MJ *ME* / day (Langlands *et al.* 1963a), and 6.43 MJ *ME* / day (Coop 1962).

SCA (1990) increased maintenance costs as level of feeding increased because of the increased size and rates of metabolism in organs and tissues. The increased costs was 9.0% of metabolisable energy intake.

B1.5.2 Energy cost of grazing

Grazing animals need extra energy for walking, prehension and chewing including the energy costs of secretions (Osuji 1974). The availability of pasture, pasture quality, topography and distance to watering points influence these grazing costs (Graham 1964b, Osuji 1974, SCA 1990). Penned / yarded sheep have no grazing costs.

Both digestibility and pasture availability will influence the rate and level of feed intake. As pasture availability declines, sheep spend more time grazing, i.e. standing, walking and selecting feed. The effect of pasture availability on grazing time was discussed earlier in Appendix One, Part A.

The increased costs for grazing relative to penned animals have been widely reported:

- 24% - on good quality pasture, Langlands *et al.* (1963b);
- 40% - on poor quality pasture with water nearby, Graham (1964a);
- 72% - on poor quality pasture with water 5 km distant, Graham (1964b);
- 25 - 50%, Osuji (1974);
- 60 - 70%, Young and Corbett (1972a);
- 20% - for sheep on abundant good quality pastures, (Corbett 1987);
- 152 - 235% - higher values as calculated by NRC (1975) occurring as pasture conditions deteriorated, Sahlu *et al.* (1989); and
- 10 - 20% for good pasture and up to 50% for hilly / large paddocks / long walks to water, (SCA 1990).

Lambourne and Reardon (1963) suggested grazing costs of sheep on short pasture were 130 - 375% greater than housed sheep. Subsequently, Corbett (1987) suggested the extra costs of grazing animals were not as great as those suggested by Lambourne and Reardon (1963), even under drought conditions. Errors in this early work probably arose from the intake of faecal pellets leading to incorrect values for faecal organic matter and faecal nitrogen. As a result, feed intakes and diet digestibility were over estimated. Similarly, Young and Corbett (1972b) reported that sheep grazing sparse pastures were likely to ingest large amounts of soil. The resultant increase in faecal nitrogen causes overestimation of digestibility and feed intakes, and probably explains the differences between their earlier results (Young and Corbett 1972a) and those of Lambourne and Reardon (1963)

SCA (1990) calculated the net energy costs of grazing as those additional costs associated with eating (selection, prehension, mastication - no additional allowance was made for the costs of rumination) plus the cost of walking / movement. Eating costs are a function of dry matter intake, dry matter digestibility and liveweight, while movement costs are a function of green feed availability, slope and liveweight. At low levels of green feed availability, total pasture availability is used instead.

B1.5.2.1 Energy cost of eating

Osuji (1974) considered the energy cost of eating, as distinct from the cost of standing and walking, to be greater for grazing animals than for penned animals. He found the energy cost of eating, which was a direct function of time spent eating, to range from 1.1 to 3.8 kJ / kg / hour for a variety of fresh / dried clovers, green / dried / chopped / pelleted grasses and concentrates. Graham (1964a) reported 2.26 kJ / kg / hour (range 1.0 - 4.1) as the energy cost of sheep eating prepared meals of either fresh herbage or hay, the higher values occurred when rate of food intake was greatest. The energy cost of eating uncut swards, i.e. grazing - small patches of pasture (soil + plant material) placed in a calorimeter, was also 2.26 kJ / kg / hour (range 1.21 - 3.30) irrespective of sward type and grazing behaviour, but the author noted that pastured sheep must spend more time eating.

Young (1966) found no difference in the rise in metabolic rate between sheep with oesophageal fistulas (*OF*) and those without. The *OF* sheep had 77% of ingested feed removed via the fistula indicating that prehension and mastication increased heat production during eating rather than the addition of food to the rumen leading to an increased metabolic rate.

B1.5.2.2 Energy cost of standing and walking (movement)

Graham (1964a) gave the cost of standing at 1.42 kJ / kg / hour (range 1.21 - 1.76) while Osuji (1974) cited the following values: 0.50 kJ / kg / hour (Hall and Brody 1933), 0.29 kJ / kg / hour (Blaxter and Joyce 1963), and 0.25 kJ / kg / hour (Osuji 1973).

Reported costs for horizontal movement include: 2.5 kJ / kg / km (Clapperton 1961), 2.1 kJ / kg / km (Webster 1979), and 2.6 kJ / kg / km (ARC 1980).

Reported costs for vertical movement include: 30.0 kJ / kg / km (Clapperton 1961), 26.5 kJ / kg / km (Webster 1979), and 28.0 kJ / kg / km (ARC 1980).

B1.5.3 Energy requirements for liveweight gain

The net energy for liveweight gain is the heat of combustion of the associated fat and protein (SCA 1990). However, the actual energy content of gain may vary with the ratio of fat to protein which is influenced by age (liveweight), sex, rate of gain and breed in the case of cattle. Additionally, water content of the liveweight gain, associated with the level of protein, may vary. A unit change in empty bodyweight (liveweight less the gastrointestinal tract) does not necessarily translate to the same change in liveweight due to variation in associated changes in gastrointestinal mass.

ARC (1980) assumed an increasing energy content of weight gain until the point of sexual maturity and a constant energy content of gain thereafter. SCA (1990) used liveweight as a proportion of the animal's *SRW* to predict the proportion of fat and protein present in each unit of empty bodyweight gain, and therefore, the energy content of gain. This value is modified for the rate of gain via the ratio of net metabolisable energy available for gain to net energy for maintenance. In cases of liveweight loss, the calculated value is modified by the ratio of net energy required from catabolism to meet the dietary deficit to net energy for maintenance. Therefore, the metabolisable energy available for liveweight gain, multiplied by the efficiency of use of this energy for gain (k_g), in conjunction with the energy content of gain, is used to predict empty bodyweight gain. This value is then converted to liveweight gain by a factor of 1.09. In cases of liveweight loss, SCA (1990) used the same equations for liveweight gain except where stated above.

B1.5.4 Energy requirement for wool growth

Experiments which estimated k_m included the growth of wool which occurs at maintenance. Estimations of k_g also include the growth of wool. SCA (1990) assumed the combustible energy of Merino greasy wool was 0.023 MJ / g, that estimates of k_m and k_g included greasy wool growth rates of 6 g / day, and the net efficiency of use of *ME* for wool growth was 0.18. This gave the following equation to calculate the *ME* requirements for daily wool growth rates in excess of 6 g / day:

$$ME_{wool}\ (MJ / day) = 0.023 * 0.18 * (\ wool\ growth\ rate - 6.0\ )$$

Since ME_{wool} is small relative to expected levels of *ME* intake, and given the accuracy of estimating *ME*, ME_{wool} can be ignored for practical applications.

B1.5.5 Energy requirements for pregnancy and lactation

The costs associated with pregnancy and lactation will not be reviewed here as this study was concerned wethers and non-breeding ewes. The reader is referred to reviews by Corbett (1987) and SCA (1990).

B1.5.6 Efficiency of energy utilisation for maintenance (k_m)

The efficiency of use of metabolisable energy for maintenance reflects the loss of energy in the processes concerned with maintenance. The energy actually used for maintenance is net energy. Wallach *et al.* (1984) and SCA (1990) followed ARC (1980) in assuming energy expended for muscular work (movement, eating) was used with the same efficiency as in resting metabolism. Both ARC (1980) and SCA (1990) calculate k_m from the energy content of the diet. SCA (1990) used a minimum value for k_m of 0.5, which increased by 0.02 units for every unit (MJ) increase in dietary *ME*. Increased costs of prehension and mastication account for some of the reduction in k_m as feed quality and *ME* content of the diet (ME_{diet}) falls. Graham (1980) reported little change with age in the efficiency of utilisation of energy for maintenance (range 0.73 - 0.8).

B1.5.7 Efficiency of use of body tissue

Where the maintenance energy requirements of animals are not met by the intake of dietary metabolisable energy (negative energy balance), body tissue is catabolised. The energy released from the mobilisation of a unit of liveweight is equivalent to the energy required (energy content) for the same liveweight gain (Searle *et al.* 1972). However, Lindsay *et al.* (1993) considered there were no reliable values for the efficiency of use of tissue fat and protein, and by default used the same value suggested by SCA (1990), 0.8.

B1.5.8 Efficiency of energy utilisation for gain (k_g)

The efficiency of metabolisable energy for protein deposition (0.44) is much less than the efficiency for fat deposition (0.74). However, because of the greater energy content of fat (39.5 *vs.* 23.8 MJ / kg), the energy cost of deposition of fat and protein are approximately equal (53.4 *vs.* 54.1 MJ / kg, Lindsay *et al.* 1993).

Webster (1988) suggested the efficiencies for fat and protein deposition were constants. Lindsay *et al.* (1993) agreed this was probably true for fat, given the relative importance of fat cell hypertrophy over hyperplasia, but it was less plausible for protein deposition which varies across tissue types. SCA (1990) considered the variability in efficiency of use of *ME* for protein deposition arose because protein deposition is the balance of two continuing processes, protein synthesis and catabolism.

It has long been recognised that the efficiency of utilisation of *ME* for gain declines with increasing forage maturity, or conversely, efficiency of utilisation of *ME* for gain increases with increasing diet quality (Armstrong 1982, Wallach *et al.* 1986, SCA 1990). SCA (1990) list the ARC (1980) equation for the efficiency of utilisation of *ME* for gain of first growth forages in terms of *ME* content of the diet:

$K_g = 0.072 * ME_{diet} - 0.318$

For all temperate pastures, Mediterranean pastures and annual legumes where *ME* content is less than 9.5 MJ / kg, and for all tropical and subtropical grasses and legumes and forage crops, SCA (1990) recommends the use of the following ARC (1980) equation developed from 'aftermath' forages:

$K_g = 0.063 * ME_{diet} - 0.308$

The second equation predicts lower k_g values for a given dietary *ME*, the difference increasing as dietary *ME* increases. SCA (1990) gave a number of reasons why *NE* value of later growth temperate pastures is reduced compared with first growth forages for the same *ME* content:

- reduction in the net efficiency of rumen microbial fermentation yielding lesser amounts of metabolites from a given intake, and changes in the composition of the *VFA*s due to changes in the water soluble carbohydrate content of forages;
- increased acetate to propionate ratio means that more acetate will be oxidised in an inefficient manner and less used for lipogenesis; and
- decreasing amounts of protein relative to *ME* means less amino acids may be available for gluconeogenesis.

SCA (1990) reported there was much less information available on the efficiency of use of energy for gain of tropical forages compared with temperate forages before citing the work of Graham (1967) and Tudor and Minson (1982). Graham (1967) used *Desmodium uncinatum* (*ME* 6.5 MJ / kg) and *Sorghum almum* (*ME* 6.7 MJ / kg) and obtained k_g values greater than would be predicted with the recommended SCA (1990) equation. Their lowest estimated k_g values were 0.16 and 0.26 while the SCA (1990) tropical forage equation predicts values of 0.10 and 0.11 for *Desmodium* and *Sorghum* respectively. Graham (1967) however warned his values were 'only approximate because maximum balance [relative to maintenance energy balance] was too low for an accurate assessment'. Tudor and Minson (1982) used the comparative slaughter technique and reported k_g values of 0.28 and 0.17 for tropical grasses with *ME* contents of 8.1 and 8.0 MJ / kg respectively. SCA (1990) predicted values are 0.20 for both grasses.

Armstrong (1982) reported that legumes, or mixtures of legumes and grasses, have higher k_g values than grasses of the same digestibility. He concluded that 'differences in nutritive value of legumes and grasses did not lie in their capacity to supply the amounts of amino acids required for protein synthesis *per se*'. Rather, the ability of many amino acids to act as glucose precursors, and the increased amino acid uptake from the intestine of legume diets, may enhance the efficiency of utilisation of *ME*.

Graham (1980) fed a mixed concentrate and forage to sheep ranging in age from two months to six years and found that k_g increased from 0.32 at two months of age to 0.55 at 10 months of age, and varied little thereafter. This change in k_g with maturity was in line with the greater efficiency of fat synthesis compared with protein synthesis, given the changes in fat / protein composition of gain that occurs with maturity (Armstrong 1982).

Webster (1980) noted that energy costs of nutrient absorption and metabolism increase markedly above maintenance, and is one reason why the net availability of metabolisable energy declines as the level of feeding rises from below to above maintenance. As stated earlier, SCA (1990) increased maintenance costs (9.0% of *MEI*) to compensate for reduced digestibility, and any loss in efficiency of gain, as a result of increased feed level.

Given the effect of type of pasture growth and legume content, SCA (1990) proposed the use of a single equation for temperate pastures which modified k_g for a given *ME*, depending on the time of year and the proportion of legume in the pasture.

B1.5.9 Compensatory growth

Compensatory growth describes the increased liveweight gain seen when animals, suffering from undernutrition, are supplied with high quality feed. The growth rate is greater than if they had not suffered a period of nutritional stress.

In early grazing (Allden 1968a, d) and pen trials (Graham and Searle 1975), the increased feed intake associated with compensatory growth was found to account for the increased liveweight gains. However, Allden (1981) reported compensatory gain was generally associated with both an increased feed intake level and increased efficiency in the conversion of feed to gain. SCA (1990) concluded that initial compensatory gain involved an increased feed intake and subsequent increased gastrointestinal mass. Reduced maintenance requirements will also persist for a period, and this in conjunction with an apparently increased use of *ME* for gain, results in the phenomenon of compensatory liveweight gain.

In contrast, Ryan *et al.* (1993a, b) reported sheep showing compensatory growth following a loss of 30.8% of bodyweight had similar feed intakes to control sheep for the first 12 weeks following realimentation. Compensatory growth during this period occurred as a result of greater efficiency of use of feed. Greater efficiency was suggested to result from reduced maintenance costs and / or a change in the ratio of fat to protein in the tissues deposited. During the period of feed restriction, sheep lost most weight from the gastrointestinal tract, liver and hide. The authors concluded that loss of tissue mass, especially from the metabolically active gut and liver, reduced maintenance costs. These costs remained reduced until the tissue mass of these organs were restored. Additionally, the restoration of these tissues required a high level of protein deposition. After this point, the compensating sheep had increased feed intakes for 35 days which were found to account for the compensatory growth during this period.

B1.5.10 Efficiency of wool production

Butler and Maxwell (1984) reviewed the efficiency with which feed is converted to wool and recognised two forms of efficiency. Firstly, gross efficiency is the amount of wool produced per unit of feed intake and follows the law of diminishing returns in response to changes in the animal's diet and bodyweight. Secondly, net efficiency is the gross efficiency of wool production at maintenance, or the genetic potential for wool growth efficiency.

Allden (1979) concluded that high wool producers within a flock consume both more feed and utilise this feed more efficiently than low wool producers, whereas differences between strains and breeds of sheep reflects differences in feed intake rather than differences in the gross efficiency of conversion of feed to wool. Pritchard (1988) also showed high producing sheep had higher intake of digestible organic matter and were better able to utilise apparently digested protein for wool production than low wool producing sheep.

Cronjé and Smuts (1994) used two year old Merino rams classed according to their clean fleece growth rates. They concluded that high wool producing rams , with greatest gross efficiency, did not utilise the available nutrients more efficiently but partitioned more of the available nutrients to wool production at the cost of body tissue deposition. The differences between groups of rams were most visible at higher rates of feed intake.

SCA (1990) assumed a net efficiency of *ME* for wool growth of 0.18 based on the work of Graham and Searle (1982) who reported a range of 0.16 - 0.19.

B1.5.11 Heat stress and tropical adaptation

When the ambient temperature rises above the zone of thermoneutrality, animal production is reduced through a reduction in feed intake (see Appendix One, Part A), but also by an increased metabolic rate with the rise in deep body attention (van't Hoff or Q10 effect, Thwaites 1985). SCA (1990) made allowances for the additional energy to alleviate cold stress, however, they recognised the lack of quantifiable data on energy costs for heat stress and made no allowance for it.

The capacity to adapt to tropical climates is especially important for sheep. They occupy a hotter 'local' environment than cattle due to the air temperature gradient above the ground given their respective body heights, 30 - 70 cm and 70 - 140 cm (Thwaites 1985). Hopkins *et al.* (1978) showed the ability of locally reared sheep in a tropical environment to maintain thermostasis under conditions of heat stress is normally distributed, as measured by rectal temperature. Thwaites (1985) considered the thyroid secretion rate, and therefore, heat production of sheep in tropical regions to be permanently reduced.

Hopkins *et al.* (1978) also showed the relatively greater importance of cutaneous water evaporative loss compared to respiratory evaporative loss (only 8 - 10% of total daily evaporative water loss) in terms of thermoregulation. Similarly, Alexander *et al.* (1987) found blood flow to the nasal mucosa and skin extremities increased with acclimatisation to heat stress, while the blood flow to the respiratory muscles was not increased further above that of the initial response to acute heat stress. This indicated heat acclamation was not due to increased ability to pant, in contrast to the importance which Thwaites (1985) attributed to respiratory evaporative cooling.

As stated previously, animals grazing under thermally stressful conditions may have reduced feed intakes if the feed has a low ratio of protein to energy. Such forages are utilised inefficiently with a higher heat increment of feeding, which, when combined with the climatic heat stress, reduces feed intake. Supplementation of these animals with escape protein, so that the ratio of protein / energy available to the animal increases, results in reduced heat increment of feeding, overall heat load and increased feed intake (Leng 1989, 1990, 1991).

Part C

Wool Growth

C1.1 Introduction

Wool production per head is one of the major factors affecting farm income (Chapter Three). Marked seasonal and annual variation occurs in the quantity and quality of wool produced (Robards 1979). Annual fleece production in the arid zone may vary by 50 - 60% (Pritchard 1988).

Robards (1979) analysed wool production data for Queensland for the years 1970-71 to 1975-76 (table A1.1). The amplitude and coefficient of variation are measures of variation. The amplitude was calculated by expressing the difference between the highest and lowest value as a percentage of the lowest value. In the west of the state there was a north - south trend for greasy fleece weight to increase and variation to decrease. A more extensive analysis of Queensland wool production is given in figure 1.1 of Chapter One, while the factors controlling wool growth are described in this section.

Table A1.1. Greasy fleece production, coefficient of variation and amplitude for Queensland regions as calculated by Robards (1979) for the period 1970-71 to 1975-76.

Statistical Division	**Greasy Fleece Weight (kg)**	**Coefficient of Variation (%)**	**Amplitude (%)**	**Estimated Clean Fleece Weight (kg)**
Downs	4.64	4.7	15.1	2.8 - 3.1
South Western	4.92	4.9	13.7	2.6 - 2.8
Central Western	4.66	6.4	21.1	2.6 - 2.8
North Western	4.25	8.0	23.7	2.0 - 2.6

Hogan *et al.* (1979) considered large framed peppins, medium South Australian Merinos, and their crosses, were capable of producing up to 20 grams of clean wool per day (28.6

grams / d greasy, assuming 70% yield). Black (1984, 1987) reported the maximum rate of wool growth, and its structure and composition, are determined by several genetically controlled factors: the number of wool follicles, the maximum number and size of cells in the follicle bulbs, the proportion of cells migrating from the bulb that enter the fibre, and the size, type and arrangement of cells within the fibre.

Potential wool growth rates only occur under optimal feed conditions that ensure an adequate supply of necessary nutrients to individual wool follicles.

C1.2 Wool morphology

Wool is comprised of three types of fibres: true wool fibres, hair fibres and kemp which vary in coarseness, structural and growth period (Thomas and Rook 1983). Clean wool is comprised of pure protein formed in bulb cells within the follicle, energy being required for cell division and formation of peptide bonds linking together chains of amino acids (Black 1984). Greasy wool is principally comprised of keratinised protein with lipids and minerals present in small amounts (Thomas and Rook 1983).

Reis (1979) classified wool proteins into three main groups: low-sulphur, high-sulphur and high-tyrosine proteins. Low-sulphur proteins, with sulphur contents less than the mean wool value, make up more than 60% of total wool protein and contain all of the methionine and most of the lysine in wool. High-sulphur proteins with sulphur contents greater than the mean wool value, contain higher proportions of cystine, proline and serine and account for 18 - 35 % of total wool protein. High-tyrosine proteins have high levels of tyrosine and glycine and may make up between 1 - 12 % of total wool protein.

Wool follicles are divided into primary and secondary follicles with further subdivision occurring based on initiation time, development and anatomy (Hardy and Lyne 1956). Primary follicle development is initiated at approximately 60 days gestation and are producing fibres by 100 days, with most follicles mature by day 110. Secondary follicle development begins from approximately 90 days gestation with maturation occurring in two waves, the first from approximately 100 days gestation, and the second 4 - 18 weeks after birth (Thomas and Rook 1983, Hocking Edwards *et al.* 1996). Structurally, primary follicles possess an apocrine sweat gland, sebaceous gland and arrector pili muscle while secondary follicles possess only a sebaceous gland (Thomas and Rook 1983). Follicles vary in shape (straight to curved), length and angle to the skin which causes marked variation in follicle depth (Orwin 1989).

Wool follicles are organised into follicle groups made up of three primary and a variable number of secondary follicles. The number of secondary follicles in each follicle group is 9 - 12 in hair sheep increasing to 70 - 80 for fine wool Merinos. The number of primary follicles per sheep is largely independent of breed and in the range of $3 - 5 * 10^6$ (Thwaites 1985). Black and Reis (1979) listed the total number of wool follicles or fibres as $34.0 - 82.0 * 10^6$ for Merinos, while Merino / Lincoln crosses had smaller values.

Within the wool follicle, cell division occurs at two sites; the follicle bulb cells surrounding the dermal papilla and the cells forming the outer root sheath (Chapman and Ward 1979). Hynd (1994a) summarised the following factors affecting wool fibre dimensions, some of which may be associated with the size and shape of the follicle bulb and dermal papilla:

- rate of cell production in the germinative region of the follicle bulb;
- proportion of new cells retained within the follicle bulb and leading to changes in the bulb size;
- proportion of migrating cells that enter the fibre and inner root sheath; and
- size and mode of packing of follicle cortical cells following keratinisation.

Follicle attributes differ in their influence on fibre diameter and fibre length (Hynd 1994a). Fibre length was moderately correlated with the size of the follicle bulb ($r^2=0.25$ $P<0.01$) and dermal papillae ($r^2=0.30$ $P<0.01$), poorly correlated with rate of division of bulb cells ($r^2=0.10$ $P<0.05$), and was highly correlated with cortical cell length ($r^2=0.62$ $P<0.01$). Fibre diameter was highly correlated with follicle bulb area ($r^2=0.56$ $P<0.01$) and papilla area ($r^2=0.59$ $P<0.01$), and moderately correlated with the rate of cell division ($r^2=0.36$ $P<0.01$) and the volume of cortical cells following keratinisation ($r^2=0.33$ $P<0.01$). A regression including terms for nutrition, phenotype and cortical cell length explained 60% ($P<0.0001$) of the variation in fibre length while nutrition, phenotype, cortical cell volume and papilla area explained 88% ($P<0.0001$) of the variation in fibre diameter. However, when Hynd (1994b) used hypothyroid and hyperthyroid sheep, fibre length was strongly correlated with rate of follicle bulb cell division ($r^2=0.60$ $P<0.01$) and the proportion of cells entering the fibre versus the inner root sheath, and negatively correlated with cortical cell length ($r^2=0.06$ ns).

The follicular efficiency measured by Hynd (1994a) in terms of fibre output per unit bulb cell produced was the same for sheep producing strong wool (27.0 μ) and fine wool (20.3 μ). The author concluded that there was no inherent inefficiency in small follicles producing fine wool, and therefore no reason why large amounts of fine wool cannot be produced.

Wool fibre growth is cyclical with alternating periods of growth and rest. Merino wool fibre growth (anagen phase) probably extends for more than eight years with a small proportion of fibres (less than 12%) being shed in a normal year (Ryder 1962, Thomas and Rook 1983, Schlink and Dollin 1995).

C1.3 Factors affecting wool production

Supply of amino acids to the follicle is generally regarded as the major factor limiting wool growth rate (Thomas and Rook 1983, Black 1984, Reis 1989, Shaw and Findlay 1990). The type and amount of amino acids and other nutrients reaching the follicle depends on the feed intake, rumen microbial digestion, abomasal and intestinal digestion, intestinal absorption and competing requirements within the animal. Thomas and Rook (1983) considered any limiting effect of dietary energy on wool production would mainly be through its influence on amino acid supply to the follicle.

C1.3.1 Pre and postnatal nutrition

The potential number of wool follicles is thought to be genetically controlled (Black 1984, 1987). Corbett (1979) considered the foetus was likely to die when nutrition was so poor as to affect development of primary follicles *in utero*. Skerritt *et al.* (1994) found no significant effect of food and water deprivation (96 hours) at day 27 and / or day 35 of gestation on primary follicle development.

The ratio of productive (mature) secondary to primary fibres (S / P) at birth can be reduced by undernutrition of the foetus during gestation (Short 1955, Schinkel and Short 1961, Everitt 1967, Cartwright and Thwaites 1976, Kelly *et al.* 1996). Reports of the carryover effects of foetal undernutrition on later wool production have been variable. Short (1955) found that restricted feed during pregnancy also affected subsequent milk production and lamb growth, despite *ad lib.* feeding. He reported sheep had reduced S / P fibre ratios at 168 days of age but no difference in wool production (200 days) because increased fibre diameter (2.2 μ) compensated for the reduced number of fibres. Unfortunately, the change in fibre diameter would reduce the value of the fleece. However, Schinkel and Short (1961) reported lambs with reduced S / P ratios at birth due to foetal undernutrition produced approximately 8.5% less wool to about 3 years of age. Similarly, Kelly *et al.* (1996) found reduced S / P ratios at birth persisted to 1.4 years of age (19.9 *vs.* 21.7 for controls, $P<0.01$) and resulted in reduced clean wool between birth and 0.4 years (0.1 kg, $P<0.01$), and 0.4 and 1.4 years (0.14 kg, $P=0.10$). Fibre diameter was increased at 1.4 years (0.1 μ, $P<0.05$) with a lower coefficient of variation of fibre diameter (0.5% units, $P<0.01$). There were no significant differences in yield, staple strength or staple length.

Postnatal (four months) nutrition did not stimulate initiation of new follicles (Schinckel and Short 1961), but severe nutritional stress in the first month of life may affect the number of secondary follicles developing to maturity (Schinkel 1955). In contrast, Schinkel and Short (1961) found no permanent depression in maturation of secondary follicles due to poor postnatal nutrition. The latter authors suggested the conflict occurred because of the interaction of prenatal nutrition and birthweight with postnatal growth rates. Allden (1968b, c, d) also showed postnatal nutritional stress was unlikely to permanently affect wool production (clean wool, S / P ratio, fibre diameter, fleece weight) in all but extreme cases, wool production being less sensitive to undernutrition than liveweight.

Lax and Brown (1967) showed secondary follicles were still producing fibres up to 16 months of age while Brown *et al.* (1966) reported the total number of fibres was increasing up to 30 months of age. Similarly, Daly and Carter (1955) reported an increase in the ratio of secondary follicles to primary follicles for Merinos between 10 and 22 months of age on unrestricted good quality feed.

C1.3.2 Nutrition of grown animals

Reis (1989) reported wool growth rates may vary by up to 400% due to the effect of nutrition. Differences in wool growth of penned sheep of different genetic potential for wool production were greatest at high levels of feed intake (Williams 1966, Williams 1995). Similarly, pasture conditions favouring higher rates of wool production cause phenotypic differences in wool production to be more prominent with both temperate (Williams 1964b, McManus *et al.* 1966) and tropical pastures (Pritchard *et al.* 1986, Pritchard 1988).

The supply of energy substrates and amino acids to the actively growing follicular bulb depends on the arterial concentration of these substances and the blood flow to the skin (Thomas and Rook 1983). More recent work has found a relationship between wool growth and staple strength with blood flow (Hocking Edwards and Hynd 1991, Thompson and Hynd 1994). The wool growth / blood flow relationship exists for sheep selected for and against clean wool growth (Hales and Fawcett 1993) and between different strains (Hocking Edwards and Hynd 1994). Hocking Edwards and Hynd (1994) found a 50% increase in the flow of blood through the skin was associated with an 85% increase in wool growth, but only 27.0% of the variation in wool growth rates between strains was accounted for by the differences in skin blood flows. No relationship was found between the area of vascular tissue per unit volume of skin and the rate of blood flow or wool production.

In general, better quality feed and / or increased feed intake has the following effects at the follicle associated with increased fibre growth (Hynd 1989, Hynd 1994a):

- increased bulb cell mitotic rate;

- increased bulb volume;
- increased dermal papillae;
- reduction in proportion of orthocortex; and
- increased ratio of fibre area to fibre plus inner root sheath area.

C1.3.3 Ruminal protein degradation and intestinal protein flow

Protein passing to the abomasum and intestines may bear little resemblance to that ingested due to microbial fermentation in the rumen. The type and level of protein available for digestion and absorption in the intestines is dependent on the amount of dietary protein escaping degradation in the rumen, and on the rate of microbial protein synthesis which, in turn, is dependent on the digestible energy content of the feed (see Appendix One, Part B). Neither plant nor microbial proteins are rich in sulphur amino acids (Thomas and Rook 1983).

Pritchard (1988) cited unpublished work of his showing an increase in wool production (20%) following supplementation with nitrogen, phosphorous, sulphur and sodium of sheep on a mulga ration. The increase in wool production was attributed to a greater quantity of protein and amino acids reaching the small intestine, primarily from improved rumen function and dry matter intake without substantial changes in nutrient composition. Similarly, polyethylene glycol, when given to sheep on mulga based diets, binds with the tannins in preference to proteins, thereby increasing nutrient availability for digestion, wool growth and liveweight gain (Pritchard *et al.* 1988).

Many workers have increased wool production by using the following methods to increase the amount of protein available for absorption (Reis 1969, Reis and Downes 1971, Black *et al.* 1973, Hynd 1989, Lee and Williams 1993, Mata *et al.* 1995):

- use of feeds that are naturally less degraded in the rumen;
- treating amino acid / protein sources to reduce ruminal degradation; and
- supplying amino acids / proteins directly to the abomasum / intestines.

Black (1984) cited Hynd (1982) who found that for sheep on diets of similar energy value, variations in the outflow of rumen protein influenced the daily rate of clean wool growth. As the amount of protein entering the intestines increased from 40 to 200 g / day, wool growth rate rose from 4 to 15 g / day. Reis (1969) reported maximal rates of wool growth were attained by sheep at maintenance energy intake when 150 g / d of amino acids were supplied for digestion and absorption in the intestines (approximately 240 g / d of digestible dry matter plus 100 - 120 g / d of abomasal casein). Similarly, Hynd and Allden (1985) found a protein flow of 150 - 200 g / day to the abomasum gave maximal wool growth rates.

Smuts *et al.* (1995) used Merino rams to show how dry matter intake (r^2=0.137 $P<0.01$) and rumen retention time (r^2=0.102 $P<0.01$) of an *ad lib.* pelleted diet were related to wool growth rates. Based on this data, and results of multiple logistic regression techniques (rumen retention time $P<0.07$, dry matter intake $P<0.34$), rumen retention time had a greater influence on wool growth rate than dry matter intake. The authors proposed that decreased rumen retention time may promote wool production in two ways. Firstly, increased flow of undegraded dietary protein into the intestines increases the amount of amino acids for absorption and wool production. Secondly, the increased rate of flow from the rumen promotes increased microbial efficiency, increasing the flow of microbial amino acid to the intestines. Restricted feeding of the same diet increased retention time and dry matter digestibility ($P<0.01$). Neither variable was related to wool growth rates. Therefore, the authors proposed that the impact of rumen retention time on wool growth rates was through its effect on dry matter intake and not digestibility. Pritchard (1988) found an inconsistent relationship between rumen retention time and wool production and, after reviewing the literature, concluded that any differences in rumen function between sheep differing phenotypically in wool production would be small.

C1.3.4 Sulphur containing amino acids

Wool proteins vary in amino acid composition amongst individual fibres from the same sheep, and may also vary along the length of a single fibre due to genetics, nutrition and physiological status of the animal (Marshall and Gillespie 1989).

Methionine, cystine and cysteine are sulphur containing amino acids that influence rate of wool production (Reis 1979). Wool protein contains approximately 13.1% cystine, 0.5% methionine and small amounts of cysteine (Marshall and Gillespie 1977). Cystine may be supplied via absorption from the gastrointestinal tract, from endogenous sources, or from the conversion of methionine via the transulphuration pathway (Pritchard 1988). Reis (1989) reported that at normal levels of intake approximately 75% of methionine is converted to cysteine. As well as being a major component of wool proteins, cysteine may influence wool growth by providing sulphydryl groups to follicle bulb cells which may influence mitotic activity (Reis 1989).

As a result of the amino acid composition of wool, the influence of rumen protein outflow on wool growth rates depends on the composition of the protein. Oral supplementation with cystine and methionine usually fails to increase wool growth due to their extensive degradation in the rumen (Reis 1969, Reis *et al.* 1978, Coetzee *et al.* 1995). Infusion of sulphur amino acids or proteins rich in them directly into the abomasum, use of proteins protected from ruminal degradation such as formalin treated casein, or intraperitoneal and intravenous administration of cystine and methionine, all increased rates of wool growth and the cystine / sulphur content in wool proteins (Reis 1969, Downes *et al.* 1970, Williams *et al.* 1972, Hemsley and Reis 1984, Lee and Williams 1993, Coetzee *et al.* 1995). Such changes in wool growth are most marked in sheep with a higher genetic potential for wool growth (Williams *et al.* 1972, Williams 1995). Smaller increases in sulphur content of wool follow change from a low to a high intake of feed (Reis 1979).

Reis (1979) reported similar responses in wool growth to abomasal supplementation of either methionine or cystine (up to 2 g / day) for sheep on roughage diets, whereas Williams *et al.* (1972) found a greater response to abomasal methionine supplementation (41 *vs.* 31% increase in wool growth rate). Given the relatively low concentration of methionine in wool protein, and the similar response to methionine and cystine supplementation, Reis (1979) suggested methionine was a precursor for cystine. The maximal response to abomasal methionine supplementation occurred with doses of 1 - 2 g / day; doses of 6 g / day or more depressed wool production. In contrast, Mata *et al.*

(1995) found a linear response in wool growth rates (4 - 38%) to ruminally protected methionine supplementation across a range of dose rates (1 - 8 g / day).

Additionally, the wool growth response to methionine and cystine supplementation appears to be affected by diet. Reis and Tunks (1974) found supplementation of 1.5 - 6 g / day of methionine to sheep on a wheat diet reduced wool growth rates. Hemsley and Reis (1984) suggested these findings, and similar results from Chapman and Reis (1978) and Lindsay *et al.* (1978) with wheat / methionine and oat / cystine diets respectively, indicated another dietary component necessary for wool growth, such as a B group vitamin, may be lacking. Later Reis (1989) reviewed the importance of lysine (a non-sulphur amino acid) and methionine to wool production and reported abomasal supplements lacking in either amino acid caused reductions in fibre strength and wool growth rates. A diet deficient in lysine (hay plus abomasal infusion of zein) resulted in a 60% depression in follicle bulb cell mitotic rate (Hynd 1989). Given the low concentration of lysine and methione in wool protein, and the relatively greater concentration in inner root sheath proteins, Hemsley and Reis (1984) and Reis (1989) speculated that some of the influence of lysine and methione deficiency may be through the synthesis of inner root sheath proteins.

Under both grazing and pen feeding situations, high wool producing sheep produce wool with a lower sulphur content compared with low wool producing sheep (Piper and Dolling 1966, Reis *et al.* 1967, Williams *et al.* 1972, Pritchard 1988) although the total output of sulphur (*ug* cm^{-2} day^{-1}) in wool will be greater in higher wool producing sheep (Williams 1995). Rate of entry of cystine into the plasma is similar for low and high wool producing sheep, while the concentration of free cystine in plasma is approximately 20 - 40% less for high wool producers (Williams 1979, 1995). This indicates that post-absorption utilisation of cystine is greater in high wool producing sheep (Pritchard 1988).

C1.3.5 Availability of energy

Although the overall importance of protein absorption to wool growth is well recognised, available energy also affects wool production. Follicle bulb cells utilise both glucose and acetate as energy sources (Black and Reis 1979). Black and Reis (1979) estimated that

5.37 mol ATP are required for the growth of 20 grams of clean wool per day, which is the maximum rate of growth for high producing sheep (Hogan *et al.* 1979). Reis (1989) calculated this was equivalent to 0.43 MJ / day or approximately 9.0% of the basal metabolic rate of a 40 kg sheep, a level which indicated that energy was unlikely to limit wool growth.

Black *et al.* (1973) used their own data from abomasally fed sheep, and the work of Walker and Norton (1971) with milk fed lambs, to show the overall importance of protein supply on wool growth, as well as the ability of excess energy to stimulate wool growth on high protein diets and reduce wool growth on low protein diets. Reis (1989) cited his unpublished work showing a large effect of intestinal protein supply (up to 101 g / day) on wool growth with energy increasing wool growth (not significant) at the highest protein levels. Reis (1989) postulated that the effect of increased energy on wool growth may occur if proteins being metabolised to provide energy are spared.

Black (1984) summarised the complex interaction of protein and energy levels on wool growth rates as:

- at constant energy levels, increased protein levels results in marked increases in wool growth up to a point at which the response plateaus or may even decline;
- at constant protein levels the response to increased energy depends on the level of protein availability;
    - low protein levels, increased energy availability results in reduced rates of wool growth but increased synthesis of body protein;
    - intermediate protein levels, increased energy availability initially results in an increased wool growth rate and then falls as availability increases;
    - at high protein levels, increased energy availability results in increased rates of wool growth.

C1.3.6 Wool growth lag period

Thomas and Rook (1983) considered a lag period of 21 - 28 days existed between changes in diet and the full impact on wool growth, which is line with the analysis that Nagorcka

(1977) carried out on the earlier work of Ferguson (1962). Lee and Williams (1993) also found a similar lag period with most effect of nutritional change occurring between the first and second monthly clipping, with up to two months before wool growth rates stabilised. Butler-Hogg (1984) found the lag period between changes in weight and wool growth to be in the range of 30 - 40 days, with more mature sheep having a longer lag period under conditions of nutritional stress. However, Black (1984) cited Hynd (1982) who reported the lag period for wool growth to stabilise to be longer at 6 - 12 weeks depending upon the relative change in feed intake. The lag period was smaller when feed intake was reduced. Hynd (1982) found the lag between changes in feed intake and wool growth rate was associated with a slow rate of change in wool follicle dimensions and in mitotic activity in the follicle bulb.

In contrast to the above reports, Revell *et al.* (1990) fed sheep in such a way as to experimentally simulate the drying off of Mediterranean pastures and found an almost immediate response to reduced nitrogen content and total feed intake. However, this experiment was too short to achieve a new equilibrium of wool growth. Downes *et al.* (1970) also reported intravenous and intraperitoneal infusions of methionine and cysteine produced the main increase in wool length growth rates and fibre diameter during the first eight days. Examination of their figures shows both length growth rates and fibre diameter increasing beyond the initial eight days and perhaps plateauing at the end of the 20 day supplementation trial. Reis and Downes (1971) reported wool growth adjusted rapidly to abomasal and parental supplementation with little change after eight days. These authors suggest that differences in observed lag periods may result from differences in wool measurement techniques or from long-term supplementation which induces a secondary and much slower change in rate of wool growth over a period of weeks, due to changes in body protein stores.

Butler-Hogg (1984) reported the time period for wool growth to return to normal following nutritional stress was positively related to the duration of the nutritional stress, and this was of more importance than severity of the stress (rate of liveweight loss). Allden (1979) cited Lyne (1964) who showed Merinos fed so as to lose 5 kg and 10 kg body weight over a period of six months, shed 10 and 40% of fibres respectively. On receiving adequate nutrition, a period of 12 weeks elapsed before all follicles regenerated fibres, despite compensatory increases in feed intake and weight gain. Butler-Hogg (1984) found no evidence for compensatory increase in rates of wool growth with realimentation after periods of nutritional stress and reduced wool growth rates.

C1.3.7 Effect of liveweight

Wool production is positively correlated with sheep liveweight and / or liveweight gain (Young and Corbett 1972a, Butler and Head 1992, Minson and Hacker 1995).

Butler-Hogg (1984) found that during periods of weight loss, the proportionate reduction in wool growth rate (57 - 74%) greatly exceeded the proportionate reduction in bodyweight (21 - 34%). Further, he found sheep experiencing high rates of weight loss (125 - 157 g / day) had wool growth rate reduced by 0.15 - 0.17 g / day for each day of nutritional stress.

Pritchard (1988) reviewed the literature concerning the genetic correlation and phenotypic relationship between clean wool weight and liveweight and concluded that a sheep's capacity to produce wool was genetically independent of its capacity to attain a mature body mass.

C1.3.8 Efficiency of wool production

This was discussed in Part B of this appendix.

C1.3.9 Photoperiod

Sheep display a seasonal wool growth cycle (greatest in summer, least in winter) which is controlled by day length. Merino sheep and their crosses show less seasonal effect than British breeds of sheep (Daly and Carter 1955, Sumner 1984). This photoperiod effect lags behind the solstices by approximately one to two months (Butler and Head 1993).

Reis and Sahlu (1994) reported that Merino sheep exhibited little seasonal rhythm in wool growth.

Other seasonal patterns, such as feed supply and quality, parasitism, disease and breeding costs, may influence the extent and timing of the seasonal wool cycle of sheep (Butler and Head 1992, 1993, Butler *et al.* 1994a, b, Reis and Sahlu 1994). Seasonal variation in wool growth may be measured by the amplitude which is the difference between the maximum and minimum wool growth expressed as a percentage of the mean (Hutchinson 1962, Butler and Head 1993). Hutchinson (1962), using strong wool Merinos at Roseworthy, South Australia, found photoperiod as indicated by shade temperatures to account for approximately half of the seasonal wool variation (48% of 83%). Similarly, Butler and Head (1993) using Merinos, Polwarths and their crosses in a pen feeding trial at Launceston, Tasmania (41^0S), found the amplitude of the photoperiod effect on wool growth to be 40.4%. However, Butler-Hogg (1984) considered the effect of season on rates of wool growth to be of minor importance relative to nutrition. Similarly, Williams (1964a) showed at lower latitudes (32^0S), Merino wool production is mainly affected by nutrition with little or no effect of photoperiod.

The seasonal cycle in wool growth is the result of two concomitant cycles for both fibre diameter and fibre length, with the fibre diameter cycle lagging behind the fibre length cycle by up to four weeks (Sumner and Wickham 1969 cited by Sumner 1984). Butler and Head (1993) found the photoperiod effect on fibre diameter was much less dramatic than its effect on clean wool production, with fibre diameter lagging 6 - 12 weeks behind clean wool production, the lag being longer for sheep on higher levels of nutrition. Butler and Head (1993) found that yield also displayed a photoperiod effect (range approximately 71-80%), similar in pattern to clean wool production.

C1.3.9 Effect of pregnancy and lactation

Estimated costs to wool production of gestation and lactation are shown in table A1.2. In line with Rose (1974) and Brown *et al.* (1966) for Queensland Merinos, Mullaney *et al.* (1969) found the effect of pregnancy on greasy and clean fleece weight was generally greater than lactation for Victorian Merinos. In contrast, Oddy (1985) found medium Merinos suffered greater wool production losses due to lactation (single and twins) than pregnancy.

Table A1.2. Reduction in wool production due to the extra nutritional requirements of gestation and lactation.

Source	Gestation cost	Lactation cost
Corbett (1979)	3[a] - 10%, annual fleece production during last two months of gestation	5[b] - 8%, annual fleece production
Hawker and Kennedy (1978)	9[a] - 24%, wool growth rates during late pregnancy	21[a] - 43%, wool growth rates during early lactation 3[a] - 26%, wool growth rates during late lactation
Oddy (1985)		12 grams for every litre of milk produced
Rose (1974)	6%, annual fleece production	3%, annual fleece production
Brown *et al.* (1966)	17.4%, annual fleece production	7.7%, annual fleece production

[a] reduction greatest during periods of poor nutrition, [b] reduction doubled with twins.

Oddy and Annison (1979) suggested the reduction in wool growth rates with pregnancy and lactation indicated sheep were unable to increase their feed intake to match the requirements of reproduction. These authors cited unpublished work of G. Robards who found high wool producing sheep, when fed at increased levels to compensate for pregnancy and lactation, still had reduced rates of wool growth. Sheep which had been selected for high weaning weights (*weight plus*), and subsequently had lower wool growth rates when non-pregnant, actually had higher wool growth rates during pregnancy and lactation. Feed intakes were similar for both groups of sheep. Oddy and Annison (1979) suggested that it was 'unnecessary to postulate changes in the hormonal status of sheep to account for the decline in wool production during pregnancy and lactation, because wool production did not fall in the *weight plus* ewes fed according to nutrients'. It appears the nutrient requirements of pregnancy and lactation reduced nutrient availability for wool growth in high producing sheep despite increased feed intake levels, whereas increased feed intake supplied adequate nutrients for pregnancy and lactation, and stimulated wool production in low wool producing sheep. Thornton (1987) hypothesised that increased levels of growth hormone during lactation stimulate milk production and divert nutrients from wool to milk production.

The limiting nutrients during pregnancy and lactation have not been fully identified. Oddy (1985) reported the amount of sulphur in milk production was close to that which did not go into wool production, but did not suggest the supply of sulphur containing amino acids was limiting wool growth during lactation. Both Williams *et al.* (1978) and Masters *et al.* (1993) found sulphur amino acids were not limiting during late pregnancy and early lactation, in contrast to the situation in non-pregnant non-lactating sheep. Williams *et al.* (1978) reported abomasal supplementation with casein increased wool production during late pregnancy / lactation (29%), while cystine and methionine supplementation produced no change in wool production. Masters *et al.* (1993) postulated that the supply of the amino acids arginine, lysine, threonine and valine may be limiting wool growth during pregnancy and lactation as indicated by their plasma levels. However, there was no response in wool production following abomasal injections of these amino acids (Stewart *et al.* 1993).

Rose (1982) found the effect of pregnancy on wool characteristics to be greater than lactation. Fibre diameter was reduced 7.0% for pregnancy and 1.5% for lactation. Yield, coefficient of fibre diameter and staple length all showed similar reductions, 2.0 - 3.0% for pregnancy and 1.0 - 1.5% for lactation. Mullaney *et al.* (1969) found the relative effects of pregnancy and lactation on yield, fibre diameter and staple length were variable.

Twin born ewes, and ewes born to maidens, cut less clean wool annually than single born ewes or ewes born to adults respectively, due to lower total fibre numbers (Brown *et al.* 1966).

C1.3.10 Effect of age

Wool growth rates vary between sheep of the same genotype and environment due to differences in age. Brown *et al.* (1966, 1968) found annual fleece weights of Merino rams and ewes in south-west Queensland increased to a maximum at 3 - 4 years of age and, thereafter, declined. Rose (1974) found Merino ewes in north-west Queensland produced heaviest greasy fleeces at 4.5 years of age and then fell such that wool production at 8.5 years was below that at 2.5 years of age. Mullaney *et al.* (1969) found fine and medium wool Merinos in Victoria, aged 3 - 8 years, had maximum fleece weights at three years, and thereafter weights declined in a linear fashion with age. The decline in wool production with increasing age recorded by Mullaney *et al.* (1969) was less than that recorded by Brown *et al.* (1966).

Brown *et al.* (1966) reported the increase in wool weight to 3.5 years was mainly due to an increase in total fibre numbers, with the subsequent decline to 6.5 years being mainly due to a reduction in fibre volume (70% of decline) along with a fall in fibre numbers (30% of decline). After 6.5 years of age, the decline in wool production was due to a further fall in fibre volume (81% of decline) and total fibre numbers (19% of decline). The reduction in fibre volume was due to a decrease in fibre length, despite a slight increase in fibre diameter up to 6.5 years of age before it also fell.

Oddy and Annison (1979) reported growing sheep produced less wool growth per unit of digestible organic matter than adult sheep (i.e. reduced gross efficiency), and suggested this was due to the nutrient requirements of growth. Little information is available regarding the efficiency of wool production by adult sheep, Corbett (1979) concluded that while variation in efficiency of wool production with age of young sheep was unclear, change in efficiency do not occur in adult sheep.

Brown *et al.* (1966) found fibre diameter reached a maxima at 6.5 years of age and Rose (1982) found fibre diameter and coefficient of variation of fibre diameter increased up to 6.5 and 7.5 years respectively, and then fell slowly. Staple length showed a gradual rise to 3.5 years followed by a marked decrease. Mullaney *et al.* (1969) reported a relatively constant Merino fibre diameter from 3 - 7 years of age which then declined, while staple length declined from three years

Brown *et al.* (1966) found clean yield reached a maxima at 5.5 years of age. Rose (1982) reported yield of ewes at Toorak increased to 2.5 years of age, remained constant between 2.5 - 6.5 years and fell sharply after 8.5 years of age. Mullaney *et al.* (1969) reported yields of Merino sheep declined from three to seven years and then plateaued while subjective measures of wool quality (colour, handle, and character) deteriorated from three years of age.

C1.3.11 Effect of sex

Corbett (1979) reported that greasy fleece production for Merino rams (16 - 24 months of age) was 20% greater than production from ewes, and wethers (16 - 48 months of age) 10 - 13% greater than production from ewes. However, Shaw and Findlay (1990) considered that differences in wool production across sex classes were related to differences in size, and therefore feed intake, rather than physiological differences.

Corbett (1979) reported the data of Brown *et al.* (1966, 1968) showed rams (1 - 6 years of age) had lower yields of clean wool from the greasy fleece relative to ewes (54.9 and 61.8% respectively). Rams also had a larger follicle population and greater staple length. Fibre diameter of young rams was slightly greater than ewes, and increases at a greater rate with age.

C1.3.12 Effect of environmental temperature

Bottomley (1979) noted heat stress is influenced by a suite of environmental conditions including temperature, wind speed, relative humidity, solar radiation, feed type and level of intake. Short term heat stress may reduce wool production by up to 20%, due to a reduction in feed intake (Thwaites 1985). This was in line with the earlier review of Hopkins and Richards (1979) who reported severe heat stress of sheep in climate chambers reduces wool production through lower feed intakes, but there was little evidence for a direct effect of heat stress on sheep at pasture.

Entwistle (1975) found that when acclimatised sheep were exposed to high summer temperatures (> 38^0C for 7 hours / day) there was no effect on feed intake, liveweight and wool growth rates. Bottomley (1979) also suggested that heat stress on acclimatised sheep probably had little effect on feed intake. The provision of shade during summer in north-west Queensland failed to increase wool production (Hopkins and Richards 1979) and actually resulted in increased greasy wool growth rates as a result of direct solar radiation. The authors postulated that heat stress may have resulted in increased cutaneous blood flow and supply of nutrients to the wool follicles. In support of this view Bottomley (1979) reported laboratory experiments where localised cooling of skin decreased wool growth length without a change in diameter. The effect of cold on wool growth in outdoor experiments has been variable. Increases in wool growth after shearing have been attributed to increased feed intakes as a result of cold stress (Wheeler *et al.* 1963, Sumner 1984, Dabiri *et al.* 1995).

C1.3.13 Effect of foetal heat stress

Heat stress during the last two-thirds of gestation at levels capable of reducing foetal growth had no effect on primary follicle numbers but reduced the number of mature and immature secondary follicles present at birth by up to 82 and 42% respectively (Cartwright and Thwaites 1976). Similarly, Hopkins *et al.* (1980) found lambs from ewes which were exposed to heat stress from day 117 of gestation (rectal temperatures of 40^0C for 16 - 17 hours daily) had marked changes in the maturation of wool follicles (lower S / P follicle ratio) although the potential S / P follicle ratios were not affected. Thwaites (1985) considered this prenatal depression in secondary wool follicle development with heat stress may be corrected postnatal by adequate nutrition, but recognised this was unlikely to occur in practice. Therefore, sheep will be left with a reduced number of secondary wool follicles and potentially reduced wool production.

Hopkins *et al.* (1980) found the rectal temperature of ewes during late pregnancy under tropical summer conditions explained 58% ($P<0.05$) of the variance in greasy fleece weight for male offspring (at 26 months of age), and 76% ($P<0.01$) of the variance for female offspring (at 14 months of age). However, the authors were unable to find any impact of ewe rectal temperature on greasy fleece weight for lambs dropped 12 months later.

C1.3.14 Effect of parasites and disease

Ectoparasites do not affect wool growth directly, but there may be damage to the fleece from rubbing (Donald 1979). Fly strike usually reduces annual fleece weights due to lower feed intakes, with more severe cases resulting in breaks in the fibres. Gastrointestinal parasites are capable of reducing wool production by up to 59%, with the initial infestation having the greatest impact prior to development of natural immunity.

C1.3.15 Effect of shearing

Wheeler *et al.* (1963) showed an increase in feed intake following shearing as the sheep attempted to maintain body temperature. Sumner (1984) suggested that dietary amino acids, in excess of that necessary for gluconeogenesis, are then available for wool production. Arnold *et al.* (1984) found Merino ewes grazing in the medium rainfall area of Western Australia grew 14% more clean wool when shorn in autumn compared with spring. The authors attributed this effect to increased feed intake following shearing but considered the spring shorn sheep were too fat to respond in a similar manner, despite the fact that the 'cold stress' experienced following shearing in autumn was less than that in spring (21^0C *vs.* 14^0C).

C1.3.16 Minerals and vitamins

Deficiencies in only two elements, zinc and copper, directly affect wool production as well as indirectly through a reduction in feed intake. However, deficiencies in fluorine, phosphorous and perhaps selenium may affect wool production by reducing feed intake, and sulphur, sodium, potassium and cobalt are thought to affect wool production by influencing rumen function and nutrient outflow from the rumen with or without affecting food intake. Manganese has no impact on wool growth (Purser 1979).

Zinc is required for follicle bulb cell division. A deficiency may result in brittle wool lacking in crimp or shedding of fibres with no growth occurring until the zinc status of the animal has improved (Thomas and Rook 1983, Black 1984). Copper is required to harden the wool fibres by catalysing the oxidation of the thiol residues of cysteine to the disulphide linkages of keratin (Black 1984, 1987). Copper deficiency may result in loss of pigmentation in coloured wools as well as reduction in wool growth and lack of crimp (Thomas and Rook 1983).

Selenium supplementation of sheep grazing deficient pastures resulted in increased wool production (Langlands *et al.* 1994). There was no response to continued selenium supplementation for animals with blood selenium levels greater than 0.07 and 0.04 μg / ml for breeding and non-breeding sheep respectively.

Reis (1989) reported that although vitamin supply had never been documented as a cause of reduced wool production, both folic acid and pyroxidine are important for wool growth.

C1.4 Yield

The effect of gestation, lactation, age and sex on the yield of clean wool from greasy wool have already been detailed. No difference between clean wool yield of non-breeding ewes and wethers was reported in the literature reviewed. Also, White and McConchie (1976) found no variation in wool yield across stocking rates, and therefore, rate of wool production.

C1.5 Wool Quality

C1.5.1 Fibre diameter

Fibre diameter and fleece weight are positively correlated (Pritchard 1988) with changes in fibre diameter markedly influencing wool production and being more important in explaining seasonal variations in fleece production than staple length (Mullaney *et al.* 1969, Entwistle 1975). Reis and Sahlu (1994) estimated the contribution of increased fibre length to increased wool growth was approximately 20 - 30%, whereas increased fibre diameter accounted for 80 - 70%. Similarly, Lee and Williams (1994) found [fibre diameter]^2 accounted for 60% of the variation in wool growth over a range of diets.

The relationship between fibre length growth rate and fibre diameter (L / D ratio) under natural feeding conditions is independent of the wool growth rate, but varies among individual sheep, breeds and strains (Downes 1971, Allden 1979, Reis 1992a, Hynd 1994a). Downes (1971), Reis (1992a) and Hynd (1994a) reported L / D ratios for individual sheep in the range of 10 - 18, 10 - 20 and 13 - 24 respectively. However, in various controlled feeding experiments the L / D ratio has been altered by the deficiency of certain amino acids (e.g. lysine), thyroidectomy and drug therapy (thyroxine and cortisone; Allden 1979, Hynd 1994b). Hynd (1994a) concluded the constant L / D ratio occurred because both factors were associated with the same follicle attributes, i.e. the rate of bulb cell division and the size of the cortical cells post-keratinisation. However, because the nature of these relationships differ, factors causing a change in cell division or cell filling events can alter the L / D ratio.

Fibre diameter also varies with the position of wool on the body. Wool from caudal sites has lower fibre length growth rate and greater fibre diameter, i.e. decreased L / D ratio, than cranial sites (Reis 1992a). Wool grown on skin folds or wrinkles has a greater fibre diameter, and greater variation in fibre diameter than wool grown on adjacent skin (Sutton *et al.* 1995).

C1.5.2 Wool strength

Wool strength varies with fibre diameter and the intrinsic strength of fibres, both of which are markedly affected by nutrition (Reis 1992b, Butler and Head 1993, Schlink and Hynd 1994).

Hynd (1995) cited unpublished data of R. Ponzoni *et al.* which showed a strong genetic influence on staple strength due to:

- different response in diameter due to nutritional and other stresses;
- differences in intrinsic fibre strength;
- differences in susceptibility of fibres to 'shutdown'; and

- differences in 'between fibre' components of the staple e.g. between fibre variability in diameter.

Rate of change of fibre diameter, rather than minimum diameter, is the more important influence on wool strength (Hansford and Kennedy 1988, Peter *et al.* 1994). Sheep returning to an improved nutritional regime following a period of nutritional stress suffered a loss of staple strength which was correlated with the rate of change in average fibre diameter. The break often occurred at a point remote to the minimum fibre diameter. The latter authors also found the body condition of sheep experiencing changing diets influenced the staple strength; sheep in poor condition having a reduced staple strength, which in some circumstances, was independent of changes in fibre diameter. Also, poor nutrition increases the risk of fibres being shed from the follicle. Schlink and Dollin (1995) found an exponential relationship between staple strength (3.6 - 77.0 N / ktex) and percentage of fibres shed (0 - 36) for non-supplemented Merino ewes and wethers. This fibre shedding, which occurred at the point of break, was an important contributor to the development of tender fleeces.

C1.6 Modelling wool growth

Allden (1979) noted that wool growth could be predicted by:

$$Y = A - A * e^{-k(X - X_0)}$$

where Y is wool growth, A is maximum wool growth rate, X is nutrient intake, X_0 is nutrient intake at which wool growth is 0, and k is incremental change in wool growth with each unit of feed intake.

The theory behind this curvilinear function is that the wool follicles have a maximum rate of utilising amino acids in the production of wool protein. Allden (1979) noted that no experimental evidence for a curvilinear relationship between wool growth rate and feed intake has been reported although the efficiency of conversion of feed to wool has been shown to decline as feed intake increases. Instead he cited numerous workers who have found a linear relationship between wool growth and feed intake:

$$Y = a + b * X$$

where X is dry matter intake. Also:

$$Y = b * X$$

where X is digestible dry matter intake.

The first linear equation implies some wool growth at zero food intake. Black (1984) reported the linear relationship of Hynd (1982) that allowed for the lag in wool growth predicted a clean wool growth rate of 1.2 g / day for fasted adult Merino wethers. Allden (1979) preferred the second linear passing through the origin since, for a given feed, wool growth is directly proportional to feed intake (given wool growth rates are below the genetic potential).

Nagorcka (1977) suggested that reductions in digestibility with increasing intake may account for some of the observed differences in the efficiency of feed utilisation for wool growth. According to Allden (1979), this was not a satisfactory explanation, and proposed other possible reasons for the variations included technical problems such as estimating carry over effects from the previous diet, experimental procedures concerned with feeding sequences, the possible influence of body weight change on conversion efficiency and interactions between nutrition and the environment.

White *et al.* (1979) found non-linear relationships between dry matter availability and dry matter digestibility explained 49.0 - 74.0% of the variation in daily wool growth across three experiments. Estimated feed intake increased the explanatory power to 62.0 - 83.0%. However, the relationship between monthly wool growth and feed intake varied throughout the year, being negatively correlated during summer and early autumn.

Lee and Williams (1993) found that adjusting nitrogen intake for metabolic body size (g N / $kg^{0.75}$) removed all significant effects of diet on wool growth. A linear model using the adjusted nitrogen intake explained 62.7% of the variation in wool growth during the four month experimental period. Inclusion of the initial wool growth (during the pre-experimental period) as a covariate allowed the model to account for 90.0% of the variation in wool growth. Use of saturation kinetics, logistic and exponential models resulted in similar levels of explanatory power as the linear model without the covariate.

Part D

Reproduction

D1.1 Introduction

ABS figures for the census year 1994-95 show that of the 4.1 million ewes mated in Queensland, only 54% raised their lambs to marking. Moule (1954) recognised that the low level of reproduction in semi-arid tropical Australia often failed to provide sufficient numbers for replacement, flock maintenance or culling. Lamb marking rates, the common measure of reproductive efficiency, may be reduced due to anoestrus, failure to mate, failure to conceive, embryonic death, foetal death and death of lambs at parturition or shortly after.

D1.2 Reproductive performance in Queensland

Reproductive performances recorded under Queensland grazing conditions are generally worse than elsewhere in Australia. Data from selected grazing trials where reproductive performance were reported are summarised in table A1.3.

The importance of each phase of the breeding cycle as a cause of reproductive wastage can vary with location, timing of joining / lambing and the season. Smith (1962) suggested this was due to the underlying physical environment at each particular phase. Pasture quantity and quality, environmental temperatures, ewe age, maternal behaviour, predators and property management all may influence reproduction.

Table A1.3. Reproductive performance in Queensland.

Location	Joining Rate (%)	Pregnancy Rate (%)	Lamb marking Rate (%)
Blackall[a]	na	89.0[1] 96.0	23.6 12.8
Augathella[b]	295.7 (90.0-100.0)	93.2 (88.0-96.0)	66.7 (22.0-128.0)
Charleville[c]	96.0 99.0	83.0 89.0	63.0 71.0
Cunnamulla[d]	98.9	91.0	86.3
Charleville[e]	na	97.0	96.0
Tropical Queensland[f]	82.0[3] (75.0-89.0) 91.0[4] (70.0-100.0)	na	54.6[5]
Toorak[g]	71.9[6] 67.8	na	38.6 32.0
South-west Queensland[h]	98.4 (93.4-100.0)	93.0[2] (77.0-100.0)	78.0 (10.0-115.0)

[a] *McMeniman et al. (1989), two groups of mature ewes, autumn / winter joined, 1976.*

[b] *Orr et al. (1988), two groups of mature ewes over four seasons, autumn joined, 1979 - 1983 .*

[c] *McMeniman and Holle (1973), maiden ewes over two seasons, autumn / winter joined, 1969 - 1970.*

[d] *Kennedy and Bettenay (1950), 3 (maiden), 4 and 5 year old ewes joined in pens, returned to paddock till lambing, placed in pens till lambed then holding yards for 3 - 4 days, autumn / winter joined 1947.*

[e] *Beale, unpublished data for 'Arabella', values are mean of two stocking rates designed so that 20 and 50% of available pasture at end of April was utilised, autumn joined, 1983 - 1984.*

[f] *Moule (1966), 24 flocks throughout tropical Queensland from 1947 - 1957.*

[g] *Rose (1976), data are for the random flock in the wrinkle selection trial, 1959 - 1972.*

[h] *Jordan et al. (1989), data are for thirty groups of ewes from 11 properties in six districts of south-west Queensland, 1976 - 1985.*

na - not available.

[1] *second figures are for ewes receiving urea / molasses supplementation.*

[2] *mean value followed by range in brackets.*

[3] *mean of four flocks joined April / May, range in brackets.*

[4] *mean of five flocks joined October / November, range in brackets.*

[5] *mean of 25 flocks.*

[6] *first value is for 1959 - 64 when ewes were joined in autumn, second value is for 1965 - 72 when ewes were joined in spring.*

Smith (1962) found failure to conceive was an important cause of wastage in autumn joined ewes in north-west Queensland, while neonatal mortality in winter joined ewes and anoestrus in spring joined ewes were identified as the major causes of reproductive wastage. Smith (1965) later reported failure to conceive as the major source of reproductive wastage in late spring / early summer joined ewes in north-west Queensland. However, Moule (1966) reported that while a high proportion of spring joined ewes failed to lamb for properties in central and north-west Queensland, a large number of lambs were lost prior to marking.

McMeniman *et al.* (1989) found lamb mortality to be the major source of reproductive wastage in autumn / winter joined ewes in central western Queensland. Similarly, O'Dempsey (1987?) found in his survey of central western Queensland that, while low pregnancy rates were generally associated with poor body condition at joining and less frequently to ram infertility, failure to raise lambs to marking was by far the most important cause of reproductive wastage. Similarly, in south-west Queensland, McMeniman and Holle (1973) and Jordan *et al.* (1989) found the greatest cause of reproductive wastage in autumn / winter joined ewes was lamb mortality from birth to marking.

It would appear that on a north - south gradient, failure to cycle / conceive / fall pregnant become less important as the cause of reproductive wastage. However, loss of lambs prior to marking is a major cost throughout the state.

D1.3 Ewe nutrition

Alexander (1968) reviewed the causes of reduced lamb marking rates and reported the following possible sequelae of inadequate prenatal nutrition, especially during the last two months of gestation:

- reduced gestation length;
- prolonged parturition;
- reduced birth weight of lambs;
- reduced density of the birth coat and therefore thermal insulation;
- reduced lamb energy reserves;
- ewe may be slow to stand and allow the lamb to suckle;
- poor lamb vigour and ability to suckle successfully; and
- delayed onset and reduced rate of lactation.

Excessive nutrition may lead to oversized lambs and a high incidence of dystocia, especially in maiden ewes.

Most of the impact of nutrition on reproduction is measured through its effect on ewe liveweight. Lindsay *et al.* (1975) found significant relationships between mean weight of ewes at joining and lambing rate (number of lambs born per 100 ewes joined) and ewe lambing rate (number of ewes lambing per 100 ewes joined) of Merino sheep in southern Western Australia. For every 5 kg increase in joining liveweight there was a 3.7 percentage point increase in ewe lambing rate (r^2=0.12 $P<0.05$) and a 5.8 percentage point increase in the lambing rate (r^2=0.18 $P<0.01$). Joining weight and lamb marking rate (number of lambs marked per 100 ewes joined) were also significantly related (r^2=0.22 $P<0.001$). Similarly, McMeniman and Holle (1973) studied autumn joined maiden ewes grazing a mulga grassland near Charleville over a two year period and found an influence of joining weight on early joining, pregnancy rate and lamb marking rate. In contrast, Jordan *et al.* (1989, 1989-90) reported no effect of season of joining, ewe weight at joining and ewe weight change during joining, on reproductive performance for autumn / winter joined ewes in south-west Queensland.

McCrabb *et al.* (1992) found that a feed restriction between days 30 - 96 of gestation, such that ewes lost 55 g / d, lowered placental weight ($P<0.05$) but not lamb birth weight. However, skeletal development was restricted as indicated by reduced crown - rump length at day 96 of pregnancy and reduced thoracic girth of foetuses at day 140 of pregnancy ($P<0.05$). The authors concluded that the early period of gestation (days 30 - 50) was a 'critical time when placental growth is sensitive to maternal feed restriction'.

McMeniman *et al.* (1989) reported on two groups of 4 - 6 year old Merino ewes near Blackall in central western Queensland, joined for eight weeks in late autumn / early winter. Pregnancy rates were 89% and 96%, with the latter group having had access to a urea / molasses mix during the last two weeks of pregnancy and throughout lactation. Lamb marking rates were poor; the non-supplemented group marked 23.6% and the supplemented group 12.8% with most lamb deaths observed to occur in the first few days following lambing. Deterioration in the quality of pasture from joining till lambing resulted in a weight loss of 8 kg (140 g / day / sheep). The authors considered the poor condition of the ewes would have delayed the onset of lactation, reduced milk production and caused poor mothering ability. Reasons for the poorer performance of the supplemented ewes included watering problems resulting in ewes becoming bogged, more frequent disturbance due to the closer proximity of this group to the homestead and the poor acceptance of the supplement by many of the ewes.

Jordan *et al.* (1989-90) studied 12 groups of Merinos in three districts of south-west Queensland and found a significant ($r^2=0.66$ $P<0.05$) relationship between ewe weight gain during the last three months of pregnancy and lamb marking rate. For every 1 kg weight gain during this period, 7.9 more lambs were marked per 100 ewes over the range of weight gain from 2.1 - 8.6 kg. No groups of sheep in the study lost weight between joining and lambing and no relationship was found between the weight of ewes prior to lambing and the lamb marking rate. A relationship which approached significance ($r^2=0.59$ $P<0.07$) existed between the lamb marking rate and ewe weight loss from immediately prior to lambing to marking. For every 1 kg weight loss during this period, 5.3 fewer lambs were marked per 100 ewes. Combining the weight change during pregnancy and post lambing explained most ($r^2=0.94$ $P=0.015$) of the variation in lamb marking rate, thereby emphasising the importance of ewe nutrition on lamb marking.

Jordan *et al.* (1989) noted a significantly better lamb marking rate for autumn / winter joined ewes in south-west Queensland when they lambed during good seasons, compared with bad seasons (89.1 *vs.* 52.7%, $P<0.01$). The number of ewes losing all their lambs was significantly less in good and average seasons compared with bad seasons (19.3 and 19.4 *vs.* 58.9%, $P<0.01$). Good seasons were defined as those in which there was abundant green grass or herbage while bad seasons were those in which only dry and / or frosted feed was available. All matings occurred in average or good seasons. Similarly, Jordan and Le Feuvre (1989) found the rate of lamb deaths from starvation, mismothering and desertion in two groups of penned ewes fed below maintenance diets were significantly greater than those fed above maintenance diets (24.7 and 26.5% *vs.* 10.1% , $P<0.05$).

Orr *et al.* (1988) found that the reproductive performance of 3 - 4 year old autumn joined Merino ewes near Augathella in south-west Queensland was sensitive to the quality of the ewe's diet at lambing because this influenced lamb survival and growth rate. Over four breeding seasons with two different groups of ewes on Mitchell grasslands, they found little variation in the percentage of ewes joined during a six week joining period (mean 95.75%, range 90 - 100%) and pregnancy rates (mean 93.25%, range 88 - 96%). However, both lamb marking rate and the weight of lambs two weeks after the end of lambing varied greatly (mean 66.75%, range 22 - 128%; mean 10.8 kg, range 7.0 - 15.2 kg respectively). Lamb marking results of one season were poorer than expected due to predation of lambs by feral pigs. High milk yields (mean 897 ml / day, range 280 - 1280 ml / day), lamb growth rates (mean 144.5 g / day, range 22 - 209 g / day) and good lamb marking performance were associated with improved diet quality, especially nitrogen content, at time of lambing.

Stephenson *et al.* (1981) also reported strong associations between nitrogen intake of ewes and milk production ($r^2=0.94$ $P<0.05$), and milk production and lamb growth rates ($r^2=0.76$ $P<0.01$) for penned sheep fed pasture hay and a variety of supplements at Julia Creek. A similar relationship was also found between milk production and lamb growth rates ($r^2=0.64$ $P<0.01$) for grazing sheep which is consistent with the findings of Orr *et al.* (1988). For penned ewes there was no relationships between milk production and ewe liveweight or lamb birth weight. Similarly, Moule (1966) found milk production to be related ($r^2=0.36$ $P<0.001$) to the feed consumption of the ewes. Milk production in turn was correlated ($r^2=0.64$ $P<0.001$) with the liveweight gains of the lambs to marking. Also, growth rates of lambs born to ewes with sound udders were significantly greater (14 g / d) than for lambs born to ewes with unsound udders (Moule 1954).

Cobon and Carter (1994) investigated the possible role of toxic forbs following summer rain in north-west Queensland on the reproductive performance of autumn lambing ewes. In two separate years ewes were grazed for 4 - 5 weeks during the last trimester on trial paddocks. Ewes in the paddocks with relatively low forb content had significantly better lamb marking percentages (82 *vs.* 51%, $P<0.01$; 50 *vs.* 40%, $P<0.05$). Liveweight gain of ewes and lambs at marking were not affected by pasture treatment. Forbs, despite being low in pasture concentrations (<10%), exceeded 80% of the diet at times. The authors concluded that, when forb content is above 7% of Mitchell grass pastures, coupled with their preferred selection, a negative effect on reproductive performance is likely.

D1.4 Puberty

Puberty occurred in autumn and spring born ewes in north-west Queensland when they reached mean liveweights of 33.2 and 33.7 kg at approximately 18 and 19 months of age respectively (Murray 1972). However, unpublished data of McMeniman (McMeniman 1985) for south-west Queensland found that other factors beside weight influence puberty. During a nine week joining period, 57.0% of 12 month old ewes were mated (mean weight 34.8 kg) while the mean weight of those not mated was 34.3 kg.

D1.5 Oestrus

Evidence of ewes being served by rams is usually gathered by means of coloured grease applied to the brisket of rams (Kennedy and Bettenay 1950) or harnesses with crayon markers (Entwistle 1972, Norton *et al.* 1990). Service is then used as a proxy for oestrus.

Reports of oestrous activity during various times of the year are inconsistent. Smith (1962) reported oestrous rates of 73 - 89% from March to July in north-west Queensland but negligible rates from mid-September to December where the ewes were losing weight (approximately 70 g / d). Similarly, Smith (1966) reported oestrous activity during spring / summer in central and north-west Queensland ewes was generally less than that during autumn / winter. For five flocks joined during autumn / winter over four years, the mean incidence of oestrus was 81.3% (68.8 - 85.9%) at day 21, and 94.0% (88.4 - 97.3%) at day 35. For seven flocks joined during spring / summer over three years, the mean incidence of oestrus was 58.0% (25.0 - 87.5%) at day 21, and 79.4% (71.0 - 94.1) at day 35. Moule (1966) reported the opposite; four flocks joined in April / May had a oestrous rate of 82% (75 - 89%) while five October / November joined flocks had a rate of 91% (70 - 100%). The majority of autumn joined ewes showed signs of oestrus within the first 18 days of joining, while the majority of spring joined ewes were not showing signs of oestrus until days 18 - 36 of joining.

Entwistle (1972) found no significant difference in the incidence of oestrus in spring (93.3%) and autumn (92.1%) joined ewes (3 - 7 years of age) at Toorak. However, there were significant (P<0.01) differences between years both within the spring and autumn joined ewes. For maiden ewes of the same age there were inconsistent results, both spring and autumn joining were significantly better during different years. Rose (1976) also reported similar oestrous activity for spring and autumn joined ewes in the random flock of the wrinkle selection trial at Toorak. From 1959 to 1964 autumn joining had a mean oestrous rate of 79.8%, while from 1965 to 1972 spring matings had a mean rate of 76.6%. Murray (1978) slaughtered aged ewes every two weeks throughout the year at Toorak and found the proportion of ewes ovulating varied between 0.78 and 1.0 (figure A1.2). He concluded failure to cycle should not affect the selected joining time for Merino sheep in the tropics.

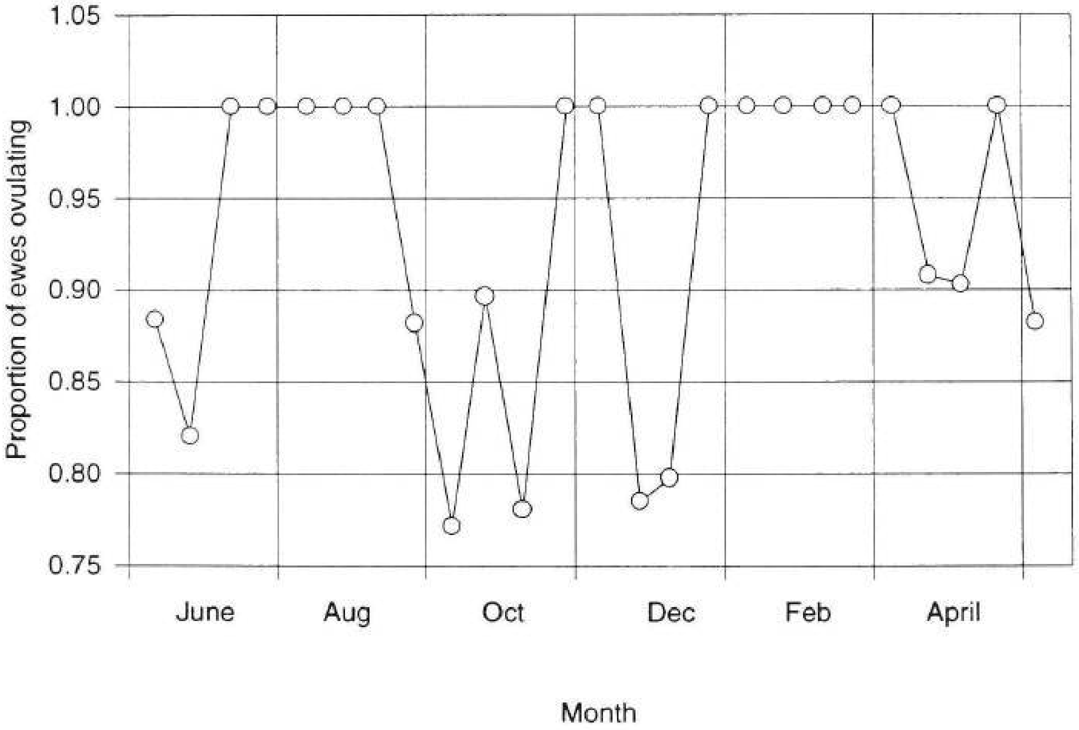

Figure A1.2. Proportion of aged ewes ovulating throughout the year at Toorak, north-west Queensland (Murray 1978).

Oestrous activity for Merino ewes joined in late spring in central and north-west Queensland, was influenced by the level of nutrition and liveweight at commencement of joining (Smith 1966). In contrast, Entwistle (1972) found the pattern of poor pasture quality prior to and during spring joining and associated liveweight losses, were not consistent with lower oestrous activity. Jordan *et al.* (1989-90) also found no consistent effect of ewe liveweight and liveweight change on autumn / winter joining in south-west Queensland. Smith (1966) found the level of oestrous activity in the first 17 days of autumn joined ewes was significantly influenced by the preceding spring nutrition, but not for the entire 35 day joining period. Winter joined ewes were initially influenced (first 17 days) in level of oestrous activity by the current level of nutrition, with preceding spring nutrition influencing oestrous activity to 35 days. Smith (1966) concluded that the variation in oestrous activity between the spring / summer and autumn / winter joined ewes was due to previous and current pasture condition, and to the interval since lambing, rather than photoperiod effects. McMeniman (1985) suggested that the negative effects of pre-joining nutrition may be overcome by a high level of nutrient intake during joining and concluded that anoestrus was not a major cause of reproductive failure throughout Queensland.

It would appear from the above evidence and the joining rates listed in table A1.3 that failure to cycle is only a concern in spring joined flocks in north-west Queensland during periods of below average pasture quantity / quality.

D1.6 Ovulation rate

The main factors controlling the rate of ovulation in sheep are nutrition, stage of the breeding season and their interaction (Lindsay *et al.* 1975).

Entwistle (1972) reported a mean ovulation rates of 104.0% (range 100.0 - 113.7%) for spring joined ewes and 118.8% (range 115.8 - 125.0%) for autumn joined ewes at Toorak, north-west Queensland. Murray (1978) estimated ovulation rates for aged ewes at Toorak to be approximately 100.0 - 145.0%, with no significant trend in multiple ovulations with time or liveweight (figure A1.3). This contrasts with the situation in southern Australia.

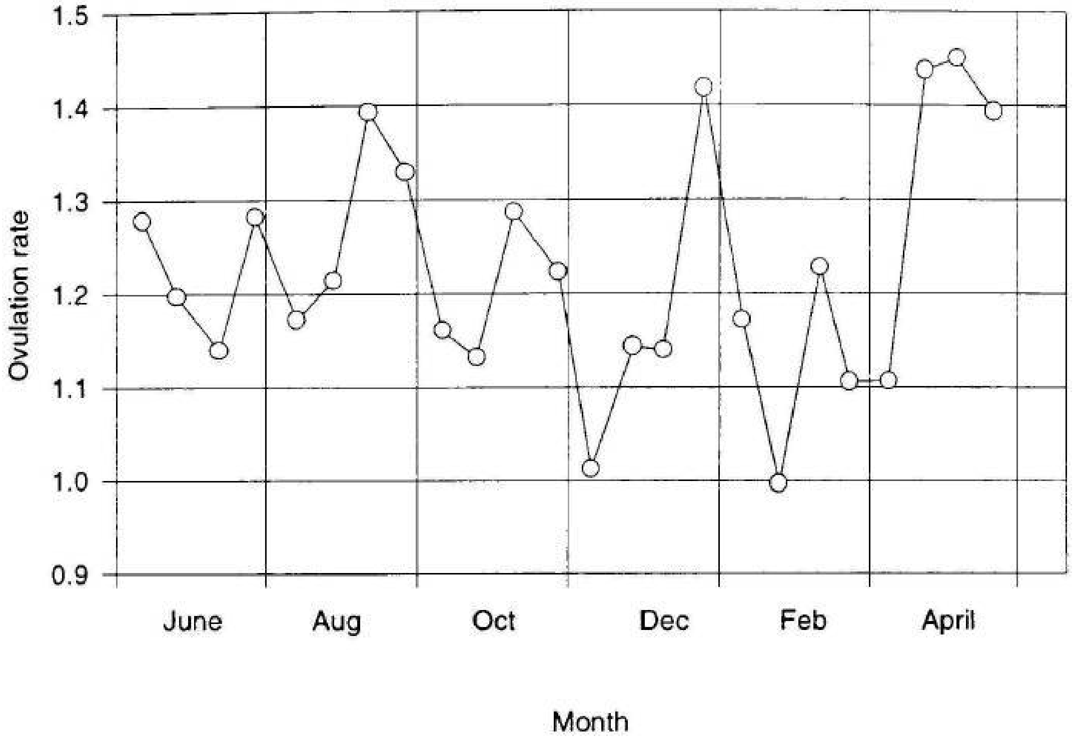

Figure A1.3. Ovulation rate of aged ewes ovulating throughout the year at Toorak, north-west Queensland (Murray 1978).

Watson (1953) reported seasonal variation in the number of ova shed at ovulation for Merino ewes in Victoria. Mating carried out in April - June and August - October were associated with significantly higher rates of multiple births (15% and 9%, $P<0.01$) than a December - February joining period (0%). Nutritional flushing was not a factor influencing the rate of multiple ovulations as the sheep were not on a plane of rising condition.

The occurrence of multiple births gives some indication of the ovulation rate in a flock. Moule (1954, 1966) reported 22.5% (range 6.6 - 35.6%) and 19.8% (range 0.0 - 75.0%) of lambs born being from multiple births for 11 flocks throughout Queensland and 25 flocks throughout central and north-west Queensland respectively. However, the latter work included flocks in which there had been selection for twin births.

Lindsay *et al.* (1975) used a laparoscopic approach to examine 2049 ewes from 53 flocks in south Western Australia and found only 2.2% of ewes failed to ovulate. The study was carried out from November through to April when ambient temperatures were high and pasture quality and quantity were declining. There were 113.7 ovulations per 100 ewes examined and multiple ovulations occurred in 14.6% of those ewes. A significant relationship was found between the mean liveweight of sheep and the mean ovulation rate (r^2=0.17 $P<0.01$), a 5 kg increase in weight resulted in a 5.9 percentage point increase in the ovulation rate. A 10% increase in the ovulation rate increased ewe lambing rate by 3.8 percentage points (r^2=0.25 $P<0.001$) and lambing rate by 6.3 percentage points (r^2=0.41 $P<0.001$). There was also a significant relationship between ovulation rate and lamb marking rate (r^2=0.42 $P<0.001$). The authors considered that the positive relationship between ovulation rate and ewe lambing rate was probably a response to a third factor such as liveweight. No relationship was found between maximum temperatures at the time of mating and ovulation rate. Kleemann *et al.* (1990) reported an even higher mean ovulation rate of 135% (123 - 165%) for mature Merino ewes in South Australia.

D1.7 Fertilisation

Entwistle (1972) found fertilisation failure to be an important cause of reproductive wastage in both spring and autumn joined ewes. He reported that for spring joined ewes at Toorak over three successive years, the percentage of recovered ova fertilised was 77.4, 65.2 and 66.9% (mean 69.0%), differences being non-significant. For ewes joined in autumn over two successive years, 55.0 and 77.4% (mean 61.2%) of recovered ova were fertilised, the difference being significant ($P<0.05$). Rose (1976) reported similar mean fertilisation rates for spring and autumn joined ewes of the random flock in the wrinkle selection trial (53.6 *vs.* 55.8% of ewes at joining). Smith (1962, 1965) also found failure to fertilise to be the most significant cause of reproductive wastage in both autumn and late spring / summer joinings. Entwistle (1972) suggested that fertilisation in spring joined sheep was influenced by the poor nutrition experienced by ewes and rams, while hot summer temperatures leading to seminal degeneration in rams may have affected the autumn fertilisation rates.

The spring and autumn joinings of Entwistle (1972) showed a non-significant decline in fertilisation rates from the beginning of the joining period. McMeniman and Holle (1973) found a high proportion of maiden ewes were joined in the first two weeks of the joining period (78.3% and 74.0%), and a significantly higher percentage of these became pregnant compared with those mated later (89.4 *vs.* 79.8% $P<0.05$ and 93.4 *vs.* 84.2% $P<0.01$). Ewes which became pregnant during the first two weeks of the joining period also reared more lambs than ewes which became pregnant later (72.6 *vs.* 51.5% and 72.4 *vs.* 64.9%). Similarly, Jordan *et al.* (1989) found pregnancy (97.6 *vs.* 92.0 $P<0.01$) and lamb rearing rates (61.6 *vs.* 41.0 $P<0.05$) of ewes joined in the first fortnight were significantly higher than those joined for the first time later.

Jordan *et al.* (1989) concluded that failure to conceive was not a significant cause of reproductive wastage in south-west Queensland while other reports (Smith 1962, 1965, Entwistle 1972, Rose 1972) indicate it becomes more important in the north.

D1.8 Embryo survival

Entwistle (1972) reported that for two successive spring matings at Toorak the percentage of corpora lutea represented by viable embryos (20 days post coitus) were significantly different (79.1 *vs.* 62.0% $P<0.05$). For the equivalent autumn joined ewes there was no significant difference between years (56.7 *vs.* 68.5%). Dolling and Nicolson (1967) reported higher values for the percentage of corpora lutea represented by viable embryos (28 days post coitus) for Merinos near Cunnamulla, Queensland, that had not returned to service within 20 days: 94.2 - 95.3% for maiden ewes, 79.4 - 81.4% for aged ewes (8.5 - 11.5 years). After adjustments for ewes that have two corpora lutea but only one viable embryo, maiden ewes had 96.2 - 97.3% and aged ewes 88.0 - 89.9% viable embryos 28 days post coitus.

Entwistle (1972) compared embryo survival with ova fertilisation rates for each joining period and found no significant differences indicating that early embryonic mortality was not an important cause of reproductive wastage. Similarly in Smith (1965), embryonic loss was not a major cause of reproductive wastage. Dolling and Nicolson (1967) estimated that 4.3% of joined ewes in their study conceived (i.e. did not return to service) but failed to carry the embryo through to term, with no significant loss between day 28 post-joining and term.

D1.9 Lamb survival

Lamb mortalities to marking, and the relative importance of the three stages within this period (parturition, neonatal excluding parturition, postnatal) are shown in table A1.4. Unfortunately few workers observed the relative importance of the three stages making generalisations difficult.

Moule (1954) found the most important causes of lamb mortality was poor mothering and predators. Similarly, Jordan and Le Feuvre (1989) found parturition problems, failure of lambs to obtain milk and predation to be the major causes. Low birthweights are also closely linked with high neonatal mortality rates, and may be associated with sex of the lamb, single or multiple births, high environmental temperatures, lack of shade and poor nutrition during pregnancy.

Kennedy and Bettenay (1950) surprisingly found no evidence that ewes with faulty udders lost more lambs than ewes with sound udders. In contrast, Moule (1954) found neonatal and postnatal lamb losses for flocks in central and north-west Queensland were significantly less for ewes with sound udders than for ewes with unsound udders (15.1 *vs.* 36.0% $P<0.001$ and 18.1 *vs.* 26.6% $P<0.05$ respectively). He found the disadvantage of lambs born to ewes with unsound udders was greater than that of multiple birth lambs. Similarly, Jordan and Le Feuvre (1989) found significantly more lambs died when ewes had unsound udders (27.1 *vs.* 13.8% $P<0.05$) of which 80% were due to starvation. Moule (1954) classified unsound udders as those having one or two blind teats, plugged teats or little or no milk. Blindness of one or both teats was thought to arise from chronic infection or shearing wounds and accounted for approximately half the unsound udders.

Table A1.4. Percentage of lambs dying in the period from parturition to lamb marking and the relative importance of three stages within this period as causes of reproductive wastage. Values in italics represent the lamb deaths occurring in each phase as a percentage of total lamb losses to marking, where they were able to be calculated.

Source	**Parturition** (% lambs born)	**Neonatal** (% lambs born)	**Postnatal** (% lambs born)	**Total losses to marking** (%lambs born)
Kennedy and Bettenay (1950)[a]	1.5 *(10.6)*	2.6 *(19.1)*	9.6 *(70.2)*	13.7
Moule (1954)	na[b]	20.6[b] *(56.5)*[b]	15.8[b] *(43.5)*[b]	36.4[b]
	1.0[c]	21.3[c]	na[c]	na
Smith (1962)	4.6	34.3	na	na
Smith (1964)	1.9[d]	29.5[d]	na	na
Smith (1965)	0.5	9.8	na	na
Moule (1966)	na	na	na	29.0
McMeniman and Holle (1973)	na	na	na	23.2
Rose (1976)	na	13.5[e] *(38.6)*	21.5[e] *(61.4)*	35.0[e]
	na	16.1[f] *(56.3)*	12.5[f] *(43.7)*	28.6[f]
Orr *et al.* (1988)	na	na	na	26.1
McMeniman *et al.* (1989)	na	na	na	73.5[g]
	na	na	na	86.6[h]
Jordan *et al.* (1989)	na	na	na	32.5
Jordan and Le Feuvre (1989)	3.3[i] *(16.5)*	na	na	20.0[i]
	1.8[i] *(19.1)*	na	na	9.4[i]
	2.1[j] *(10.5)*	na	na	20.0[j]
Kleemann *et al.* (1990)	na	na	na	24.5

[a] *Kennedy and Bettenay (1950), 3 (maiden), 4 and 5 year old ewes joined in pens, returned to paddock till lambing, placed in pens till lambed then holding yards for 3 - 4 days, autumn / winter joined 1947.*

[b] *Moule (1954) based on seven observations, deaths at parturition not listed separately from neonatal deaths.*

[c] *Moule (1954) based on 11 observations, parturition and neonatal deaths only reported.*

[d] *Smith (1964) Border Leicester lambs.*

[e] *Rose (1976) autumn joined ewes, 1961 - 64, random flock , deaths at parturition not listed separately from neonatal deaths.*

[f] *Rose (1976) spring joined ewes, 1965 - 72, random flock, deaths at parturition not listed separately from neonatal deaths.*

[g] *McMeniman et al. (1989), mature ewes, autumn / winter joined, 1976 control group.*

[h] *McMeniman et al. (1989), mature ewes, autumn / winter joined, 1976 supplement group.*

[i] *Jordan and Le Feuvre (1989) field trial.*

[j] *Jordan and Le Feuvre (1989) pen trial.*

na - not available.

The impact of ewe nutrition on milk production and lamb growth and survival has already been discussed (Moule 1966, Stephenson *et al.* 1981, Orr *et al.* 1988, McMeniman *et al.* 1989). The findings of Stephenson *et al.* (1981), using tritiated water measurements, of the inability of milk to meet the fluid requirements of lambs in north-west Queensland, further emphasises the importance of ewe milk production as well as easy lamb access to watering points to avoid dehydration.

D1.9.1 Neonatal period

Moule (1954) defined the neonatal period as birth plus three days afterwards, which is slightly different to table A1.4 where mortalities at parturition and during the first three days of life were considered separately. Jordan and Le Feuvre (1989) found the mean age of lambs dying in their pen study was 2.7 days, this value being biased upwards by a small number of lambs surviving for longer than a week. Similarly, Stephenson *et al.* (1984) and McMeniman *et al.* (1989) found most deaths to marking occurred in the first few days.

D1.9.1.1 Parturition

Mortalities due to dystocia are usually a small component of total neonatal mortalities (table A1.4). Most cases are associated with relatively large lambs (foeto-maternal disproportiation), the majority of which are single born males (Smith 1962, 1964). However, Kennedy and Bettenay (1950) believed foetal malpresentation was the major cause of dystocia in their pen study.

Pathological lesions found on examination of lambs dying during parturition or immediately after include many typical of traumatic deliveries: haemorrhages of the meninges and ventricles of the brain, haemorrhages of the meninges of the spinal cord, haemorrhages and / or rupture of the liver, foetal membranes covering the nostrils, blood clots blocking the major airways of the lungs, subcutaneous oedema of the head and neck (Jordan and Le Feuvre 1989). Kennedy and Bettenay (1950) and Smith (1962) also reported lamb deaths due to ewes failing to break or remove the foetal membranes covering the nose and mouth of the lamb.

D1.9.1.2 The first few days

There are various causes of lamb mortality in the 72 hours following parturition (table A1.5). The values listed are intended for comparison only since various workers classified lamb mortalities differently. There is also marked overlap in the various fields e.g. *failure of lambs to stand and / or suckle* and *poor mothering and desertion*. As well, lambs classified in these two fields may also have qualified for the *predators* field and vice versa.

Table A1.5. Causes of lamb mortality in the first 72 hours following parturition and their relative importance.

Source	**Cause and percentage of total neonatal mortalities**					
	Failure of lambs to stand and / or suckle	*Poor mothering and desertion*	*Predators*	*Exposure*	*Infectious*	*Other causes*
Kennedy and Bettenay (1950)[a]	0.0	50.0	11.1	na	na	44.4
Moule (1954)[b]	0.0	31.3	36.0	11.6	1.9	19.2
Smith (1962)	5.7	77.0	0.0	0.0	0.0	17.3
Smith (1964)	10.0[c]	70.0	>27.0	0.0	0.8	0.0
	na[d]	na	36.2	na	3.8	na
Smith (1965)	10.4	na	60.4	na	na	na
Jordan and Le Feuvre (1989)	80.2[e]	na	10.4	na	na	na
	68.6[e]	na	31.1	na	na	na
	86.0[f]	na	0.0	na	na	na

[a] *Kennedy and Bettenay (1950). 3 (maiden), 4 and 5 year old ewes joined in pens, returned to paddock till lambing, placed in pens till lambed then holding yards for 3 - 4 days, autumn / winter joined 1947.*
[b] *Moule (1954) based on 11 observations, parturition and neonatal deaths only reported.*
[c] *Smith (1964) five Merino flocks in central western Queensland.*
[d] *Smith (1964) two Border Leicester flocks in south-west Queensland.*
[e] *Jordan and Le Feuvre (1989) field trial.*
[f] *Jordan and Le Feuvre (1989) pen trial.*
na - not available.

Delivery of the lamb is normally followed by the ewe quickly getting to her feet and beginning to groom the new born lamb (Alexander 1968). Grooming stimulates the lamb as well as drying the coat. The lamb then searches for the teats and begins to suckle while the ewe stands quietly. Moule (1954) reported ewes varied in their 'mothering instinct'; those exhausted at the conclusion of lambing were often observed to display poor mothering instinct. Poor mothering / desertion results in lambs dying from dehydration and hypoglycaemia. These weak lambs are also more prone to attack from predators (Smith 1964). However, Smith (1965) reported desertion was rarely a cause of lamb mortality in autumn and winter lambings unless associated with blindness due to entropian or ant attacks (*Iridomyrmex obscurus*).

Smith (1964) reported lamb deaths due to starvation / desertion were related to parity (single lambs having lower mortality rates), presence of fly strike, ewe body condition, heat prostration of lambs and blindness of lambs caused by entropian or irritation by ants. Jordan and Le Feuvre (1989) also observed an association between desertion and ewes on below maintenance diets. In one group of sheep Smith (1962) observed that most lamb desertions occurred following 6 - 12 hours of mothering. Lambs born to ewes with unsound udders are also twice as likely to die during the neonatal period, on one occasion the rate of mismothering in the neonatal period was increased due to a severe wave of sandflies (*Simulids*, Moule 1954). The sandflies caused the ewes to congregate together, limiting their movement and feeding, as well as increasing mismothering. Cobon and Carter (1994) suggested the prostrate diffuse growth pattern of forbs and their presence in large numbers in Mitchell grass pastures could affect the ability of lambs to move freely, and therefore, increase the risk of desertion during the neonatal period.

Small, lighter lambs have been shown to take longer to stand, have reduced ability to suckle effectively and are far more likely to die within the neonatal period (Moule 1954, Stephenson *et al.* 1984, Jordan and Le Feuvre 1989). Moule (1966) reported birth weights of 25 flocks in tropical Queensland to range from 0.9 - 5.7 kg, and to be normally distributed in all flocks except one where abortions occurred. Ram lambs generally have heavier birthweights than ewe lambs, and single birth lambs heavier than multiple birth lambs (Kennedy and Bettenay 1950, Moule 1954, Smith 1962). Kennedy and Bettenay (1950) found the lambs from multiple births were more likely to die at both the neonatal period and the intervening period to lamb marking; less than half the ewes with twins raised both to marking. Also, Moule (1954), unexpectedly found lambs born to ewes with unsound udders had lower birth weights. The author suggested that Seyles stress theory may possibly explain this finding where blindness of the teats was due to infectious causes.

Rose (1972) attributed the high neonatal mortality rates of autumn born lambs in north-west Queensland to their summer gestation and subsequent low birth weight (2.9 kg compared with 3.7 kg for spring born lambs). Hopkins *et al.* (1980) also reported the mean birth weight of autumn lambs at Toorak, which died before marking, was less than those lambs which were marked (2.31 *vs.* 3.30 kg $P<0.01$). Similarly, Rose (1978) reported the mean birth weight of Toorak autumn and spring joined lambs surviving the first three days was 3.4 kg while those that died had a mean birth weight of 2.8 kg. Jordan and Le Feuvre (1989) found the mean birth weight of lambs that died in their Charleville pen study was 3.0 kg. Those lambs that died of starvation lost 0.22 kg daily with a mean loss to autopsy of 0.35 kg.

Hopkins *et al.* (1980) noted that hyperthermia (42 - 43^{0}C) can occur in lambs less than four days old under high ambient temperatures, and is associated with extreme respiratory effort and subsequent exhaustion as lambs attempt to reduce body temperature. Moule (1954) reported that afternoon rectal temperatures of neonatal lambs held in shaded yards during November often exceeded 40.6^{0}C, and following a brief period of brisk exercise, 41.7^{0}C. Hopkins *et al.* (1980) postulated that such exhausted lambs are unlikely to suckle especially if their ewes are grazing during the cooler evening hours. Moule (1954) and Smith (1964) found that lambs, prostrated by heat and unable to follow their mothers to water, may be deserted and succumb to predators. Stephenson *et al.* (1984) found higher survival rates (84 *vs.* 65%, ns) in lambs born during cooler periods, independent of lamb birth weight. Similarly, Roberts (1984) reported that increased ambient temperatures (28 *vs.* 36^{0}C) at Toorak resulted in increased lamb mortalities (14.0 *vs.* 36.0% respectively).

D1.9.2 Postnatal period

The postnatal period extends from approximately three days post-lambing to lamb marking. Kennedy and Bettenay (1950) report the mean lamb age at marking was six weeks while Moule (1954) studied a number of flocks with a range of lamb ages at marking. Lamb marking in other trials was usually carried out 2 - 3 months after the commencement of lambing (Jordan *et al.* 1989, Jordan *et al.* 1989-90, Norton *et al.* 1990).

Postnatal lamb mortalities appear to be of lesser importance than mortalities immediately after birth (table A1.4) although there is marked variation from property to property and season to season. Moule (1954) reported a mean mortality rate of 19.9% of all lambs born with the range for the seven flocks being 8.6 - 69.2%. The importance of Kennedy and Bettenay's (1950) postnatal lamb mortalities relative to neonatal losses listed in table A1.4 may be misleading as their ewes lambed in pens and spent the neonatal period in yards prior to being released into paddocks.

Factors influencing postnatal lamb mortalities include udder soundness, fly strike and blindness. Moule (1954) found that of the postnatal period, the greatest percentage was from ewes with unsound udders (26.6 *vs.* 18.1% $P<0.05$). Fly strike led to desertion by ewes of lambs up to two weeks of age (Smith 1964). Entropian and occular irritation by the ant, *I. obscurus*, leading to chemosis and blindness were also identified as minor but consistent causes of lamb mortality (Smith 1962, 1964, 1965).

D1.9.3 Post-marking period

Rose (1972) reported a mean post-marking lamb loss of 10.5% for spring born Toorak lambs (1965 - 1970) most of which occurred prior to weaning due to poor nutrition. In the autumn lambing flock (1953 - 1964), 25.0% of marked lambs died after weaning as pasture quality declined.

D1.10 Ewe age

Turner and Dolling (1965) presented age-specific reproductive data for a flock of medium peppin Merino ewes at Cunnamulla, south-west Queensland (table A1.6). Reproductive capacity rose from two years of age and peaked at the following ages:

- 5 - 6 years for ewe lambing rate;
- 6 years for survival rate of single and twin lambs;
- 6 years for number of lambs weaned per ewes joined;
- 7 years for lambing rate; and

- 7 - 8 years for number of multiple births per ewe joined.

Table A1.6. Reproductive maxima versus age for sheep near Cunnamulla (Turner and Dolling 1965).

Reproductive measurement	**Value as maidens**	**Peak value (and age)**	**Value as 10 year olds**
Percentage of ewes lambing	82.0	92.0 (5 - 6)	86.0
Percentage of multiple births	2.0	20.0 (7-8)	17.0
Lambing rate (%)	84.0	111.0 (7)	104.0
Weaning rate (%)	62.0	89.6 (6)	71.0

Following these peaks, production fell as the animals aged (maximum age 10 years) with the 10 year old values being greater than values for two year olds in most cases. Turner and Dolling (1965) also cited Riches (1958) who reported that for a number of Merino strains, the lamb marking percentage increased with age of ewes up to 5 - 6 years while the figures beyond this are scanty with no consistent pattern. It should be noted that Turner and Dolling (1965) in their calculations used the number of ewes joined and present at lambing as the number of ewes joined; ewe losses from joining to lambing were approximately 2%.

Rose (1972) also presented age-specific reproductive data for a flock at Toorak for 1953 - 1970. The flock was joined in autumn until 1964, and from 1965 onwards was joined in spring. The reproductive performance of the autumn joined ewes, as judged by lambs born and proportion surviving till marking, increased until age 5.5 years (age at joining) and declined thereafter. Reproductive performance at 10.5 years was below that of the maiden ewes (1.5 years). The spring joined ewes attained their peak a year earlier at 4.5 years, and declined more rapidly with their productivity at both 9.5 and 10.5 years below that of the maiden ewes. Significant differences between the autumn and spring joined flocks for lambing rate were present in the 5.5, 6.5 and 7.5 year age groups, for lamb mortality in the 6.5 year age group, and for lamb marking rate in the 5.5 and 7.5 year age groups.

Jordan *et al.* (1989) reported that, of four properties where within year comparisons were made, maiden ewes had significantly lower ($P<0.05$) pregnancy rates than older ewes on two properties. Similarly, for all observations (30 observations on 11 properties between 1976 - 1985), the mean pregnancy rate of maiden ewes was 88.0% compared with 94.7% for mature ewes.

Lindsay *et al.* (1975) found age to be significantly related to lambing rate ($r^2=0.21$ $P<0.01$) for Merino and Merino cross sheep joined over summer / autumn in south Western Australia. In contrast, Kennedy and Bettenay (1950) found no effect of ewe age on lambing rate, which is in line with the findings of Norton *et al.* (1990) where the percentage of ewes pregnant at four months was similar across all age groups.

D1.10.1 Oestrus and ovulation

Entwistle (1972) reported that for four out of five observations at Toorak, oestrous activity in both spring and autumn joined maiden ewes was less ($P<0.01$) than for mature ewes, probably because of delayed onset of puberty. Similarly, Norton *et al.* (1990) reported that for sheep in south-west Queensland, 88.1% of maiden ewes and 99.4, 98.7 and 97.3% of 3, 4 and 5 year old ewes respectively were joined. However, one of three groups of maiden ewes had a joining rate of only 68.2% which reduced the age mean dramatically.

Other workers have found maiden ewes to have similar joining rates to mature ewes. For example, McMeniman and Holle (1973) reported maiden ewe joining rates of 98.9 and 97.4%; Jordan *et al.* (1989) found 93.0% of maiden ewes and 99.0% of mature ewes were mated during the joining period; and Kennedy and Bettenay (1950) also found age of ewes (3 - 5 years) did not influence the percentage of ewes showing oestrus.

Multiple births increased with age in the data of Kennedy and Bettenay (1950) and Turner and Dolling (1965). This trend can be interpreted as the effect of age on ovulation rate, assuming there is no effect of age on fertilisation or embryonic mortality.

D1.10.2 Fertilisation and embryonic mortality

McMeniman and Holle (1973) found that 85.5 and 89.8% of maiden ewes mated were pregnant 4 - 5 months after joining, while Dolling and Nicolson (1967) reported losses for maiden ewes near Cunnamulla failing to conceive were 13.6 - 14.5%, and fell to 3.3 - 4.8% at 10 years of age. The reverse trend was seen for losses from sheep conceiving but failing to lamb, 2.7 - 3.8% for maiden ewes increasing to 10.1 - 12.0% at 8.5 - 11.5 years of age. In contrast, age of ewes over a narrower range (3 - 5 years) was not correlated with the percentage of ewes failing to conceive (Kennedy and Bettenay 1950).

D1.10.3 Parturition and maternal behaviour

Alexander *et al.* (1993) found that Merinos at Armidale, New South Wales, differed in their duration of lambing, depending on parity and age. Two year old maiden ewes had a shorter parturition than five year old maiden ewes (51.3 *vs.* 80.2 min $P<0.05$), and a longer duration than multiparous five year old ewes (51.3 *vs.* 22.0 min $P<0.01$). Duration of parturition was the time from first appearance of membranes till birth. Ewes which required assistance (7.1% of two year old maidens, 13.1% of five year old maidens, 0.0% of multiparous ewes) were not included in the above results and would be expected reinforce the trends. No differences in duration of parturition were found for non-maiden ewes of various parity.

Maiden ewes are generally expected to be poorer mothers. Kennedy and Bettenay (1950) found evidence to support this during the neonatal period, but concluded that maiden ewes mother as well as older ewes afterwards. The incidence of mismothering by maiden ewes during the neonatal period in their study could have been elevated due to the large number of ewes lambing together in a confined space. Alexander (1968) and Alexander *et al.* (1993) reported maternal behaviour of primiparous ewes to be characterised by the following:

- less grooming of lambs immediately after birth;
- greater occurrence of non-cooperative behaviour during initial attempts of the lamb to suck; and

- more desertions.

Alexander *et al.* (1993) used maiden ewes aged up to five years of age and found the above traits, as well as the incidence of malpresentation, were marked in these older primiparous ewes. The authors concluded that the superior maternal behaviour of multiparous ewes was associated with previous experience in lambing and independent of age of ewe.

D1.10.4 Birth weight and lamb mortality

Alexander *et al.* (1993) found primiparous ewes had longer labour and greater lamb losses than multiparous ewes. Kennedy and Bettenay (1950) found age (3 - 5 years) was significantly associated with lamb mortality and birth weight of lambs. Lambs from five year old ewes (4.09 ± 0.56 kg) were significantly heavier than lambs from three (3.91 ± 0.58 kg) and four year olds (3.98 ± 0.64 kg). In contrast, Norton *et al.* (1990) found the percentage of lambs surviving till marking from maiden ewes was less, but not significantly, at 81.6% compared with 86.8, 89.1 and 90.7% for the other age groups. Similarly, Jordan *et al.* (1989) found the mean survival rate of lambs to marking for maiden and mature ewes (for all observations) were similar; 86.4 and 83.0%.

D1.10.5 Ram fertility

McMeniman and Holle (1973) found no effect of ram age and previous experience on fertility for an autumn joined flock using 3% rams.

D1.11 Heat stress

D1.11.1 Joining and pregnancy

Thwaites (1985) reported that oestrus and fertilisation are generally unaffected by periods of heat stress, although the onset of the breeding season may be delayed as a result of heat stress. However, he considered early embryonic death (less than seven days) is more likely as a result of heat stress. Roberts (1984) agreed with the latter finding of Thwaites (1985) but considered heat stress was also capable of suppressing oestrus and causing fertilisation to fail.

Entwistle (1970) reported fertilisation rates of 72.7 - 80.4% for tropically adapted ewes joined from September to December with high ambient temperatures (mean maximum temperature > 34.0°C) and sub-maintenance feed. The percentage of abnormal ova (12.0%) was in line with reports for sheep in temperate climates whereas the losses of potentially fertilisable ova (19.6 - 27.3%) were greater. In contrast to the conclusions of Thwaites (1985) and Roberts (1984), post-fertilisation embryonic mortality (up to 20 days post-coitus) was low and of minor importance, and fertilisation failure was the major cause of reproductive wastage to 20 days. Lindsay *et al.* (1975) found significant negative relationships between mean maximum summer temperatures at mating and both the ewe lambing rate (r^2=0.10 $P<0.05$) and the lambing rate (r^2=0.10 $P<0.05$). Temperatures for the three week period following mating were also negatively related to lambing rate (r^2=0.08 $P<0.05$). Post mating temperature was examined because it may have affected embryonic mortality. The mean number of days / week during mating with maximum temperatures greater than 32.2°C and 35.0°C were both negatively correlated to ewe lambing rate (r^2=0.12 $P<0.05$ and r^2=0.14 $P<0.01$ respectively) and lambing rate (r^2=0.12 $P<0.05$ and r^2=0.14 $P<0.01$ respectively). The authors concluded that this response was due to the impact of ambient temperature on embryo survival. Similarly, Moule (1966) reported a significant correlation (r^2=0.32 $P<0.01$) between the percentage of ewes conceiving on their first oestrus and the consecutive number of months prior to joining with mean maximum temperature less than 35°C. Much of the reported variation in effect of heat stress on fertilisation and early embryonic mortality may arise from variation in design, particularly the selection of heat adapted sheep and the method of applying heat stress (Entwistle 1970, 1972).

Moule (1954) cited Lee and Robinson (1941) and Robinson and Lee (1946, 1947) who found that adult Merino sheep tolerated high temperatures. Also, sheep on high planes of nutrition had higher rectal temperatures, pulse and respiratory rates than those on poorer feed following exposure to high temperatures. However, there is between animal variation in their ability to tolerate high temperatures. McCrabb *et al.* (1993b) identified two groups of tropically reared non-pregnant ewes based on lower rectal temperatures during heat stress. These ewes were subsequently joined and carried lambs over the following summer. The group with lower rectal temperatures had higher joining (89% *vs.* 63%) and lambing rates (82% *vs.* 50%). Liveweights and condition score of the two groups were similar, but sheep which failed to lamb had lower liveweights at mid-pregnancy and time of lambing. However, there was no difference in rectal temperature and breathing rate between ewes with and without lambs within groups.

The impact of heat stress on birth weight lambs, compared with poor nutrition, is greater under Queensland grazing conditions (Moule 1954, Cartwright and Thwaites 1976, Hopkins *et al.* 1980, Alexander *et al.* 1987). Hopkins *et al.* (1980) showed that restricted nutrition during the last 78 days of pregnancy reduced ewe lambing weight (34.4 *vs.* 44.5 kg for control) and lamb birthweights (3.2 *vs.* 3.9 kg $P<0.01$), but not to the same extent as severe heat stress during the last month of pregnancy (2.3 *vs.* 3.4 kg $P<0.01$). Stephenson *et al.* (1984) also found that restricted nutrition during the last month of gestation was less important than shade in autumn lambing ewes in north-west Queensland. As stated earlier, Leng (1989, 1990, 1991) suggested climatic heat stress and poor feed may combine to increase the heat stress experienced by breeding ewes. Diets with low protein / energy ratios available for absorption increase the heat increments of feeding (lowered efficiency of utilisation) and overall heat stress. Therefore, poor nutrition may lower birthweights by reducing availability of nutrients to the foetus and increasing heat stress.

Hopkins *et al.* (1980) used climate control rooms to cause ewes to have rectal temperatures of 40.0^0C for 16 - 17 hours daily from day 117 of gestation. As described earlier, lambs born to these ewes had mean birthweights of 2.3 kg, much less than the 3.4 kg of lambs born to control ewes ($P<0.01$). The same authors found over two successive lambings of grazing sheep, a decrease of 1.42 and 1.58 kg in lamb birth weight for every 1.0^0C increase in rectal temperature during late pregnancy. McCrabb *et al.* (1993b) also found lamb birth weight was negatively correlated with ewe afternoon rectal temperature at both the time of selection ($r^2=0.30$ $P<0.001$) and during the second half of the gestation

(r^2=0.46 $P<0.001$). Low rectal temperature ewes produced lambs with a mean liveweight of 3.8 kg while high rectal temperatures ewes produced lambs with a mean liveweight of 3.2 kg ($P<0.001$). Moule (1966) found a significant relationship (r^2=0.58 $P<0.001$) between mean birth weight of single lambs and the number of months during pregnancy in which air temperatures were below 35.0^{0}C, but no relationship between mean birth weight and hot weather during the last two months of gestation.

Heat stress is also associated with reductions in skeletal size that may lead to 'dwarfing'. McCrabb *et al.* (1993b) reported that the differences in skeletal measurements indicate disproportional growth, including restricted soft tissue growth. Alexander (1968) reported that the 'degree of dwarfing is closely correlated with the mean elevation of ewe rectal temperature towards the end of daily heat exposure', while Hopkins *et al.* (1980) found that for lambs of ewes suffering heat stress in the climate control rooms, the reduction in skeletal size was 'less striking' than the reduction in birth weight.

Alexander and Williams (1971) observed that heat stressed foetuses had disproportionally larger heads, body length, kidney and adrenal weights while the liver, thyroid and thymus were disproportionally smaller. McCrabb *et al.* (1993b) made the following observations regarding skeletal size of lambs born to high and low rectal temperature ewes:

- Ponderal Index (PI) was greater for lambs of low rectal temperature ewes ($P<0.05$), where $PI = Wt / (cr)^3$, Wt is lamb birth weight (kg), and cr is crown rump length (mm);
- thoracic girth and biparietal width were smaller (mm / kg) for lambs of low rectal temperature ewes ($P<0.01$); and
- length of the tibia and radius was smaller (mm / kg) for lambs of low rectal temperature ewes ($P<0.01$) while there was no difference in lengths of the humerus and femur between the two groups of lambs.

The actual mechanisms by which heat stress causes low birth weights is not fully understood. Alexander and Williams (1971) showed that heat stress during early pregnancy markedly reduced the placenta by decreasing the weight but not number of cotyledons. The reduction in placental size was closely associated with low lamb birthweights. Hopkins *et al.* (1980) concluded that if restricted foetal nutrition is responsible for low lamb birthweights, this must arise from abnormalities of placental uptake or alterations in uterine blood flow. Alternatively, if availability of nutrients is not limiting foetal growth, 'metabolic dyscrasia' due to foetal hyperthermia may cause poor foetal development. Thwaites (1985) concluded that a reduction in uterine blood flow, and therefore, nutrition supply to the foetus, a reduction in placental supply and a general increase in metabolic rate (van't Hoff or Q10 effect) are responsible for the retarded foetal growth during foetal heat stress.

More recent work of Bell *et al.* (1987) and McCrabb *et al.* (1993a) supported the hypothesis that reduced foetal growth during heat stress arises from a restriction in placental growth and functional development. Bell *et al.* (1987) reported a diurnal pattern of heat stress during days 45 - 120 caused variable reductions in placental weight, and lesser but correlated reductions in foetal weight. They suggested that heat stress in ewes reduced placental growth, and therefore, supply of oxygen and nutrients to the foetus thereby producing smaller rates of foetal growth. Alexander *et al.* (1987) reasoned the reduction in placental blood flow precedes and causes the reduction in placental size. Acute heat stress led to a 14% reduction in flow of blood through the maternal side of the cotyledonary placenta. The reduced blood flow persisted while the ewes were exposed to excessive heat. McCrabb *et al.* (1993b) concluded the mechanisms that reduce foetal growth rates during heat stress are restricted maternal blood supply and transport of nutrients across the placenta. These authors also suggested that the 'duration of time for which ewes experience elevated body temperature on hot days, in addition to maximum (afternoon) body temperature, determine the extent to which foetal growth is affected'.

D1.11.2 Parturition

Stephenson *et al.* (1984) found no difference in duration of parturition (25 ± 3 min.) for ewes with or without shade and for different planes of feeding in the last month of gestation.

D1.11.3 Lactation

Alexander (1968) reported that heat stress during pregnancy may reduce lactation.

D1.12 Cold stress

Alexander and Williams (1966) found cold and wet conditions reduce the teat seeking behaviour of new born lambs, independent of their energy reserves and normal rectal temperatures. A short period (4 - 5 hours) of cold stress will not affect lamb survival provided their temperature returns to normal. However, continued cold stress usually leads to death of lambs due to starvation or terminal hypothermia.

Moule (1954) considered the mean minimum temperatures in winter for semi-arid Queensland (rarely less than 5.6^0C) were unlikely to affect lambs. However, it was noted that strong dry winds during winter may cause hypothermia in 'wet' new born lambs due to loss of body heat as placental fluids evaporate. Such lambs were observed to die quickly in one observation.

D1.13 Predators

The importance of predators as a cause of lamb mortality is not clear, especially when the interplay between starvation / desertion and predation are considered. In central western Queensland, Smith (1964) found 27% of neonatal lambs examined show signs of predator attack, while only 14% of these were not starving at the time of death. In contrast, Smith (1965) found predators to be the most important cause of neonatal mortality accounting for 58% of all lamb deaths, the majority of which appeared to be viable. Moule (1954) reported that during the neonatal period, 34.2% of lamb deaths (7.3% of all lambs born) were due to predators.

Smith (1964, 1965) found the wedge tailed eagle (*Aquila audax*) and raven (*Corvus coronoides*, more commonly called crows) were the most important predators, mainly for lambs immediately following birth, and some older deserted lambs. Lambs in the open were susceptible to attack by eagles, while ravens would often intimidate ewes into leaving their newborn lambs which they would then attack. Ravens have been reported to attack lambs as soon as their heads presented during birth (Moule 1954). Ravens were the most important cause of mortality in Border Leicester lambs born in south-west Queensland over two successive breeding seasons, with twin lambs more prone to predation than single lambs (51.4 *vs.* 13.7% $P<0.001$, Smith 1964). Moule (1954) found ravens, feral pigs and foxes to be the most important predators, while Jordan and Le Feuvre (1989) reported pigs and foxes to be the most important.

Moule (1954) noted the heavy impact that feral pigs may have on lambing. A paddock close to a water hole in which 40 pigs were shot during the course of the study had a lamb marking rate of 6%, while control sheep in another paddock had a lamb marking rate of 36%. Similarly, Plant *et al.* (1978) while investigating a property with poor reproductive performance reported the use of electric fencing to exclude pigs from a paddock in north-west New South Wales. The exclusion paddock had a lamb marking rate of 117% whereas the adjoining control paddock had a lamb marking rate of 80%. The authors noted the owner had not considered feral pigs a problem, and cited the survey of Riches (1958) which found few sheep producers considered feral pigs as serious pests. In contrast, a survey in central west Queensland (Pearse 1990) found 95% of producers recognised predation as a cause of lamb losses; pigs, foxes and eagles being considered the most important. Smith (1964) reported that the importance of both feral pigs and foxes as predators was unable to be gauged accurately as they tend to consume the whole carcass. Orr *et al.* (1988), O'Dempsey (1987?) and Jordan *et al.* (1989) also noted the negative impact feral pigs may have on lamb marking percentages. Payne (1978) found only 67% of graziers in the Blackall shire of central western Queensland carried out a predator control program every year.

Red foxes (*Vulpes vulpes*) appear to be of little importance as predators, despite the findings of Moule (1954), Jordan and Le Feuvre (1989) and Pearse (1990). Palmer (1995) reported that although sheep were the most important feed source of foxes (25% by wet weight) in their two year survey near Cunnamulla, nearly all sheep meat had been scavenged from dead adults with lamb being found in only one of 74 stomachs examined.

The frequency of sheep in the stomach was greater in foxes from Mitchell grass and sandhill habitats compared with mulga grasslands.

In a survey, Pearse (1990), found producers in central west Queensland considered dingoes to be of little concern as predators, especially on Mitchell grass and gidgee country. This lack of importance, no doubt, relates to the distribution of dingoes and the general exclusion of sheep from these areas.

D1.14 Ram fertility

Smith (1962) examined 582 Merino rams from two properties near Aramac, north-west Queensland, and found palpable scrotal lesions in 15.6% of the rams. Approximately 66% of these lesions involved the epididymis and were attributed to *Brucella ovis* infection. Other abnormalities included testicular hypoplasia, varicocoele and cryptorchidism. As well, seasonal variation in semen quality was noted.

Any condition or environment causing an increase in scrotal temperature may lead to a reduction in fertility or infertility. Thwaites (1985) reported that 2 - 3 days of heat stress may be enough to affect the early stages of spermatogenesis with a resultant impact on ram fertility 3 - 5 weeks later. Smith (1962) found sperm abnormalities were lower and percentage live spermatazoa greater during June and September compared to values recorded during December and March. Entwistle (1972) found that fertilisation rates tended to decline along with percentage motile spermatozoa and percentage unstained spermatozoa.

Prolonged periods of drought may also result in seminal degeneration and infertility of rams on Mitchell grass pastures due to low vitamin A intakes, based on the work of Gunn *et al.* (1942) cited by McMeniman (1985). These early workers found feeding rams vitamin A deficient diets for six months or more caused infertility from seminal degeneration. McMeniman (1985) suggested the levels of ß carotene in mulga leaves, and their ready availability, excluded such a problem in mulga grasslands.

Despite the prevalence of reproductive tract abnormalities noted by Smith (1962), and the ability of heat stress and drought to affect fertility, O'Dempsey (1987?) reported the perceptions by graziers of poor ram performance as a cause of reproductive wastage were largely unfounded.

D1.15 Disease

Alexander (1968) reported that infectious causes of foetal death, weak lambs and neonatal mortality rates may be important in individual flocks, but on a national level, disease probably accounts for less than 10% of lamb deaths.

Smith (1964, 1965) found no evidence of pathogenic involvement in lamb deaths up to parturition. In the 1964 study, pneumonic lesions were identified in 0.8% and 3.8% of Merino and Border Leicester lambs dying a number of days post-partum respectively (causative organism not isolated), while in the 1965 study no lamb deaths were attributed to infectious causes. Moule (1954) reported 1.8% of lamb losses during the neonatal period being due to infections, the majority infected through the umbilicus and subsequent omphalitis. Hence, infection appears to play an insignificant role in reproductive wastage in Queensland sheep.

D1.16 Property management

Although seasonal effects on reproduction are marked, the impact of different management options under similar climatic conditions have been noted (O'Dempsey 1987?). The survey of Payne (1978) found many management practices correlated with better lamb marking performance (though not necessarily a cause) in central western Queensland (table A1.7).

Table A1.7. Correlation (r^2) of management practices on lamb marking performance from Payne (1978).

Management practice	**Correlation with improved lamb marking rates (r^2)**	**P value**
Positive correlations		
classing flock	0.466	<0.01
effective predator control program	0.413	<0.01
selecting special paddocks based on watering capabilities	0.407	<0.01
lambing maiden ewes separately	0.404	<0.05
25% or more of flock are maidens	0.404	<0.01
casting ewes at 5 - 6 years of age	0.392	<0.01
culling rams on age	0.376	<0.01
predator control program prior to lambing	0.357	<0.05
introducing portion of ram flock to ewes at intervals	0.350	<0.05
classing own flocks	0.327	<0.05
transporting rams to joining paddocks	0.324	<0.05
crutching prior to lambing	0.311	<0.05
shearing prior to joining	0.307	<0.05
selecting joining paddocks based on factors such as feed, water, sheep behaviour	0.304	<0.05
ram examination for scrotal abnormality	0.299	<0.005
selecting special paddocks for lambing	0.293	<0.05
replacing portion of ram flock annually	0.286	<0.05
ram examination more than six weeks prior to joining	0.279	<0.05
Negative correlations		
feeding ewes over lambing	0.282	<0.05
examining and treating rams for overgrown hooves	0.286	<0.05
increased stocking rate	0.290	<0.05
shearing prior to lambing	0.316	<0.05
mustering ewes to yards for joining	0.330	<0.05

Jordan *et al.* (1989-90) found increasing stocking rate (0.90 - 1.13 ewes / ha) to be negatively correlated with the following measures of reproductive performance on one Muckadilla property:

- lamb marking rate (r^2=0.98 $P<0.01$);
- percentage of ewes rearing a lamb (r^2=0.90 $P<0.01$);
- percentage of lambs which were twins (r^2=0.74 $P<0.01$); and
- lamb weight at marking (r^2=0.88 $P<0.01$).

The authors suggested that reduced stocking rates allowed for greater selection of a more nutritious diet. There was a four fold difference in lambs marked / ha between the highest and lowest stocking rates; optimal lamb production per hectare occurred approximately midway in the stocking rate variation.

Central and north-west Queensland properties have two distinct joining periods (Moule 1954, Entwistle 1972). Spring joining is associated with high environmental temperatures, poor pasture quality and ewes carrying lambs through the hot summer months. However, lambing usually occurs during a period of good feed availability and quality. Autumn joining generally occurs when pasture availability and quality is better and temperatures are declining, but lambs are born when temperatures are rising and pasture availability and quality are declining. Current DPI recommendations for sheep in north-west Queensland are spring joining so that lambing occurs after the wet season when pasture conditions are at an optimum (Cobon *et al.* 1994b). A recent survey of the north-west by Thompson (1993) found 72% of respondents practiced spring joining.

In central western Queensland there is effective winter (April - September) rainfall in 66% of years (Farmer *et al.* 1947 cited by McMeniman *et al.* 1989) which promotes the growth of winter forbs (Orr and Holmes 1984). The availability of forbs ensures a good quality diet which is especially important for pregnant and lactating ewes during the late winter / spring period. Failure of winter rains results in pasture and dietary quality similar to that which occurs in the north-west of the state (McMeniman *et al.* 1989). Current joining practice in central-west Queensland slightly favours spring joining (37%), followed by autumn (24%) and summer (12%, Pearse 1990). Nineteen percent of central-west producers reported they joined depending on the current season.

Properties in south-west Queensland normally join in autumn enabling lambing to occur on pastures benefiting from expected winter rainfall (McMeniman 1985, Jordan *et al.* 1989, Jordan *et al.* 1989-90, Norton *et al.* 1990).

In most of the studies in various regions of the state, joining lasted 6-8 weeks (range 6 - 12 weeks) using 2.0 - 2.5% (range 1.5 - >3.0%) rams.

D1.17 Prediction of reproductive performance

Lindsay *et al.* (1975) used multiple linear regressions for variables measured at the time of mating to explain variation in ewes lambing ($r^2=0.35$ $P<0.01$) and lambing rates ($r^2=0.38$ $P<0.01$). The equations were:

$$Ewe\ Lambing\ Rate = 61.6 + 0.3 * Wt + 2.5 * Age - 2.7 * Heat\ Days$$

$$Lambing\ Rate = 52.6 + 0.6 * Wt + 3.7 * Age - 3.5 * Heat\ days$$

where *Wt* is liveweight in kg at mating, *Age* is age in years at mating, and *Heat Days* is the mean number of days / week when maximum temperature was equal to or greater than 32.2^{0}C.

The authors considered that measurement of such variables at the time of mating could be used to predict reproductive performance.

Cobon and Carter (1994) found that reproductive performance could be explained by biomass of forbs or the proportion of forbs in total biomass. Their initial trial found lamb marking percentage was able to be predicted from the following:

- ratio of grass to forbs ($r^2=0.90$ $P<0.01$);

  $Lamb\ Marking\ Rate = 43.7 + 1.63 * ratio\ of\ grass\ to\ forbs\ (kg / ha)$
- total forb biomass ($r^2=0.78$ $P<0.05$);

  $Lamb\ Marking\ Rate = 60.9 - 27.3 * total\ forb\ biomass\ (t / ha)$
- forbs as a percentage of total biomass ($r^2=0.77$ $P<0.05$);

  $Lamb\ Marking\ Rate = 63.7 - 0.451 * forbs\ as\ percentage\ of\ total\ biomass$

A following trial two years later found lambing percentage was able to be predicted from the following:

- total forb biomass ($r^2=0.98$ $P<0.08$);

  $Lambing\ Rate = 91.7 - 7.75 * total\ forb\ biomass\ (t / ha)$

- forbs as a percentage of total biomass ($r^2=0.98$ $P<0.09$);

  $Lambing\ Rate = 91.8 - 0.132 * forbs\ as\ percentage\ of\ total\ biomass$

Lambing percentages in both trials were found to be unrelated to the following individual pasture components: grasses, C4 forbs, C3 forbs.

Entwistle (1972) attempted to develop a regression equation to predict fertilisation rate based on the tendency for percentage unstained spermatazoa and percentage motile spermatazoa to decline with fertilisation rates. However, the resulting coefficients of the equation were not significant.

White (1978) used a multiple linear regression technique to predict lamb marking rates ($r^2=0.36$) in his integrated property model:

$$Lamb\ Marking\ Rate = 11.49 + 0.664 * WI - 1.322 * PI + 0.212 * YI + 6.71 * shire$$

where *WI* is the weight index for lamb marking, *PI* is the parasite index, *YI* is time in years from 1945, and *Shire* is a dummy variable (0 for northern shires, 1 for southern shires).

The parasite index was based on an environmental stress index, temperatures in spring and summer were optimal as were high values for the rainfall / evaporation ratio. The weight index assumed that potential lamb marking rates were determined by ewe weight at joining, with subsequent changes in weight influencing the index. The weight index was more sensitive to changes in nutrition in late pregnancy compared with early pregnancy. The time trend allows for approximately one percentage point improvement in lamb marking every five years. The dummy variable was necessary as spatial trends in production were not accounted for by the model. A vector was used to modify the calculated lamb marking rate for each ewe age group, in the flock. This vector was based on data of Rose (1972) for the Toorak spring joined flock.

The Grazplan model of Freer *et al.* (submitted) used the following functions to predict conception rates (those embryos surviving to the third trimester):

$$CR_{\geq n} = (1.0 - 0.3 * (1.0 - \sin (2 * pi (t + 10.0) \ / \ 365.0))) * SF$$

$$SF = 1.0 \ / \ (1.0 + \exp (- (Z * BC) - (C_{F2n} + C_{F3n}) \ / \ 2.0) * (5.88 \ / \ (C_{F3n} - C_{F2n})))$$

where $CR_{\geq n}$ is the probability of an animal conceiving at least a given number (n) of young, t is time of the year, Z is the relative size of the animal (ratio of normal weight to Standard Reference Weight, maximum value 1.0), BC is the ratio of current base weight to normal weight, $C_{F2n} = 0.2$ when n is 1.0 and 0.7 when n is 2.0, and $C_{F3n} = 1.1$ when n is 1.0 and 1.5 when n is 2.0 (for Merino sheep only).

The probability of conceiving a specific number of young are then calculated by subtraction:

Given $CR_{\geq 0} = 1.0$

$$Cr_n = CR_{\geq n} - CR_{\geq n+1}$$

The calculated conception rates are applied to sexually mature, non-pregnant females once per oestrous cycle.

Work by Moore *et al.* (1995) using the Queensland data of Rose (1972, 1974, 1976, 1978, 1982) and Jordan *et al.* (1989) found the probability of pregnancy was not accurately estimated by the original Grazplan model. Re-estimation of the Grazplan parameters, together with a third equation, allowed 87% of the variation in observed pregnancy rates to be explained:

$$CR = (1 - 0.33 * (1 - \sin (2\pi / 365 * (DOY + 10)))) * x$$

$$x = 1 / (1 + \exp [- \{ (2 * (\ln (0.95) - \ln (-0.05)) / (1.03 - 0.60)\} * \{ Z * BC - (0.60 + 1.03)/ 2\}])$$

$$PR = 1 - (1 - CR)^n$$

where PR is pregnancy rate, CR is probability at least one young would be conceived per oestrous cycle, n is the number of cycles, and DOY is day of year (1-365).

More recent work (Pepper *et al.* 1996) has focused on using simple climatic, soil and pasture variables to estimate reproductive rates. Additional data (O'Dempsey 1987?), which were not used in the previous work (Moore *et al.* 1995) because liveweights were not recorded, were available for analysis. The following functions were found to explain 81% of the observed variation in lamb marking:

$$LMR_j = 0.429 + 0.00798 * swi_{j-1} + 0.1333 * age - 0.01292 * age^2 - 0.404 * e^{-0.00267 * tsdmjoin}$$
$$+ 0.0418 * \Delta N + 0.00436 * rddays - 0.0034 * f - 0.000886 * day_{j-1}$$

where LMR_j is number of lambs as a proportion of the number of ewes at joining, swi_{j-1} is the number of days the soil water index was higher than 0.4 in the two year period to mid-joining, *age* is age of ewes in years, *tsdmjoin* is total standing dry matter (kg/ha) at mid joining, ΔN is change in proportion of pasture nitrogen from mid-joining to marking, *rddays* is number of rain days in the growing period, f is a measure of frost and its severity on pasture as defined by Σ(2 - minimum temperature) if minimum temperature 2^0C or less in the period from end of growing period to mid joining, and day_{j-1} is days from end of previous growing season.

Part E

Mortality

E1.1 Introduction

Very little information has been published on mortality rates and especially regarding the quantification of those factors affecting the likelihood of death occurring.

Unpublished data of I. Beale found death rates of 8.8 and 13.9% for Merino ewes near Charleville (grazing at utilisation rates of 20 and 50%) from joining to lamb marking, climbing to 14.7 and 20.9% at weaning. McMeniman *et al.* (1989) reported two groups of ewes in central western Queensland, which lost 140 g / day between joining and lambing, had 12 and 28% mortality during or shortly after parturition. Jordan *et al.* (1989) found ewe losses from joining to marking for 30 groups of Merino ewes throughout the south-west of the state averaged 7.4% (0 - 36%). Orr *et al.* (1988) reported two years of lower than normal lamb marking rates, due to poor pasture conditions at lambing, were also associated with pregnancy toxaemia and ewe mortality rates of 26 and 19% compared to <6% in other years. However, Norton et al. (1990) reported mean ewe mortality between joining and weaning in south-west Queensland of 16.5% (range 4.9 - 26.1%), with some evidence of higher mortality rates in maiden ewes compared with 3 - 6 year old ewes.

E1.2 Age specific mortality rates

Moule (1966) reported age specific mortality rates (up to eight years) for 25 flocks of breeding Merino ewes from central and north-west Queensland (figure A1.4). These were similar to those rates reported by Rose (1972) for the Toorak Research Station experimental breeding flock (1953 - 1970). Large losses occurred in young stock before

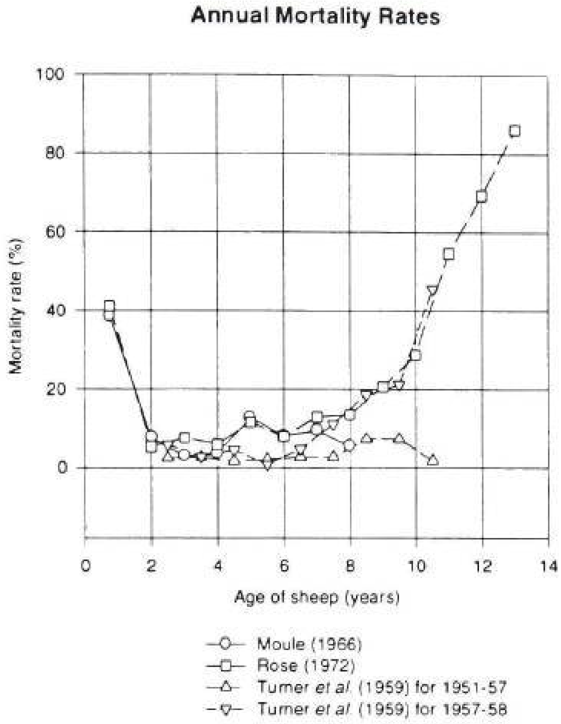

Figure A1.4. Age specific mortality rates from Turner et al. (1959), Moue (1966) and Rose (1972).

they were joined and included in the breeding flock. Annual mortality rates for adult stock were minimal up to approximately eight years of age. Beyond this Rose (1972) found the mortality rate increased with age, with few ewes surviving beyond 12 years of age.

Turner *et al.* (1959) reported age specific mortality rates for breeding ewes grazing mainly mulga grasslands on Gilruth Plains near Cunnamulla for 1951 - 1957. The results of their work were presented for two separate periods:

- 1951 - 57, ewes mated each year; and
- 1957 - 58, due to effects of drought (1956 - 58), lambs were weaned early and ewes not joined in 1958.

The mortality rates for 1951 - 57 were slightly lower than those reported by Moule (1966) and Rose (1972), and failed to show an increase for aged sheep prior to being cast for age at 10.5 years. The mortality rates recorded during 1957 - 58 when pasture conditions were sufficient to cause management changes, but no supplementary feeding, were similar to those reported for the central and north-west of the state.

E1.3 Prediction of mortality rate

Grazplan (Freer *et al.* submitted) uses a set daily mortality rate which may be modified if body condition and daily weight gain of growing animals are below preset thresholds. The mean weight of survivors is adjusted upwards, assuming those sheep dying were 10% lighter than the group mean.

$MR = 2.8 \times 10^{-5}$ (basal mortality rate)

if $\delta W < 0.2(dN/dA)$ $MR = C_{D1} + C_{D2}\ max(0.0, C_{D3} - BC)$

otherwise $MR = C_{D1}$

where W is weight of the sheep, fleece and conceptus free, N is normal weight, A is age in days, MR is mortality rate, C_{D1} is basal mortality rate; 2.8×10^{-5}, BC is body condition, the ratio of current W to N, $C_{D2} = 0.5$, and $C_{D3} = 0.6$.

Work by Moore *et al.* (1995) using Queensland data found mortality rates from pre-joining to marking were not well estimated by the Grazplan model. Further analysis developed the following function which explained 78% of the variation in the observed data:

$$AMR = 1 / (1 + e^{-y})$$

$$y = 14.51 + 0.20 * age - 22.41 * BC_{min} - 13.07 * P + 17.59 * BC_{min} * PR$$

where AMR is annual mortality rate, age is age in years, BC_{min} is minimum condition at pre-joining, post-joining, pre-lambing and marking, and PR is pregnancy rate (0 - 1).

Functions to predict lamb marking and mortality rates were later developed using simple climatic, soil and pasture variables (Pepper *et al.* 1996). The following function was found to explain 63% of the observed variation in mortality:

$$DR = -3.218 + 0.2383 * age - 0.00226 * tswi_j - 0.00062 * tsdm + 0.1587 * f - 0.01025 * rdbreak + 0.002513 * day_{j-1} - 0.001345 * rd_{j-1}$$

where DR is annual mortality rate, $twsi_{j-1}$ is number of days the soil water index was higher than 0.4 and the average temperature greater than 14^0 C for Mitchell and 9^0C for mulga in the year prior to mid joining, *rdbreak* is the rainfall if current season breaks - from that time to mid joining, day_{j-1} is days from previous growing season, and rd_{j-1} is rainfall in the previous growing season.

Appendix Two

B. J. White Model Code

```
      PROGRAM WHITE

C   Version 18. Created by Wayne Hall, c/- Climate Impacts and Spatial Systems group,
C   Queensland Department of Natural Resources.
C
C   This is my copy, slightly altered of Barry Whites original code.  Started 11.1.94.
C   This version includes an economic component similar to Bill Holme's Breedewe
C   model.  Supplementary feeding has not been included.  This version has most imperial
C   calculations converted to metric.  This version follows on from orig 16 but
C   has been corrected for mistakes found during the flock validation process and the
C   sensitivity analysis.
************************************************************************
C
C   Declarations
C
************************************************************************
      IMPLICIT none
      INTEGER w, n, I, t, y(10000), m(10000), da(10000), J, jdate, NYR,
     +     NFS3, NFS7, INYR

      REAL MeanEo(52), ASWlag, Glag, Dlag, Wt, CNGlag, G2DH, AGED,
     +     AGEG, GR, PastUtil, Growth(13), Intake(13), C(30), F(100),
     +     MEo(13), Ygrowth, Yintake, AREA, Num, SR, Wtlag,
     +     RAIN(10000), DIGlag, Mrain, CNG, DIGXR, MRUNOFF, MPET,
     +     AET, ASW, SMIN, TASW, GroAge, Wrain, RUNOFF, Eo, PET,
     +     APratio, DIG, TI, OldWoolRate, G, D, DR, TotBought,
     +     Shvalue, TotParIndex, ParIndex, Dth(14,2), P(14,2), Wool,
     +     TWTI, TBOGI, BOGR, RamBuy, RATS, Gmtotal, NumBought,
     +     Flock(22,9), FPROP(21), RWL(21), DLM(21), D7(21), D13(21),
     +     YAVSE, RV(21), BOGI, var(60), Tx, MWu, OldTotParInd,
     +     CFN(21), TotWethers, WoolClip, D813, S813, SheepShorn,
     +     COMP, Shorn(21), WoolPriceFactor(21), Fleece(21),
     +     WoolBasisFactor, CleanPrice, Purc(21), Shear(4),
     +     Crutch(4), OthVarCosts(5), RamPrice, dum(21)

      CHARACTER var_name(60)*15,dummy*10,C_name(30)*10,F_name(100)*10

C   Flock(I,1) represents the flock structure at the beginning of the calendar year.
C   Flock(I,2) represents the numbers sold in each class at March forced
C   sales, reset to 0 at start of calendar year.
C   Flock(I,3) represents the numbers dying in each class at t=7.
C   Flock(I,4) represents the number in each class after March forced
```

```
C    sales and t=7 mortalities.
C    Flock(I,5) represents the number sold for each class in forced sales
C    after shearing.
C    Flock(I,6) represents the number sold for each class in routine sales
C    after shearing.
C    Flock(I,7) represents the number of animals in each class at the
C    beginning of the new financial year, i.e. t=8.
C    Flock(I,8) represents the numbers dying in each class at t=13.
C    Flock(I,9) represents the number in each class at the end of the
C    calendar year, i.e. after t=13 mortalities have been calculated.
******************************************************************************
C
C    Open data files
C
******************************************************************************
      OPEN(unit=8,file='toorak.gra',status='old')
      OPEN(unit=2,file='month.dat',status='unknown')
      OPEN(unit=11,file='week.dat',status='unknown')
      OPEN(unit=12,file='test.dat',status='unknown')
      OPEN(unit=13,file='test2.dat',status='unknown')
      OPEN(unit=14,file='wt.dat',status='unknown')
      OPEN(unit=15,file='DIG.dat',status='unknown')
      OPEN(unit=16,file='Wool.dat',status='unknown')
      OPEN(unit=17,file='sr.dat',status='unknown')
      OPEN(unit=18,file='fin.dat',status='unknown')
      OPEN(unit=99,file='temp.dat',status='unknown')
      OPEN(unit=19,file='whitemet.var',status='old')
      OPEN(unit=20,file='whitemet.par',status='old')
      OPEN(unit=21,file='dmi.dat',status='unknown')


      WRITE(11,900)
      WRITE(12,910)
      WRITE(13,920)
      WRITE(14,930)
      WRITE(15,940)
      WRITE(16,950)
      WRITE(18,960)
******************************************************************************
C
C    Initialisation
C
******************************************************************************
C    Initialising variables and parameters using the whitemet.var and whitemet.par files

      I=0
140   CONTINUE
         I=I+1
         READ(19,155,end=145)var(I),var_name(I)
         GOTO 140
145   CONTINUE


C    FROP array is used to proportion sheep out of the total number into
C    each age and sex class.
C    RWL array contains the ratios for each class for fleece weights
C    compared to the flock average.
C    DLM array contains the ratios for specific age group lamb marking
```

```
C     rates and the flock average lamb marking rates.
C     D7 array contains the ratios for specific age groups * sex and
C     flock average mortality rate for the period t=1 to t=7.
C     D13 array contains the ratios for specific age groups * sex and
C     flock average mortality rate for the period t=8 to t=13.
C     RV array contains age specific sale price ratios.  The ratios were based on
C     the ratio of combined ewe and wether prices to the weighted average of all
C     sales off shears.

      READ(20,135) (C(I),C_name(I),I=1,30)
      READ(20,135) (F(I),F_name(I),I=1,51)
      READ(20,135) (FPROP(I),dummy,I=1,21)
      READ(20,135) (RWL(I),dummy,I=1,21)
      READ(20,135) (DLM(I),dummy,I=1,21)
      READ(20,135) (D7(I),dummy,I=1,21)
      READ(20,135) (D13(I),dummy,I=1,21)
      READ(20,150) (dum(I),dummy,I=1,21)
      READ(20,135) (RV(I),dummy,I=1,21)
      READ(20,135) (MeanEo(I),dummy,I=1,52)
      READ(20,135) (WoolPriceFactor(I),dummy,I=1,21)
      READ(20,135) (Shear(I),dummy,I=1,4)
      READ(20,135) (Crutch(I),dummy,I=1,4)
      READ(20,135) (OthVarCosts(I),dummy,I=1,5)

C     OldTotParInd= the value for the total parasite index for the previous calendar year.

      ASWlag=var(1)
      Glag=var(2)
      Dlag=var(3)
      DIGlag=var(4)
      Wt=var(5)
      CNGlag=var(6)
      G2DH=var(7)
      AGED=var(8)
      AGEG=var(9)
      GR=var(10)
      Yintake=var(11)
      Ygrowth=var(12)
      PastUtil=var(13)
      ParIndex=var(14)
      P(1,1)=var(16)
      Wtlag=var(18)
      Wool=var(19)
      OldWoolRate=var(20)
      TWTI=var(21)
      TBOGI=var(22)
      TotParIndex=var(23)
      RamBuy=var(29)
      RATS=var(30)
      NumBought=var(33)
      n=INT(var(37))
      Area=var(38)
      Num=var(39)
      OldTotParInd=var(40)

C     SR is the stocking rate in sheep equivalents per unit of land.
C     CleanPrice=price of clean wool on a per unit weight basis.
C     S813= number of sheep present after t=7 and at the beginning of t=8.
```

```
C   D813 at t=7 annual mortality rate, at t=13 appears to be the number of
C   mortalities between t=8 and t=13.

      SR=F(18)
      CleanPrice=F(40)
      SHvalue=F(41)
      RamPrice=F(42)
      WoolBasisFactor=F(50)

      D813=0.05*Num
      S813=D813+Num

C   Arrays holding monthly values for pasture yield and utilization
C   over the past year are initialised.

      DO 40 I=1,6
        Growth(I)=YGrowth*0.143
        Intake(I)=YIntake/13.0
40    CONTINUE

      DO 50 I=7,13
        Growth(I)=Ygrowth*0.02
        Intake(I)=YIntake/13.0
50    CONTINUE

C   Austclim Eo data is usually in mm/day, and needs to be summed
C   to give a weekly total. However the data from Barry White's code
C   and stored in whitemet.par is already in weekly totals of mm.
C   Then a weekly average for each month is calculated.

      DO 20 I=1,13
        MEo(I)=0.0
        DO 30 J=1,4
          MEo(I)=MEo(I)+MeanEo(4*(I-1)+J)/4.0
30      CONTINUE
20    CONTINUE

C   The year, month, day and daily rainfall (mm) are read. The rainfall
C   weekly total is calculated.
C   As well, INYR, is assigned the year of the first day's rainfall that
C   is read.

      DO 60 I=1,n
        RAIN(I)=0.0
        DO 70 J=1,7
          READ(8,100)y(I),m(I),da(I),DR
          RAIN(I)=RAIN(I)+DR
          IF(I.EQ.1)INYR=y(I)
70      CONTINUE
60    CONTINUE
************************************************************************
C   TotBought is the total number of ewes bought during the life of the run.
C   NFS3=number of forced sales in March during the run.
C   NFS7=number of forced runs in July during the run.
C   GMtotal=the total gross margin for the duration of the run.

      TotBought=0.0
      NFS3=0.0
```

```
      NFS7=0.0
      GMtotal=0.0

C     Proportion flock to various classes

      DO 80 I=1,21
        Flock(I,9)=Num*FPROP(I)
        Flock(I,8)=0.0
80    CONTINUE

C     YAVSE and SR in this model attributes 1.0 to ewes 1.5 years+ which are
C     incremented for pregnancy up to 1.4 DSE in the last month of pregnancy,
C     weaners equal 0.75 DSE, lambs to weaning 0.3 DSE (due to increased
C     pressure exerted by their mothers), wethers 1.5 years+ = 1.0 DSE
C     and rams are equal to 2 DSE, this is different to both Breedewe and
C     Barry's original code.

      YAVSE=0.0
      DO 77 I=1,21
        IF(I.EQ.1)THEN
          YAVSE=Yavse+0.3*Flock(1,9)*0.5
        ELSEIF(I.EQ.2)THEN
          YAVSE=Yavse+2.0*Flock(2,9)*0.5
        ELSEIF(I.EQ.11.OR.I.EQ.3)THEN
          YAVSE=YAVSE+Flock(I,9)*0.75*0.5
        ELSE
          YAVSE=YAVSE+FLOCK(I,9)*1.0*0.5
        ENDIF
77    CONTINUE

************************************************************************
C     Actual runing of model.
C     t is the 4 week period of the physical year(1-13).
C     w is the current week that model is running for.
C     NYR is the current physical year of the model run.

      t=0
      NYR=0
      DO 85 w=1,n

        IF(MOD(w,4).EQ.1)t=t+1
        IF(MOD(t,14).EQ.0)t=1

        IF(t.EQ.1.AND.MOD(w,4).EQ.1)THEN
          NYR=NYR+1

C         Set Accumulators and place last physical years values into 'lag' variables.
C         Calculate some flock subtotals.

            TotWethers=0.0

C         Calculate the number of  wethers.

           DO 110 I=1,21
             IF(I.GT.2.AND.I.LT.11)TotWethers=TotWethers+Flock(I,9)
             Flock(I,2)=0.0
             Flock(I,5)=0.0
             Flock(I,6)=0.0
```

```
C   Transfer last physical years flock structure from col 9 to col 1,
C   and then to the CFN array. CFN standing for current flock number.

          Flock(I,1)=Flock(I,9)
          CFN(I)=Flock(I,1)

110       CONTINUE


      ENDIF


      CALL Soil_Water(RAIN, C, ASWlag, MeanEo, Mrain, CNG, MRUNOFF,
   +     MPET, Glag, AET, ASW, SMIN, TASW, GroAge, w, Wrain,
   +     RUNOFF, Eo, PET, APratio)

      CALL Pasture(w, AET, TASW, SMIN, SR, GR, CNG, Glag, C, AGEG,
   +     AGED, PastUtil, t, Dlag, Eo, GroAge, AREA, G2DH, MPET,
   +     CNGlag, Mrain, Wt, Wtlag, MEo, MRUNOFF, y, m, da ,Growth,
   +     Intake, ASWlag, ASW, DIGlag, Wrain, RUNOFF, APratio, PET,
   +     DIGXR, DIG, TI, jdate, G, D, Tx, MWu, BOGI, YAVSE,
   +     CFN, COMP, BOGR)

     IF(MOD(w,4).EQ.0)THEN
      CALL BodyWeight(C, Wt ,SR, DIGXR, DIG, TI, jdate,
   +     OldWoolRate, Wool, t, P, y, m, da, w)

      CALL MOB(t, AREA, Flock, SR, BOGI, Tx, MRUNOFF, MWu, MEo, C,
   +     TBOGI, P, D, Wt, TWTI , F, TotParIndex, OldTotParInd,
   +     DLM, CFN, ASW, DIG, TotWethers, RWL, Wool, D7, D813,
   +     S813, WoolClip, SheepShorn, RATS, NumBought, TotBought,
   +     ParIndex, Dth, jdate, NFS3, D13, NYR, INYR, G, NFS7,
   +     RamBuy, Shorn, Fleece, Purc)

      IF(t.EQ.7)THEN

C   The financial subroutine is called at this point. In Barry's
C   original code he carried the value of the clip and t=7
C   sales/purchases decisions made at this time into the next financial
C   year, as one would expect to do so if preparing accounts for taxation
C   purposes.  However, when examining production economics it is better
C   to include any product produced in the relevant time period but still
C   not sold. For this reason, wool, sheep sales and purchases will be
C   included in calculations for the financial year ending t=7.

        CALL FINANCIAL(Shorn, WoolPriceFactor, Fleece,
    +        WoolBasisFactor, CleanPrice, Flock, RV, P, Shvalue,
    +        Purc, Shear, Crutch, OthVarCosts, RamBuy, RamPrice,
    +        F, GMtotal)
      ENDIF
    ENDIF

85  CONTINUE
**********************************************************************
C
C   Format statements
C
```

```
************************************************************************
100  FORMAT(x,I4,I2,I2,17x,F6.1)
135  FORMAT(f10.5,A10)
150  FORMAT(I4,6x,A10)
155  FORMAT(f10.4,x,A12)
700  FORMAT(47x,f5.1)
900  FORMAT('#w  ASWlag Wrain RUNOFF TASW   Eo    CNG   Glag  PET ',
   +       ' SMIN APratio AET  ASW TASW-SMIN  Wu   GIP  SR ',
   +       '  IG    GR   AWX  I  AGT    AGR   DOMG   GPX  PUX ',
   +       ' P.U. t  TX     NG GroAge ')
910  FORMAT('w   MrainMRUNOFF MPET   MWu   CNG  GTOD CNGlag  ',
   +       ' Glag AGEG    AG GroAge DTOH AGED CFR2 WinDa',
   +       ' G2DH   Dlag  ',
   +       ' MG    MD')
920  FORMAT(' #w    AD    AXX   WTX  Wtlag  Wt   DG   GIP DIGGX',
   +       '   b   a   DD   DIG DIGXR ',
   +       'DMX COMP  TIP   TI    MEo BOGR BOGI DIGlag IG   ID',
   +       '   TG   TD     G      D',
   +       ' PastUtil')
930  FORMAT('#Julian Date  Wt')
940  FORMAT('#Julian Date  DIG')
950  FORMAT('#Julian date   Wool Growth Rate')
960  FORMAT('ClPrice WoolBF WlPrice   Sales  Purc  T_Gain #Shorn '
   +       ' $Clip  Receipts  Ram_P  ShCosts  CrCosts OthCosts '
   +       'LmbMkCosts VarCosts   GM    GMtotal ')
************************************************************************
C
C    Closing Data files
C
************************************************************************
      CLOSE(unit=8)
      CLOSE(unit=2)
      CLOSE(unit=11)
      CLOSE(unit=12)
      CLOSE(unit=13)
      CLOSE(unit=14)
      CLOSE(unit=15)
      CLOSE(unit=16)
      CLOSE(unit=17)
      CLOSE(unit=18)
      CLOSE(unit=19)
      CLOSE(unit=20)
      CLOSE(unit=21)
      CLOSE(unit=99)
************************************************************************
      END
************************************************************************
************************************************************************

      SUBROUTINE Soil_Water(RAIN, C, ASWlag, MeanEo, Mrain, CNG,
     +      MRUNOFF, MPET, Glag, AET, ASW, SMIN, TASW, GroAge, w,
     +      Wrain, RUNOFF, Eo, PET, APratio)

      IMPLICIT none
      INTEGER w
      REAL RAIN(10000), Wrain, Mrain, GroAge, C(30), ASWlag, RUNOFF,
     +      TASW, PET, APratio, MeanEo(52), Eo, SMIN, CNG, MRUNOFF,
     +      MPET, Glag, ASW, AET
```

```
************************************************************************
      Wrain=RAIN(w)

      IF(MOD(w,4).EQ.1)THEN
        GroAge=0.0
        Mrain=0.0
        CNG=0.0
        MRUNOFF=0.0
        MPET=0.0
      ENDIF

C     Calculate Runoff

      IF(Wrain.GT.C(3).AND.(C(1)-ASWlag).GT.C(4))THEN
        RUNOFF=Wrain-(C(1)-ASWlag)*TANH(Wrain/(C(1)-ASWlag))
      ELSE
        RUNOFF=MAX(Wrain-(C(1)-ASWlag),0.0)
      ENDIF

      TASW=ASWlag+Wrain-RUNOFF

      IF(MOD(w,52).EQ.0)THEN
        Eo=MeanEo(52)
      ELSE
        Eo=MeanEo(MOD(w,52))
      ENDIF

      PET=Eo*(MIN(0.8,(CNG+0.8*Glag)/3732.4+0.5))
      SMIN=MIN(0.0,12.5-Eo/2.0)

      APratio=(TASW-SMIN)/(C(1)-SMIN)
      IF(Eo.LT.50.0)APratio=MIN(1.0,
     +     (TASW-SMIN)/(C(1)-SMIN)*(2.0-Eo/50.0))

      AET=MAX(0.0,PET*APratio)

      ASW=TASW-AET


      Mrain=Mrain+Wrain
      MRUNOFF=MRUNOFF+RUNOFF
      MPET=MPET+PET

      RETURN
      END
************************************************************************
************************************************************************
      SUBROUTINE Pasture(w, AET, TASW, SMIN, SR, GR, CNG, Glag, C,
     +     AGEG, AGED, PastUtil, t, Dlag, Eo, GroAge, AREA, G2DH,
     +     MPET, CNGlag, Mrain, Wt, Wtlag, MEo, MRUNOFF, y, m, da,
     +     Growth, Intake, ASWlag, ASW, DIGlag, Wrain, RUNOFF,
     +     APratio, PET, DIGXR, DIG, TI, jdate, G, D, Tx, MWu, BOGI,
     +     YAVSE, CFN, COMP, BOGR)

      IMPLICIT none
      INTEGER w, I, t, y(10000), m(10000), da(10000), date, jdate, day,
     +     month, year, J
```

```
      REAL Wu, AET, TASW, SMIN, MWu, GIP, IG, SR, GR, Glag, C(30),
     +     AWX, AGT, AGR, DOMG, CNG, GPX, AGEG, AGED, PastUtil, PUX,
     +     AWX2, WTSM, Dlag, TX, Eo, NG, GroAge, AREA, GTOD, G2DH,
     +     DTOH, AG,AD, CFR2, WinDa, MPET, CNGlag, Mrain, MG, MD,
     +     Wt, Wtlag, AXX, WTX, DG, DD, DIG, DIGGX, aa, b, MEo(13),
     +     BOGR, BOGI, TIP, TI, COMP, DIGXR, MRUNOFF, G, D, TG, TD,
     +     Growth(13), PET, YAVSE, Intake(13), ASWlag, ASW, DMX,
     +     DIGlag, ID, Ygrowth, Yintake, Wrain, RUNOFF, APratio,
     +     MAET, StockRate, CFN(21)

      LOGICAL legal
************************************************************************

      day=da(w)
      month=M(w)
      year=y(w)

      Date=day+month*100+year*10000

      IF(MOD(w,4).EQ.1)THEN
        MWu=0.0
        MAET=0.0
      ENDIF

      Wu=MIN(AET,MAX(0.0,TASW-SMIN))
      IF(Wu.GT.TASW)Wu=MAX(TASW,0.0)

      MWu=MWu+Wu
      MAET=MAET+AET

      GIP=MIN(1.0,SQRT((MAX(1.0,GR))/560.0))
      IG=GIP*9.1*SR

      GR=0.8*Glag+CNG-IG
      IF(GR.LE.0.0)GR=0.0

      NG=0.0
      AGT=0.0
      AGR=0.0
      DOMG=0.0
      I=0.0
      AWX=0.0
      GPX=0.0
      TX=0.0
      PUX=0.0

      IF(Wu.GE.0.25)THEN

        AWX=MIN(1.0,C(9)+(1.0-C(9))/C(10)*TASW/C(1))

        IF(MOD(w,4).EQ.0)THEN
          I=4
        ELSE
          I=MOD(w,4)
        ENDIF

        AGT=((AGEG+I/4.0)*0.8*Glag+CNG/2.0)/MAX(1.0,0.8*Glag+CNG)
        AGR=AGT*(1.0+IG/(1.0+GR)/0.66)
```

```
        DOMG=GR*MAX(0.56,0.81-AGR/6.0)
        GPX=MIN(1.0,C(11)+(1.0-C(11))/C(12)*DOMG)

        PUX=MIN(1.0,0.75+1.66*PastUtil)

        IF(PastUtil.GT.0.25)PUX=MAX(0.5,(7.0-4.0*PastUtil)/6.0)

        IF(t.GE.4.AND.t.LE.10)THEN
          GPX=GPX*MAX(1.0,1.5-(Glag+Dlag)/2241.7)
          PUX=0.5+PUX/2.0

          AWX2=MIN(1.0,TASW/62.5)
          WTSM=MIN(1.0,GR/224.0)
          AWX=AWX*WTSM+AWX2*(1.0-WTSM)
        ENDIF
        TX=MAX(0.5,Eo*(2.0-Eo/50.0)/25.0-1.0)
        NG=Wu*C(8)*AWX*GPX*PUX*TX
        GroAGE=((GroAge+0.25)*CNG+NG*0.125)/(CNG+NG)

      ENDIF

      CNG=CNG+NG


      WRITE(11,900) w,ASWlag,Wrain,RUNOFF,TASW,Eo,CNG,Glag,PET,SMIN,
     +     APratio,AET,ASW,(TASW-SMIN),Wu,GIP,SR,IG,GR,
     +     AWX,I,AGT,AGR,DOMG,GPX,PUX,PastUtil,t,TX,NG,GroAge

      ASWlag=ASW

900   FORMAT(I3,x,f6.1,3(x,f5.1),x,f5.1,x,f6.1,x,f6.1,x,f5.1,x,f6.1,
     +     x,f5.3,x,f6.2,x,f5.1,x,f5.1,x,f5.1,x,f4.2,x,f4.2,x,f5.2,x,
     +     f6.1,x,f4.2,x,I2,x,f5.3,x,f5.3,x,f7.3,3(x,f4.2),x,
     +     I2,x,f4.2,x,f5.1,x,f4.2)
************************************************************************
      IF(MOD(w,4).EQ.0)THEN

C     SR in this model attributes 1.0 to ewes 1.5 years+ which are
C     incremented for pregnancy up to 1.4 DSE in the last month of pregnancy,
C     weaners equal 0.75 DSE,lambs to weaning 0.3 DSE (due to increased
C     pressure exerted by their mothers), wethers 1.5 years+ = 1.0 DSE
C     and rams are equal to 2 DSE, this is different to both Breedewe and
C     Barry's original code.

        SR=StockRate(CFN, t, Area)
        IF(t.EQ.8)YAVSE=0.0
        YAVSE=YAVSE+SR*AREA/13.0
        SR=MAX(0.028,SR)

        BOGR=0.0
        GTOD=C(16)*(1.0-MWu/MPET)

        IF(t.GT.4.AND.t.LT.11)GTOD=(CNGlag*(MIN(C(16),
     +        1.5*GTOD)-GTOD)+Glag*GTOD)/MAX(Glag,1.0)
        GTOD=MIN(C(16),GTOD)
        IF(t.LT.5.OR.t.GT.10)GTOD=GTOD*MIN(1.0,0.4+0.3*AGEG)
        AG=Glag*(1.0-GTOD/2.0)+CNG*GroAge
        DTOH=0.16/(1.0+AGED/2.0)
```

```
      WinDa=0.0

      IF(Mrain.GE.5.0)THEN
        CFR2=MAX(0.012,0.045-AGED/500.0)
        DTOH=MIN(0.8,DTOH+CFR2*(Mrain/25.0)**2)

        IF(t.GE.5.AND.t.LE.10)THEN
          WinDa=0.25*MIN(1.0,(Mrain/12.5)**2)*MIN(1.0,
     +          (AGED/5.0)**2)
          DTOH=MAX(DTOH,WinDa)
          AGED=AGED+12.0*WinDa
        ENDIF
      ENDIF
      DTOH=MIN(0.8,DTOH)
      IF(t.GT.5.AND.t.LT.12)DTOH=(G2DH*MIN(0.75,
     +     DTOH*2.0)+(Dlag-G2DH)*DTOH)/Dlag
      DTOH=MIN(0.8,DTOH)

      MG=Glag*GTOD
      MD=Dlag*DTOH

      AGED=((Dlag-MD)*(AGED-2.0*DTOH+1.0)+MG/2.0)/(Dlag-MD+MG)
      AGEG=(CNG*GroAge+(Glag-MG)*MAX(1.5,
     +     1.0+AGEG-GTOD))/MAX(CNG+Glag-MG,1.0)

      AD=Dlag*(1.0-DTOH/2.0)+GTOD*Glag/2.0
      AXX=AG+AD

      WTX=(1.0-Wt/90.9)*Wt/22.73
      WTX=MAX(0.66,WTX)
      Wtlag=Wt

      IF(AG.LE.4.48)THEN
        DG=0.0
        GIP=0.0
      ELSE
        DIGGX=MAX(1.0-C(24),1.0-C(24)*(MEo(t)-25.0)/25.0)
        DIGGX=1.0+(DIGGX+C(24)-1.0)*CNG/AG*GroAge
        DG=MIN(0.775,DIGGX*MAX(0.53,0.83-AGEG/6.0))

        b=SQRT(MIN(1.0,AG*DG/448.34))
        aa=SQRT(MIN(AG/AD,1.0))

        GIP=(aa+2.0*b)/3.0
      ENDIF

      DD=MAX(0.42,0.5-AGED/160.0)
      DIG=DG*GIP+DD*(1.0-GIP)
      DIGXR=MIN(1.0,C(27)+(1-C(27))*(DIG-0.4)/0.08)
      DMX=MIN(1.0,(1.0/(C(23)+AXX))*AXX)

      COMP=MIN(1.0,DIG/0.66)

      TIP=WTX*DIGXR*DMX
      IF(Wt.LT.36.0.AND.DIG.GT.0.5)TIP=MAX(TIP,(TIP+2.0*COMP)/3.0)
      TI=C(25)*SR*TIP
      IF(t.EQ.8)TI=TI*1.1
```

```
       IF(MEo(t).GT.50.0)TI=TI*(1.2-MEo(t)/250.0)
       BOGI=0.0

C       Calculating the monthly bogging index which is used to modify
C       total intake in certain circumstances, and is then passed to
C       the subroutine MOB.

       IF(Mrain.GE.100.1.AND.MRUNOFF.GE.0.25)THEN
         BOGR=MIN(Mrain*0.04-4.0,10.0)
         BOGI=MIN(15.0,(0.1+0.25*(10.0*(0.7-DIGlag))**3)*BOGR**(
     +          0.5+5.0*(DIGlag-0.4)))
         TI=TI*(1.0-BOGI/100.0*1.5)

       ENDIF

       IG=TI*GIP
       ID=TI-IG

       G=MAX(Glag*(1.0-GTOD)-IG+CNG,0.0)
       TG=IG*MIN(1.25,G/560.0)
       G=G-TG
       AGEG=AGEG*(1.0+(IG+TG)/(G+0.1))
       IF(G.LT.4.4)G=0.0
       D=MAX(Dlag*(1.0-DTOH)-ID+GTOD*Glag,8.9)
       TD=ID*MIN(1.25,D/1120.0)
       D=D-TD
       AGED=AGED*(1.0+(ID+TD)/D)

       IF(G.GT.0.0)DG=DG*MAX(0.8,1.0-0.5*IG/G)
       DD=DD*MAX(0.9,1.01-2.0*ID/D)
       DIG=MAX(0.38,DG*GIP+DD*(1-GIP))

***************************************************************************
C
C    First the julian date is calculated.
C
      call  legal_date(legal,day,month,year)
      if (legal) then
       call  julian_date(jdate,day,month,year)
      ELSE
        PRINT*,'ILLEGAL DATE, PROGRAM TO STOP'
        STOP
      ENDIF

    WRITE(2,500)jdate,Date,MWu,Mrain,CNG,G,D,G+D
500  FORMAT(xI7,x,I8,x,f7.1,x,F6.1,x,f6.1,x,f7.2,x,f7.2,x,f7.2)

    WRITE(12,510)w,Mrain,MRUNOFF,MPET,MWu,CNG,GTOD,CNGlag,
    +     Glag,AGEG,AG,GroAge,DTOH,AGED,CFR2,WinDa,G2DH,Dlag,MG,MD
510  FORMAT(I3,4(x,f5.1),x,f6.1,x,f4.2,2(x,f6.1),x,f4.2,x,f6.1,
    +     x,f4.2,x,f4.2,x,
    +     f5.2,2(x,f4.2),x,f5.1,x,f6.1,2(x,f5.1))
    WRITE(13,520)w,AD,AXX,WTX,Wtlag,Wt,DG,GIP,DIGGX,b,aa,
    +     DD,DIG,DIGXR,DMX,COMP,TIP,TI,MEo(t),BOGR,BOGI,
    +     DIGlag,IG,ID,TG,TD,G,D,PastUtil
520  FORMAT(I3,2(x,f6.1),x,f4.2,2(x,f5.1),11(x,f4.2),x,f5.1,x,f6.1,
    +     f4.1,x,f4.1,x,f3.1,x,f5.1,x,f4.1,
```

```
     +     x,f4.1,x,f4.1,x,f6.1,x,f6.1,x,f4.2)
      WRITE(15,*)jdate,DIG
      write(21,530)date,TI/SR/28.0
530   FORMAT(I8,3x,f5.3)
************************************************************************
         DIGlag=MIN(0.7,DIG)

         DO 50 J=12.1,-1
           Growth(J+1)=Growth(J)
           Intake(J+1)=Intake(J)
50        CONTINUE
         Growth(1)=CNG
         Intake(1)=TI

         YGrowth=0.0
         Yintake=0.0
         DO 60 J=1,13
           Ygrowth=Ygrowth+Growth(J)
           Yintake=Yintake+Intake(J)
60        CONTINUE
         Ygrowth=MAX(1.0,Ygrowth)
         PastUtil=MIN(1.0,Yintake/Ygrowth)

         G2DH=CNGlag*MIN(2.0*GTOD,C(16))
         CNGlag=CNG
         Glag=G
         Dlag=D

      ENDIF

      RETURN
      END
************************************************************************
************************************************************************

      SUBROUTINE Bodyweight(C, Wt, SR, DIGXR, DIG, TI, jdate,
     +     OldWoolRate, Wool, t, P, y, m, da, w)

C     Operating on a 4 weekly timestep

      IMPLICIT none
      INTEGER jdate, t, y(10000), m(10000), da(10000), w
      REAL C(30),Wt, SR, DIGXR, DIG, TWK, TI, MEI, MERM, EWG,
     +     WoolRate, OldWoolRate, EBAL, WTC, Wool, P(14,2)
************************************************************************

C     Calculate MEI

      TWK=TI*0.223/SR/0.89/DIGXR*MIN(1.0,0.825+0.175*(DIG-0.4)/0.08)
      MEI=TWK*3.2*DIG

C     Calculate MERM(Mcal/hd/wk),Function of Wt

      IF(Wt.LT.30.0)then
        MERM=C(22)
      ELSE
        MERM=C(21)*Wt+(-5.25)
      ENDIF
```

```
**************************************************************************
C     Calculate EWG

      WoolRate=-0.584+1.330*SQRT(MEI/MERM)+0.277*OldWoolRate
      EWG=WoolRate*MAX(0.1,0.0066*(Wt-20.0))*4.0
      OldWoolRate=WoolRate
      Wool=Wool+EWG

**************************************************************************
C     Calculate EBAL and Wt change

      EBAL=MEI-MERM-5.4/16.0*EWG

C     The conversion of EBAL to weight change is achieved by assuming
C     a constant energy content of 5.5Mcal/kg and a constsnt effeciency
C     for liveweight gain of 50%.For negative EBAL weight loss was
C     calculated was calculated using an 80% effeciency of catabolized
C     energy.

      IF(EBAL.GE.0.0)then
        WTC=EBAL*C(20)/5.5
        Wt=MIN(1.125*Wt,Wt+4.0*WTC)
      ELSEIF(EBAL.LT.0.0)THEN
        Wt=Wt+5.0*EBAL/5.5
      ENDIF

      Wt=MAX(18.0,MIN(Wt,57.0))

C     Below is different to Barry's code but is what I think was intended
C     The P() values below are used in calculating lambmarking values

      IF(t.EQ.10)THEN
        P(1,1)=Wt
      ELSEIF(t.EQ.1)THEN
        P(2,1)=Wt
      ELSEIF(t.EQ.4)THEN
        P(3,1)=Wt
      ENDIF

**************************************************************************
      WRITE(14,100)jdate,y(w),m(w),da(w),Wt
100   FORMAT(x,I7,3x,I4,I2,I2,3x,f4.1)
      WRITE(16,*)jdate,WoolRate

      RETURN
      END

**************************************************************************
**************************************************************************

      SUBROUTINE MOB(t, AREA, Flock, SR, BOGI, Tx, MRUNOFF, MWu,
     +     MEo, C, TBOGI, P, D, Wt, TWTI, F, TotParIndex,
     +     OldTotParInd, DLM, CFN, ASW, DIG, TotWethers, RWL, Wool,
     +     D7, D813, S813, WoolClip, SheepShorn, RATS, NumBought,
     +     TotBought, ParIndex, Dth, jdate, NFS3, D13, NYR, INYR, G,
     +     NFS7, RamBuy, Shorn, Fleece, Purc)

C     This model also produces the marketable outputs of sheep and wool
```

```
C     which then provide the income flow to the finance model.
C     Performance here is controlled by both the physical environment
C     and management.

C     Working on a 4 weekly timestep.
C     Lambings at t=4.
C     Mortalities calculated at t=7 and t=13.
C     Wool production calculated at t=7.
C     Flock is aged at shearing, before calculation of sales.

      IMPLICIT none
      INTEGER  t, I, J, NFS3, NFS7, NYR, INYR, Limit,
     +      jdate
      REAL Num, AREA, Flock(22,9), SR, L1, L2, L3, WL1, WTI, BOGI,
     +      ParFecunIndex, Tx, MRUNOFF, MWu, MEo(13), C(30),
     +      ParIndex, TBOGI, Purc(21), StockRate, P(14,2), Dth(14,2),
     +      WTD, Wt, TWTI, F(100), TotParIndex, OldTotParInd,
     +      AvCarCap, DLM(21), CFN(21), PredWt, ASW, DIG,
     +      ForcedSales3, TotWethers, Sale, RWL(21), Wool, x, DLOSS,
     +      D7(21), D813, S813, WoolClip, SheepShorn, RATS, PredWt2,
     +      EwesJoined, G, D,Fleece(21), Shorn(21), NumBought,
     +      TotBought, RamBuy, D13(21), ForcedSales7, NorSale
************************************************************************
C     Parasite Index - 4 weekly timestep. The parasite index takes
C     the form of a population model with the ratio of population change in
C     each four week period dependent on an environmental stress index.
C     The index assumed that temperatures in spring and autumn were
C     optimal and that high values of the rainfall/evaporation ratio
C     were optimal. Mean weekly evaporation rates were used as a proxy
C     for temperature. The functions are such that the average seasonal
C     pattern of the parasite index has a major peak in Autumn and a
C     minor peak in spring which is in keeping with regional experience.

C     TotParIndex is a 6 monthly total for the parasite index, it is reset to
C     0 at t=7 and 13 after being used in mortality and shearing calculations.
C     OldTotParIndex which is the TotParIndex from the preceding period,
C     t=7 to t=13, is used in conjunction with current TotParIndex in predicting
C     the average flock lambmarking rate and the flock average
C     clean fleece weight.

      ParFecunIndex=TX*MIN(1.0,SQRT(MAX(MRUNOFF+MWu,1.0)/MEo(t)/4.0))
      ParIndex=MAX(0.1,ParIndex*(C(29)+10.0*ParFecunIndex**C(5)))
      TotParIndex=TotParIndex+ParIndex


C     Bogging Index - 4 weekly timestep.  The bogging index takes
C     non-zero values during periods of intense rainfall which produces
C     run-off and it varies inversely with sheep condition as
C     determined by digestability of intake.
C     TBOGI is a half yearly total of monthly bogging indices and is
C     reset to 0 after the calculation of mortalities at t=7 and t=13.

      TBOGI=TBOGI+BOGI

C     TWTI is a half yearly total of a monthly bodyweight index which
C     is used as a weight index for the calculation of mortalities.
C     TWTI, as with TBOGI is reset to 0 following calculations at
C     t=7 and t=13.
```

```
      WTD=MAX(10.0,(Wt-C(30))*2.2)
      WTI=1000.0/WTD/WTD
      TWTI=TWTI+WTI
************************************************************************

      IF(t.EQ.3)THEN

C        Forced sales at March, as mortalities are closely related to
C        Wt, the decision rule operates such that the proportion sold
C        increases as expected mortalities increase.  As this is close
C        to lambing ewes are not sold.
C        Predicting body weight at shearing given current bodyweight,
C        stocking rate and a pasture level and quality index.

        PredWt=F(8)+F(9)*Wt+F(10)*((G+D)/4.48*DIG+ASW)+F(11)*SR
        ForcedSales3=0.0

C        If the predicted value of the shearing weight is below a given
C        weight then forced sales result. 33kg was taken to be the
C        minimum predicted liveweight at shearing below which forced
C        sales are triggered.  Wethers are sold in complete
C        age groups from the oldest with the proportion sold increasing
C        linearly to 100% if the decision rule weight  exceeds the
C        predicted weight by more than 6 kg.  To ensure sales are of a
C        viable size, a minimum of 400 need to be sold.

        IF(PredWt.LE.F(7))THEN
          x=TotWethers*MAX(0.0,MIN(1.0,(PredWt-F(7))/
     +          (F(4)-F(7))))
          IF(x.GE.F(6))THEN
            x=ForcedSales3
            Sale=0.0
            I=10

C             Flock(I,2) holds the number of wethers sold in March
C             forced sales.

48            CONTINUE
            IF(Sale.LT.ForcedSales3.AND.I.GE.3)THEN
              Flock(I,2)=Flock(I,1)
              Sale=Sale+Flock(I,1)
              CFN(I)=0.0
              I=I-1
              GOTO 48
            ENDIF
            ForcedSales3=Sale
            IF(ForcedSales3.GT.0.0)NFS3=NFS3+1
          ENDIF
        ENDIF
      ENDIF
************************************************************************
C   Calculating lambs (usually t=4)

      IF(t.EQ.4)THEN

C   Bodyweight indices -  The weight index assumes that the potential
C   lamb marking percentage is determined by Wt at mating, e.g. October.
```

```
C    The final value of the index is determined by Wt trends in each
C    of the succeeding three month periods. Lamb marking percentage
C    was assumed to be less sensitive to low levels of nutrition in
C    early pregnancy cf late pregnancy (range 0-100).

C    P array is used to store information regarding production, while
C    the Dth array stores information regarding mortalities. They are reset
C    or partially reset to zero prior to lambmarking calculations,Dth(1,I),
C    Dth(2,I) and Dth(3,I) contain values for the body weight index, the
C    bogging index and the parasite index. Lamb marking is the first
C    procedure of the calendar year.

       DO 42 I=1,14
         DO 43 J=1,2
           IF(I.GT.3)P(I,J)=0.0
           Dth(I,J)=0.0
43         CONTINUE
42      CONTINUE

       L1=MIN(1.0,F(36)+(P(1,1)-F(37))/20.0)
       L2=SQRT(MAX(0.1,F(38)*(P(2,1)-F(39)*P(1,1))))
       L3=MIN(1.0,F(38)*(P(3,1)-F(39)*P(2,1)))
       WL1=L1*L2*L3**2

C       P(4,I) represents the average flock lamb marking rate as given
C       by the function using the weight index, parasite index and
C       time in years from 1945.

       P(4,1)=F(31)*(F(34)+F(33)*WL1*100.0+
     +         F(32)*ALOG10(TotParIndex+OldTotParInd)+
     +            F(35)*REAL(INYR+NYR-1946))/100.0

C       Calculating total number of ewes joined is equal to the
C       number at end of the year plus half of those that died in
C       the final half of the year as contained in Flock(I,8).
C       P(6,I) contains the number of lambs marked from the flock.
C       P(7,I) contains the number of ewes joined.

       DO 46 I=12,20
         P(6,1)=P(6,1)+MAX(0.0,P(4,1)+DLM(I))*(Flock(I,
     +         9)+Flock(I,8)/2.0)
         P(7,1)=P(7,1)+Flock(I,9)+Flock(I,8)/2.0
46      CONTINUE

C       Calculating the lambmarking percentages for all classes,
C       given class lamb marking differences have been calulated for above.

       IF(P(7,1).GT.0.0)P(5,1)=P(6,1)/P(7,1)*100.0

C       Totalling the number of lambs marked into the current flock
C       number file and updating the total flock number.

       CFN(1)=P(6,1)
       Flock(1,1)=CFN(1)
     ENDIF
************************************************************************

     IF(t.EQ.7)THEN
```

```
C     Calculate mortalities for the period t=1 to t=7.

        Dth(1,1)=TWTI
        Dth(2,1)=TBOGI
        Dth(3,1)=TotParIndex
        TWTI=0.0
        TBOGI=0.0
        ForcedSales3=0.0

C       Dth(4,I) holds the value for mortality rates as calculated by
C       the regression equation using the weight index for mortalities,
C       bogging index and the parasite index.

        Dth(4,1)=(F(25)+F(22)*Dth(1,1)+F(23)*Dth(2,1)+F(24)*
     +          ALOG10(Dth(3,1)+0.3))/100.0

        DO 60 I=1,21

C          Dth(7,I) contains the number of sheep over which the calculated
C          mortality rate is applied, making allowance for the wethers
C          sold in March which were present for half the period over
C          which mortalities are to be calculated.
C          DLOSS is the recalculated mortality rate after making
C          allowances for age and sex differences.
C          Flock(I,3) contains the number of sheep dying in each class
C          for the period t=1 to t=7.
C          Dth(6,I)=total number of mortalities during the period.

          Dth(7,1)=Dth(7,1)+Flock(I,1)-0.5*Flock(I,2)
          DLOSS=Dth(4,1)*D7(I)/F(21)+MAX(0.0,Dth(4,1)-F(21)+
     +         D7(I))
          Flock(I,3)=DLOSS/2.0*(Flock(I,1)-0.5*Flock(I,2))
          Dth(6,1)=Dth(6,1)+Flock(I,3)
          IF(NFS3.GE.1)THEN

C          Recalculting the number of forced sales so as to take into account
C          the number of deaths in those age groups sold prior to the sale date.

            IF(Flock(I,2).GT.0.0)Flock(I,2)=Flock(I,2)-Flock(I,3)
            ForcedSales3=ForcedSales3+Flock(I,2)
          ENDIF

C          Updating flock numbers taking into account March forced sales
C          and July mortalities.

          Flock(I,4)=Flock(I,1)-Flock(I,2)-Flock(I,3)
          CFN(I)=Flock(I,4)
60      CONTINUE

C       Calculating July mortality rates.

        IF(Dth(7,1).GT.0.0)Dth(5,1)=Dth(6,1)/Dth(7,1)*100.0

C       D813 appears to at this point to represent the annual
C       mortality rate. S813 represents the number of sheep present at
C       the beginning of t=8 last year.
```

```
      D813=(D813+Dth(6,1))/S813*100.0
*************************************************************************
C   Shearing.

C   Wool Production (usually t=7).
C   The calculation of annual fleece weights from unit area growth
C   rates requires an estimate of the surface area producing wool.
C   Wool growth rate is in mg/cm^2/day.  For animals which differ in
C   skeletal size, the general relationship of area and volume to
C   the 2/3rds power could be expected to apply.  However it seems
C   unlikely that such a relationship would apply to an indivdual
C   animal with a fluctuating Wt in the short term.  In this program
C   surface area is assumed to be constant for bodyweights of less
C   than 35kg.

C   Because wool growth has taken place over the past 12 months, the
C   parasite index for the entire preceding year is included.

      P(8,1)=WOOL
      P(9,1)=OldTotParInd+TotParIndex
      WOOL=0.0
      TotParIndex=0.0

C   Calculating estimated clean fleece weight using predicted fleece wt,
C   P(8,I), time in years from 1945 and a parasite index,  P(9,I).
C   P(10,I) holds the value for the estimated clean fleece weight
C   as calculated by the regression equation.  F(28) in following equation ,
C   was reported as having two different values from two different sources,
C   0.1 or 0.0.  The whole regression equation below is
C   uncertain as Barry's code has a markedly different regression to the
C   monograph.  The regression used below is that the one that gave the
C   closest results to the Winton ABS shire data.

      P(10,1)=F(26)*(F(30)+F(27)*P(8,1)+F(28)*REAL(INYR+NYR-1946)+
   +        F(29)*ALOG10(P(9,1)-0.3))
      P(10,1)=(1.212+0.314*P(8,1)+0.01*REAL(INYR+NYR-1946)-
   +        0.051*ALOG10(P(9,1)-0.3))*0.7

C      Calculating total clean wool production.
C      P(13,I) contains information regarding total clean wool
C      production for the flock.
C      P(12,I) contains information on the total number of sheep shorn.
C      Shorn array contains the number of sheep shorn in each class.
C      Fleece array contains the fleece weight for each class.

      DO 260 I=1,20
        P(13,1)=P(13,1)+CFN(I)*P(10,1)*RWL(I)
        P(12,1)=P(12,1)+CFN(I)
        Shorn(I)=CFN(I)
        Fleece(I)=P(10,1)*RWL(I)
260    CONTINUE

C      Calculating average clean fleece weight over the whole flock from
C      total wool production and total sheep shorn.

      IF(P(12,1).GT.0.0)P(11,1)=P(13,1)/P(12,1)

      WoolClip=P(13,1)
```

```
      SheepShorn=P(12,1)
*************************************************************************
C     Age sheep after shearing

      DO 270 I=4,21
        Flock(I,4)=CFN(I-1)
270   CONTINUE
      Flock(1,1)=0.0

      DO 275 I=1,21
        CFN(I)=Flock(I,4)
275   CONTINUE

C     Proportioning lambs to 1 year old age groups.  RATS is the number
C     of wether weaners killed for rations.

      Flock(3,4)=MAX(0.0,CFN(1)*0.5-RATS)
      Flock(11,4)=CFN(1)/2.0
      Flock(1,4)=0.0
      CFN(3)=Flock(3,4)
      CFN(11)=Flock(11,4)
      CFN(1)=0.0
*************************************************************************
C     Routine culling off shears

      NorSale=0.0

C     If the current stocking rate is higher than the desired long term
C     stocking rate of the property, then a proportion of maiden ewes
C     is culled.  The desired long term average stocking rate is generally
C     stated as about 1 sheep/4 acres or 0.62 sheep/ha.  The stocking
C     rate at which routine culling for age commenced was set at 30%
C     above the long term average so as to allow for flock expansion
C     during good seasons.

C     Below, 20% of maiden ewes are culled in above average seasons as
C     indicated by the current stocking rate.  The influence of selection
C     on life-time productivity and genetic progress are not included.
C     Flock(I,6) is used to record those numbers for each class that are
C     sold normally at t=7, following shearing.

      SR=StockRate(CFN,t,Area)
      IF(SR/F(18).GE.1)THEN
        Flock(12,6)=0.2*Flock(12,4)
        Flock(12,4)=0.8*Flock(12,4)
        NorSale=Flock(12,6)
        CFN(I)=0.0
      ENDIF

C     8 year old wethers and 11 year old ewes are routinely culled after
C     shearing and ageing.

      DO 280 I=10,21,11
        Flock(I,6)=Flock(I,4)
        Flock(I,4)=0.0
        NorSale=NorSale+Flock(I,6)
        CFN(I)=0.0
280   CONTINUE
```

```
C      Wethers are assumed to be desirably cast for age at 4, ewes at 8.
C      Whether sales actually takes place depends on stocking rate.  Age
C      groups of ewes and wethers are sold down until the new stocking
C      rate is less than the stocking rate which triggers culling.
C      If the stocking rate is still above the trigger rate and all
C      excess age groups have been sold then another age group of
C      ewes and wethers may be sold

C      Wethers are culled first.

      SR=StockRate(CFN,t,Area)
      IF(SR/F(18).GE.F(3))THEN
        IF(F(2).LE.7.AND.F(2).GE.1)THEN
          DO 290 I=9,F(2)+2,-1
            IF(SR/F(18).GE.F(3))THEN
              Flock(I,6)=Flock(I,4)
              Flock(I,4)=0.0
              NorSale=NorSale+Flock(I,6)
              CFN(I)=0.0
              SR=StockRate(CFN,t,Area)
            ENDIF
290       CONTINUE
        ENDIF

C      If the SR is still above the SR at which culling is triggered
C      then ewes are culled.

        IF(SR/F(18).GE.F(3))THEN
          IF(F(1).LE.10.AND.F(1).GE.1)THEN
            DO 300 I=20,F(1)+10,-1
              IF(SR/F(18).GE.F(3))THEN
                Flock(I,6)=Flock(I,4)
                Flock(I,4)=0.0
                NorSale=NorSale+Flock(I,6)
                CFN(I)=0.0
                SR=StockRate(CFN,t,Area)
              ENDIF
300         CONTINUE
          ENDIF

C      If culling down to the specified age groups for
C      both wethers and ewes results in the SR still being higher than
C      the stocking rate that triggers culling then 1 additional age
C      group is culled first from the wethers then from the ewes.

          IF(SR/F(18).GE.F(3))THEN
            Limit=F(2)+1
            IF(Limit.GE.3.AND.Limit.LE.8)THEN
              Flock(Limit,6)=Flock(Limit,4)
              Flock(Limit,4)=0.0
              NorSale=NorSale+Flock(Limit,6)
              CFN(Limit)=0.0
              SR=StockRate(CFN,t,Area)
            ENDIF
            IF(SR/F(18).GE.F(3))THEN
              Limit=F(1)+9
              IF(Limit.GE.11.AND.Limit.LE.18)THEN
```

```
              Flock(Limit,6)=Flock(Limit,4)
              Flock(Limit,4)=0.0
              NorSale=NorSale+Flock(Limit,6)
              CFN(Limit)=0.0
              SR=StockRate(CFN,t,Area)
            ENDIF
          ENDIF
        ENDIF
      ENDIF
    ENDIF
************************************************************************
C     Forced sales at shearing

C     Predicting body weight at the end of the year given current
C     bodyweight, stocking rate adjusted for normal sales and a
C     pasture level and quality index.

      PredWt2=F(13)+F(14)*Wt+F(15)*((D+G)/4.48*DIG+ASW)+F(16)*SR
      ForcedSales7=0.0

C     If the predicted value of the end of year weight is below
C     a given weight then forced sales result.  The proportion
C     sold increasing linearly to 50% of the flock if the decision
C     rule weight  exceeds the predicted weight by more than 6 kg.
C     To ensure sales are of a viable size, a minimum of 400 need
C     to be sold.Sales are made of complete age-groups in the
C     following sequence until the required proportion is achieved.
C       1. wethers to age 2, or 1 year lower than the normal culling
C          age as specifed, whichever is the greatest, in
C          descending order.
C       2. ewes to age 6, or 1 year lower than the normal culling
C          age as specified, whichever is the greatest,in
C          descending order.
C       3. wethers down to and including those aged 1.

      IF(PredWt2.LE.F(12))THEN

        Num=0.0
        DO 303 I=1,21
          Num=Num+CFN(I)
303     CONTINUE

        x=0.5*Num*MAX(0.0,MIN(1.0,(PredWt2-F(12))/
     +      (F(5)-F(12))))
        IF(x.GE.F(6))THEN
          ForcedSales7=x
          Sale=0.0
          I=9
          Limit=MAX(4,F(2)+1)

C         Wethers are first of all sold off.

305       CONTINUE
          IF(Sale.LT.ForcedSales7.AND.I.GE.Limit)THEN
            Flock(I,5)=Flock(I,4)
            Flock(I,4)=0.0
            Sale=Sale+Flock(I,5)
            CFN(I)=0.0
```

```
          I=I-1
          GOTO 305
        ENDIF

C         Ewes are then sold off if necessary.

        IF(SALE.LT.ForcedSales7)THEN
          I=20
          Limit=MAX(16,F(1)+9)
310         CONTINUE
          IF(Sale.LT.ForcedSales7.AND.I.GE.Limit)THEN
            Flock(I,5)=Flock(I,4)
            Flock(I,4)=0.0
            Sale=Sale+Flock(I,5)
            CFN(I)=0.0
            I=I-1
            GOTO 310
          ENDIF

C           Wethers down to and including aged 1 are then sold if necessary.

          IF(Sale.LT.ForcedSales7)THEN
            I=MAX(4,F(2)+1)
320           CONTINUE
            IF(Sale.LT.ForcedSales7.AND.I.GE.3)THEN
              Flock(I,5)=Flock(I,4)
              Flock(I,4)=0.0
              SALE=SALE+Flock(I,5)
              CFN(I)=0.0
              I=I-1
              GOTO 320
            ENDIF
          ENDIF
        ENDIF

        ForcedSales7=Sale
        IF(ForcedSales7.GT.0.0)NFS7=NFS7+1
      ENDIF
    ENDIF

C     Recalculating numbers in each class following routine and forced
C     sales of shears as well as the number of ewes available for
C     joining.

    EwesJoined=0.0

    DO 340 I=1,21
      Flock(I,7)=Flock(I,4)
      IF(I.GE.12)EwesJoined=EwesJoined+Flock(I,7)
340   CONTINUE
**************************************************************************
C     Buy sheep i understocked.

C     A predicted weight in excess of 35kg so as to avoid purchases
C     during drought years.  Purchases were limited to the number required
C     to bring carrying capacity up to one-half of the long term average
C     subject to a maximum purchase equivalent to one-third of average carrying
C     capacity.  Assuming that the available DSE to be purchased were equivalent
```

```
C     to 1 dry ewe.  TotBought is the number bought during the life of the run.

        AvCarCap=F(18)*Area
        SR=StockRate(CFN,t,Area)
        NumBought=0.0
        IF(SR*Area.LE.0.5*AvCarCap.AND.PredWt2.GE.35.0)THEN
          NumBought=MIN(0.5*AvCarCap-SR*Area,0.3*AvCarCap)
          TotBought=TotBought+NumBought

C         The sheep bought are ewes and are assumed to be bought
C         here in 3 even age groups; 4, 5, 6 years of age.

          DO 360 I=14,16
            Flock(I,7)=Flock(I,7)+NumBought/3.0
            Purc(I)=NumBought/3.0
            CFN(I)=CFN(I)+NumBought/3.0
360       CONTINUE
        ENDIF

C     Buying rams

C     This occurs following normal and forced sales.  A culling rate
C     of 20%-25% is assumed and rams are purchased so that they are
C     equivalent to 2.5% of ewes joined.

        RamBuy=F(19)*(EwesJoined+NumBought)
        RamBuy=ANINT(MAX(0.0,RamBuy-Flock(2,4)*0.8))
        Flock(2,7)=0.8*Flock(2,4)+RamBuy
        Flock(2,6)=Flock(2,4)*0.2
        CFN(2)=Flock(2,7)
      ENDIF
************************************************************************
C     End of year losses, t=8 to t=13.

      IF(t.EQ.13)THEN
        OldTotParInd=TotParIndex
        Dth(8,1)=TWTI
        Dth(9,1)=TBOGI
        Dth(10,1)=TotParIndex
        TotParIndex=0.0
        TWTI=0.0
        TBOGI=0.0

C     Dth(11,I) holds the value for mortality rates as calculated by
C     the regression equation using the weight index for mortalities,
C     bogging index and the parasite index.

        Dth(11,1)=(F(25)+F(22)*Dth(8,1)+F(23)*Dth(9,
     +            1)+F(24)*ALOG10(Dth(10,1)+0.4))/100.0
        DO 380 I=1,21

C         Dth(14,I) contains the number of sheep over which the calculated
C         mortality rate is applied.
C         DLOSS is the recalculated mortality rate after making
C         allowances for age and sex differences.
C         Flock(I,8) contains the number of sheep dying in each class
C         for the period t=8 to t=13.
```

```
C         Dth(13,I)=total number of mortalities during the period.

          Dth(14,1)=Dth(14,1)+Flock(I,7)
          DLOSS=Dth(11,1)*D13(I)/F(21)+MAX(0.0,Dth(11,
     +          1)-F(21)+D13(I))
          Flock(I,8)=DLOSS/2.0*Flock(I,7)
          Dth(13,1)=Dth(13,1)+Flock(I,7)*DLOSS/2.0
          Flock(I,9)=Flock(I,7)-Flock(I,8)
          CFN(I)=Flock(I,9)
380     CONTINUE

C       Calculating mortality rates for the period t=8 to t=13.

        IF(Dth(14,1).GT.0.0)Dth(12,1)=Dth(13,1)/Dth(14,1)*100.0

C       S813 represents the number of sheep at the beginning of the
C       second half of the calendar year, D813 represents those mortalities
C       during the second half of the year.

        S813=Dth(14,1)
        D813=Dth(13,1)
      ENDIF

************************************************************************
C     Output Stocking Rate

      SR=StockRate(CFN,t,Area)
      write(17,*)jdate,sr

      RETURN
      END
************************************************************************
************************************************************************

      SUBROUTINE FINANCIAL(Shorn, WoolPriceFactor, Fleece,
     +     WoolBasisFactor, CleanPrice, Flock, RV, P, Shvalue, Purc,
     +      Shear, Crutch, OthVarCosts, RamBuy, RamPrice, F, GMtotal)

      IMPLICIT none
      INTEGER I
      REAL Shorn(21), WoolPriceFactor(21), WoolPrice, Fleece(21),
     +   WoolBasisFactor, CleanPrice, EweWool, WeanerWool, RamWool,
     +   WethWool, SheepSales, SheepPurc, Flock(22,9), RV(21),
     +   Shvalue, Purc(21), ShTrading, Shear(4), Crutch(4), EweShear,
     +   F(100), Gmtotal, WethShear, WeanerShear, RamShear,
     +   EweCrutch, WethCrutch, WeanerCrutch, RamCrutch,
     +   OthVarCosts(5), EweVarCosts, WethVarCosts, WeanerVarCosts,
     +   RamVarCosts, GM, CashReceipts, TotVarCosts, RamPurc, RamBuy,
     +   RamPrice, VarCosts, ShearCosts, CrutchCosts, ClipValue,
     +   MarkingCosts, P(14,2)

************************************************************************
C     Calculate whole flock gross margins adopting the procedure of
C     Breedewe.

C     EweWool contains the value for net wool sales of all ewes 1+.
C     WethWool contains the value for net wool sales of all wethers 1+.
C     WeanerWool contains the value for net wool sales of all weaners.
```

```
C   RamWool contains the value for net wool sales of all rams.
C   EweCrutch contains the cost of crutching ewes.
C   WethCrutch contains the cost of crutching wethers.
C   WeanerCrutch contains the cost of crutching weaners.
C   RamCrutch contains the cost of crutching rams.
C   EweShear contains the cost of Shearing ewes.
C   WethShear contains the cost of Shearing wethers.
C   WeanerShear contains the cost of Shearing weaners.
C   RamShear contains the cost of Shearing rams.
C   EweVarCosts contains the cost of other items such as contract labour,
C   licks, vaccines, drenchs, marking, mulesing etc. carried out on ewes.
C   WethVarCosts contains the cost of other items such as contract labour,
C   licks, vaccines, drenchs, marking, mulesing etc. carried out on wethers.
C   WeanerVarCosts contains the cost of other items such as contract labour,
C   licks, vaccines, drenchs etc. carried out on weaners.
C   RamVarCosts contains the cost of other items such as contract labour,
C   licks, vaccines, drenchs, marking, mulesing etc. carried out on rams.
C   MarkingCosts contains the total cost for lambmarking procedures.
C   Shorn array carries the number of sheep shorn in each class.
C   WoolPriceFactor array carries values for the ratio of price
C   received/kg clean for each class to the average price received.
C   WoolPrice is the net price/kg clean for whole clip. WoolPrice is the
C   product of the WoolBasisFactor * clean price/kg. The
C   WoolBasisFactor in this model takes the CleanPrice to a price
C   for the whole clip, clean (compared with breedewe where it becomes
C   a greasy price), net of freight and selling costs.
C   Fleece array carries the average clean fleece weight/ sheep shorn
C   for each class.
C   SHvalue contains the sale price for the average sheep.
C   Purc array contains the number of sheep bought, if any for each
C   class apart from rams.
C   Shear and Crutch are arrays that holds the different prices for
C   shearing  and crutching of ewes, wethers, lambs and rams.
C   OthVarCosts array contains the cost for various variable costs such
C   as lambmarking, drenches etc.
C   SheepSales is the total receipts of normal sales in t=7 and forced
C   sales in t=3 and t=7, taking into account different sale prices
C   for classes relative to the average price received.
C   SheepPurc is the total cost of any ewes purchased after shearing,
C   usually equal numbers of 4,5 and 6 year olds are bought.
C   Flock(I,2/5/6) contains the number of sheep for each class that were
C   sold in normal or forced sales.
C   Flock(I,9) contains the number of sheep in each class at the end
C   of the calendar year after mortalities have been calculated. It
C   is these numbers which are used in calculating crutching costs.
C   ClipValue=net value of the whole wool clip.
C   ShTrading is the value of sales less purchases.
C   CashReceipts is the total of all cash received.
C   ShearCosts is the total shearing costs of all sheep.
C   CrutchCosts is the total Crutching costs of all sheep.
C   VarCosts contains the value of OthVarCosts across all the classes.
C   TotVarCosts is the total of all variable costs of the whole flock.
C   GM is the gross margin

      WoolPrice=WoolBasisFactor*CleanPrice

      SheepSales=0.0
      SheepPurc=0.0
```

```
      EweWool=0.0
      WethWool=0.0
      WeanerWool=0.0
      RamWool=0.0
      EweShear=0.0
      EweCrutch=0.0
      EweVarCosts=0.0
      WethShear=0.0
      WethCrutch=0.0
      WethVarCosts=0.0
      WeanerShear=0.0
      WeanerCrutch=0.0
      WeanerVarCosts=0.0
      RamShear=0.0
      RamCrutch=0.0
      RamVarCosts=0.0

      DO 80 I=1,21
        IF(I.GE.11)THEN
          EweWool=EweWool+Shorn(I)*WoolPriceFactor(I)*WoolPrice*
     +          Fleece(I)
          EweShear=EweShear+Shorn(I)*Shear(1)
          EweCrutch=EweCrutch+Flock(I,9)*Crutch(1)
          EweVarCosts=EweVarCosts+Shorn(I)*OthVarCosts(1)
        ENDIF

        IF(I.GE.3.AND.I.LE.10)THEN
          WethWool=WethWool+Shorn(I)*WoolPriceFactor(I)*WoolPrice*
     +          Fleece(I)
          WethShear=WethShear+Shorn(I)*Shear(2)
          WethCrutch=WethCrutch+Flock(I,9)*Crutch(2)
          WethVarCosts=WethVarCosts+Shorn(I)*OthVarCosts(2)
        ENDIF

        IF(I.EQ.1)THEN
          MarkingCosts=P(6,1)*OthVarCosts(5)
          WeanerWool=Shorn(I)*WoolPriceFactor(I)*WoolPrice*Fleece(I)
          WeanerShear=Shorn(I)*Shear(3)
          WeanerCrutch=Flock(I,9)*Crutch(3)
          WeanerVarCosts=Shorn(I)*OthVarCosts(3)
        ENDIF

        IF(I.EQ.2)THEN
          RamWool=Shorn(I)*WoolPriceFactor(I)*WoolPrice*Fleece(I)
          RamShear=Shear(I)*Shear(4)
          RamCrutch=Flock(I,9)*Crutch(4)
          RamVarCosts=Shorn(I)*OthVarCosts(4)
        ENDIF

C       The assumption with sheep sales is that forced sales at t=3
C       receive 75% of the normal price and that forced sales at t=7
C       receive 50% of the normal price.

        SheepSales=SheepSales+(Flock(I,5)*0.5+Flock(I,6)+Flock(I,
     +        2)*0.75)*SHvalue*RV(I)
        SheepPurc=SheepPurc+Purc(I)*(SHvalue+F(47))*RV(I)

C       Reset Purc array to 0.0
```

```
        Purc(I)=0.0
 80   CONTINUE

      ClipValue=EweWool+WethWool+WeanerWool+RamWool
      ShTrading=SheepSales-SheepPurc

      CashReceipts=ClipValue+ShTrading

      RamPurc=RamBuy*RamPrice
      ShearCosts=EweShear+WethShear+WeanerShear+RamShear
      CrutchCosts=EweCrutch+WethCrutch+WeanerCrutch+RamCrutch
      VarCosts=EweVarCosts+WethVarCosts+WeanerVarCosts+RamVarCosts

      TotVarCosts=RamPurc+ShearCosts+CrutchCosts+VarCosts+MarkingCosts

      GM=CashReceipts-TotVarCosts
      GMtotal=GMtotal+GM

      WRITE(18,200)CleanPrice,WoolBasisFactor,WoolPrice,SheepSales,
     +     SheepPurc,ShTrading,P(12,1)+P(12,2),ClipValue,
     +     CashReceipts,RamPurc,ShearCosts,CrutchCosts,VarCosts,
     +     MarkingCosts,TotVarCosts,GM,GMtotal

 200  FORMAT(2x,f4.2,3x,f4.1,4x,f4.2,2x,f7.0,x,2(f6.0,x),f6.0,
     +     2(f8.0,x),x,f5.0,3x,4(f6.0,3x),f7.0,x,f7.0,x,f8.0)

      RETURN
      END
************************************************************************
************************************************************************

      REAL FUNCTION StockRate(CFN, t, Area)

      REAL CFN(21), Area, BreedEwes, DSE
      INTEGER t

C     Calculate the number of breeding ewes, assuming maiden ewes
C     joined at 2 years of age.

      DSE=0.0
      BreedEwes=0.0

      DO 77 I=1,21
         IF(I.EQ.1)THEN
            DSE=DSE+0.3*CFN(I)
         ELSEIF(I.EQ.2)THEN
            DSE=DSE+2.0*CFN(I)
         ELSEIF(I.EQ.11.OR.I.EQ.3)THEN
            DSE=DSE+CFN(I)*0.75
         ELSEIF(I.GE.4.AND.I.LE.10)THEN
            DSE=DSE+CFN(I)*1.0
         ELSEIF(I.GE.12)THEN
           BreedEwes=BreedEwes+CFN(I)
         ENDIF
 77   CONTINUE

     IF(t.LT.5)BreedEwes=BreedEwes+BreedEwes*REAL(t)/10.0
```

```
      DSE=DSE+BreedEwes*1.0
      StockRate=DSE/AREA

      RETURN
      END
************************************************************************
************************************************************************
      subroutine legal_date(legal, day, month, year)

       integer days_in_month(12)
       integer year
       integer len
       integer leapyr
       integer day
       integer month
       logical legal

       data days_in_month /31,28,31,30,31,30,31,31,30,31,30,31/
       leapyr = 365
       len = year / 4
       len = len * 4
       if (year .eq. len) leapyr = 366
       if (year .eq. 1800 .or. year .eq. 1900) leapyr = 365
       if (leapyr .eq. 366) days_in_month(2) = 29

        legal = .true.
        if(month .lt. 1 .or. month .gt. 12) legal = .false.
        if(year .lt. 1 .or. year .gt. 2030) legal = .false.
        if(day .gt. days_in_month(month))  legal = .false.
        if(day .lt. 1 )                    legal = .false.
      return
      end
c=====================================================================
      subroutine julian_date(jdate, kday, month, nyear)

      integer m8
      integer y8
      integer month
      integer nyear
      integer jdate
      integer kday

c     calculates a 7 digit julian date relative to 24/10/4713 (BC)
      if(month .gt. 2) then
        m8 = month -3.0
        y8 = nyear
      else
        m8 = month + 9.0
        y8 = nyear - 1.0
      endif
      c8 = int(y8/100.0)
      d8 = y8-100.0 * c8
      jdate = int(146097.0*c8/4.0)+kday+int(1461*d8/4.0)+1721119.0+
     +       int((153*m8+2.0)/5.0)
      return
      end
c=====================================================================
```

Appendix Three

EPBTS Model Code

```
      PROGRAM EPBTS
C
C    This program is a static Fortran copy of the Grazfeed equations written to investigate
C    their applicability for tropical animal production. This model avoids problems of diet
C    selection by considering only one pool of feed and therefore the digestibility of the
C    pool is the same as the digestibility of intake. As well the need for calculating the
C    relative availability of each digestibility class is avoided.
C
C    Only dry empty animals are considered, pregnancy and lactation costs are avoided
C
C    When calculating NEmove it is assumed here by the setting of the variable
C    representing availability of green forage to 0.0 that overall herbage availability will be
C    used to calculate the energy cost.
C***********************************************************************
C
C    Declarations
C
      IMPLICIT none

      INTEGER J,I,jdate,Day,Month,Year,DOY,a,b,DOYear

      REAL var(30),par(80),N,Z,PDMI,Rel_Avail,Rel_Ing, Wtinit, Rel_intake,
     +    DMIf, ME_Diet, MEIf, MEIs, Km,Kg,NEgraze,BC, Nemetab, Memaint,
     +    MEgain, Feed_Level, Negain, EVG, EBG,LWG,MEI, Wt,Pnet, HighWt,
     +    herbage, DigIntake, Ninit, Photo, MEf, DP,ADudp,ADPLSmcp, ADPLS, limit,
     +    Tmin, Tmax,Tmean,  Young,WoolD, Newool, CFWpot,Ud,dayL, Kadpls, Pgain,
     +    PCG, TF,ZF,HR,HF, RateEat,TimeEat, DMDs, OMDs,Age,FMEIs, Rel_IngS,
     +    Rel_AvailS, Rel_Availf, Rel_IntakeS, DMIs, Nemove, EFP,EUP, Pmaint, RDPI,
     +    RDPIf, RDPIs,UDPI,CPI,RDPR,CPf,CPs, Cpfdegrad, CPsdegrad,CP, Lat,
     +    Legume, DF,hrsSunshine,Pi,DMI, LWGobs, DMIobs

      PARAMETER (Pi=3.141592654)

      CHARACTER input1*13, input2*13, input*10, var_name(30)*16,
     +    par_name(80)*16

C***********************************************************************
      input='sheep'
      input1='sheeplor.var'
      input2='sheeplor.par'

      OPEN(unit=1,file=input1,status='old')
      OPEN(unit=4,file=input2,status='old')
```

```
      OPEN(unit=9,file='compare.dat',status='old')

      DO 50 I=1,68
                READ(4,*) par_name(I),par(I)
                IF(I.LE.22)READ(1,*) var_name(I),var(I)
50     CONTINUE

      HighWt=42.0

C**********************************************************************
C
      READ(9,*)
 5    CONTINUE
      READ(9,830,end=999)year,month,day,lat,Tmax,Tmin,herbage,Age,Wt,
     +          DigIntake,CPf,DMIobs,LWGobs

      CPf=CPf*6.25/1000.0
      IF(WT.GT.HighWt)HighWt=Wt

C     Calculate mean daily temperature and convert kg yield to tonnes.
C     Tmean=mean daily temperature
C     Tmin=minimum daily temperature
C     Tmax=maximum daily temperature

       Tmean=(Tmax+Tmin)/2.0
       herbage=herbage/1000.0

C     Wt init is calculated for output purposes only.

       Wtinit=Wt

C     Begin calculations.
C
C     The standard reference weight,SRW, is the weight of an animal when it reaches
C     mature skeletal size and has a condition score in the middle of the range(excluding
C     fleece and conceptus). The normal weight,N, is the weight of a growing animal
C     when its condition score is in the middle of the range (In grazfeed technical manual,
C     SRW refers to the wt of a female, castrated males having this value multiplied by 1.2
C     or by 1.1 for classes of unweaned young taken to be a mixture of females and
C     castrated males). Because of interrupted growth patterns normal weight is generally
C     defined as the lesser of N and the highest weight attained so far. The standard
C     birthweight of a lamb is assumed to be 0.1 of the ewe SRW, for a calf it is 0.07 of the
C     cow's SRW.
C
C     var(1)=SRW(kg).
C     var(2)=standard birthweight(kg).
C     Age=age of the animal in months.

       IF(input.EQ.'sheep')THEN
                var(2)=0.1*var(1)
       ELSEIF(input.EQ.'cattle')THEN
                var(2)=0.07*var(1)
       ENDIF

C     Age in months is converted to days , this is done by multiplying it by 30.5.

       N=var(1)-(var(1)-var(2))*EXP(-Age*30.5*0.015/var(1)**0.27)
       Ninit=N
```

```
C     Wt=actual liveweight(fleece and conceptus free)
C     BC, body condition or relative condition is the ratio of current base weight to the
C     normal weight.

C     The calculation of N is done before the calculation of body condition in immature
C     animals.  This is not the case for mature animals.

      N=min(N,HighWt)

C     As stated above Z is normally the ratio of N to SRW where N is the minimum of
C     calculated N or the maximum base weight attained so far.  This is true for growing
C     animals but for mature animals N as used to calculate Z is taken as that calculated by
C     the equation above. Maturity occurs in sheep at 24 months of age and in cattle at 36
C     months of age.

      IF(input.EQ.'sheep'.AND.Age.GE.24.0.OR.input.EQ.'cattle'.AND.Age.GE.36.0)
     +           THEN
                 Z=Ninit/var(1)
                 BC=Wt/Ninit
      ELSE
                 Z=N/var(1)
                 BC=Wt/N
      ENDIF

C     Using SRW and relative size,Z, (ratio of N to SRW,max of 1) potential dry matter
C     intake (kg/day) is calculated. Intake reaches a peak when Z = 0.85.  In Grazfeed for
C     all immature animals and those mature animals with a BC<1 Z is used, while for
C     mature animals with BC>1, BC is used.  No modification is made here to potential
C     intake for those young which do not yet have fully developed rumen capacity and the
C     effects of lactation as in Grazfeed.

C     Potential intake is depressed if the ambient temperature remains high over the 24
C     hours by 2% per degree celcius for Bos taurus, and by 1% per degree celcius for Bos
C     indicus cattle and all sheep.

C     par(13)=0.01 for sheep and B. indicus, 0.02 for B. taurus.
C     par(14)=25.0
C     par(15)=22.0

      IF(Tmean.GT.par(14).AND.Tmin.GT.par(15))THEN
                 TF=1.0-par(13)*(Tmean-par(14))
      ELSE
                 TF=1.0
      ENDIF

C     par(1)=0.025 for cattle, 0.04 for sheep.

      IF(BC.LE.1.0.OR.input.EQ.'sheep'.AND.Age.LT.24.0.OR.
     +      input.EQ.'cattle'.AND.Age.LT.36.0)THEN
                 PDMI=par(1)*var(1)*Z*(1.7-Z)*TF
      ELSE
                 PDMI=par(1)*var(1)*BC*(1.7-BC)*TF
      ENDIF

C     The proportion of an animal's potential intake which can be satisfied from a grazed
C     pasture is a function of two man factors;
C           1.relative ingestability and
```

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C        2.relative availability.

C     Relative availability as calculated below is a product of relative rate of eating and
C     relative time spent grazing.  The factor ZF accomodates the smaller mouth size of
C     young cattle, allowing them to achieve their potential intake at a lower level of
C     herbage availability than would be needed by adults.

C     par(16)=1.0 for sheep, 0.5 for cattle.
C     par(17)=0.0 for sheep, 1.0 for cattle.

      IF(input.EQ.'cattle'.AND.Z.LT.par(16))THEN
                 ZF=1.0+(par(17)-Z/par(16))
      ELSE
                 ZF=1.0
      ENDIF

C     HF is a factor that increases the availability of feed as a result of HR. In cases where
C     there are multiple feed classes HR, the ratio of the height of each herbage class, will
C     need to be calculated. In our situation here we are assigning a value of 3.3 to HR. In
C     tropical tussock pasture a rough value of 10 cm/tonne is probably OK, therefore HR
C     will be approximately 3.3.

C     par(18)=1.0 for sheep, 0.5 for cattle

      HR=var(22)/3.0
      HF=MAX(1.0,1.0-par(18)+par(18)*HR)

C     par(2,3)=constants used in calculating relative availability.
C     par(2)=0.001 for sheep, 0.0005 for cattle.
C     par(3)=0.6 for sheep and cattle.
C     herbage=pasture yield (t DM/ha).

C     The rate of eating and time spent eating equations below include '(1.0+1.0)', this in
C     fact represents '(1.0+the proportion of total dry matter that is in this digestibility class)'.

      RateEat=1.0-EXP(-(1.0+1.0)*par(2)*herbage*1000.0*HF*ZF)
      TimeEat=1.0+par(3)*EXP(-(1.0+1.0)*(par(2)*HF*ZF*
     +       herbage*1000.0)**2)
      Rel_Avail=RateEat*TimeEat

C     Relative ingestability is a function of  digestibility.

C     par(5)=pasture co-effecient, 1.7 for intro pasture, 1.0 for native pastures.
C     There is evidence that the intake of native grasses falls more slowly with declining
C     digestability than is the case with the main introduced grasses.

C     DigIntake=digestibility of feed pool.
C     var(7)=proportion of legume in the sward (0 - 1).
C     par(61)=0.8


      Rel_Ing=1.0-par(5)*(par(61)-DigIntake)+0.17*var(7)

C     Relative intake is then calculated.

      Rel_intake=Rel_Ing*Rel_Avail
C******************************************************************************
C     When feeding supplements, the supplement is integrated into the hierarchy of
```

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C     herbage classes on the assumption that animals will select the supplement before it
C     selects herbage of the same or lower quality. In our situation here we are assuming
C     that any supplement fed will be of a higher metabolisable energy concentration than
C     the pasture being grazed. The effect of lactation and those supplements with a low
C     ratio of organic matter digestibility to protein concentration are ignored at this stage.

C     var(8)=amount of supplement on offer.
C     var(9)=ME content of supplement.
C     par(19)=1.7 as in the calculation of relative ingestability of forage.
C     par(20)=0.8 as in the calculation of relative ingestability of forage.

C     Given: ME=17.0*DMD-2.0, then DMD=(ME+2.0)/17.0.
C     OMDS not used at this stage.
C
      DMDs=(var(9)+2.0)/17.0
      OMDs=1.05*DMDs-0.01
      Rel_IngS=1.0-par(19)*(par(20)-DMDs)

      J=0
500     Continue
      J=J+1

      Rel_AvailS=MIN(1.0,10.0/var(9),var(8)/PDMI/Rel_IngS)

      Rel_IntakeS=Rel_AvailS*Rel_IngS

C     Actual intake is in kg DM/day.

      DMIs=PDMI*Rel_IntakeS

C     If a supplement is fed, recalculate intake of forage, at this stage no effect of lactation
C     or supplements with low OMD:protein is taken into account in calculating substitution.

      IF(var(8).GT.0.0)THEN
                Rel_Availf=Rel_Avail*(1-Rel_AvailS)
      ELSE
                Rel_Availf=Rel_Avail
      ENDIF
      DMIf=Rel_Availf*Rel_Ing*PDMI
      DMI=DMIf+DMIs

C     Calculation of ME content of diet and MEI. In the technical manual MEs is
C     calculated in the same way as the forage. We are assuming here that MEs is supplied.
C     par(62)=17.0
C     par(63)=2.0

      MEf=par(62)*DigIntake-par(63)

      ME_Diet=(MEf*DMIf+DMIs*var(9))/DMI

      MEIf=MEf*DMIf
      MEIs=DMIs*var(9)
      MEI=ME_Diet*DMI
C*********************************************************************
C     Effeciency of ME for maintenance, Km. Assumes an average gross energy content of
C     18.4 MJ/kg DM . Km increases with increasing ME content of the diet.

      Km=0.5+0.02*ME_Diet
```

```
C     Net energy requirements of grazing include in this case the requirements for
C     movement.(MJ net energy/day).
C
C     par(4)=0.05 for sheep and cattle.
C     par(6)=0.05 for sheep,0.006 for cattle.
C     par(7)=1.0,1.5,2.0 for level, undulating or hilly terrain.
C     var(11)=availabilty of green forage,t DM/Ha. If this is so low that in effect dead
C     pasture alone is available, it is suggested that total forage be used.
C     The NEmove allows for the vertical and horizontal movements of grazing and is
C     reduced to 0 for animals not grazing.

      IF(var(11).GT.0.1)THEN
                NEmove=Wt*par(7)*par(4)/(var(11)+3.0)
      ELSEIF(var(11).LE.0.1.AND.herbage.GT.0.1)THEN
                NEmove=Wt*par(7)*par(4)/(herbage+3.0)
      ELSE
                NEmove=0.0
      ENDIF

      NEgraze=Wt*par(6)*DMIf*(0.9-DigIntake)+NEmove

C     par(8)=1.0 for sheep,1.4 for B. taurus,1.2 for B. Indicus, crossbreeds have a pro rata  value.
C     par(9)=sex factor,1.0 for castrates and females,1.15 for entire males.
C     par(60)=0.26 basal metabolism , weight scalar (MJ/kg^0.75 ).

      NEmetab=par(8)*par(9)*(par(60)*Wt**0.75*MAX
                          (EXP(-0.00008*Age*30.5),0.84))

      MEmaint=(NEgraze+NEmetab)/Km+0.09*MEI

      Feed_Level=MEI/MEmaint-1.0
C*********************************************************************
C     The maintenance protein requirement, Pmaint is the sum of the endogenous urinary
C     protein, EUP, the endogenous faecal protein, EFP,and for cattle the endogenous
C     dermal protein,DP.SCA allows a 20% reduction for Bos indicus cattle in the
C     calculation of EUP, not allowed for here at this stage.

C     par(21)=0.0152 for sheep and cattle.
C     par(22)=1.47*10^-4  for sheep, 0.037 for cattle.
C     par(23)=3.375*10^-3 for sheep, 4.22*10^-2  for cattle.
C     par(24)=0.0 for sheep, 1.1*10^-4  for cattle.

      EFP=par(21)*DMI

      IF(input.EQ.'sheep')THEN
                EUP=par(22)*Wt+par(23)
                DP=0.0
      ELSE
                EUP=par(22)*ALOG10(Wt)-par(23)
                DP=par(24)*Wt**0.75
      ENDIF

      Pmaint=EFP+EUP+DP

C     At this point the rumen degradation of dietary protein is calculated as a function of
C     the feeding level; the intakes of rumen degraded and undegraded protein are
C     calculated and the intake of rumen degraded protein is compared with the amount
```

```
C     required. If a deficiency is indicated, the intake of dry matter is reduced in proportion
C     and all the calculations of intake and basal metabolism are repeated. In this run I am
C     using digestability to predict CP% and degradability.

      CPfdegrad=DigIntake+0.1
      CPsdegrad=DMDs+0.1

C     The way in which crude protein is calculated at this point assumes there is no
C     legume component in the herbage.  Supplement crude protein equation is a
C     regression of known digestibility against known CP% from Grazfeed.

      IF(CPfdegrad.GT.0.89)THEN
              CPf=0.25
      ELSEIF(CPfdegrad.GT.0.79)THEN
              CPf=0.18
      ELSEIF(CPfdegrad.GT.0.69)THEN
              CPf=0.12
      ELSEIF(CPfdegrad.GT.0.59)THEN
              CPf=0.07
      ELSEIF(CPfdegrad.GT.0.49)THEN
              CPf=0.03
      ELSEIF(CPfdegrad.GT.0.39)THEN
              CPf=0.01
      ENDIF

      CPs=0.47+1.7*DMDs-1.78*SQRT(DMDs)

      RDPIf=DMIf*CPf*CPfdegrad
      RDPIs=DMIs*CPs*CPsdegrad

C     In SCA the following comments are made; ignoring endogenous N, the requiremnt
C     for RDP of microbes will equal the net rate of synthesis of MCP if N substrates from
C     the RDP are captured with an efficiency of 1. With diets not containing excessive
C     amounts of N and with true protein, an efficiency of 1 is assumed. For diets where N
C     is in the form of urea or other degradable NPN then an effeciency of of 0.8 is
C     assumed, if given in small amounts at frequent intervals with a suitable energy source
C     and not in excess.

C     par(25)=0.3
C     par(26)=0.25
C     par(27)=0.1

      RDPI=(1.0-(par(25)-par(26)*DigIntake)*MAX(Feed_Level,0.0))
     +        *RDPIf+(1.0-par(27)*MAX(Feed_Level,0.0))*RDPIs
      CPI=DMIf*CPf+DMIs*CPs
      CP=CPI/(DMIf+DMIs)
      UDPI=CPI-RDPI

C     par(28)=0.007
C     par(29)=-0.35
C     par(57)=0.005
C     par(58)=16.4
C     par(59)=1.6

C     Calculate the Julian Date  and the day of the year. DOY is taken to be the 15th of the
C     nominated month.

      day=15
```

```
      CALL JULIAN(day,month,year,jdate)
      a=1
      b=1
      CALL JULIAN(a,b,year,DOYear)
      DOY=jdate-DOYear+1

      DF=1.0+0.1*Lat/40.0*SIN(2.0*Pi*REAL(DOY)/365.0)
      FMEIs=(par(58)*DMDs-par(59))*DMIs
      RDPR=(par(28)+par(57)*(1.0-EXP(par(29)*(Feed_Level+1.0))))*
     +     (DF*MEIf+FMEIs)
C      ***************
C     At this point if RDPR exceeds RDPI then the potential intake of dry matter is
C     reduced by the factor RDPI/RDPR and all equations up to this point that involve
C     intake are re-calculated. It is assumed by SCA that recycling of urea to the rumen
C     will offset the remaining deficiency of RDP.
C
      IF(RDPR.GT.RDPI.AND.DMI.GT.0.0.AND.(RDPI/DMI).LT.0.1.AND.
     +                    J.LE.1)THEN
              PDMI=PDMI*RDPI/RDPR
              GOTO 500
      ENDIF
C*************************************************************************
C     PTN requirements are expressed as ADPLS, the animals net requirements being
C     converted to this form by assuming ADPLS is used with an efficiency of 0.7 for all
C     purposes, except for wool growth where an efficiency of 0.6 is assumed. MCP
C     leaving the stomachs is assumed to be 70% true PTN, the rest nucleic acids and other
C     non-amino N compounds. Grazfeed assumes 0.85 as the apparent digestibilty of true
C     microbial protein while SCA uses 0.7. As microbial protein is the dominant PTN
C     entering the duodenum, the digestability of UDP, in feeds other than forages, can be
C     taken to be the same as that of the MCP leaving the stomachs.Therefore the
C     following formula is used to calculate the Apparent Digestibility of UDP resulting
C     from forages because of the probable increasing association of UDP with fibre.

C     par(30)=0.05, minimum value of ADudp that may exist.
C     par(31)=4.55, co-effecient used in calculating ADudp.
C     par(32)=0.147, co-effecient used in calculating ADudp.
C     par(33)=1.0, MCP effeciency of conversion from RDP.
C     par(34)=0.7, true PTN content of MCP.
C     par(35)=0.85, apparent digestibility of microbial true PTN.

      ADudp=MAX(par(30),MIN(par(31)*CP-par(32),1.0))
      ADPLSmcp=par(33)*par(34)*par(35)*RDPR
      ADPLS=ADudp*UDPI+ADPLSmcp
C*************************************************************************
      IF(input.EQ.'sheep')THEN

C     Wool Growth
C     The net PTN requirement for wool growth is equal to the rate of growth of clean
C     wool fibre. The Standard Fleece Weight is taken to be that of an adult sheep(2 years
C     or older) of a particulat type (breed,strain,sex). It is the annual greasy fleece
C     production(kg) expected in a year with good climatic conditions for pasture growth,
C     and for ewes is the production expected if they had neither borne nor reared a lamb.
C     This assumes a clean scoured yield of 0.6-0.7.

C     The daily wool growth is predicted using the variable limit which is the minimum
C     growth given available protein/energy.
C     In this situation are ignoring energy and PTN costs of pregnancy/lactation.
```

```
C     par(36)=0.012, MEI/ptn limitation.
C     par(38)=0.7, UDP limitation.
C     par(56)=0.032, photoperiod effect.

C     The number of hours of sunlight is calculated given the day of the year and latitude.

      dayL=hrsSunshine(Lat,DOY)

      Photo=1.0+par(56)*(dayL-12.0)
      limit=MIN(par(36)*MEI,ADPLS)

C     The daily clean wool growth rate is reduced for ages of less than 2 years.
C     par(40)=0.011, age factor.

      IF(Age.LT.24.0)THEN
                Young=(1.0+EXP(-par(40)*Age*30.5))*Z**(2.0/3.0)
      ELSE
                Young=1.0
      ENDIF

C     var(14)=SFW (4.2kg in the case of the Lorimer's merinos).
C     par(41)=0.04, lag factor.
C
      WoolD=var(14)/var(1)*Young*limit*Photo

C     The net energy cost of daily wool growth is calculated after allowing for the basal
C     rate included in the standard function for basal metabolism. The value for WoolD-
C     par(43)*Z is not allowed to become negative.

C     par(42)=24, energy content of greasy wool MJ/kg.
C     par(43)=0.004, basal clean wool growth.
C     par(44)=0.7, ratio of clean to greasy i.e. yield.

      NEwool=par(42)*(MAX(0.0,WoolD-par(43)*Z))/par(44)

C     The diameter of the day's new growth(Ud) is estimated as a proportion of the
C     maximum diameter specified for the animal type.
C     var(15)=22 for Lorimer's merinos.
C     Umax - the maximum fibre diameter specified for the animal type.
C     CFWpot=represents the potential daily clean wool growth rate for a particular type
C     of sheep of any age.

      CFWpot=par(44)*var(14)*((1.0+EXP(-par(40)
     +               *Age*30.5))*Z**(2.0/3.0))/365.0

      Ud= var(15)*(WoolD/CFWpot)**(1.0/3.0)

      ENDIF
C***********************************************************************
C     Kg increases as the ME content of the diet increases, but not with the level of
C     feeding. In general the digestibilty of a feed decreases with level of feeding, but SCA
C     ignores this, being offset by the calculation of maintenance requirements being
C     incremented by 9% of the total MEI.

C     Efficiency of use of energy for gain deals with concentrate supplements only,
C     roughage concentrates are treated in the same way as tropical pastures.

C     par(10)=0.063
```

```
C     par(11)= -0.308
C     par(51)=0.9, effects % legume in diet.
C     par(52)=0.3, effects % legume in diet.
C     par(53)=0.043, ME of forage and concentrates.
C     par(54)=0.01, time of year effect.
C     par(55)=15.4, time of year effect.

      Legume=par(51)+par(52)*var(7)
      DF=Lat/40.0*SIN(2.0*Pi*REAL(DOY)/365.0)-1.0
      Kg=Legume*(par(53)*MEf+par(54)*(par(55)-MEf)*DF)

C     First step is to calculate provisionally the amount of energy and PTN available.
C     Efficiency of use of ADPLS depends on it's source; milk or solids. However milk is
C     ignored here.

C     par(48)=0.6, ADPLS efficiency of use for wool
C     par(49)=0.7, ADPLS efficiency of use for other purposes, when ADPLS from solids.

C     It should be noted that SCA use Adj_Rate cf Feed_Level and that Wt/SRW is used
C     instead of Z.

      Kadpls=par(49)
      Pgain=Kadpls*(ADPLS-(Pmaint/Kadpls)-WoolD/par(48))

C     NEwool is ignored while a provisional ME balance is calculated to see whether Kg
C     needs to be modified for weight loss.
C     par(64)=0.8, efficiency with which stored energy is used for maintenance
C     requirements during periods of weight loss.

      MEgain=MEI-MEmaint
      IF(MEgain.GT.0.0)THEN
              Kg=Kg
      ELSE
              Kg=Km/par(64)
      ENDIF
      NEgain=Kg*(MEI-MEmaint)-NEwool

C     Energy(EVG) and protein(PCG) content of empty bodyweight gain are then
C     calculated.
C     par(12)=20.3, breed factor for all sheep, BI and most BT breeds (excluding
C     charolais, simmental, chianina etc).
C             =16.5 for simmental etc,
C             =18.4 for xbreeds.
C     par(50)=0.14 for sheep and cattle, apart from European breeds such as Charolais etc
C     where it is 0.12. This is to account for their higher protein and lower fat content of
C     gain even at maturity.
C     par(65)=6.7
C     par(66)=2.0
C     par(67)=0.212
C     par(68)=0.004

      EVG=par(65)+par(66)*(Feed_Level-1.0)+(par(12)-2.0*
     +        (Feed_Level-1.0))/(1.0+EXP(-6.0*(Z-0.4)))

      PCG=par(67)+par(68)*2.0*(Feed_Level-1)-(par(50)-0.004*2.0*
     +        (Feed_Level-1.0))/(1.0+EXP(-6.0*(Z-0.4)))

C     Then given the weight change due to NEgain and EVG, will the available PTN
```

```
C     support such a change.

      Pnet=Pgain-PCG*NEgain/EVG

C     If Pnet is negative, in lactating animals lactation is reduced so as to allow more PTN
C     and energy available for change - this is not included here.
C     In this case if Pnet is negative (PTN is limiting) then Negain is reduced.

      IF(Pnet.LT.0.0.AND.NEgain.GT.0.0)NEgain=NEgain+0.5*
     +      EVG*MIN(0.0,Pnet)/PCG

      EBG=NEgain/EVG
      LWG=1.09*EBG

      Wt=Wt+LWG
      Pgain=MIN(Pgain,EBG*PCG)

C**********************************************************************
Goto 5
999   continue

      CLOSE(unit=1)
      CLOSE(unit=4)
      CLOSE(unit=9)

      END
C**********************************************************************

      SUBROUTINE JULIAN(day,month,year,jdate)

C     This program is written to take normal dates from the file and pass back a julian date

      IMPLICIT none
      logical legal
      INTEGER day,month, year,jdate

C     Day=day of the month 1-31
C     Month=month of the year 1-12
C     jdate=the julian date
C     legal is a logical variable, returned by a sub once the date has been found to be legal.

      call  legal_date(legal,day,month,year)
      if (legal) then
              call  julian_date(jdate,day,month,year)
      else
              PRINT*,'ILLEGAL DATE, PROGRAM STOPPED'
              STOP
      endif

      RETURN
      end

C**********************************************************************
      subroutine legal_date(legal,day,month,year)

      integer days_in_month(12)
      integer year
      integer len
```

```
      integer leapyr
      integer day
      integer month
      logical legal

      data days_in_month /31,28,31,30,31,30,31,31,30,31,30,31/
      leapyr = 365
      len = year / 4
      len = len * 4
      if (year .eq. len) leapyr = 366
      if (year .eq. 1800 .or. year .eq. 1900) leapyr = 365
      if (leapyr .eq. 366) days_in_month(2) = 29

      legal = .true.
      if(month .lt. 1 .or. month .gt. 12) legal = .false.
      if(year .lt. 1 .or. year .gt. 2030) legal = .false.
      if(day .gt. days_in_month(month))  legal = .false.
      if(day .lt. 1 ) legal = .false.
      return
      end
C***********************************************************************
      subroutine julian_date(jdate,kday,month,nyear)

      integer m8
      integer y8
      integer month
      integer nyear
      integer jdate
      integer kday

c     calculates a 7 digit julian date relative to 24/10/4713 (BC)
      if(month .gt. 2) then
              m8 = month -3.0
              y8 = nyear
      else
              m8 = month + 9.0
              y8 = nyear - 1.0
      endif
      c8 = int(y8/100.0)
      d8 = y8-100.0 * c8
      jdate = int(146097.0*c8/4.0)+kday+int(1461*d8/4.0)+1721119.0+
     +                      int((153*m8+2.0)/5.0)
      return
      end
C***********************************************************************
C     Routine to calculate a quick approximation for the number of hours of sunshine
C     in the day, as a function of latitude and time of year.

C     Applicability:
C     Given the existance of twilight, this calculation is probably not very meaningful too
C     close to the poles. Be warned.

C     Abstraction:
C     The critical features of the abstraction used here are as follows. The earth is a
C     sphere, centered on the origin, with the axis of rotation aligned with the z axis.
C     There exists a plane P, which divides day from night. This plane passed through the
C     origin. The orientation of this plane is a function of time of year. To orientate this
C     plane correctly, begin with it in the y-z plane. Rotate about the z axis for the time of
```

```
C     year (360 deg = 1 year). Then rotate about the y-axis for the earth's axial tilt (23.5
C     deg). The plane P is then correctly orientated.  Where it intersects the circle of a
C     particular parallel of latitude, it divides night from day. The angular proportion in the
C     day side is the proportion of 24 hours which is in daylight.

C     Inputs:
C     lat    Latitude in degrees (North positive, South negative)
C     J      Julian day (1 = Jan 1st, 365 = Dec 31 , or 366 in leap years).

C     Symbols:
C     P       Plane dividing night from day
C     alpha   Angle between P and earth's axis
C     phi     Latitude, in radians
C     d       Time-of-year angle = (J-Js)/365.25 * 2*PI
C                                  where J = Julian day
C                                  where J = Julian day of solstice (22 Dec)
C     A       Axial tilt of earth = 23.5 degrees
C     theta   angle of arc of latitude circle which is in daylight.
C     (x, y)  Position of Sunrise point (z is fixed by latitude).
C***********************************************************************
C     Neil Flood. May 1994.

      real function hrsSunshine(lat, J)
      integer J
      real phi, lat

      real A, PI, daysInYear
      parameter (PI = 3.1415926535, A = 23.5*PI/180.0)
      parameter (daysInYear = 365.25)
      integer Js
      parameter (Js = 356)
      real alpha, sinAlpha, d, x, y, theta, cosPhi

      phi = lat*PI/180
      d = 2*PI*(J - Js)/daysInYear
      sinAlpha = sin(A) * cos(d)
      alpha = asin(sinAlpha)

      x = sin(phi) * tan(alpha)
      cosPhi = cos(phi)
      if (x*x .le. cosPhi*cosPhi) then
                y = sqrt(cosPhi*cosPhi - x*x)
                theta = 2 * atan2(y, x)
      else

C     Cope with midnight sun/midday darkness. i.e. P does not intersect latitude circle.

        if (x .gt. 0) then
                theta = 0
      else
        theta = 2*PI
      endif
      endif

      hrsSunshine = theta*24/(2*PI)
      return
      end
C***********************************************************************
```

Appendix Four

Plots Used in Selection of Wool Model

The plots used in the selection of the wool model as detailed in Chapters Six and Seven are presented here.

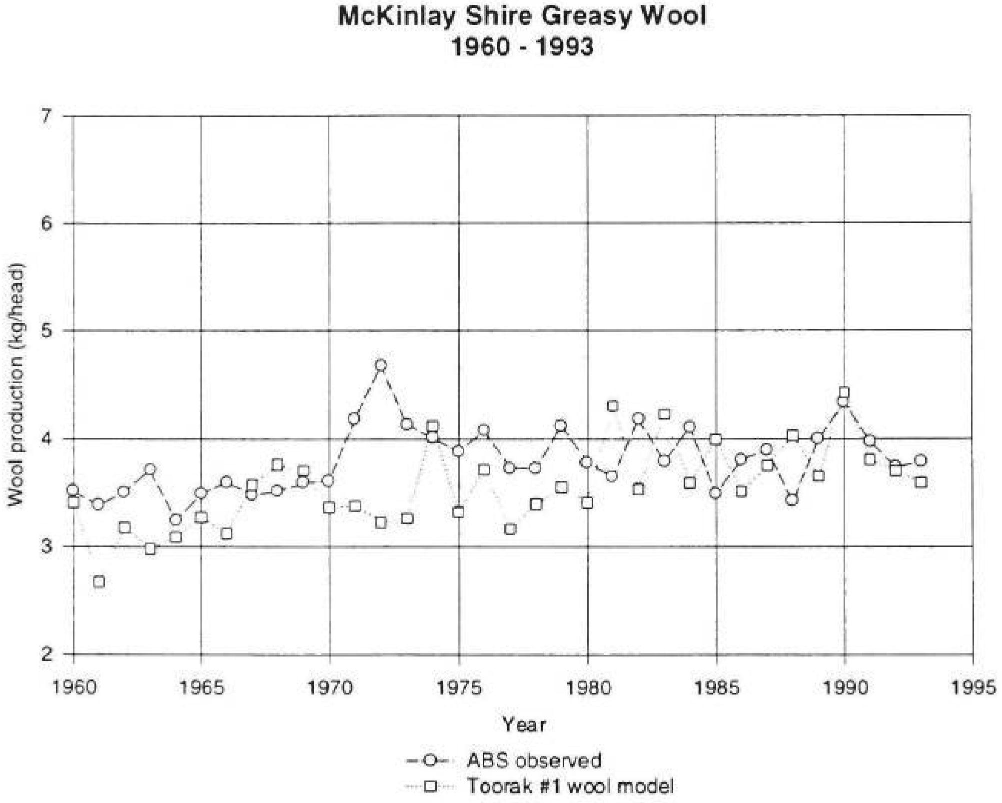
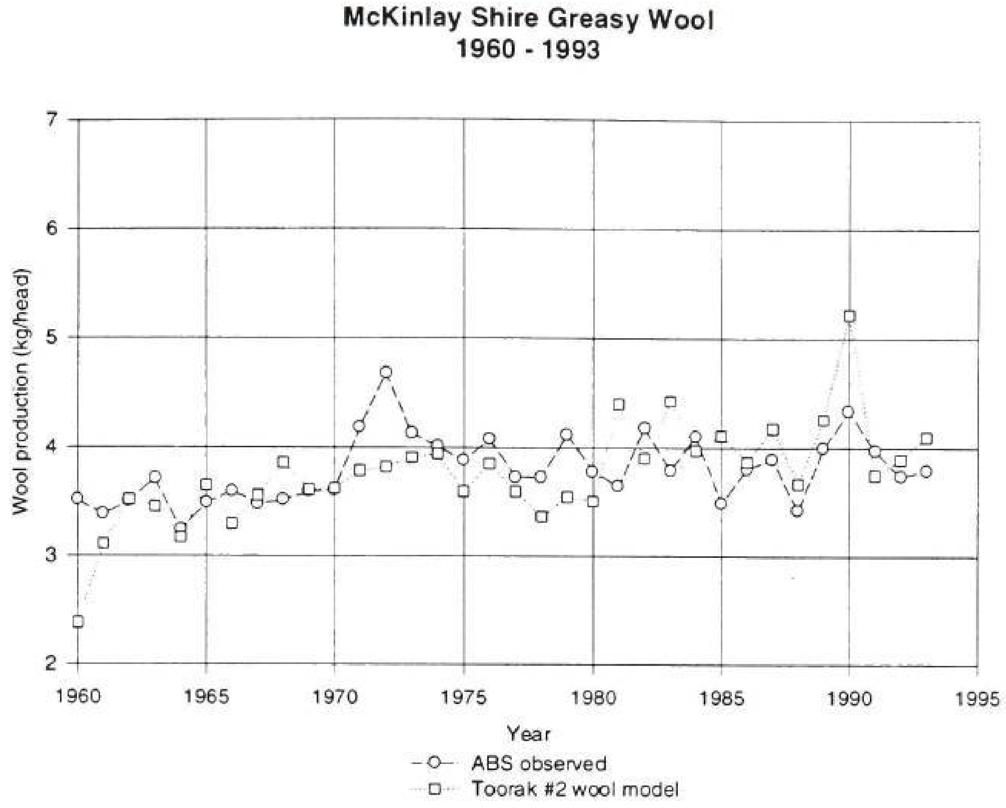


Figure A4.1. Predicted greasy fleece weights using Julia Creek climatic data and grazing trial models versus ABS McKinlay fleece weights.



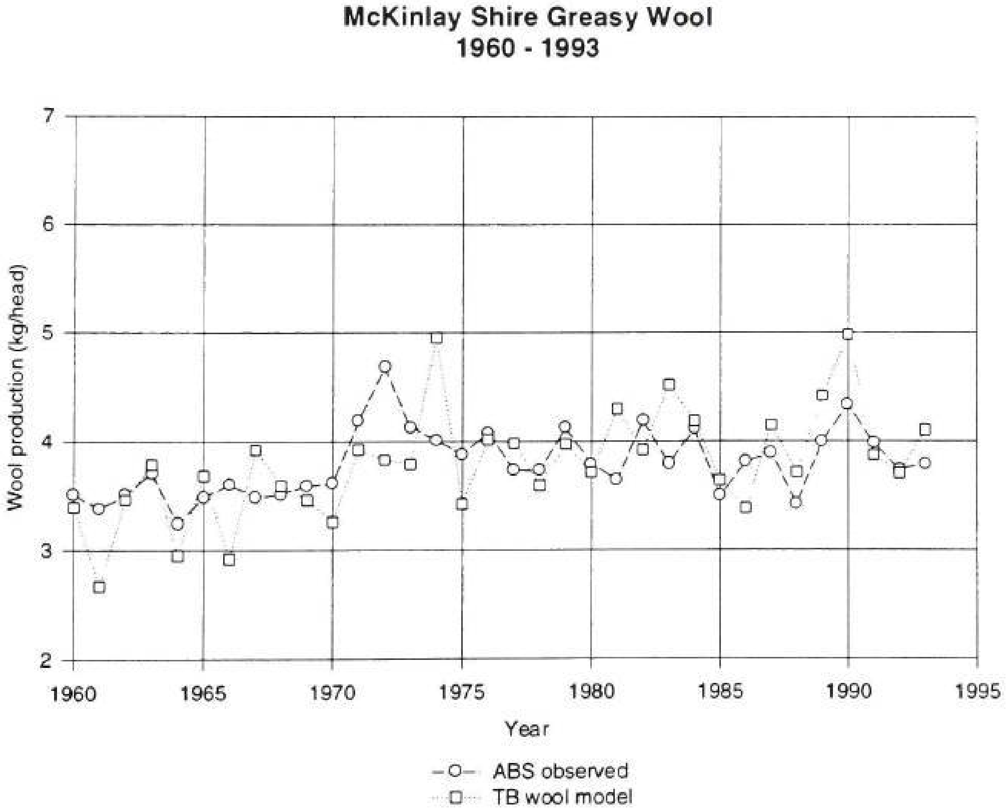


Figure A4.1 continued.

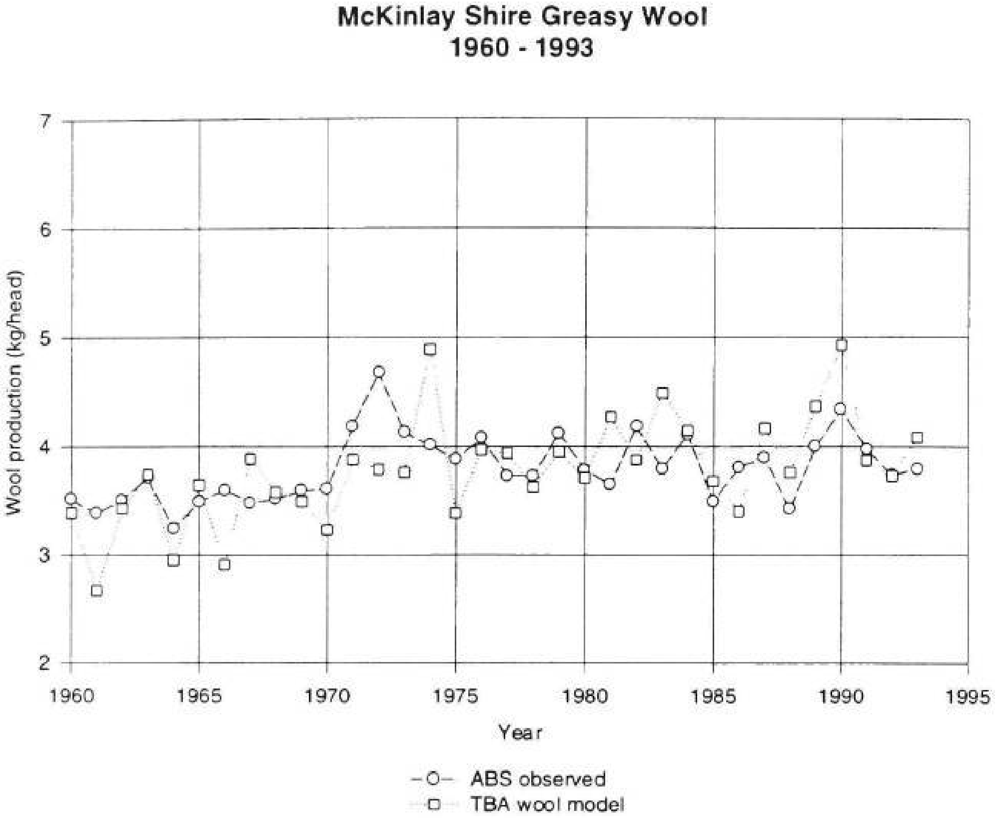


Figure A4.1 continued.

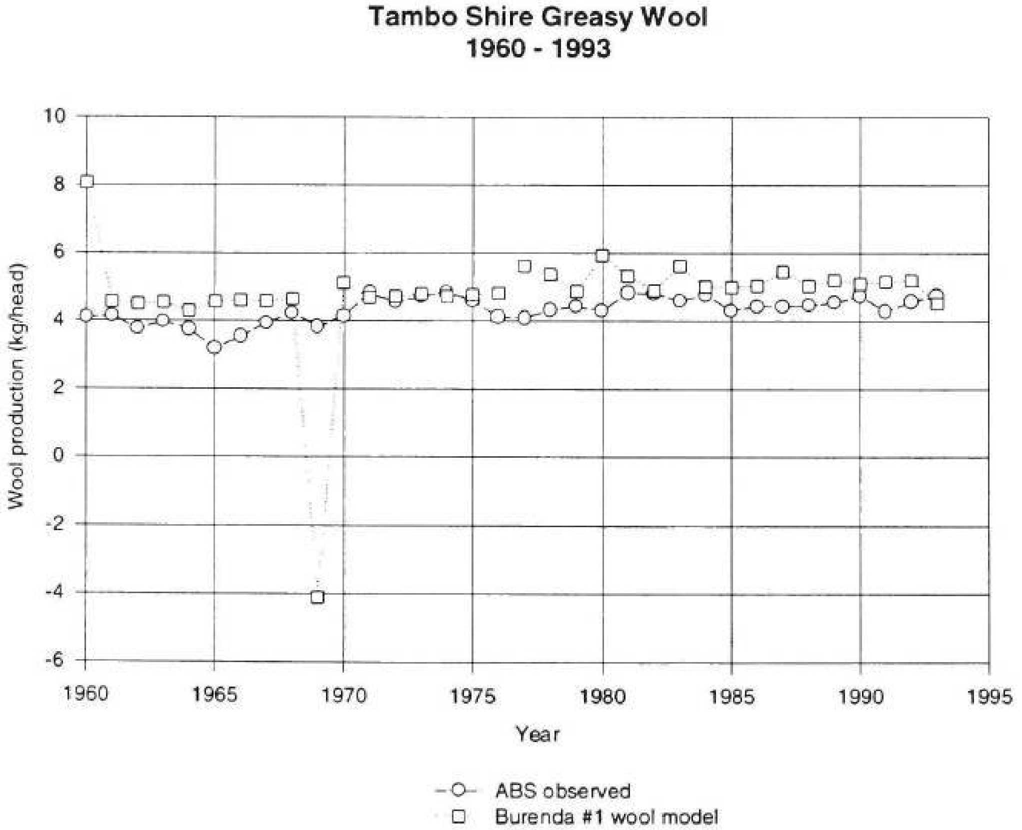
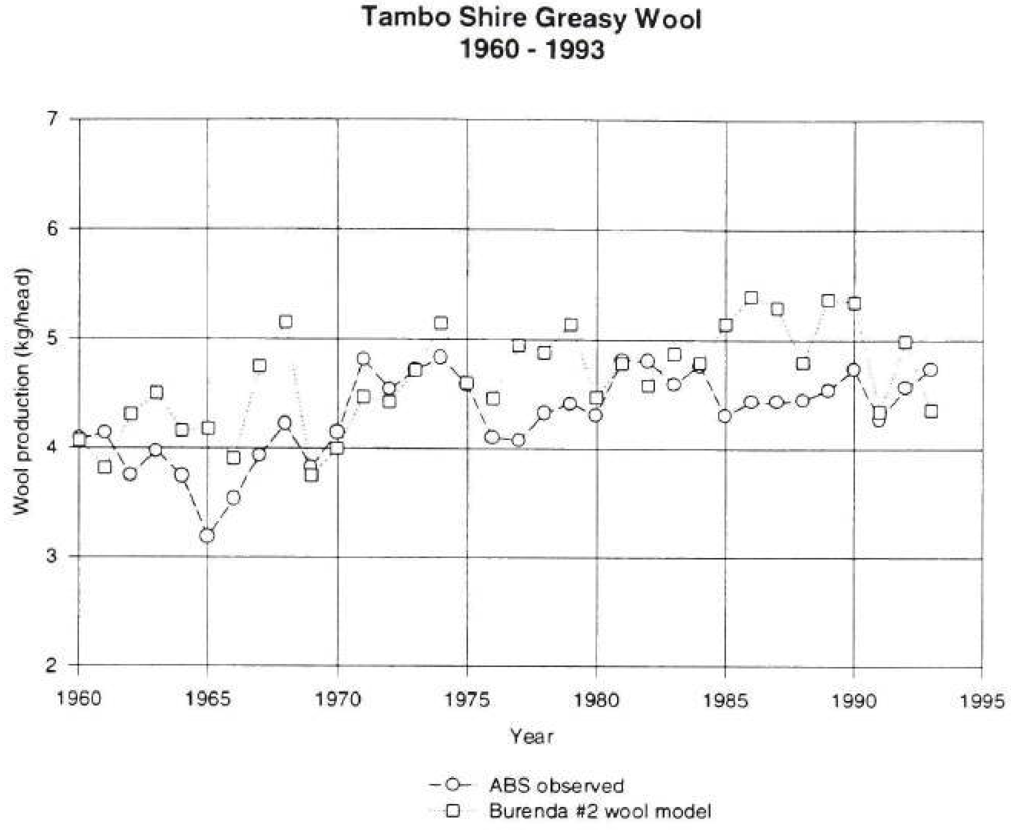


Figure A4.2. Predicted fleece weights using Tambo township climatic data and grazing trial models versus ABS Tambo shire fleece weights.



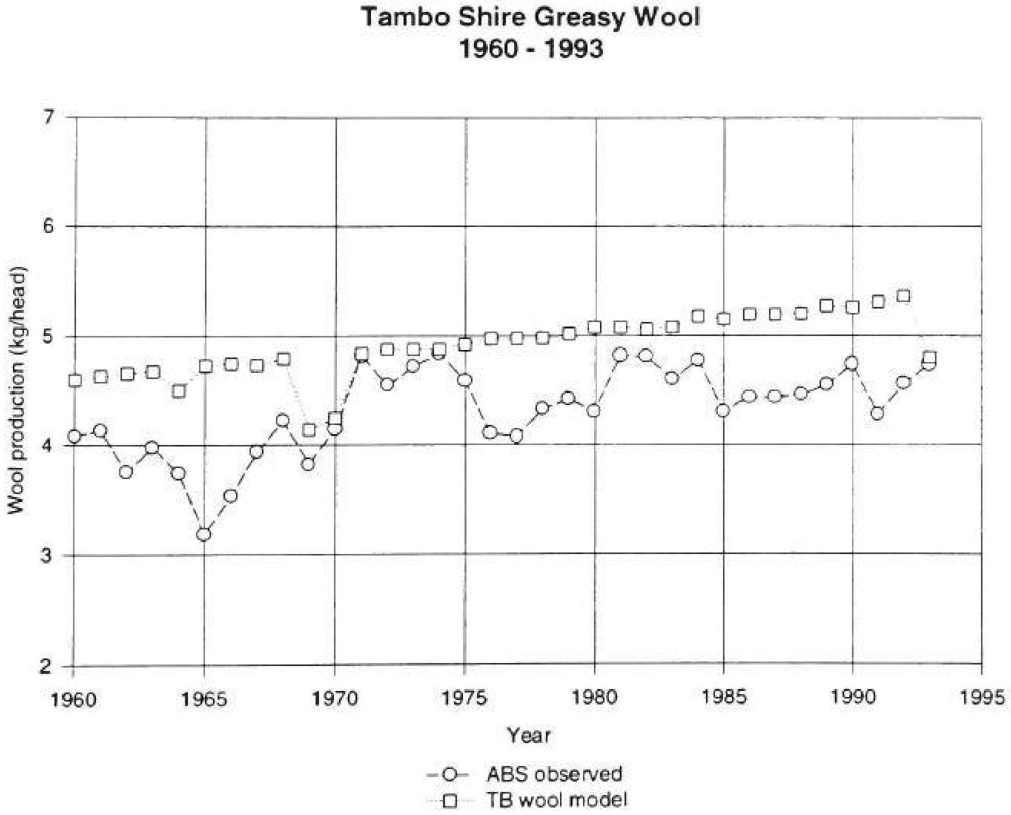


Figure A4.2 continued.

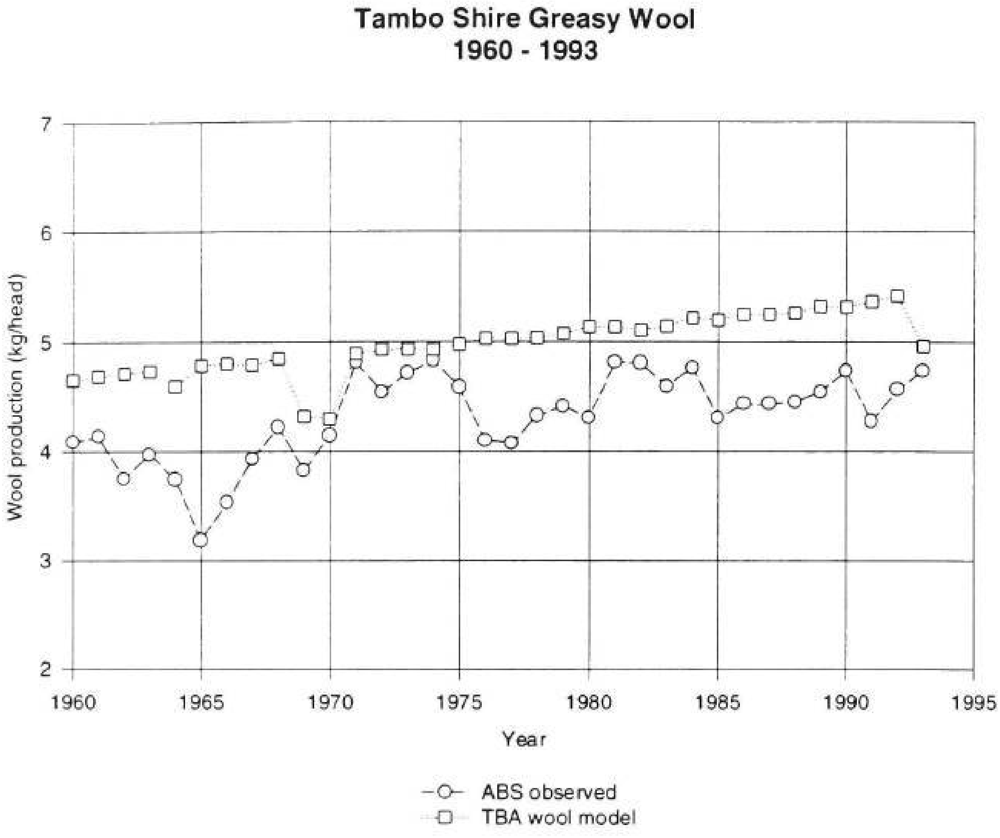


Figure A4.2 continued.

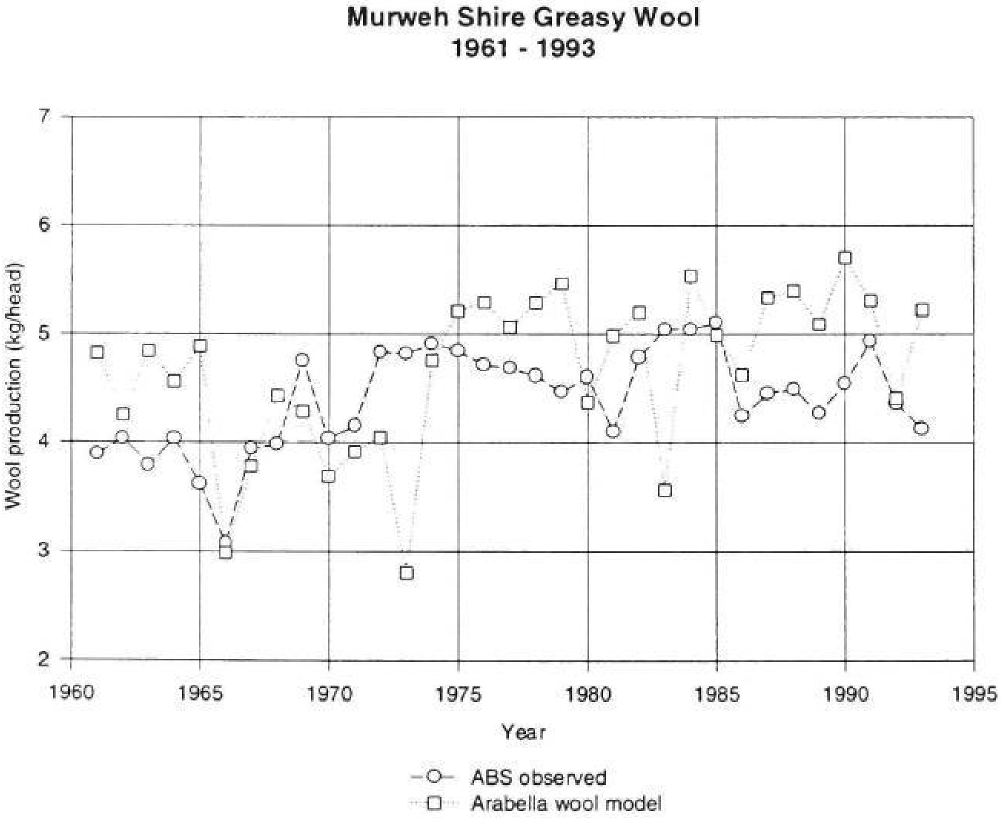


Figure A4.3. Predicted fleece weights using Charleville climatic data and grazing trial models versus ABS Murweh fleece weights.

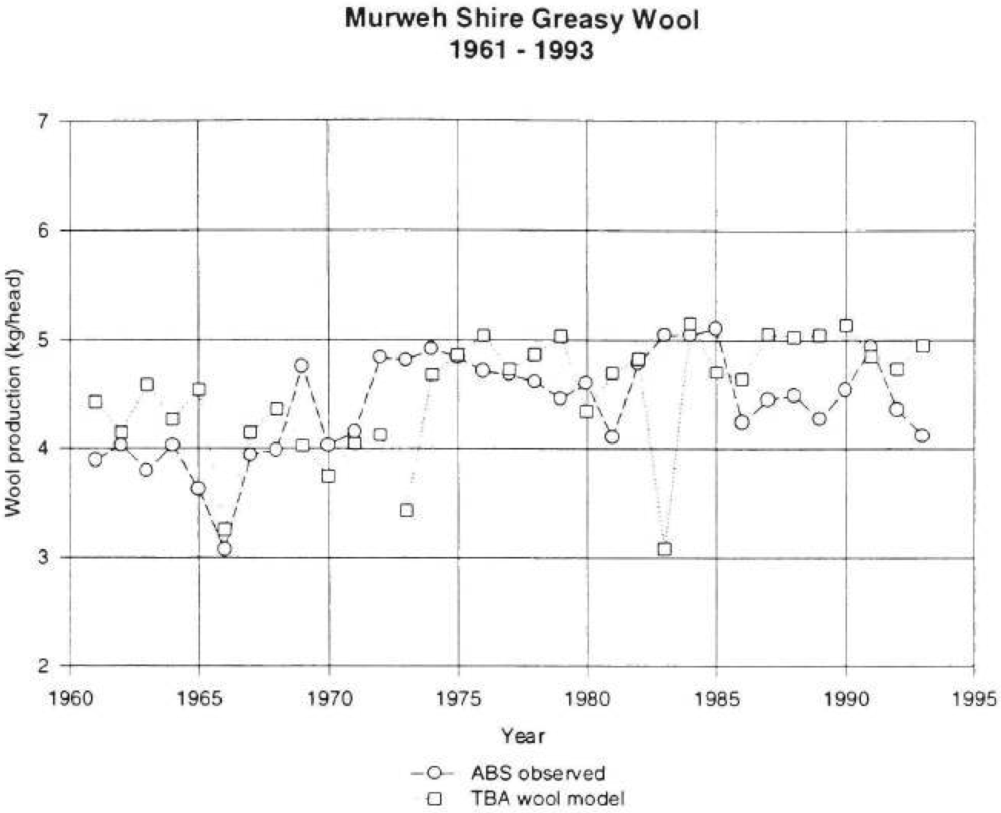


Figure A4.3 continued.

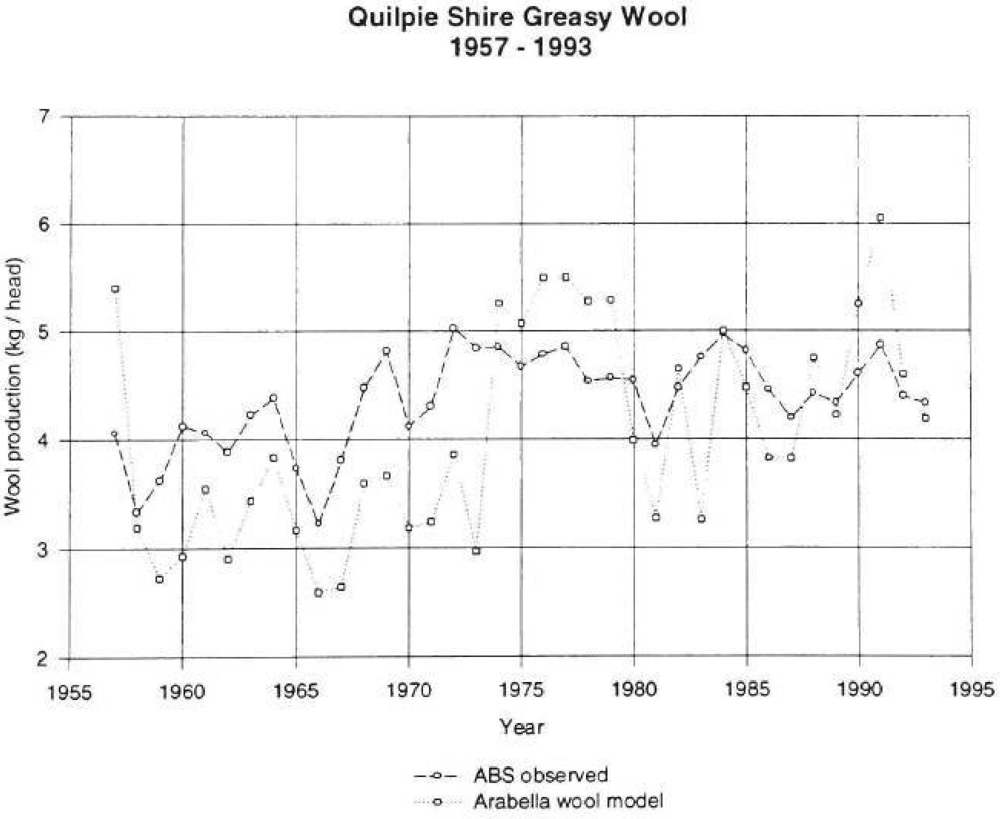
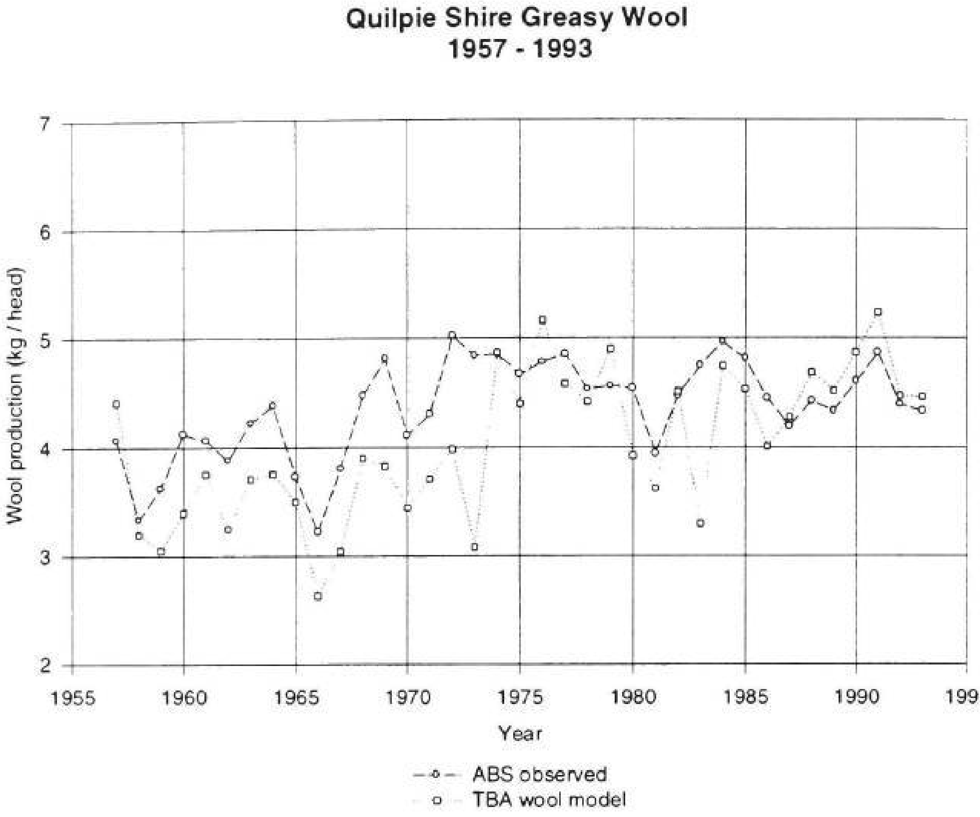
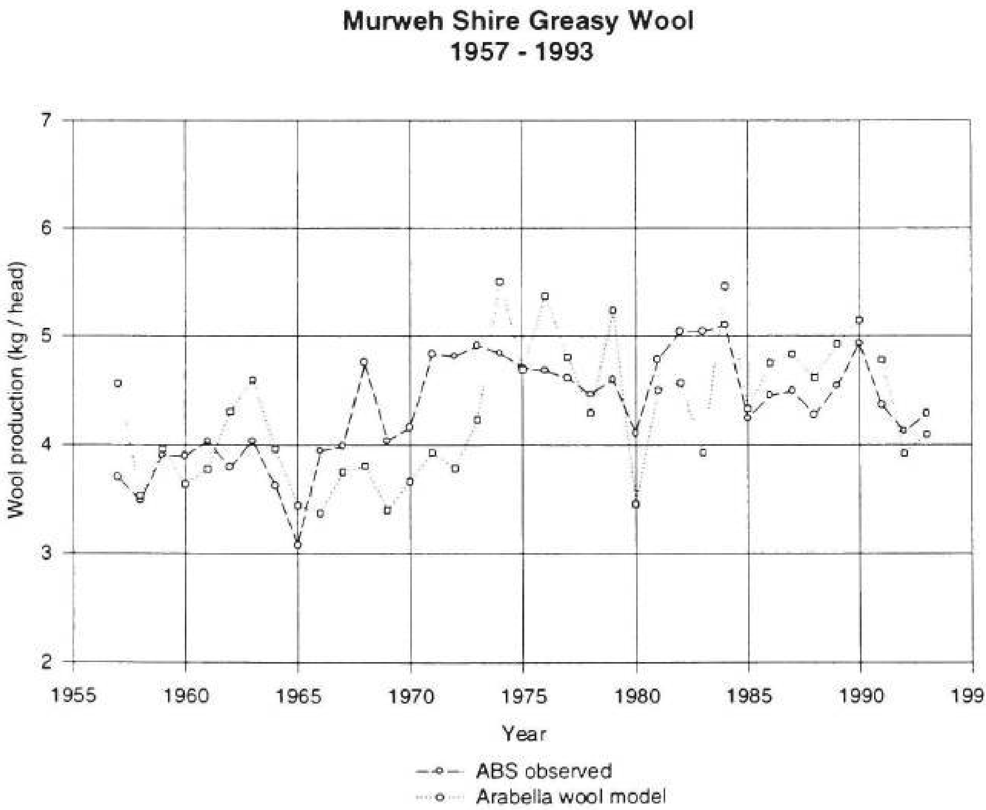


Figure A4.4. Predicted and observed fleece weights for selected mulga shires using Arabella and TBA wool models.





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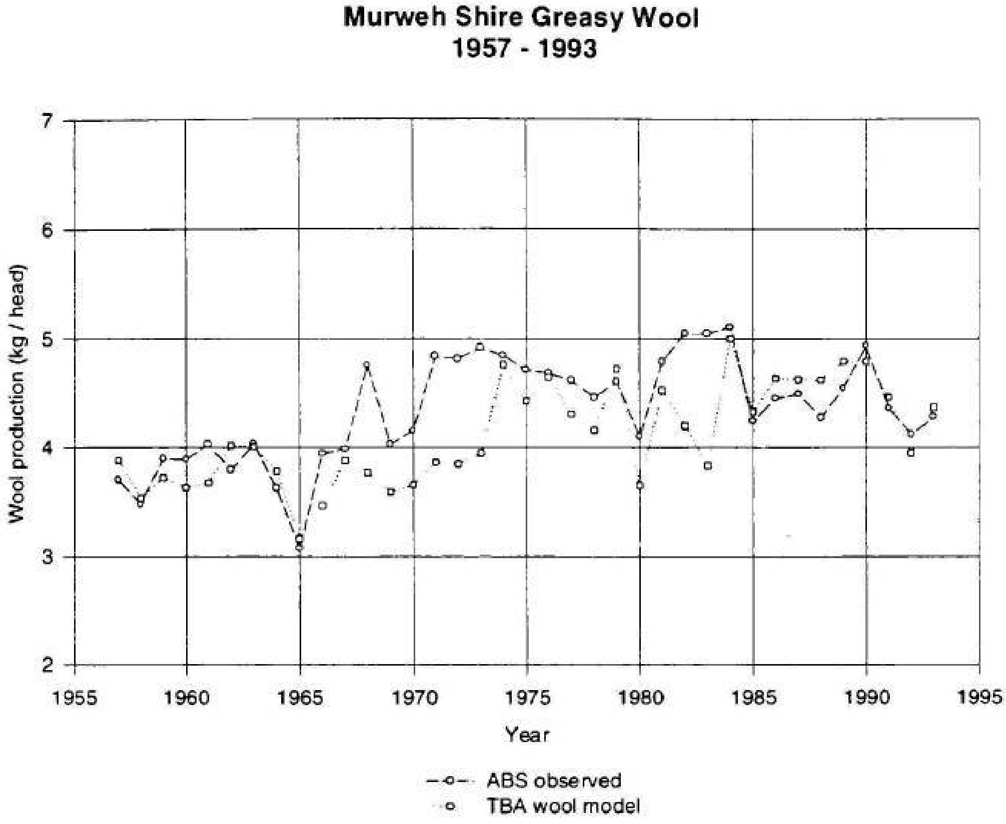

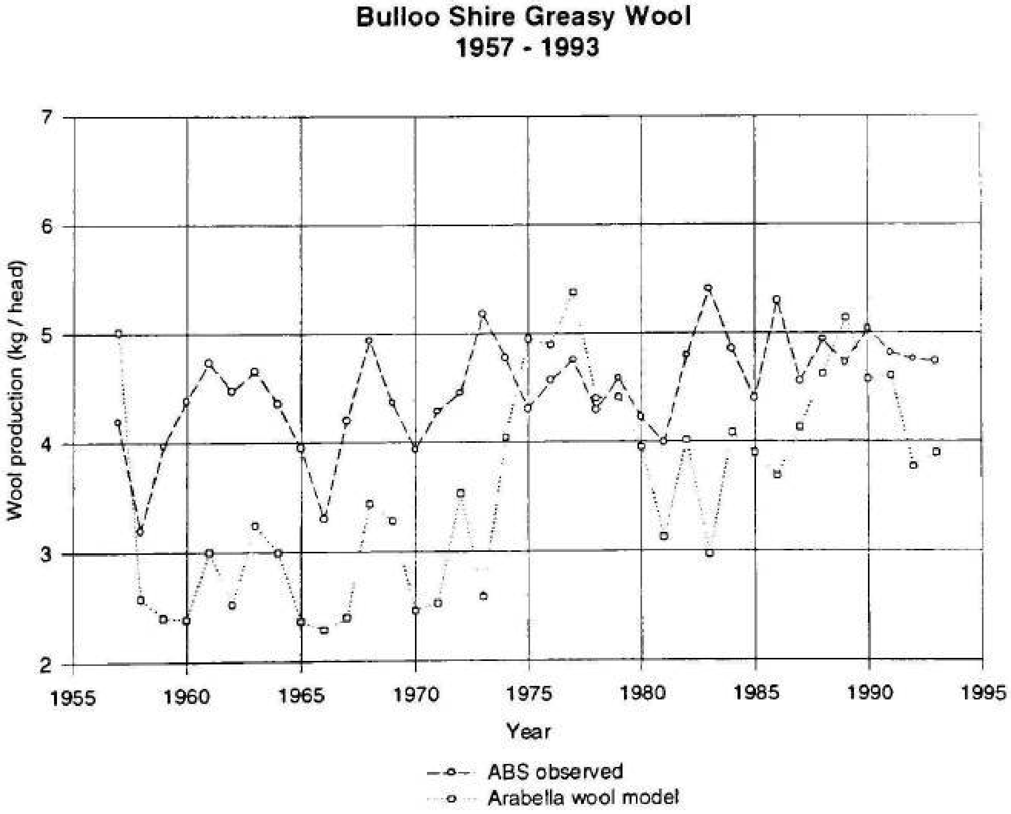

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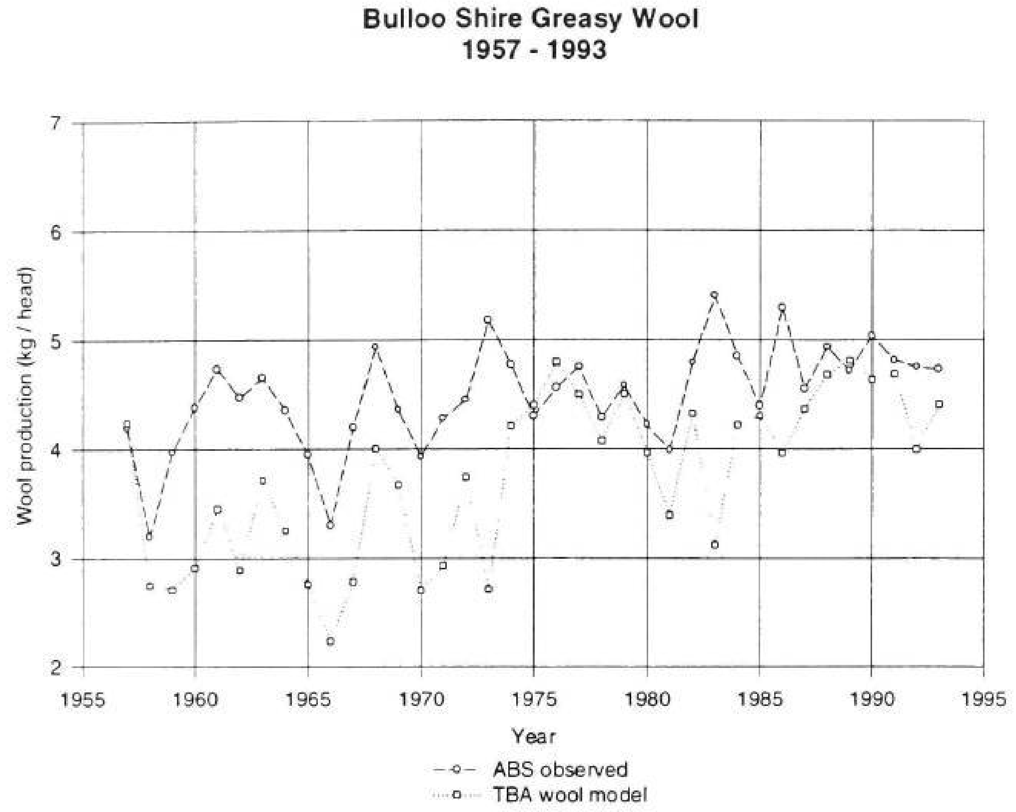

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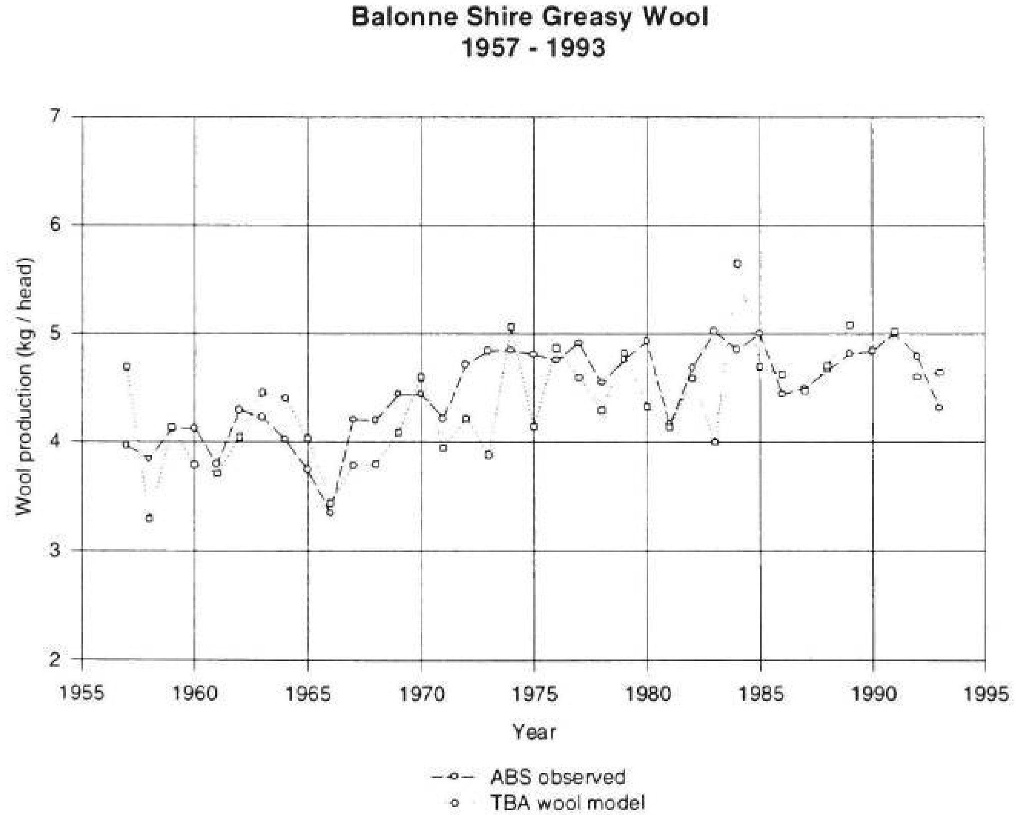
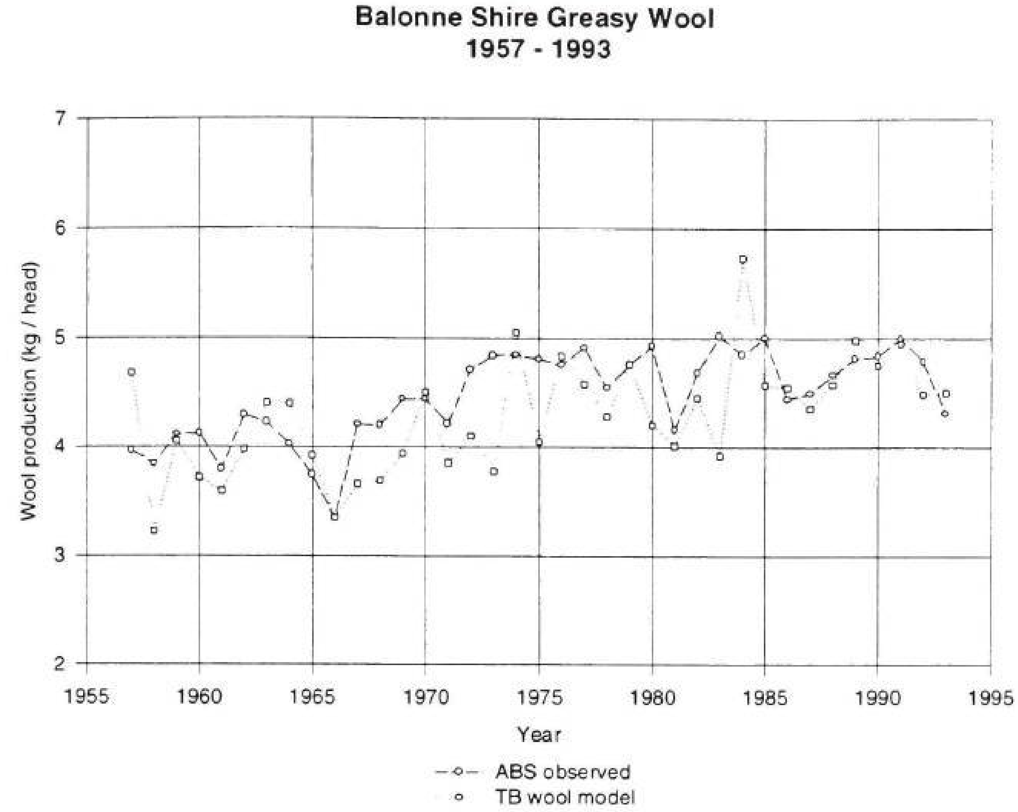
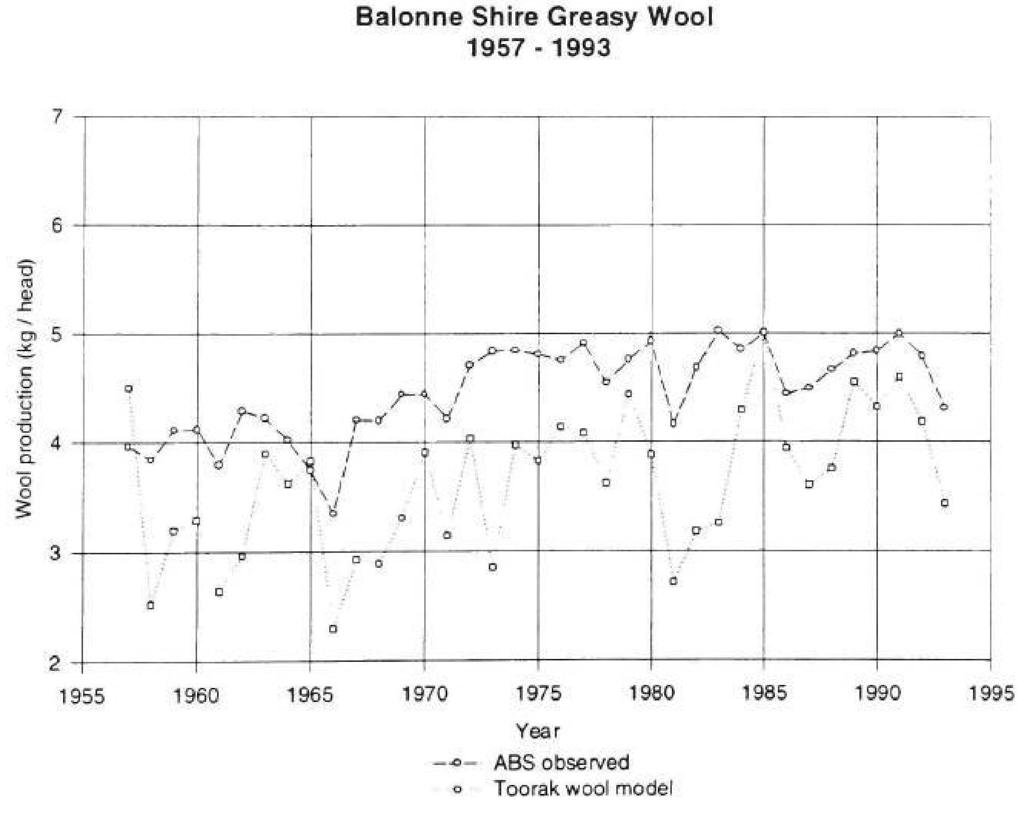


Figure A4.5. Predicted and observed fleece weights for selected Mitchell grass shires using TBA, TB and Toorak wool models.





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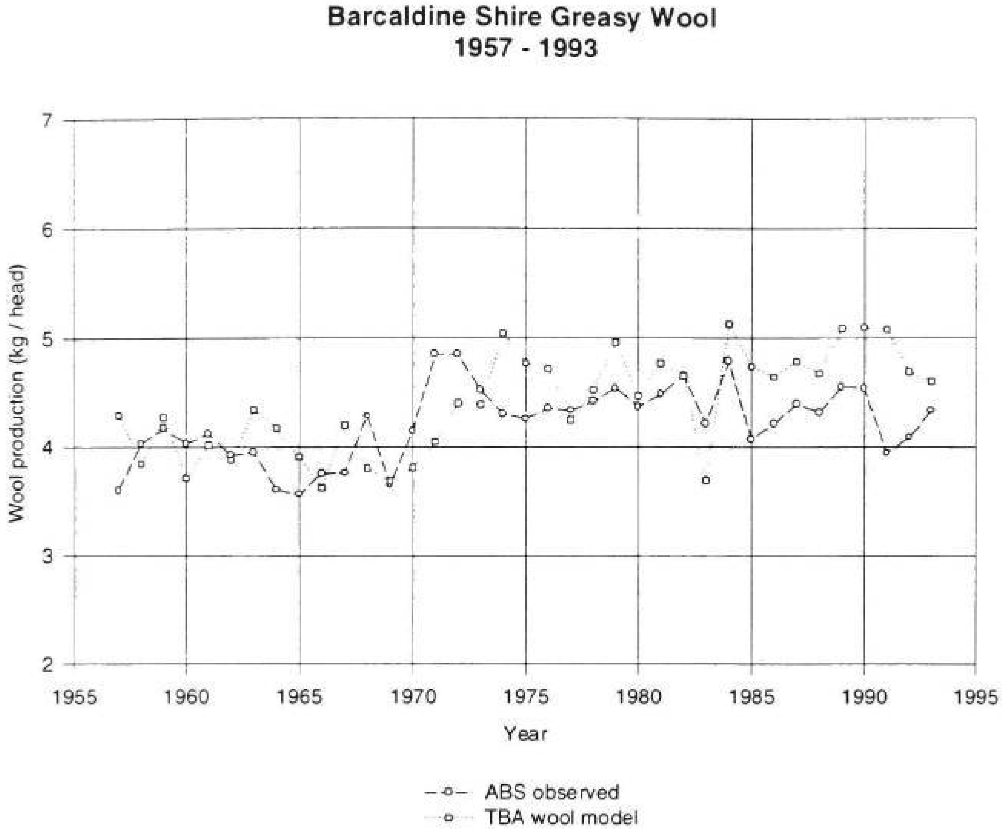


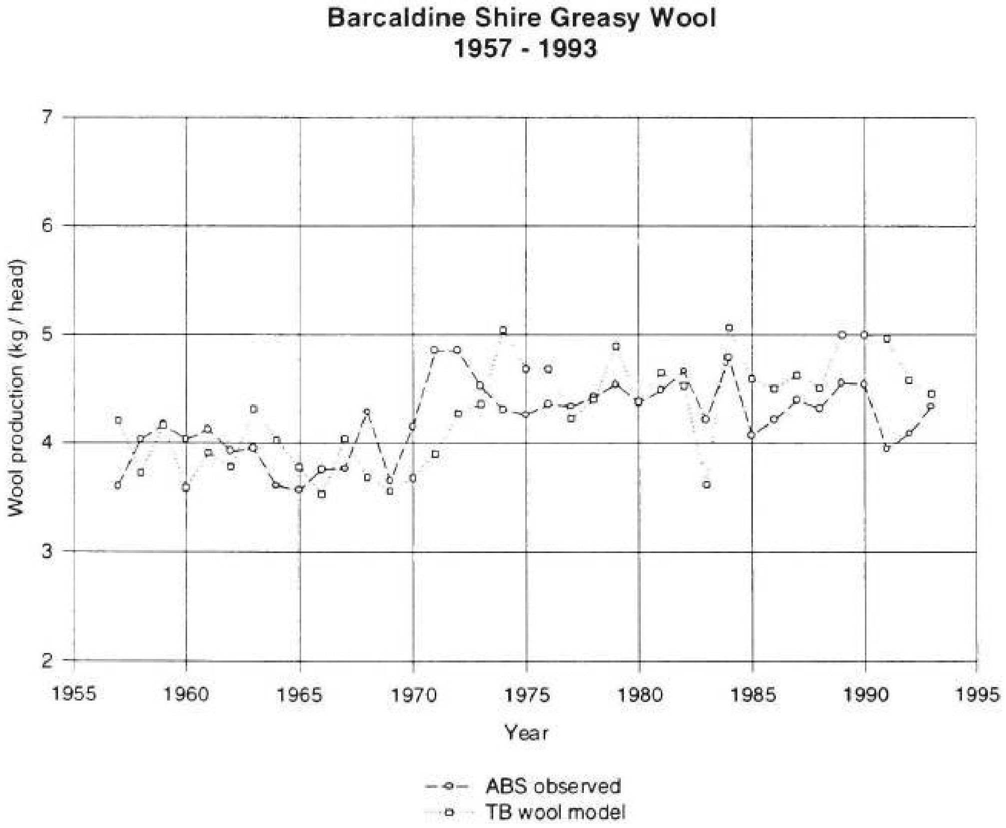
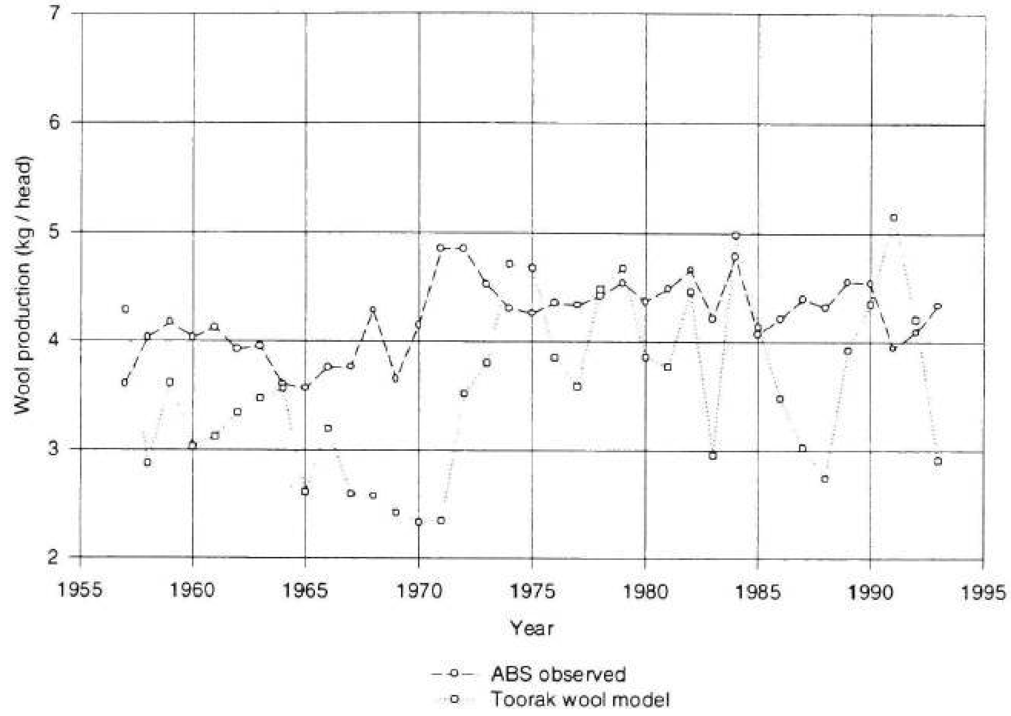
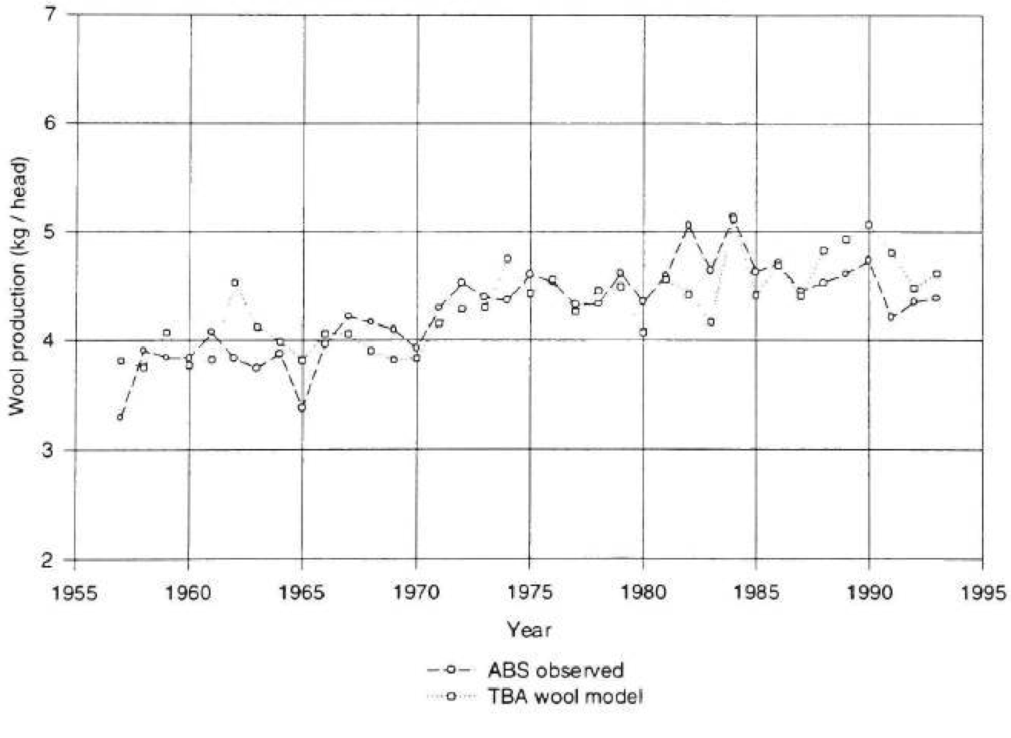


Figure A4.5 continued.

Barcaldine Shire Greasy Wool
1957 - 1993



Bungil Shire Greasy Wool
1957 - 1993



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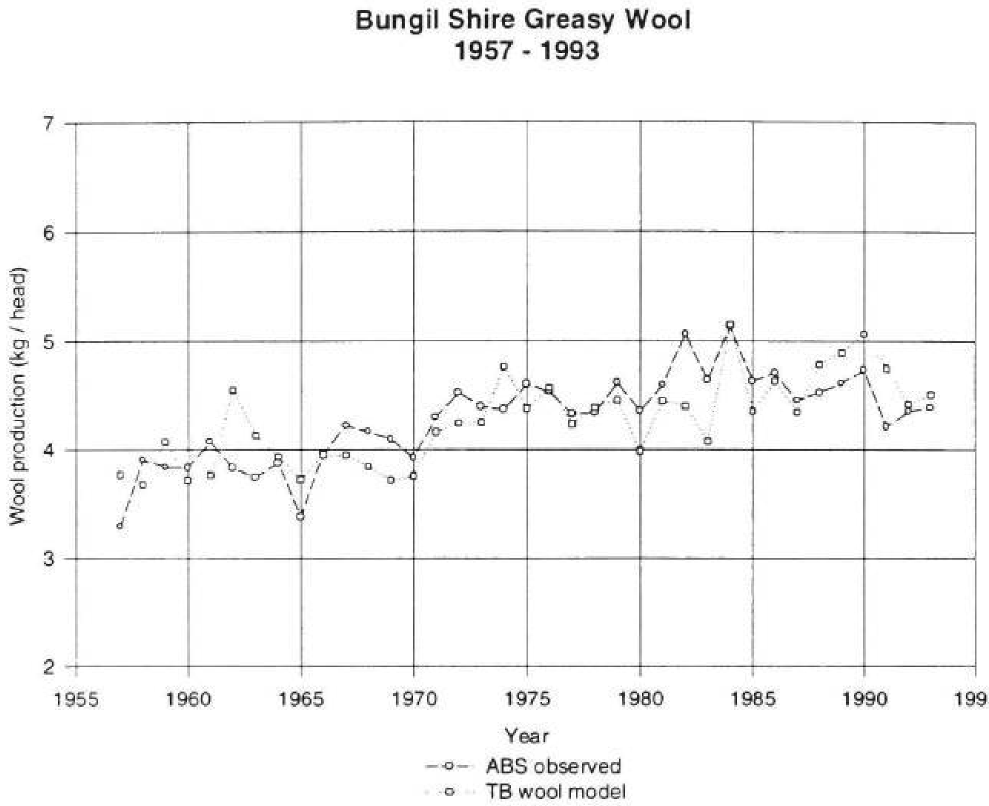

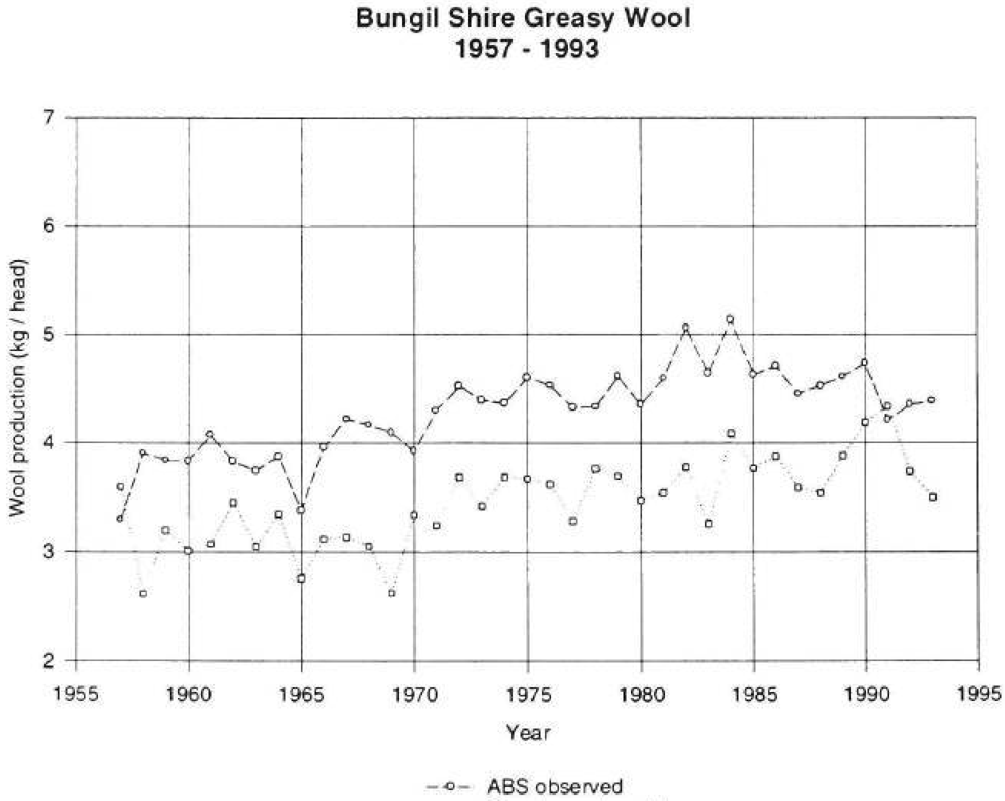

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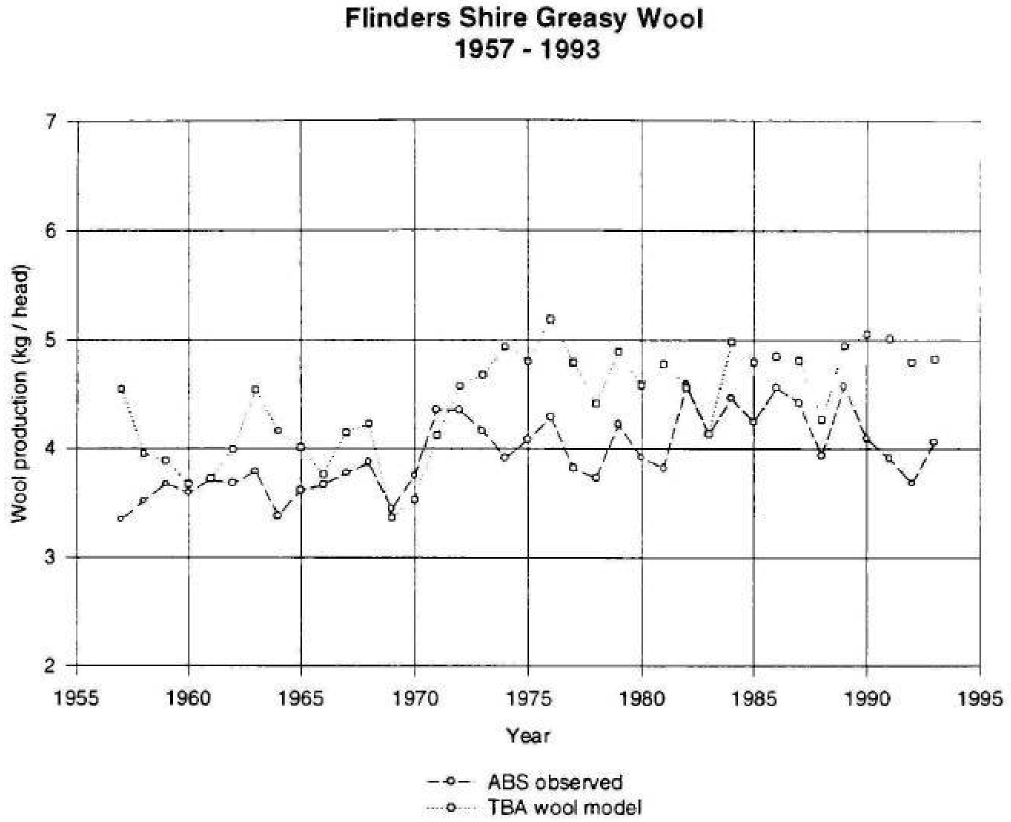
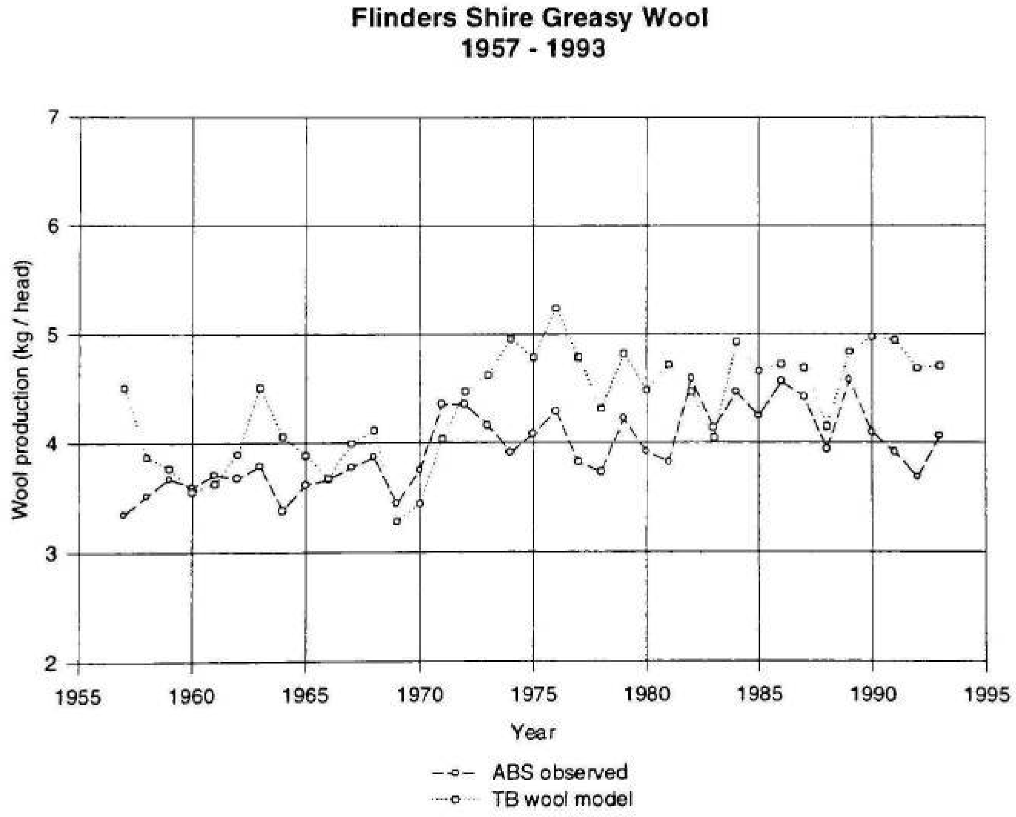
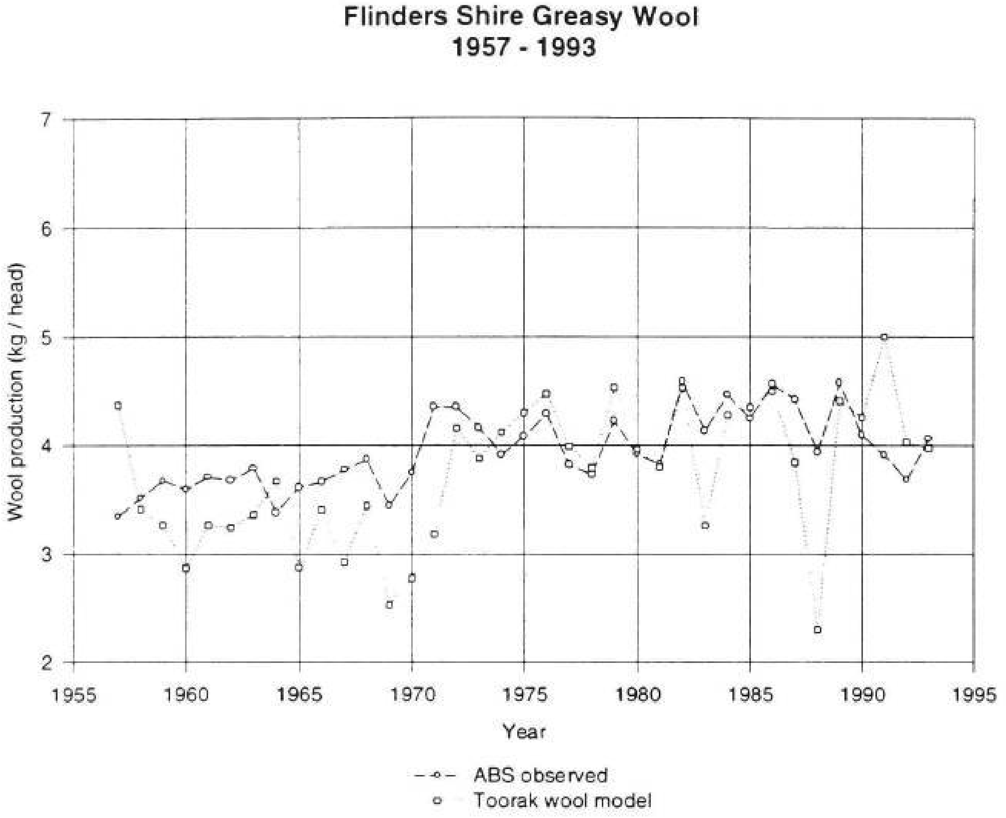


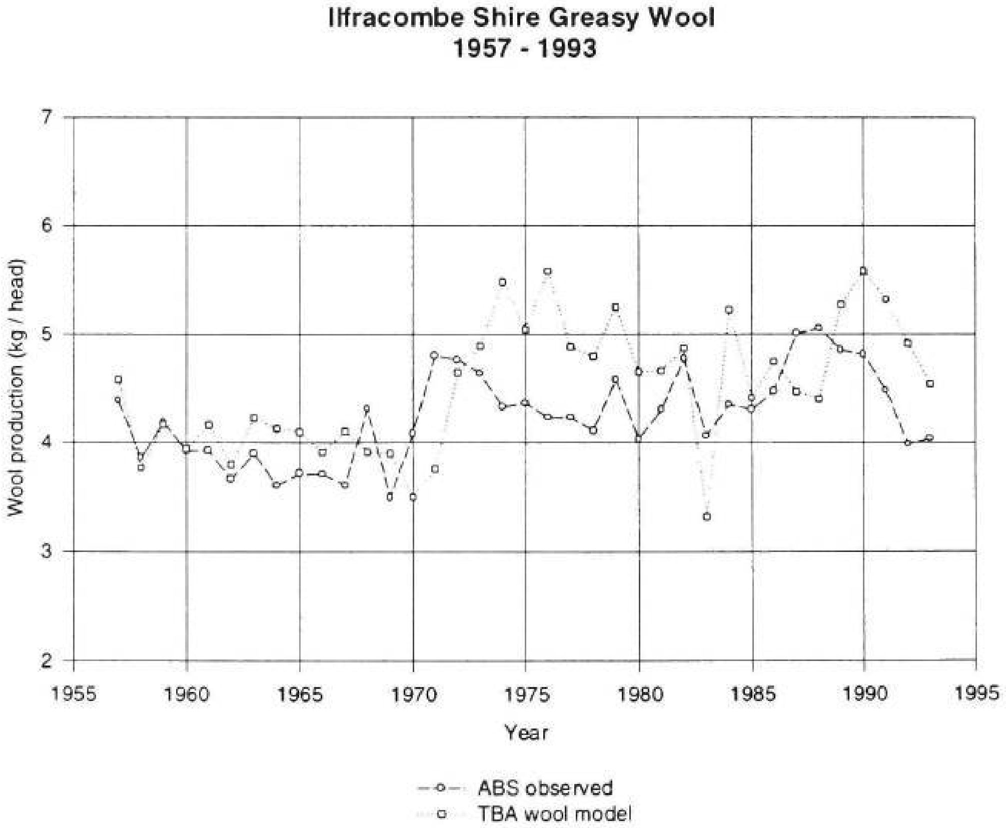
Flinders Shire Greasy Wool
1957 - 1993



Flinders Shire Greasy Wool
1957 - 1993

Figure A4.5 continued.





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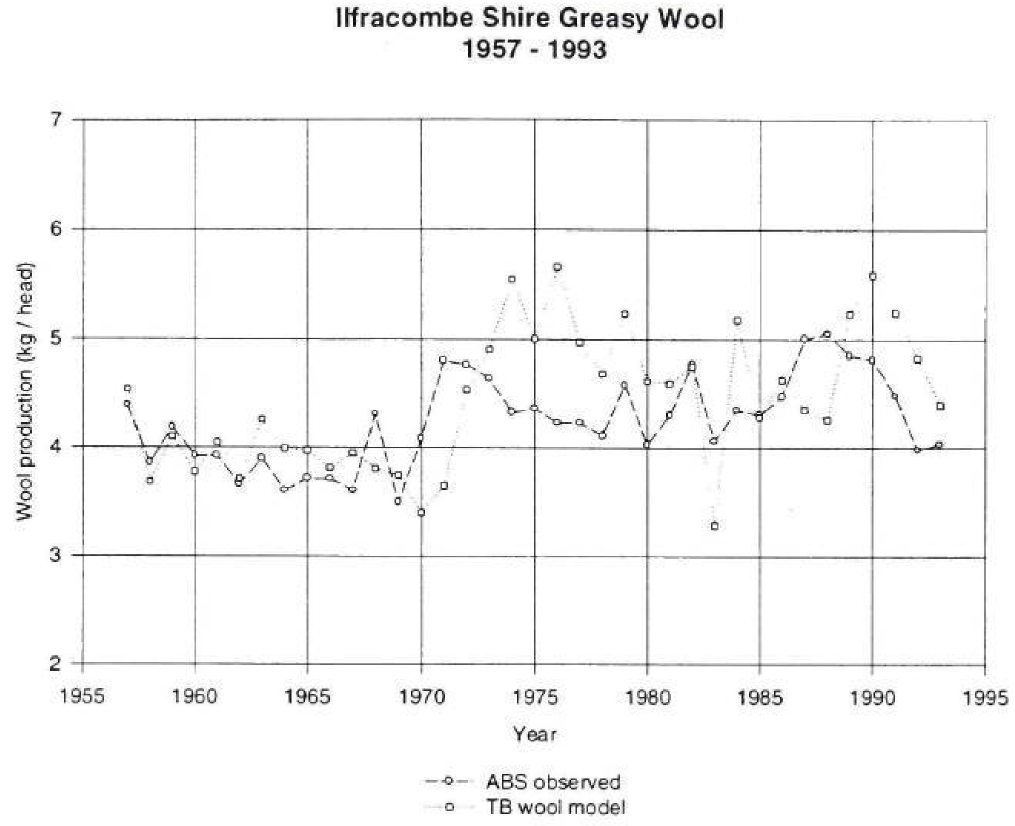

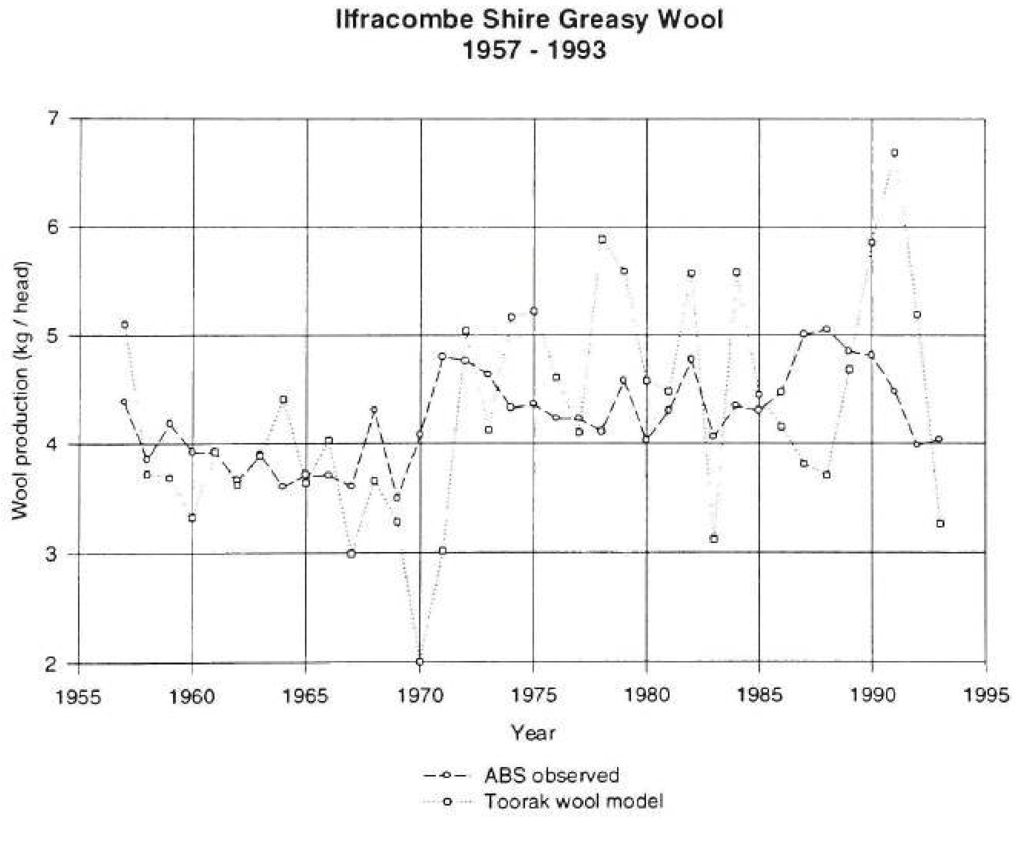

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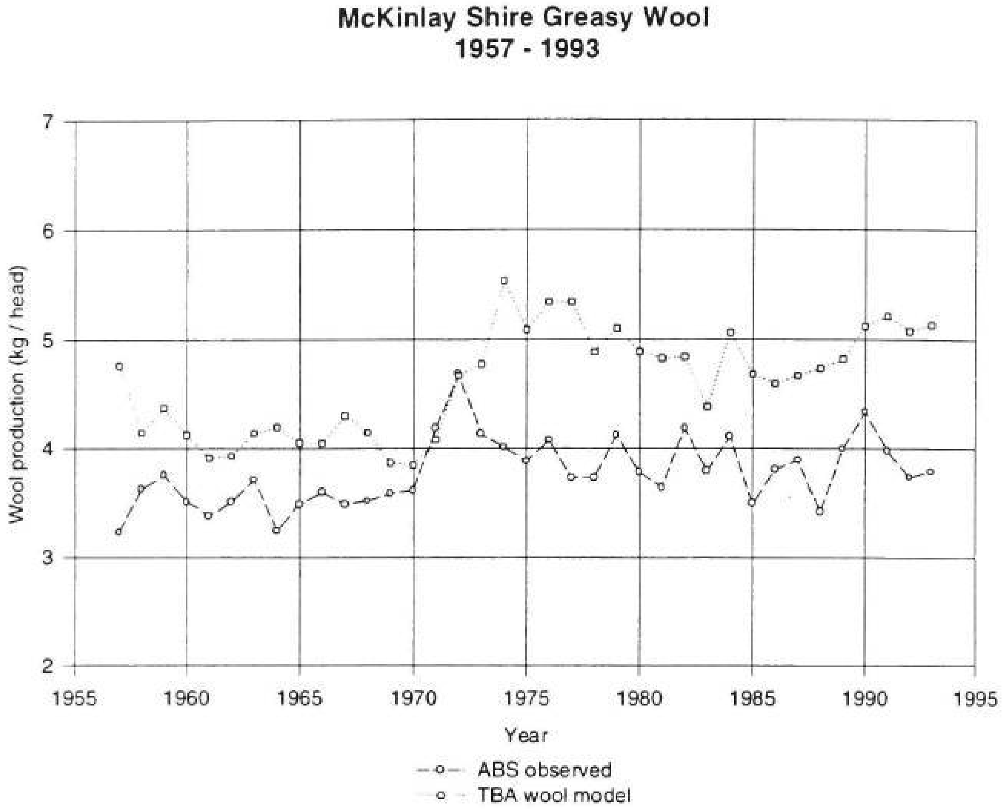

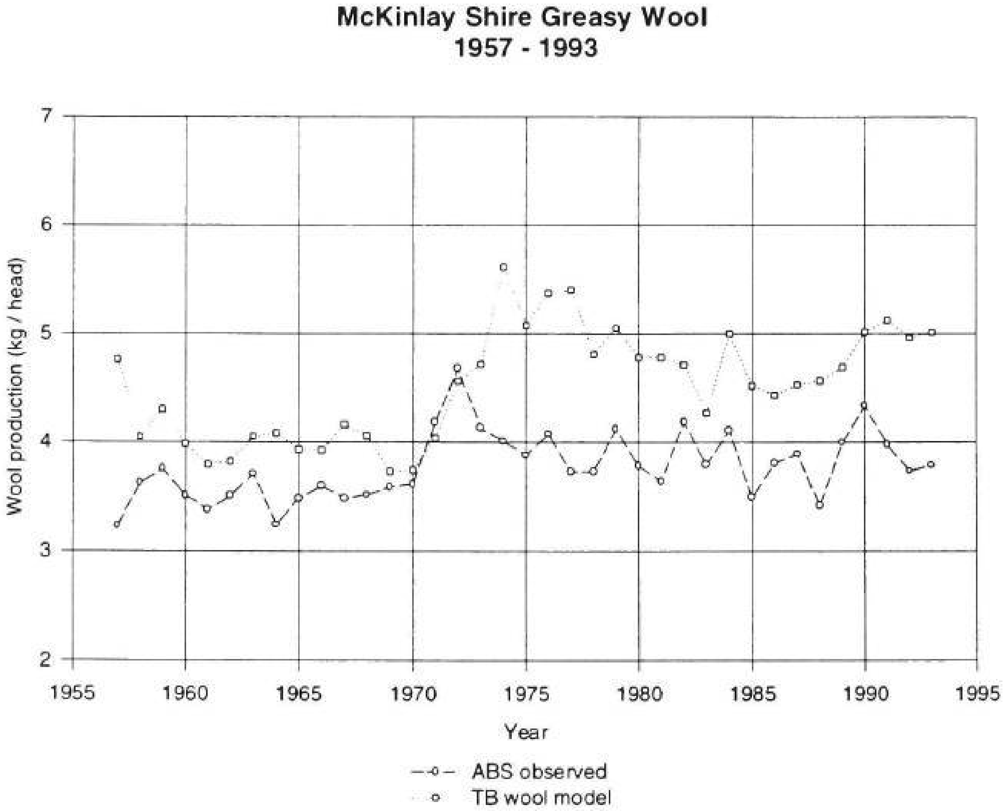

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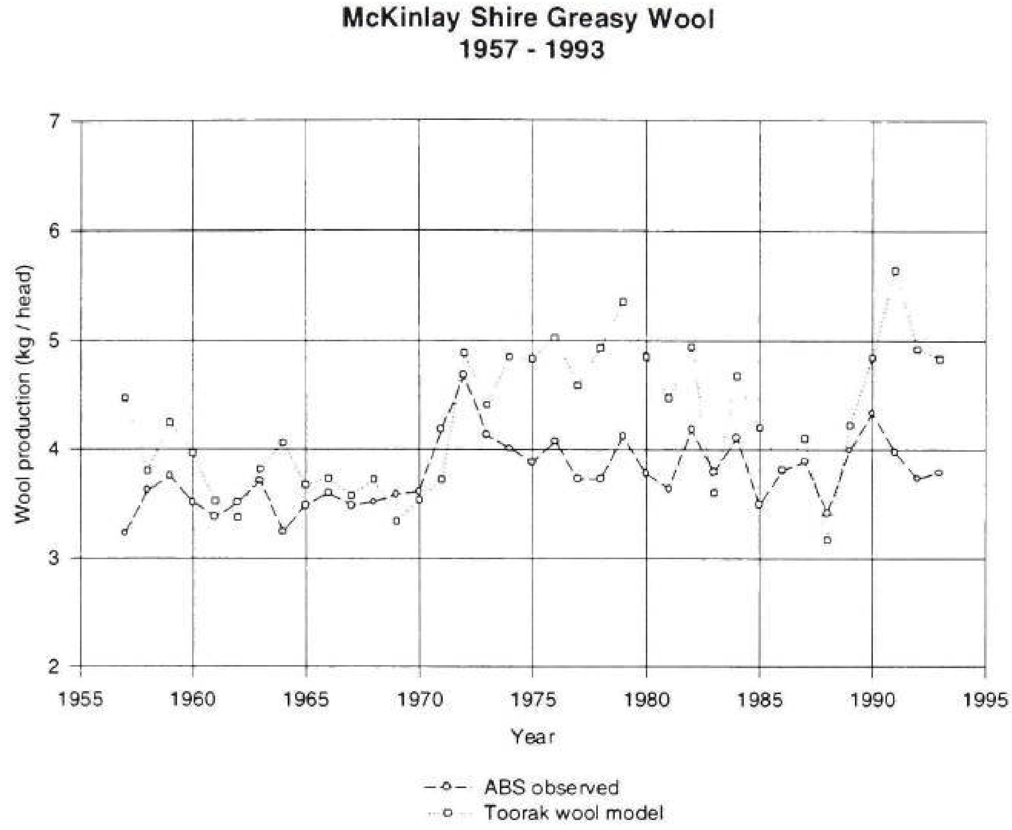

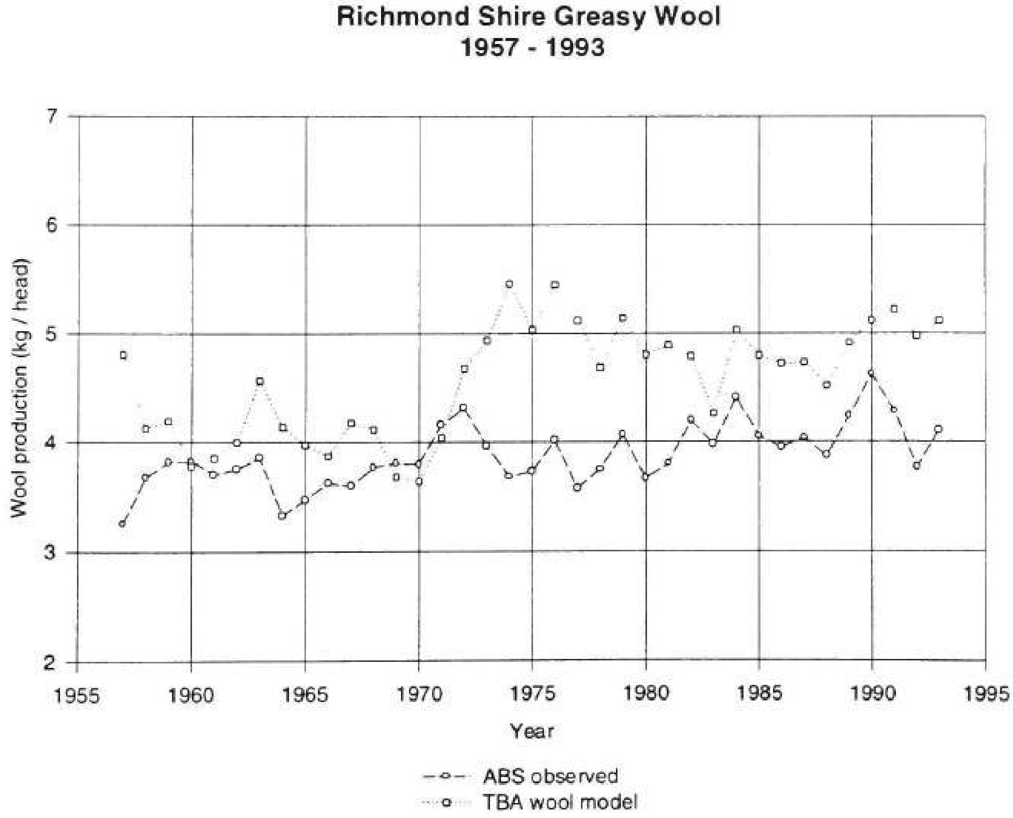

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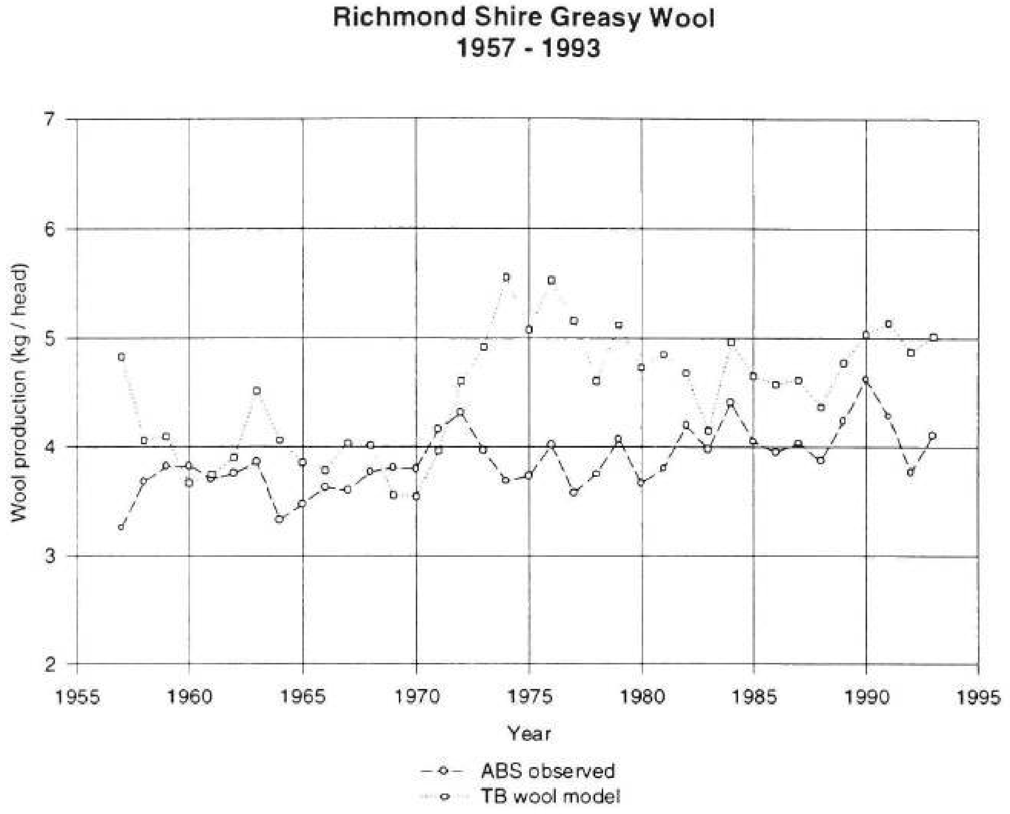

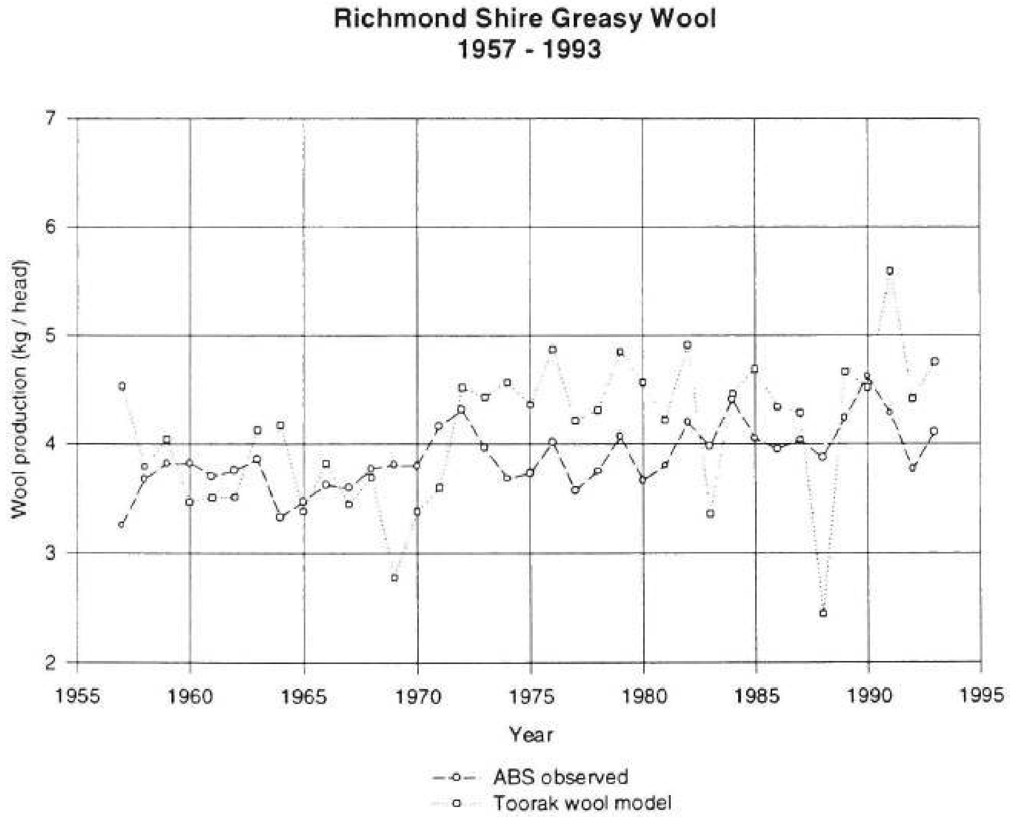

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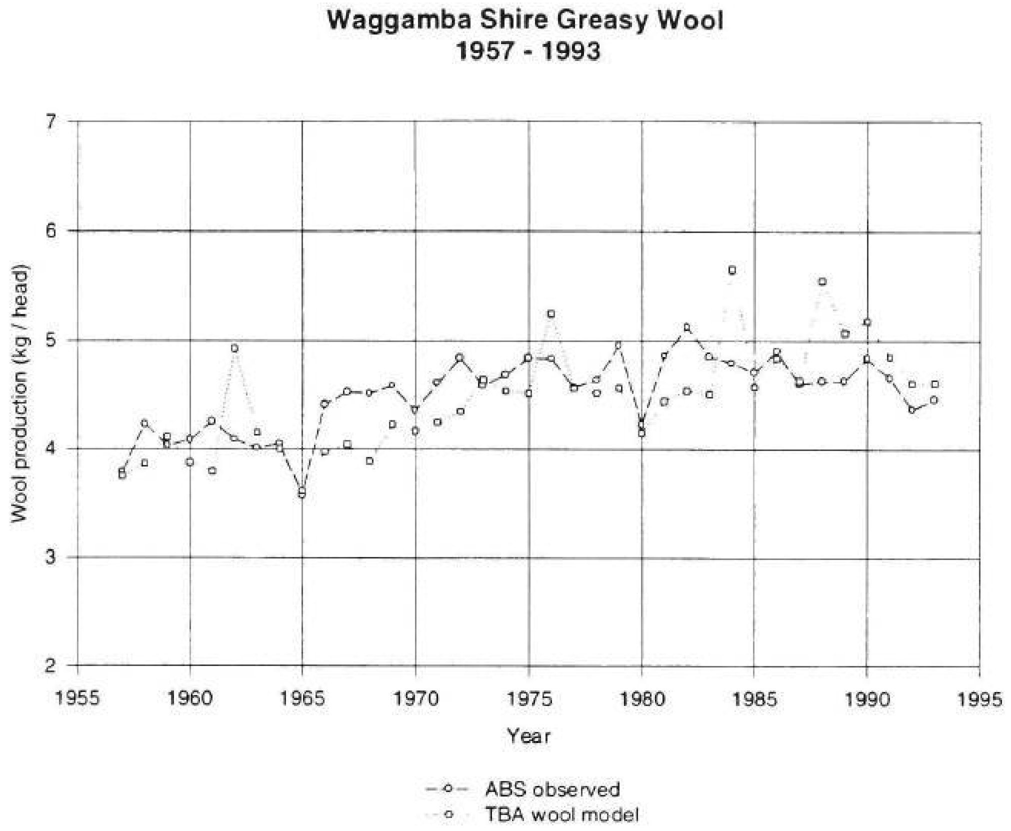

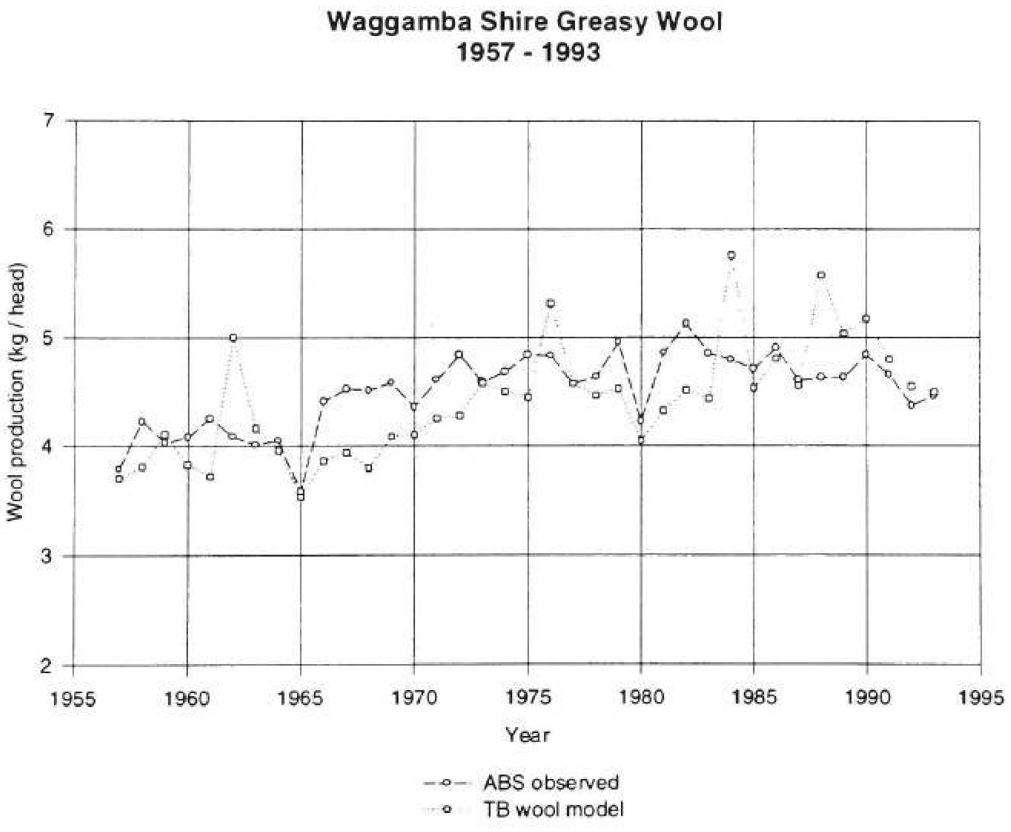

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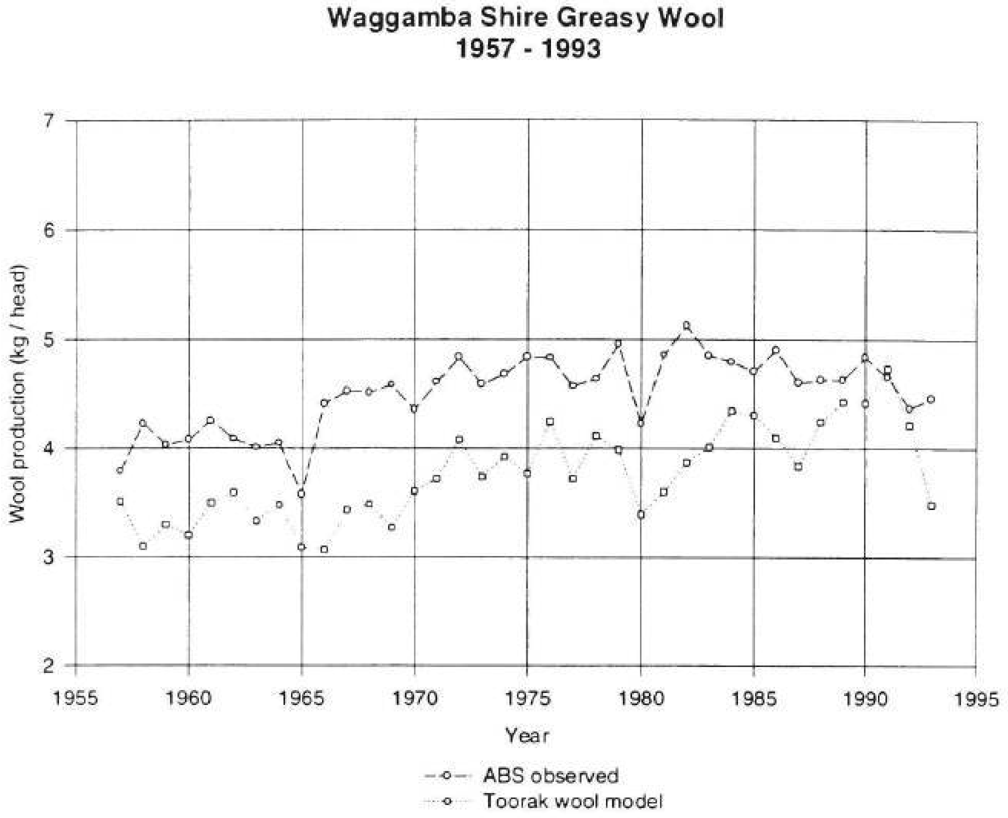

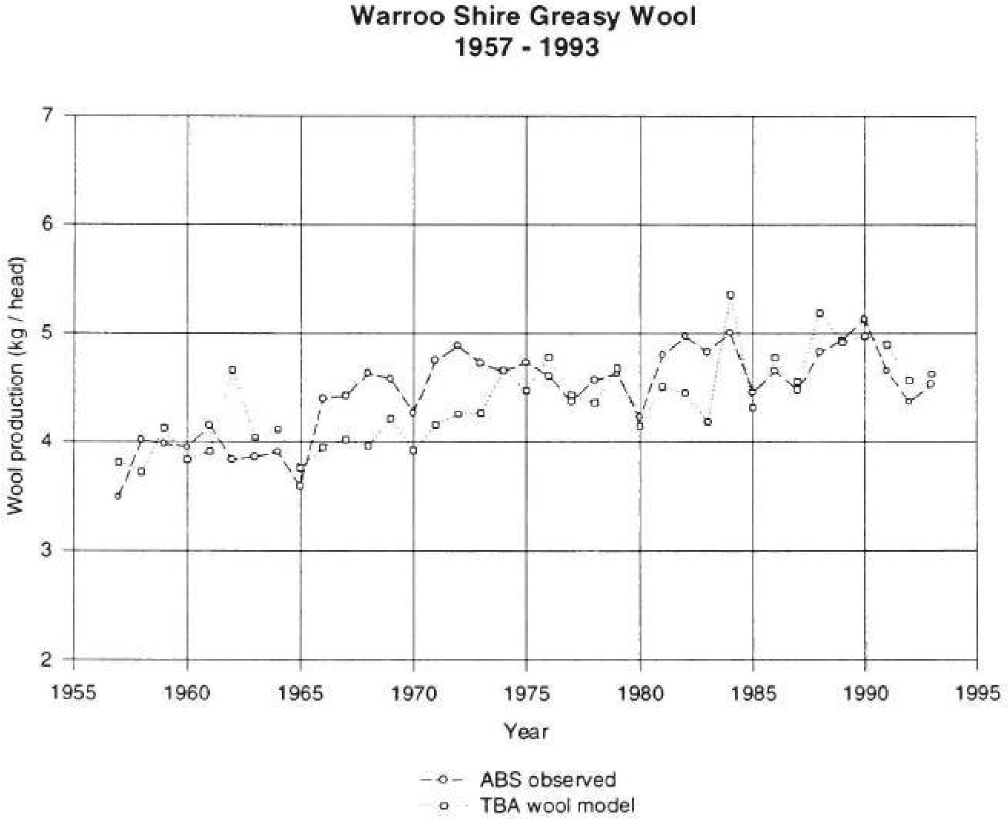

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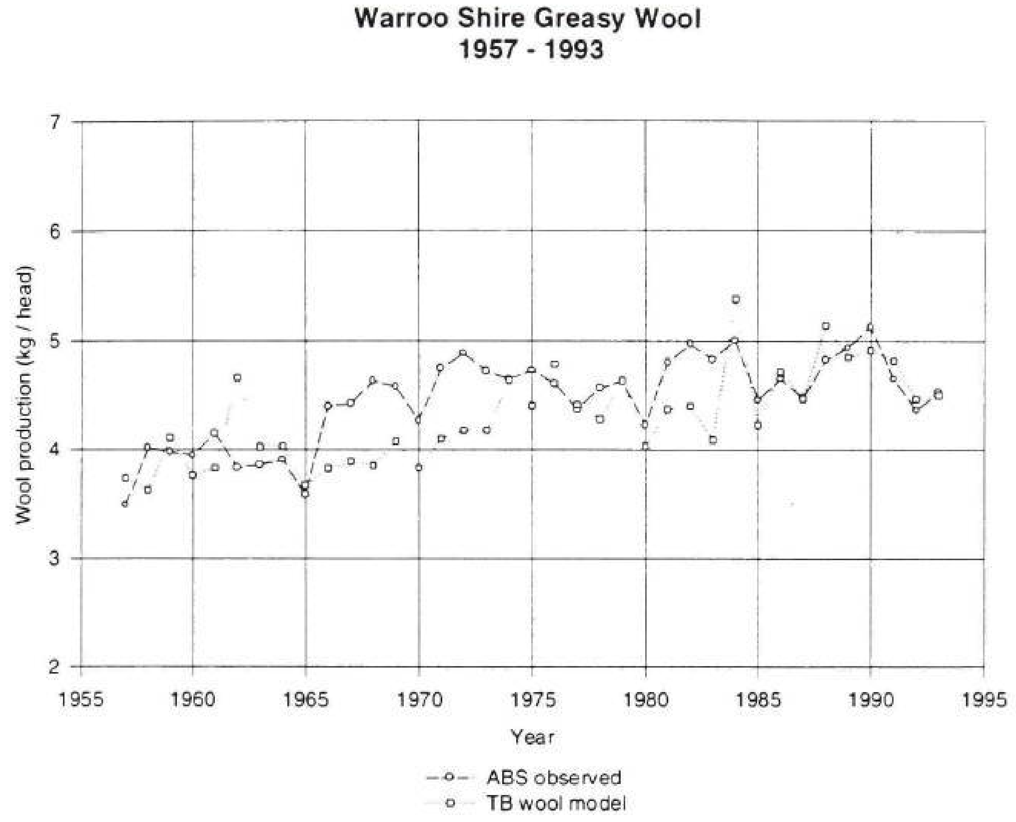

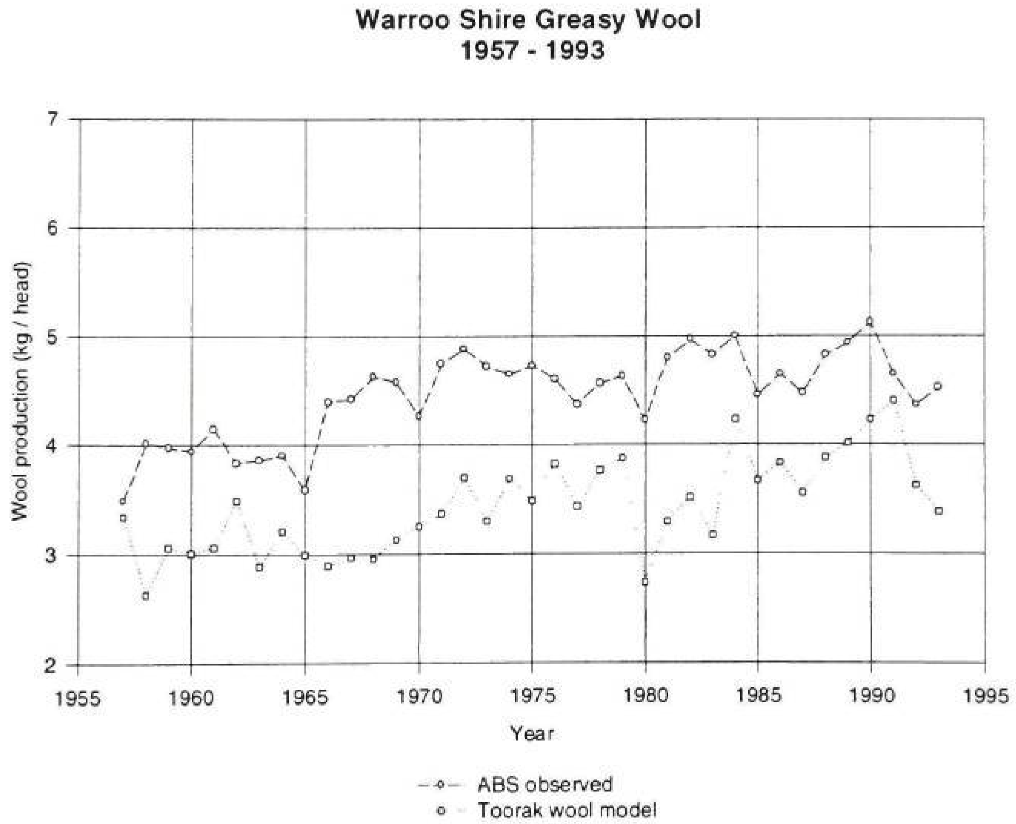

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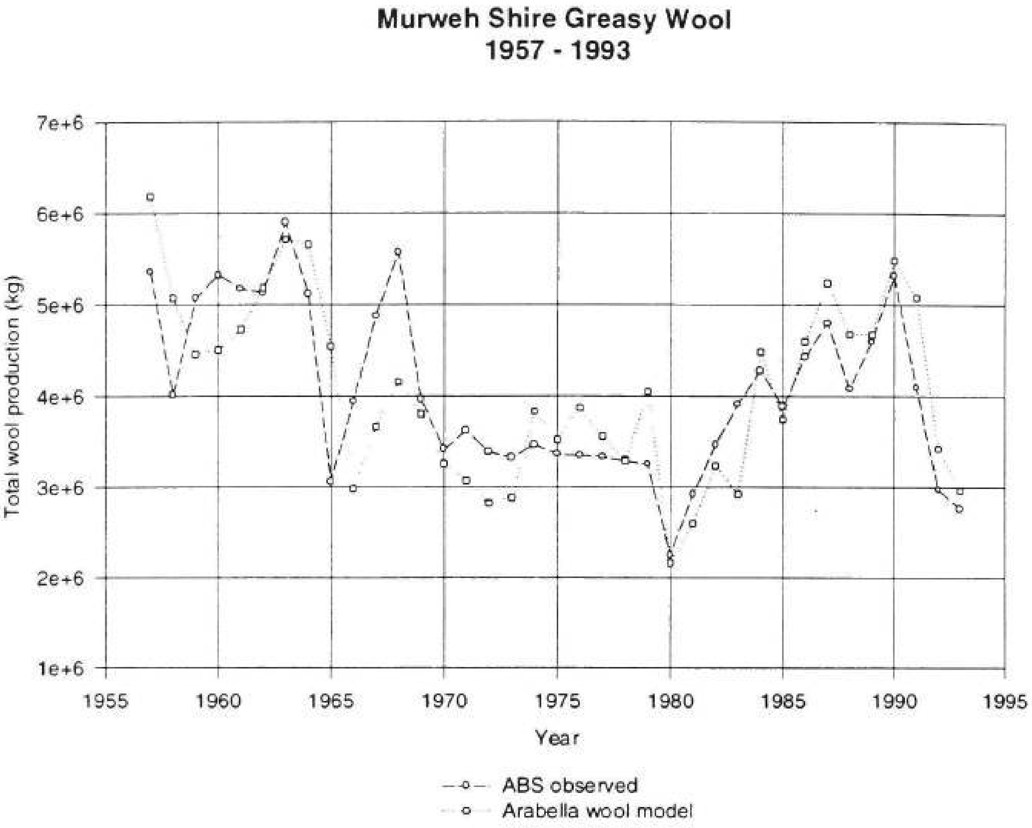


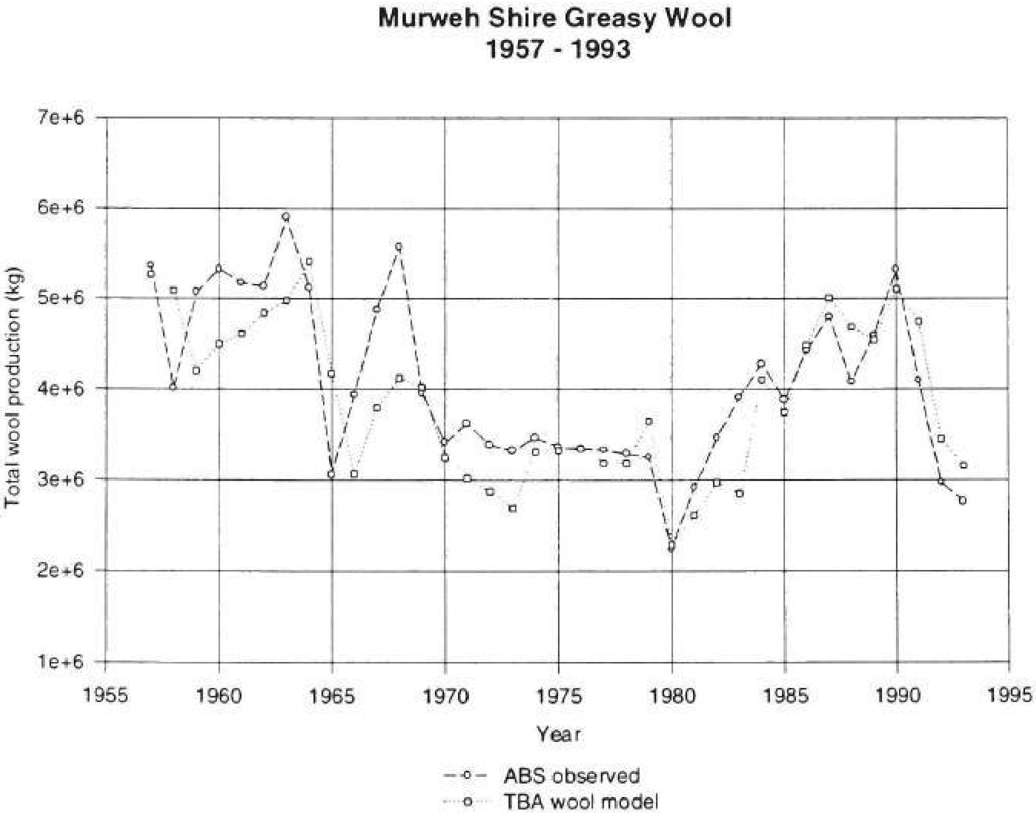
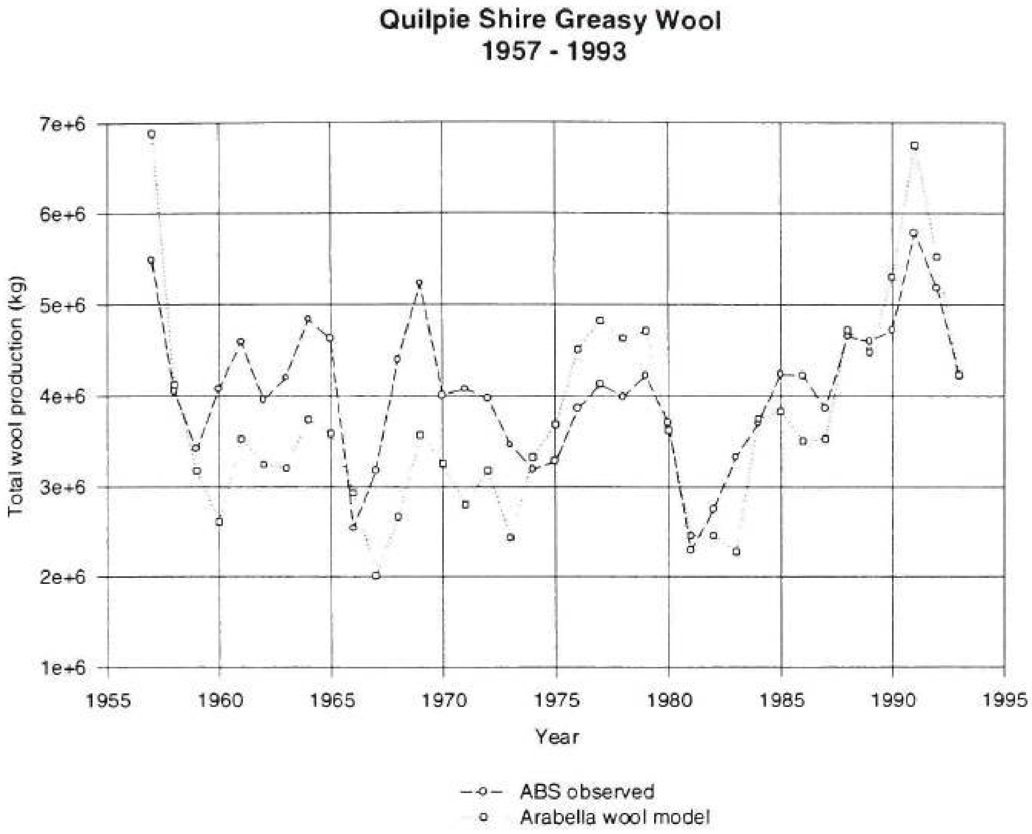
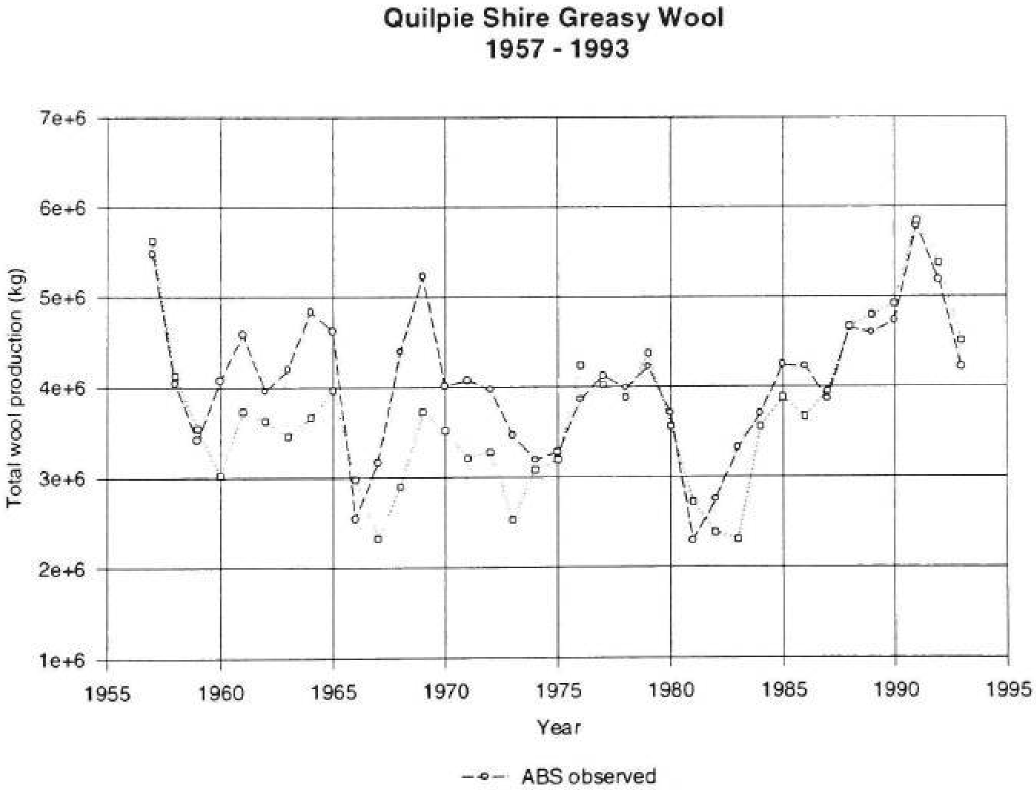


Figure A4.6. Predicted and observed total greasy wool production for selected mulga shires using Arabella and TBA wool models.





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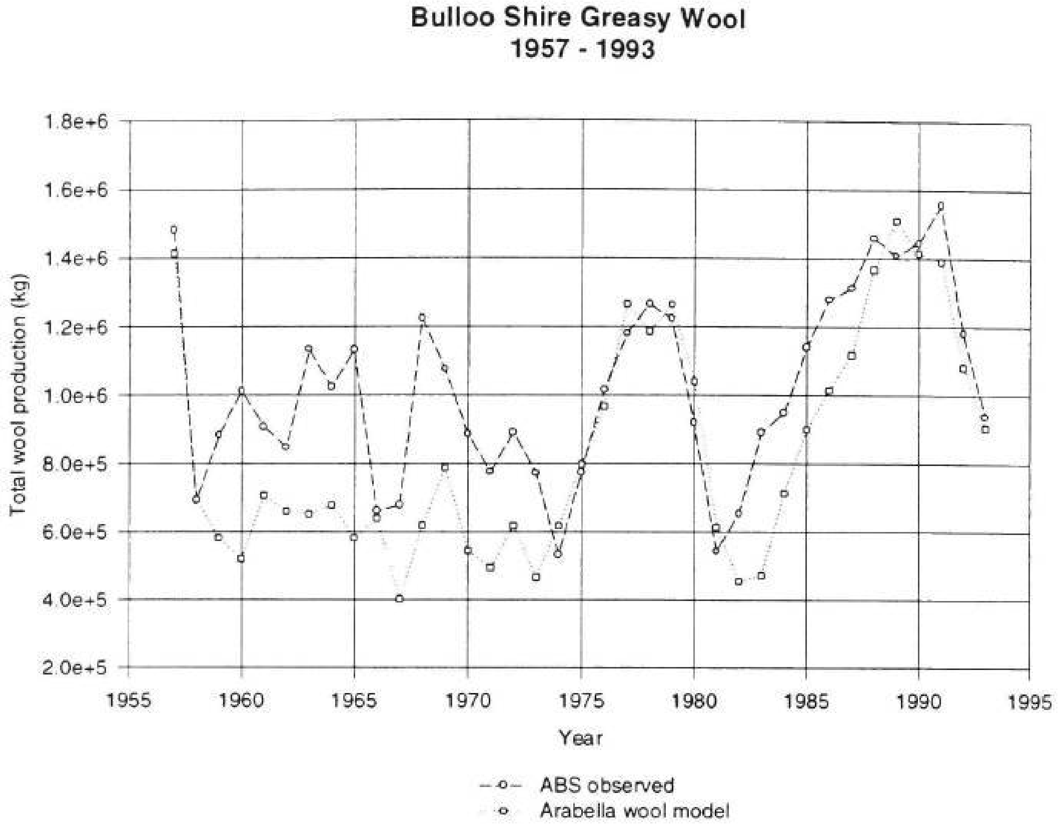

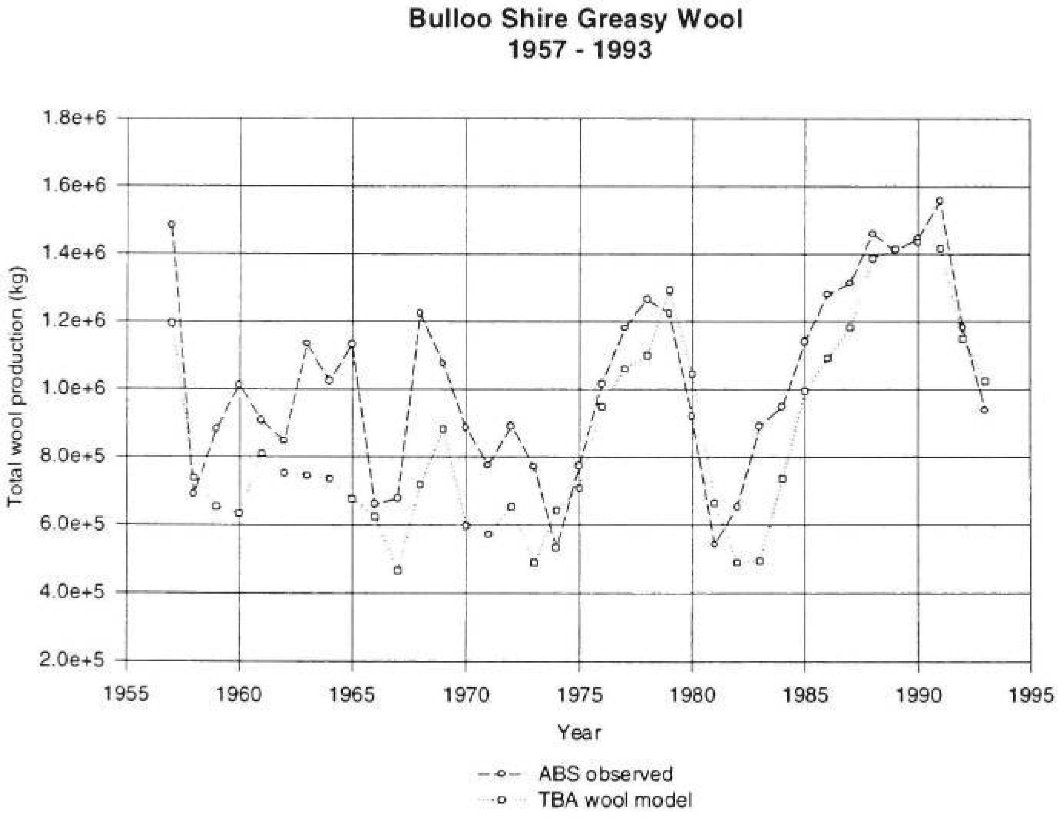

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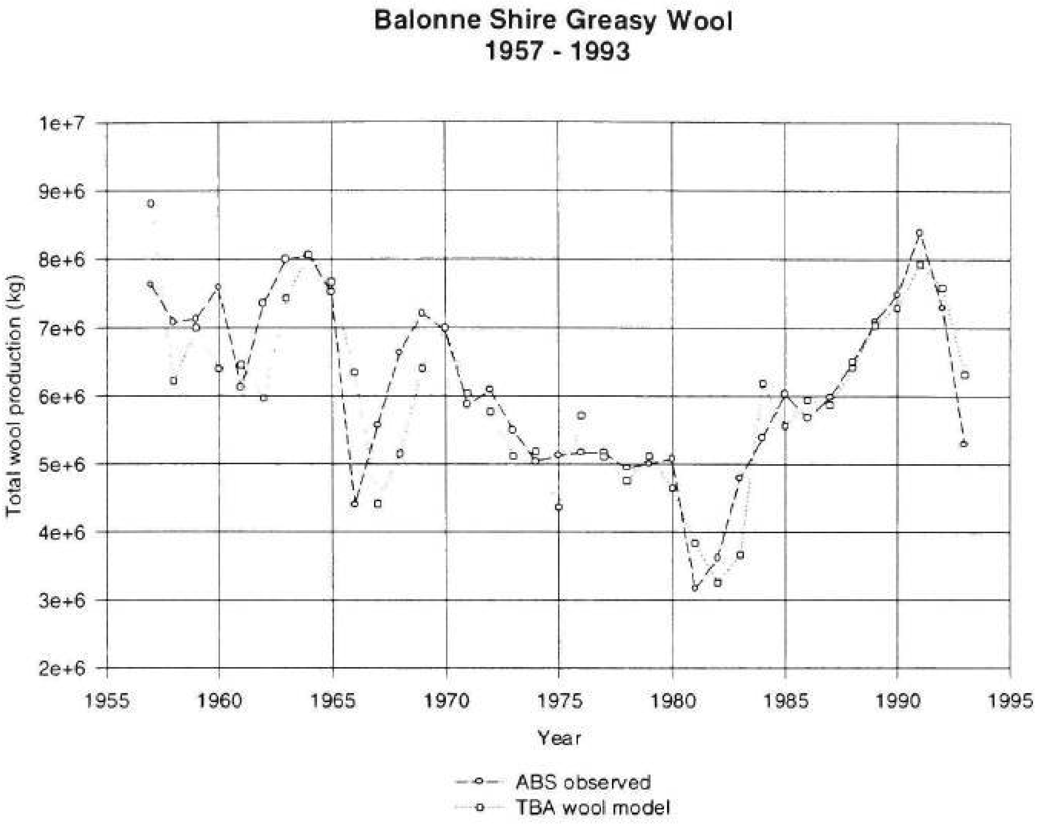


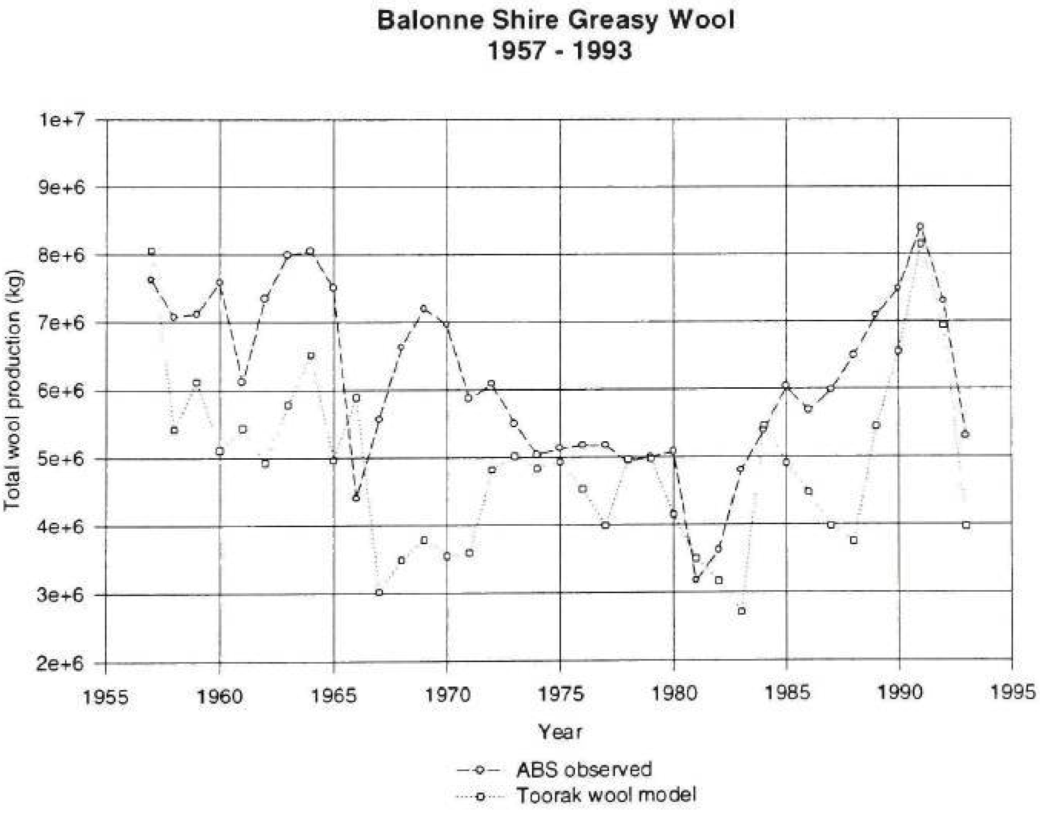
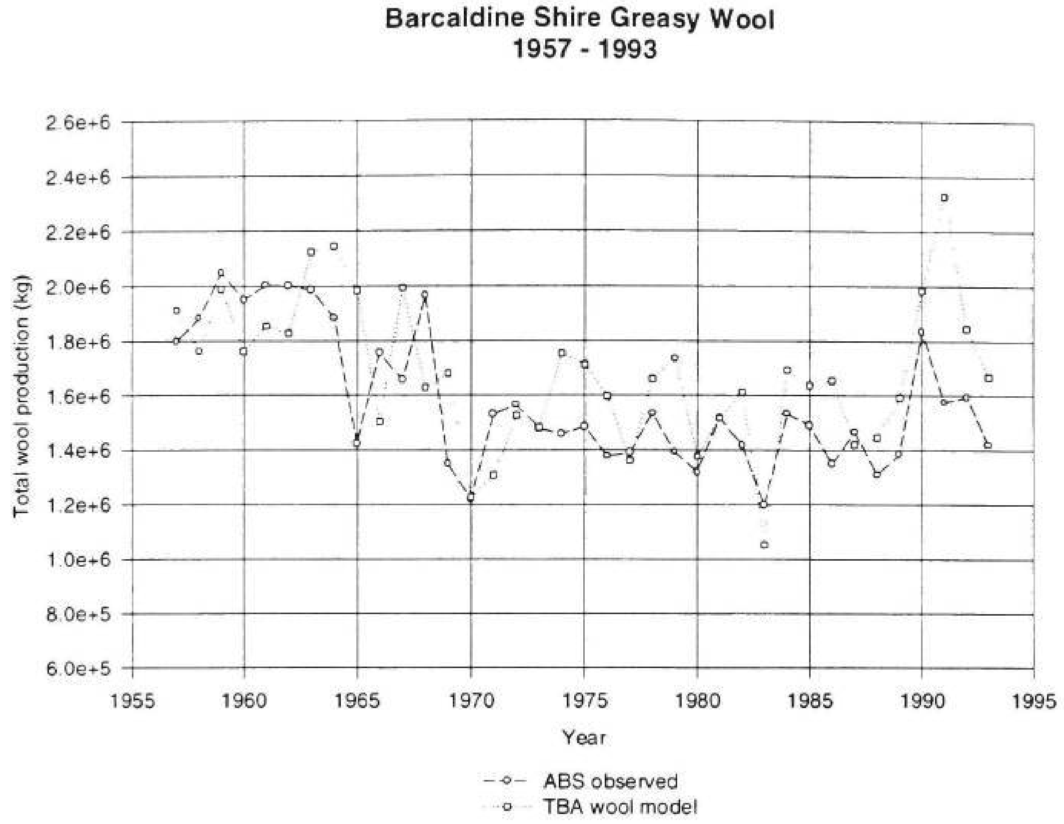
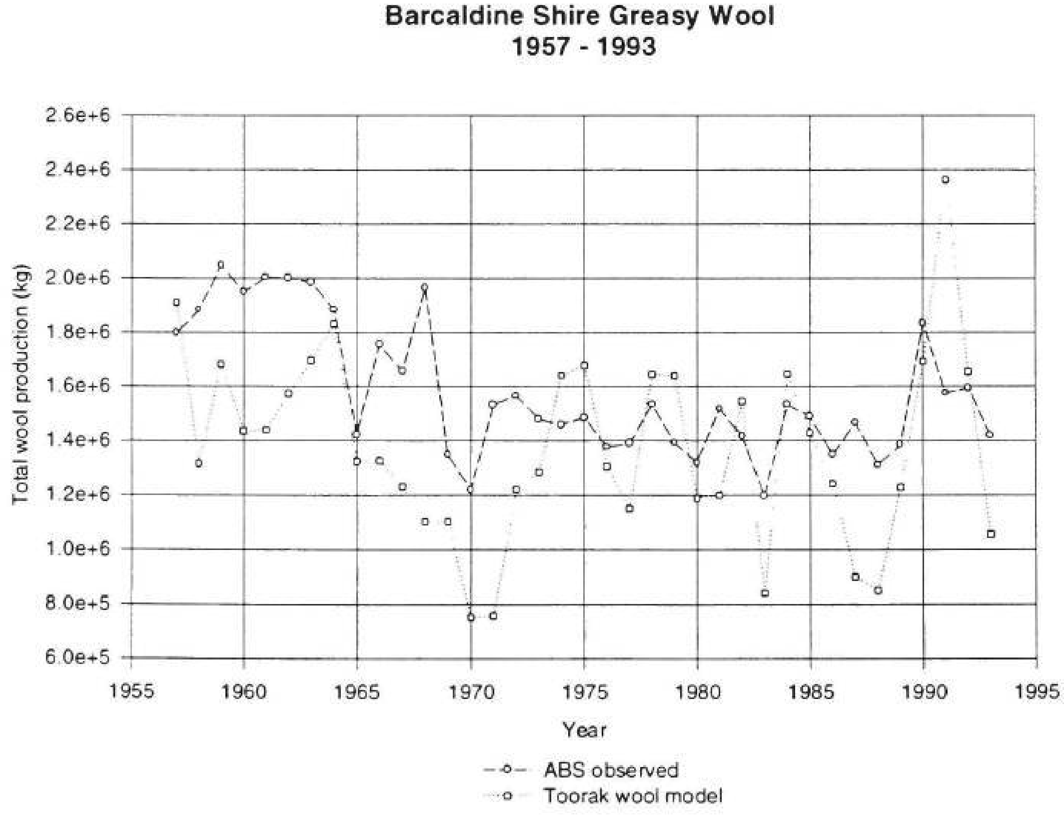


Figure A4.7. Predicted and observed total greasy wool production for selected non-mulga shires using Toorak and TBA wool models.





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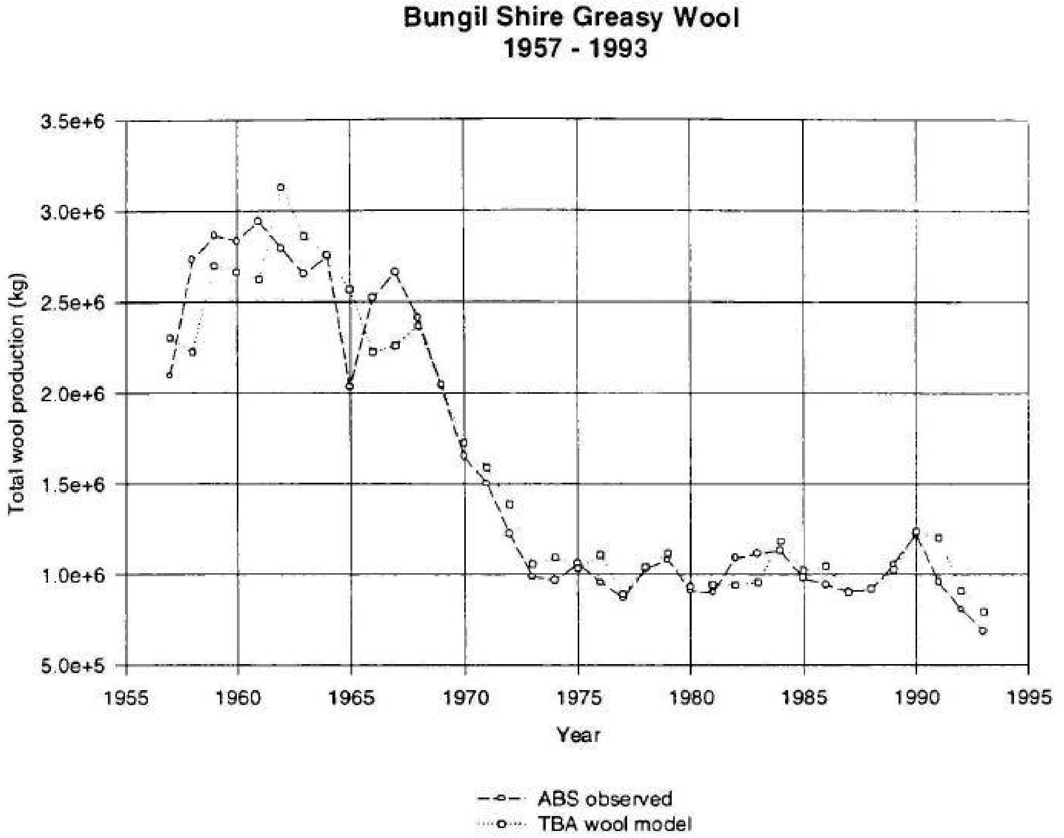

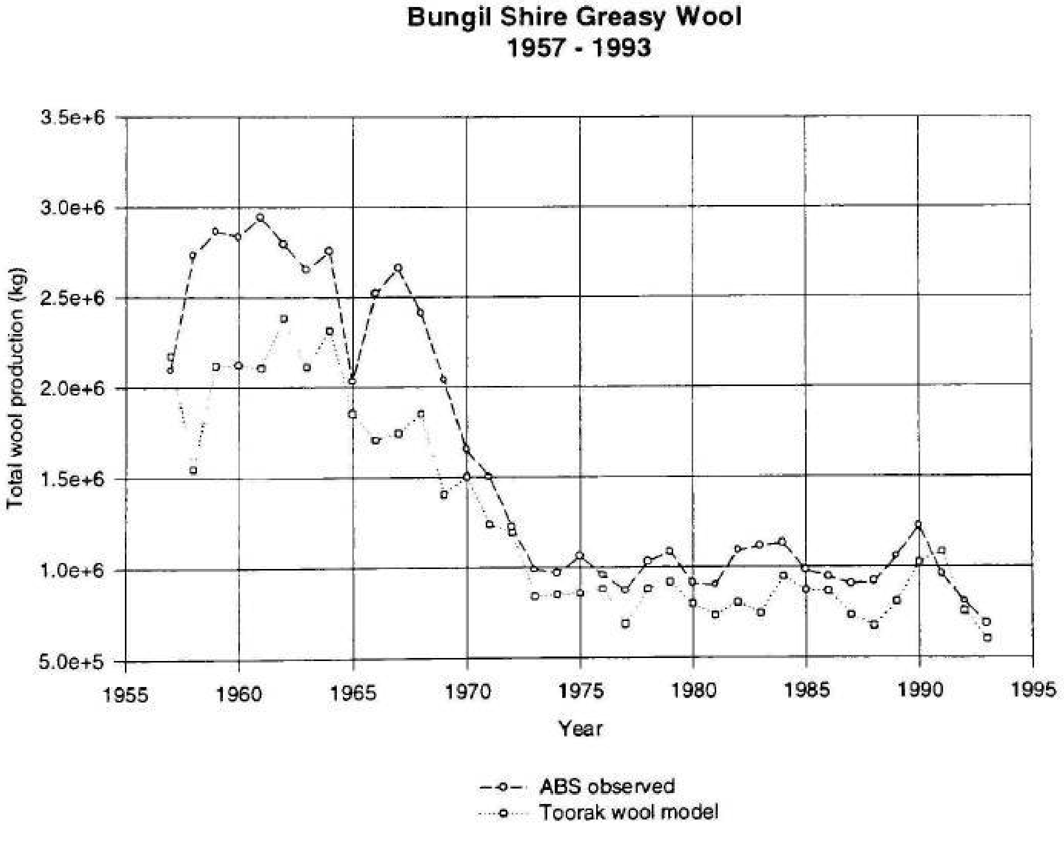

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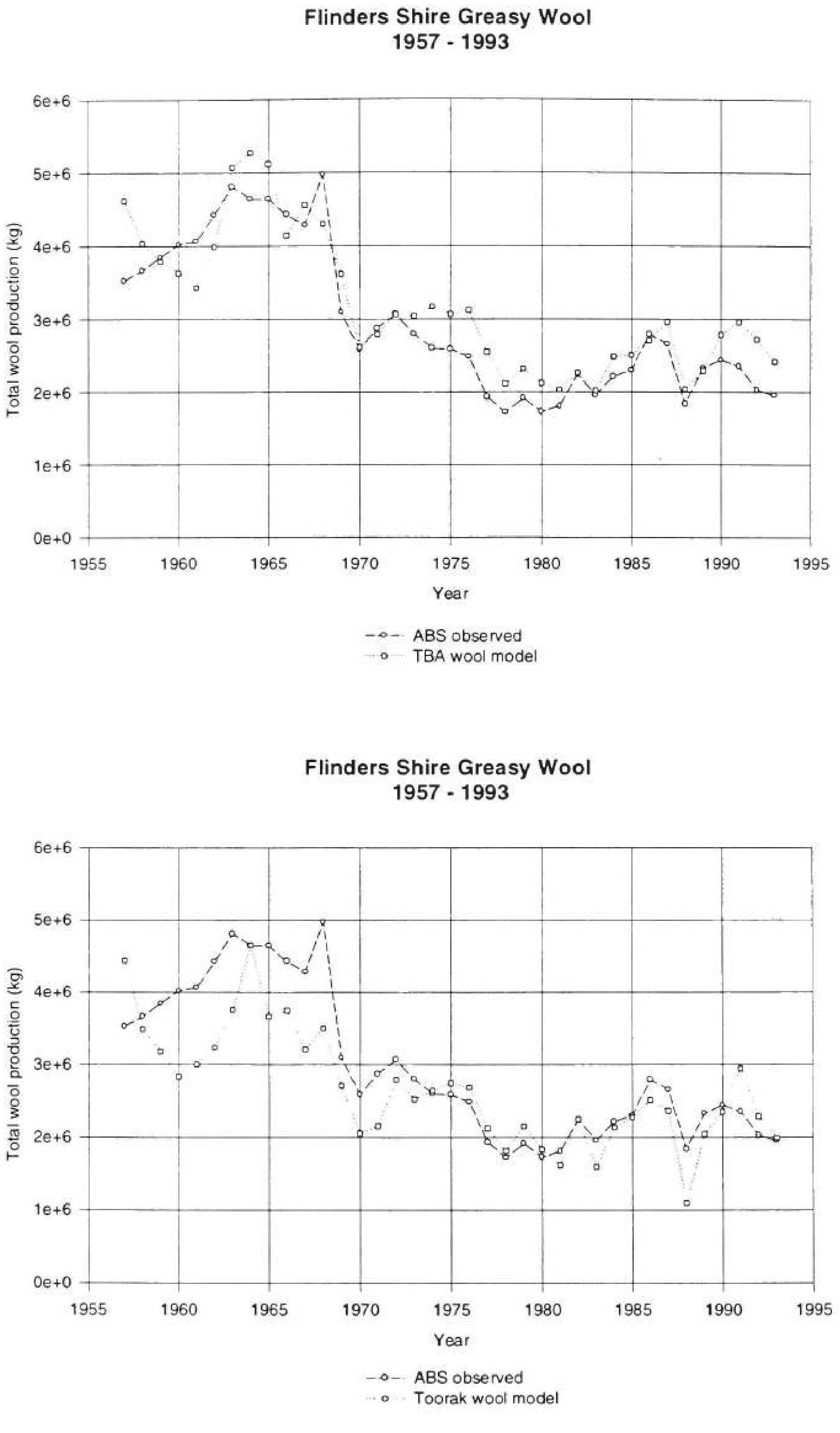

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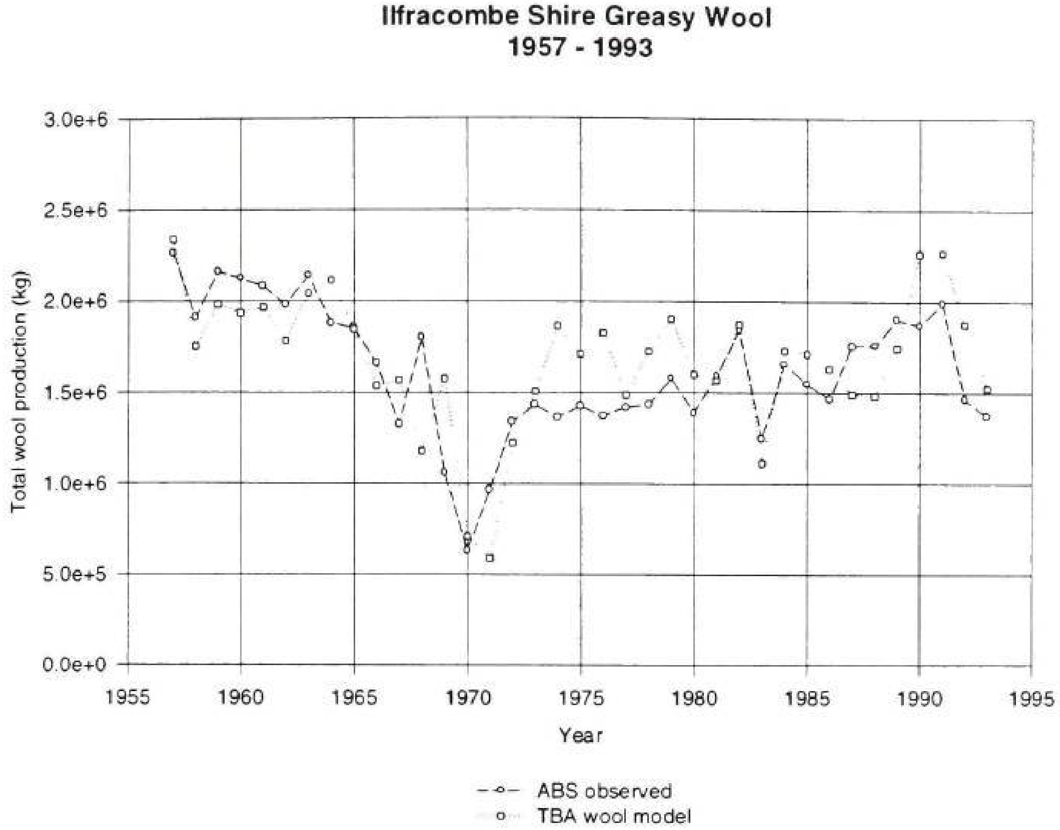

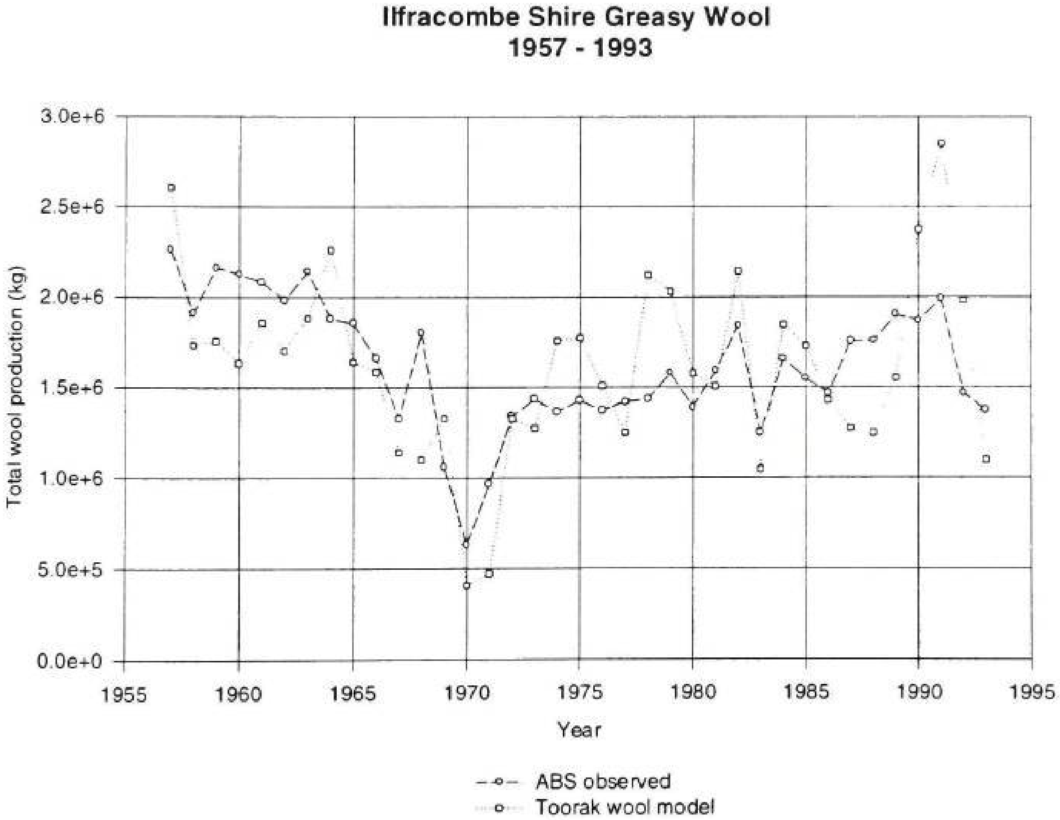

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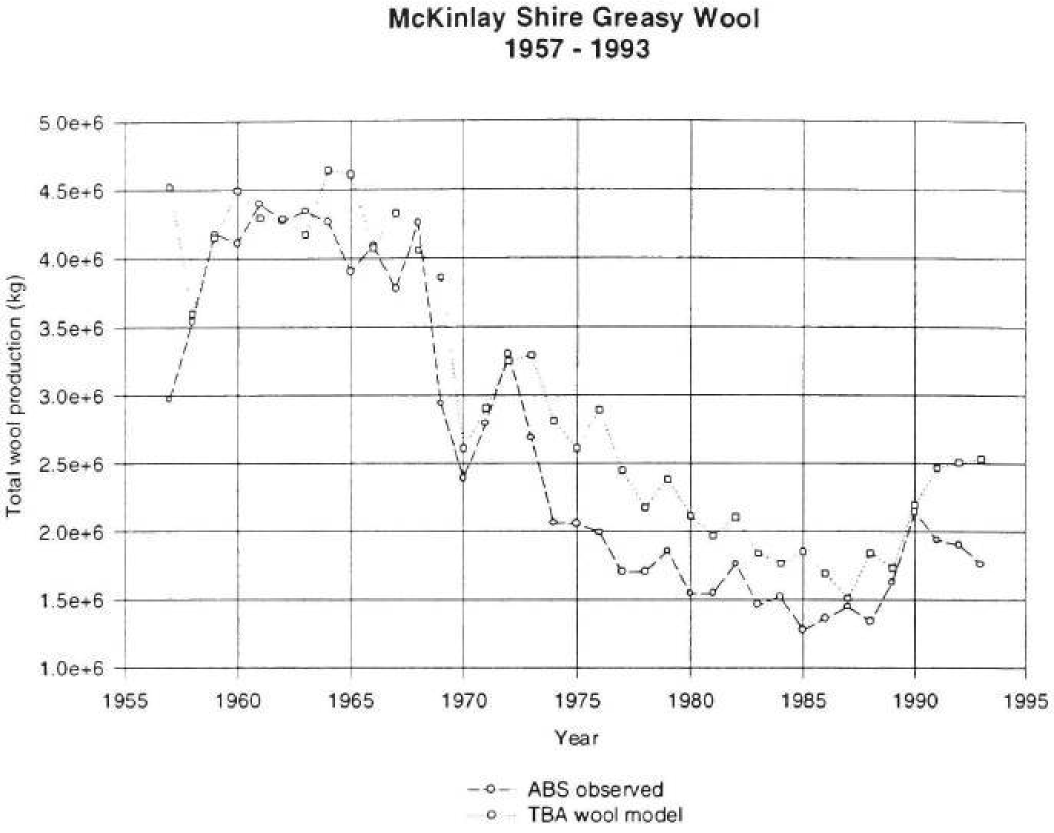

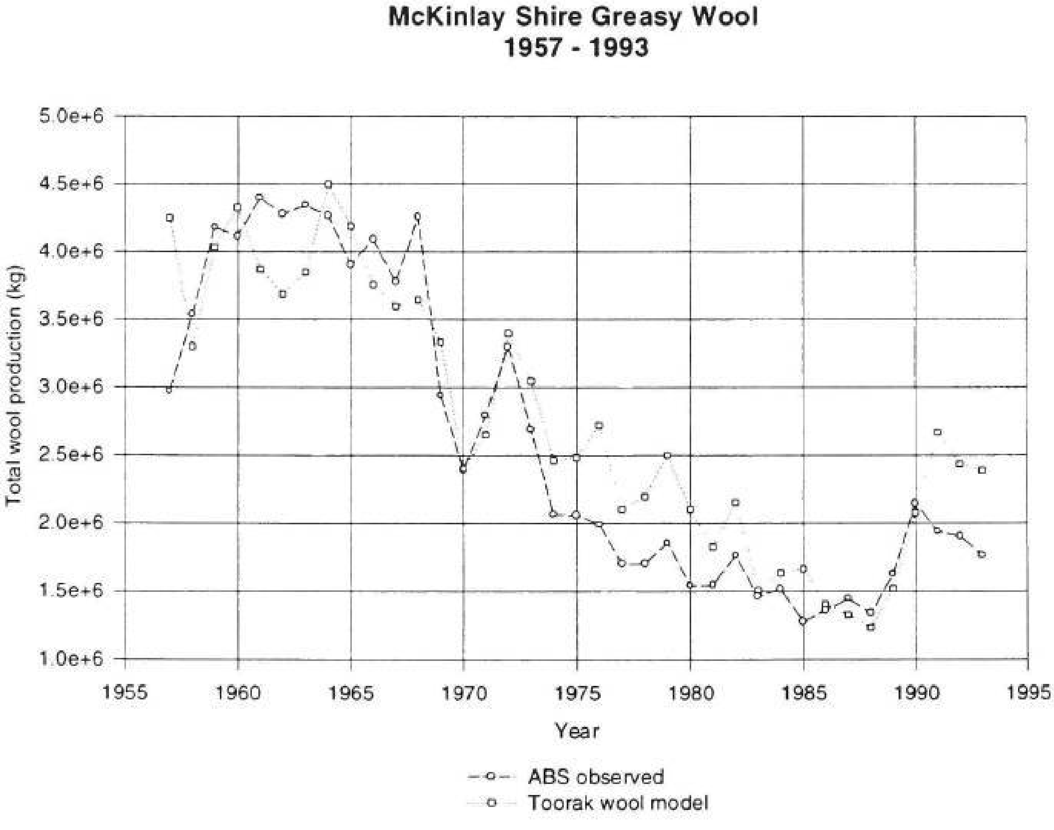

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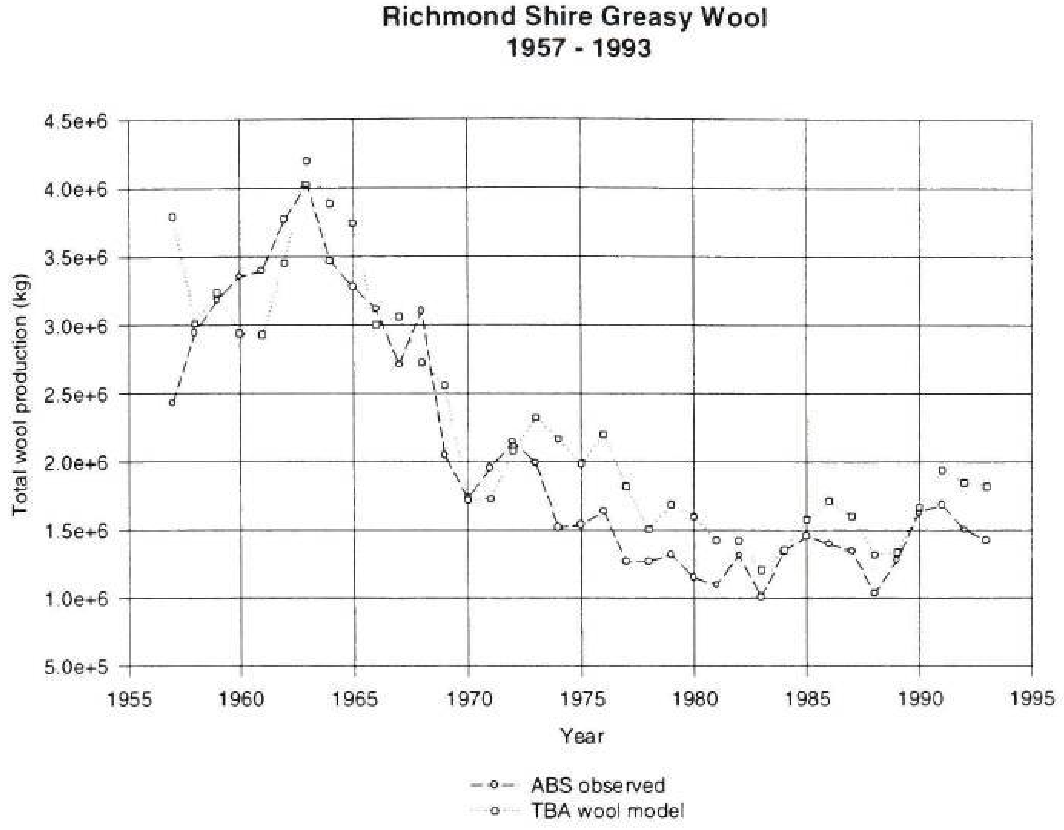

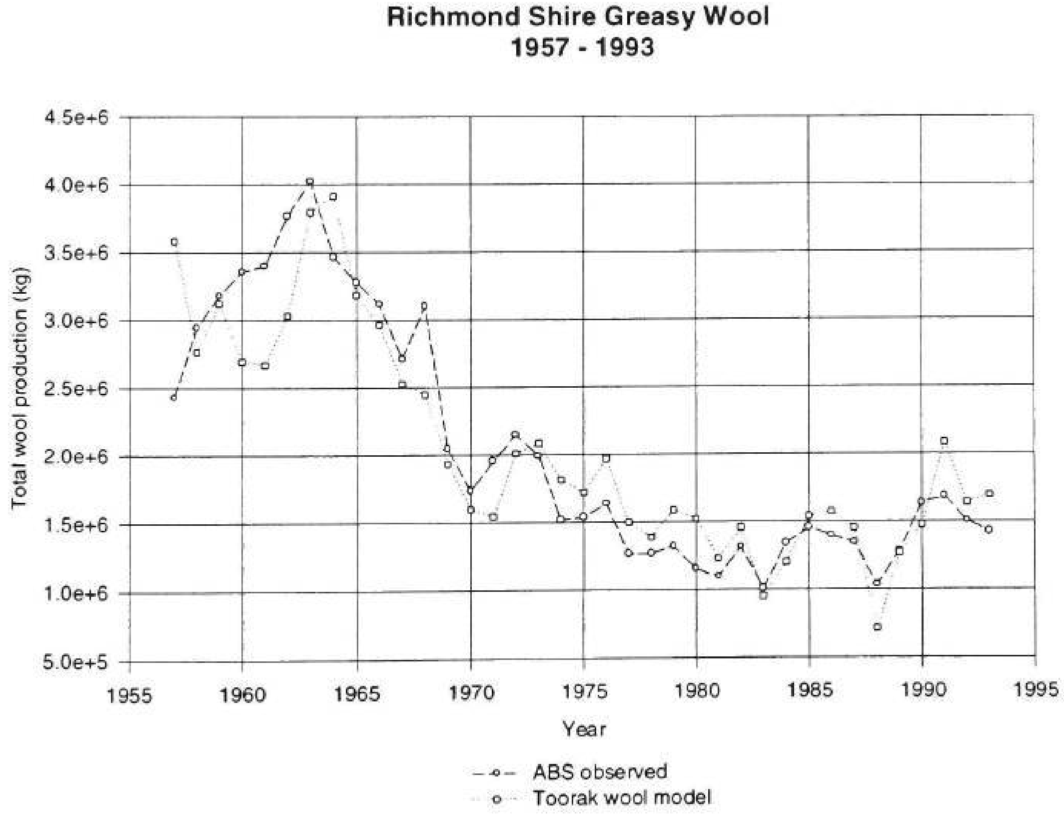

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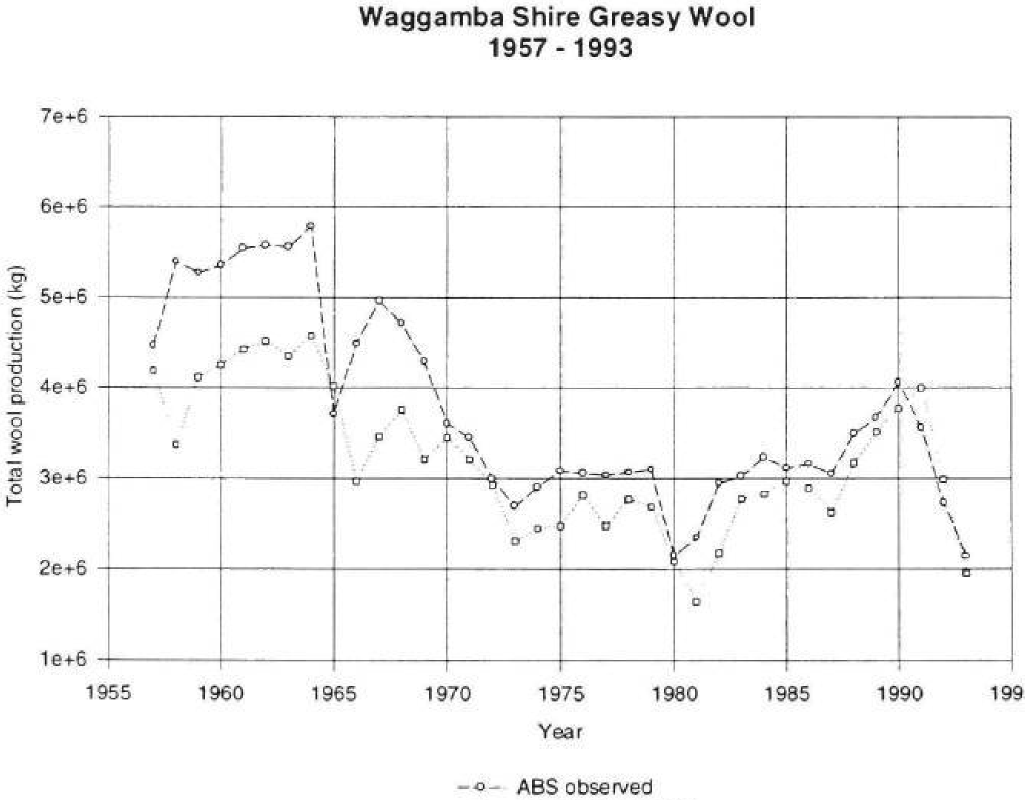

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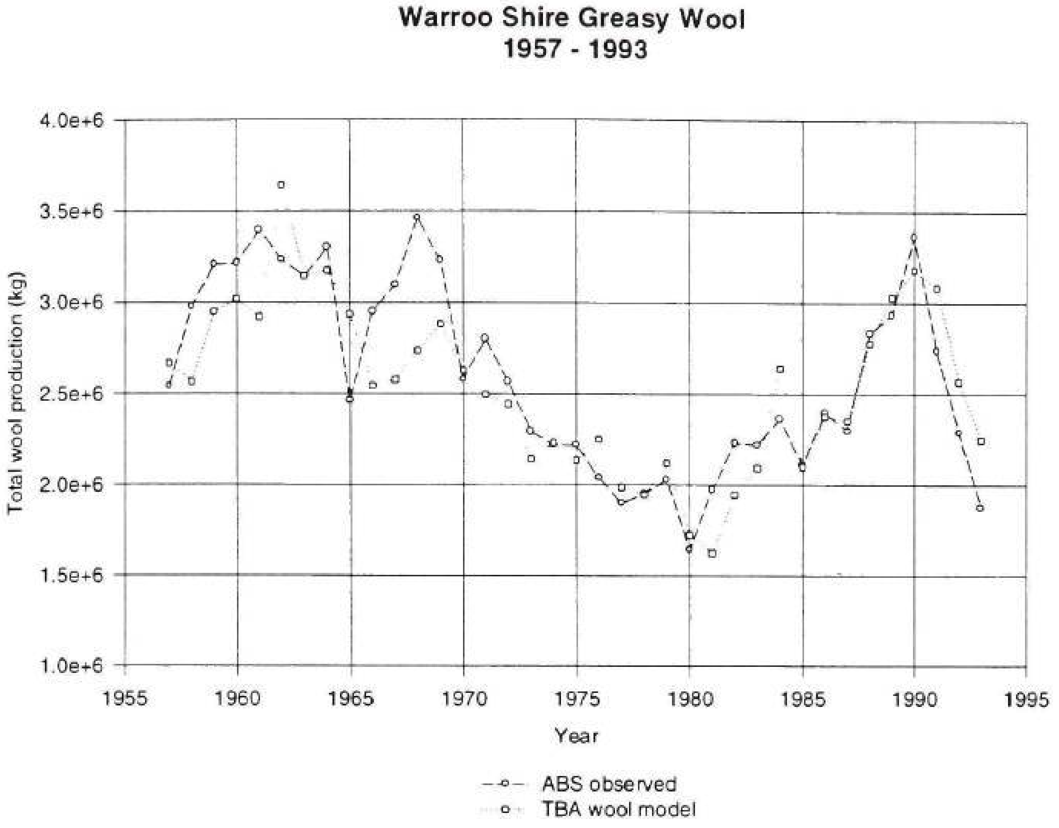

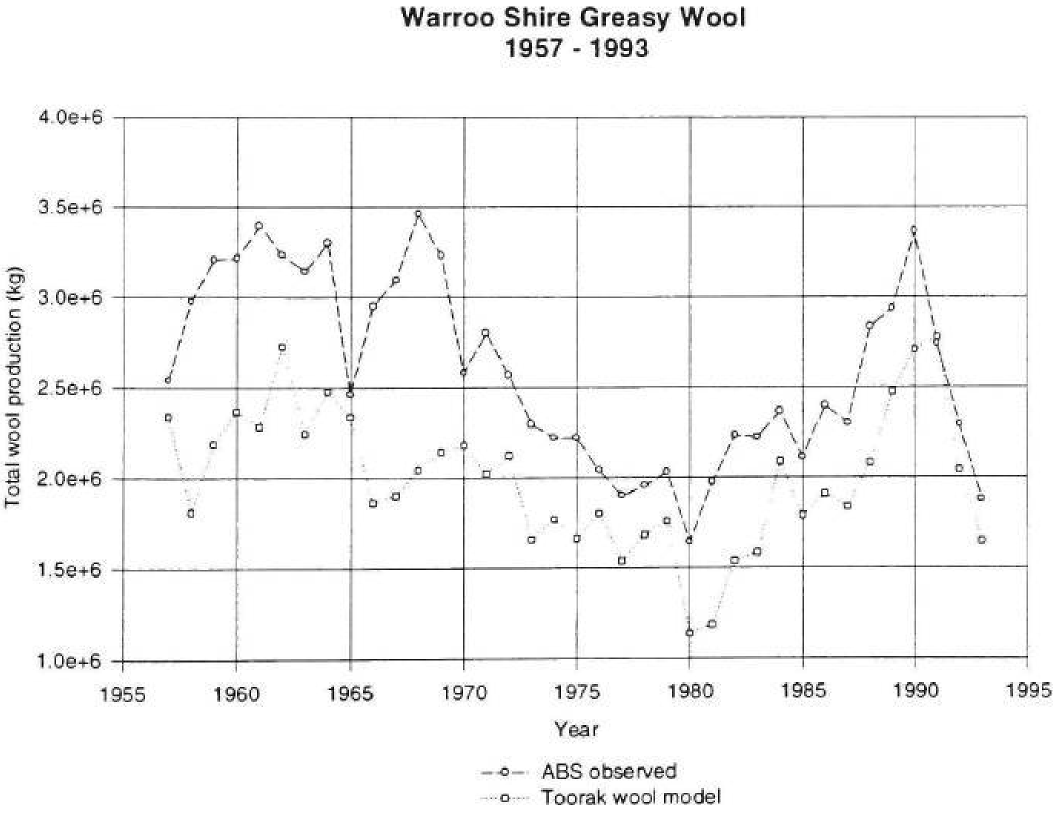

Figure A4.7 continued.

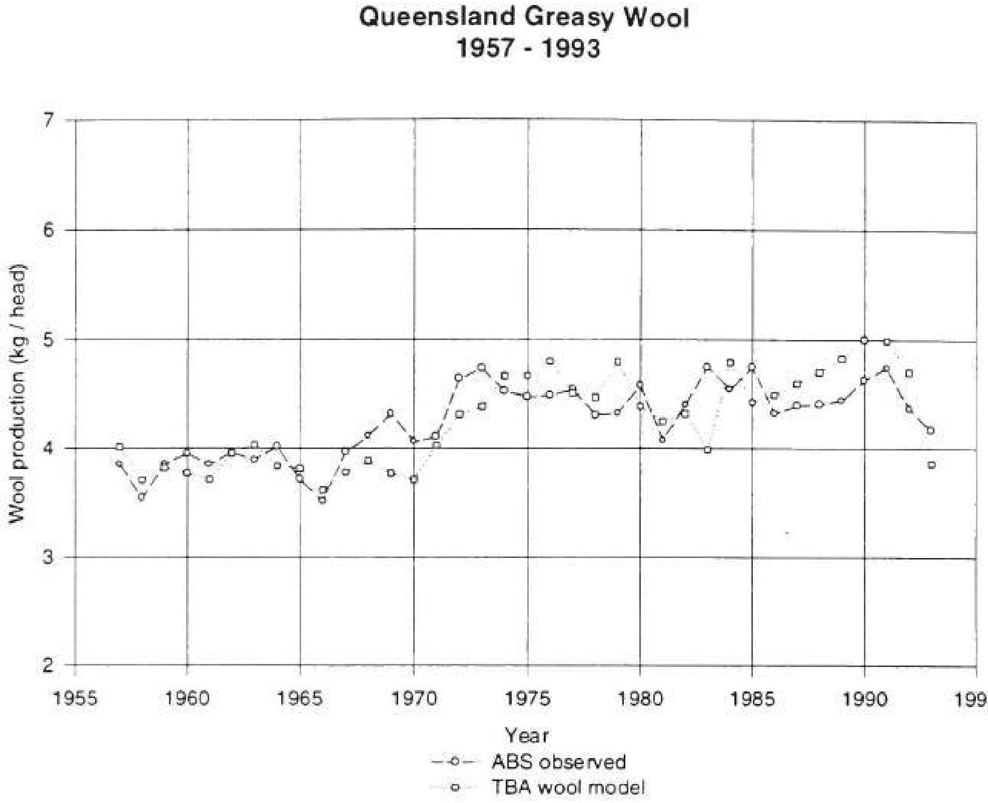

Figure A4.8. Predicted and observed mean greasy fleece weights for Queensland using the TBA wool model.

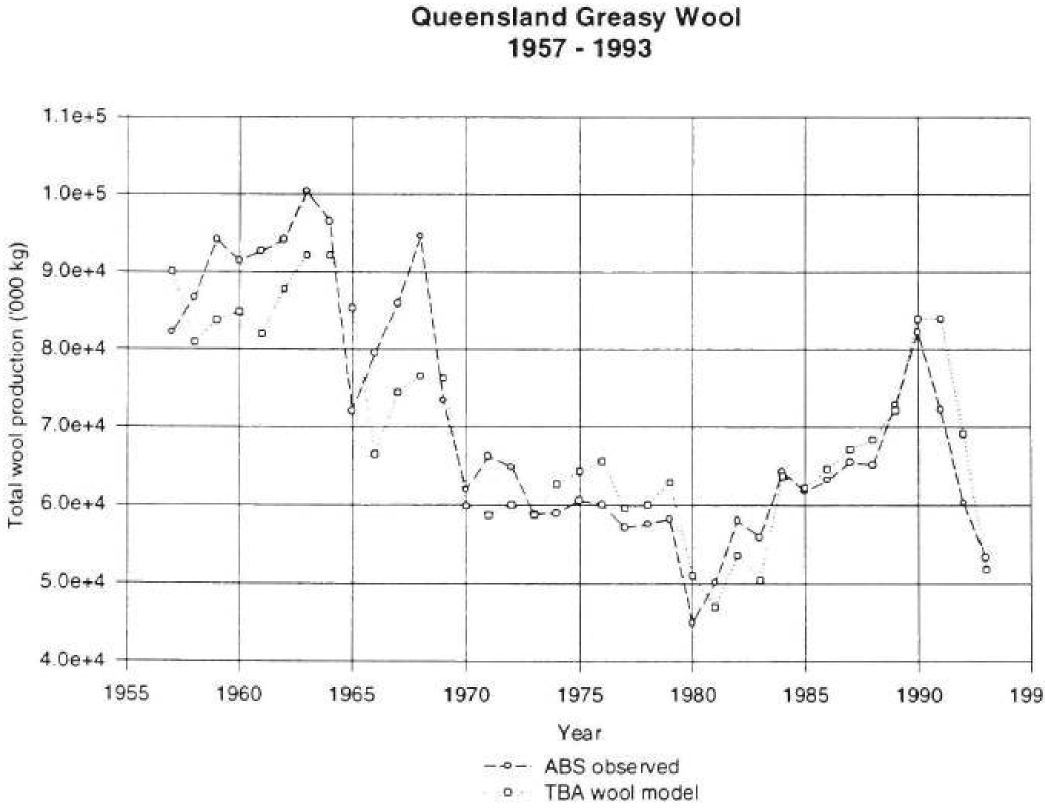

Figure A4.9. Predicted and observed total greasy wool production for Queensland using the TBA wool model.

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