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Grazing Capacity of Native Pastures in the Mulga Lands of South-Western Queensland: A Modelling Approach.

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DECLARATION OF ORIGINALITY

This thesis reports the original research work of the author, except where acknowledged in the text. The material has not been submitted, either in whole or in part for a degree at this or any other University.

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ABSTRACT

Grazing capacities for individual sheep properties were estimated and related to sustainable levels of pasture utilisation through the measurement of key plant processes and the extrapolation of these over time and space.

Measurements of forage production from dominant land systems in south-west Queensland Australia were used to calibrate the GRASP forage production model. This model uses daily climatic records and links a soil water balance to forage growth via a water use efficiency (transpiration) characteristic for each forage. From short term, point observations of forage growth, historical climatic records were used to examine the temporal and spatial variation in water use efficiency (kg/ha/mm rainfall). "Average" water use efficiencies and historical rainfall records were then used to estimate average annual forage growth and "safe" long term grazing capacities for individual grazing properties.

Combining actual stock, climatic and land condition data enabled the estimation of real-time forage growth and utilisation for 46 properties for the period 1986 to 1989. Estimates of annual forage utilisation (5-95%) by sheep and cattle on these properties were compared to known "safe" levels of utilisation (15-25%). These were derived from the combined experience of (1) re-analysis of the results of grazing trials, (2) reaching a consensus on local knowledge and (3) examination of existing grazing practice on "benchmark" grazing properties.

If land managers and administrators used such an ecological approach to assess grazing capacity, improved land management practices may follow as a result of more informed decision making. This thesis quantifies the key ecological relationships in a practical model for estimating the grazing capacity of individual properties in south-west Queensland. When used in a spreadsheet or as a series of manual calculations, "safe" grazing capacities for individual properties and paddocks were estimated by both land managers and administrators. Land managers evaluating the model recommended that the "various relevant bodies and particularly the grazing industry accept the methodology for estimating the grazing capacities in the Mulga lands of south-west Queensland". Through application of such an approach, our understanding of the risks associated with grazing in south-west Queensland, and our ability to "safely" utilise the resource will be improved

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1.0 INTRODUCTION

Achieving sustainable production from grazed native pastures in south-west Queensland requires an understanding of their productivity, dynamics and grazing capacity. Pastures are composed of annual grasses and forbs, perennial grasses and shrubs, and trees. Their structure and composition are determined by rainfall, frequency of fire, soil type, topography, history of use and grazing pressure. Due to the high degree of variability in the seasonal incidence, amount and reliability of rainfall, the structure and composition of pastures varies from place to place and from year to year (Purdie and McDonald 1990). Managing grazing animals in an environment characterised by such variability is difficult and requires skill.

Prior to European settlement, pastures evolved under light or migratory grazing to produce a landscape dominated by grasses and forbs. Following settlement, the advent of sheep and cattle, artesian water, continuous grazing, utilisation of browse trees Mulga (*Acacia aneura* F. Muell. ex. Benth.), clearing and reduced fire frequency have caused a major shift in pasture productivity as grasses and forbs have been replaced by woody shrubs and trees.

Despite the changes in pasture composition and productivity which occurred over the last 130 years, the region supports a productive grazing industry producing wool and meat. The average gross value of agricultural production for the nine shires in south-west Queensland was 217 million dollars (1988/89 to 1993/94) (Table 1.1). However, evidence has "demonstrated that the mulga lands of south-western Queensland are seriously affected by land degradation" (Mills *et al.* 1989 page 46) and if current levels of animal production are to be maintained, improved management of the pasture resource is necessary.

Table 1.1 Value of the major agricultural commodities ($ 000) produced in south-west Queensland (Shires of Barcoo, Blackall, Bulloo, Diamantina, Isisford, Murweh, Paroo, Quilpie and Tambo) from 1988/89 to 1993/94. (Australian Bureau of Statistics)

Year	Wool and Sheep ($)	Beef and Cattle ($)	South-west Queensland Total ($)	Proportion of Queensland's Wool (%)	Proportion of Queensland's Beef (%)
1988/89	157236	87010	250016		
1990/91	135324	112267	248946	35	8
1992/93	70671	120582	192213	33	7
1993/94	71504	104016	176833	39	6
Average	108684	105969	217002	36	7

One approach to improved management is to provide sound knowledge of the components of the pasture/grazing system. More importantly, the components need to be considered together to develop an understanding of the whole grazing system. A systems analysis, in which the components of the grazing system are brought together and the interactions between them examined offers an approach for examining whole systems. A 'whole' systems analysis approach would include the important linkages between social / economic and scientific / technical aspects of regional productivity. In south-west

Queensland and three other regions of semi-arid Australia, Freeman and Benyon (1983) documented such an approach.

In this thesis the systems analysis approach is confined to a subset of the 'whole' system, and examines the links between rainfall, soil moisture, pasture growth, grazing and forage utilisation with the objective of calculating sustainable ("safe") grazing capacities. The "safe" grazing capacity for an individual property is the number of livestock that can be safely run in the long-term without detriment to the pasture resource. “Safe” stocking is defined here as the long-term average of a flexible stocking policy aimed at matching stock numbers to seasonal conditions. The result of flexible stocking is a stocking rate for a particular property for a particular season.

Adjusting stocking rates in response to varying seasonal conditions is the main management option available to producers in south-west Queensland. In the past, graziers have relied on "gut feeling" and local knowledge to make these decisions, and may have expectations biased by short term favourable conditions. The objective estimation of "safe" grazing capacities based on ecological principles aims to assist in this decision making process to achieve sustainable management of the pastoral resource.

This thesis establishes the pastoral importance of the region and the reliance of its grazing industries on production from native pastures. Characteristics of vegetation communities are described and their influence on grazing management examined. The thesis then quantifies an approach for estimating "safe" grazing capacities for individual properties. The approach is based on estimates of plant productivity and safe levels of plant utilisation.

The hypothesis to be tested, is that grazing capacities for individual properties can be estimated through measurement and extrapolation over time and space of key plant production relationships.

2.0 REVIEW OF LITERATURE AND DEVELOPMENT OF A SYSTEMS ANALYSIS

2.1 Significance and characteristics of the mulga zone

The mulga zone of Queensland occupies an estimated 22 million hectares in the semi-arid to arid south-west region of the state (Figure 2.1). It is characterised by the dominance of mulga (*Acacia aneura* F. Muell. ex. Benth.) associations defined by Perry (1970) as Acacia Low Woodland. The combination of climate, soils and vegetation makes it a unique area, and as a result, it is likely to require specialised management.

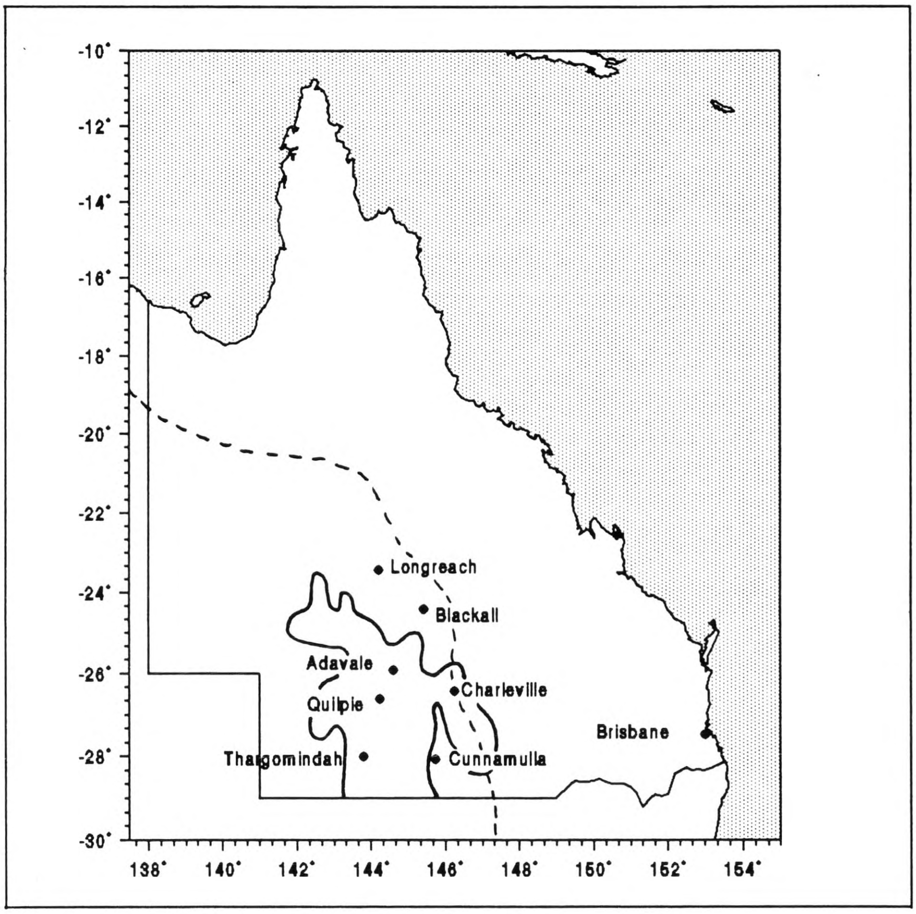


Figure 2.1 Location of the semi-arid zone (dashed line represents the 500 mm average annual rainfall isohyet) and the mulga lands in Queensland (solid line).

2.1.1 Current Land Use and Productivity

Prior to European settlement in the 1860's the region supported a number of aboriginal tribes who were thought to have been in the area for at least 20,000 years (Blake 1979). Since European settlement, the extensive grazing of sheep, cattle and horses has been the major industry. This industry has brought changes to the management and condition of the land and pastoral resources of the region. Continuous grazing and improvements such as fencing and improved water facilities are the major management changes to have taken place.

Proceeds from wool and sheep (average $109M from 1988/89 to 1993/94) and beef cattle (average $106M from 1988/89 to 1993/94) form the major source of income for the region (ABS data). Approximately thirty-six percent of Queensland's wool is produced in the region and 7% of the state's total beef production is derived from the region. In the mulga zone, small cattle herds are generally run in conjunction with predominantly sheep enterprises. To the west of the mulga zone and the dingo barrier fence, cattle grazing is the main enterprise. Grazing properties in the mulga zone range in size from 10,000 ha to more than 120,000 ha and carry 4,000 to 12,000 sheep and 100 to 300 head of cattle (Sullivan *et al.* 1986). Passmore (1990) reports an average property size of 33,000 ha for the mulga region carrying an average 7,000 sheep and 380 head of cattle. When converted to approximate dry sheep equivalents (DSE) (1 dry beast = 8 DSE) this equates to 10040 DSE or 30 DSE/km^2 which is 20% lower than the average of the long-term (1890-1989) livestock numbers from the Murweh and Paroo shires (38 DSE/km^2) reported by Mills and Purdie (1990).

Productivity of grazing enterprises varies widely within the region as a consequence of seasonal conditions, differences in animal husbandry, property management and inherent differences in soils and vegetation among properties and districts. Annual wool production averages 4.5 kg/head and lambing percentages range from 40 to 70%. Steer growth rates vary from 30 to 160 kg/head/year depending on seasonal conditions and brandings average 50% (Sullivan *et al.* 1986). Prior to the decline in wool prices in February 1991, Passmore (1990) reported return on capital, "adjusted to full equity", averaged $34,000 per property or $1.13/ha or $2.66/ DSE.

Concern at the decline in production (pastures and livestock products) from the region has been expressed by a number of authors e.g., Ratcliffe (1937), Burrows and Beale (1969), Pressland (1976, 1984), Mills (1986), WGA (1988), Mills *et al.* (1989) Miles (1989), Passmore and Brown (1992) and Anon (1993). Reliance on feed from browse trees and maintenance of inappropriate stocking rates at critical times have caused pasture degradation and production losses in the region. In the mulga zone, a lack of ground cover, accompanied by increases in sheet erosion and woody shrub cover, are the most common forms of degradation. The processes and extent of degradation have been documented by Burrows (1973), Brown (1981), Beale (1986), Pressland and Cowan (1987), Mills (1986), Mills *et al.* (1989), and Miles (1993). Mills (1989) estimated the gross value of wool production from the "Paroo" mulga area (3 M ha bounded by Charleville, Quilpie, Thargomindah and Cunnamulla) had been reduced by $4.4 M (4.2%) per annum by the effects of erosion and woody shrub cover.

To address these concerns a need to review "carrying capacities" / "stocking rates" was suggested by the Warrego Graziers Association (1988), Mills *et al.* (1989), Miles (1989) and Anon. (1993). This review is currently (July 1996) a component of an integrated regional adjustment and recovery program for south-west Queensland termed "The South West Strategy" (Williams 1995). This thesis develops an approach to address the determination of appropriate grazing capacities for use in strategic (20-30 year) decisions on livestock numbers as a central issue for the natural resource management component of the South West Strategy initiative. If appropriate grazing capacities can be estimated and adopted, a closer examination of methods to better estimate tactical (seasonal-annual) stocking rates could then be made. While recognising the linkage between short term stocking rates and longer term grazing capacities this thesis focuses on the establishment of "safe" grazing capacities as a starting point for sustainable grazing land management. Once these are established, mechanisms to examine short term stocking rates could then be developed. This thesis does not aim to explore the examination of short term stocking rates.

In south-west Queensland the grazing capacity issue is not confined to sheep and cattle. Kangaroos, feral goats, rabbits, termites and locusts do graze the same pastures as sheep and cattle though the relative densities of species varies across the landscape and over time. The term "total grazing pressure" accounts for the total level of pasture utilisation resulting from domestic, feral and native animals. Due to the nomadic nature of feral and native grazers it is difficult and sometimes controversial to quantify the pressure exerted by these animals on the pasture resource. The contribution to total grazing pressure and degradation from these animals is only now being determined quantitatively (Wilson 1991, Norbury *et al.* 1993, Hacker *et al.* 1995 and Landsberg *et al.* 1996).

In semi-arid areas it is often difficult to determine whether observed degradation is the result of year to year variation (reversible), or a long-term rundown in resource condition. This is due to the difficulty both graziers and land administrators have in separating the effects of management from year to year variation. Within the mulga zone, pasture biomass can fluctuate from less than 100 kg/ha to 1200-1500 kg/ha in a decade (Mills 1986). In addition, animal productivity is not always a good indicator of pasture condition as animal production can be maintained for some time after pasture deterioration has occurred (Beale *et al.* 1984). A long-term approach to managing livestock in the region is therefore required. Similarly, a long-term approach to monitoring regional productivity is also required. Despite the lag between a decline in livestock productivity and a decline in pasture productivity, Abel and Blaikie (1989) suggest that 'the rate at which the land yields livestock products' is still a valuable indicator of degradation for pastoralism within rangeland systems, and that livestock productivity should be monitored. In recognising these complexities, a systems analysis using computer modelling with historical climate, livestock and financial records potentially offers an approach to separate the effects of management from the effects of year to year climatic and economic variability. This thesis develops this approach.

2.1.2 Significance of native pastures

Native pastures have contributed significantly to the rural industry and economy of Queensland for the last 145 years.

Queensland has the largest area of native pasture (151 M ha or 87% of total area) of all the Australian states (Lloyd and Burrows 1988). In addition, the proportion of the state's total native pasture area used as natural grazing land is greater than any other state in Australia or any other country in the world. The mulga zone represents 14.5% of the State's native pastures.

Most of Queensland's cattle and virtually all of its sheep graze native pastures, indicating approximately one third of Queensland's primary producers substantially depend on these pastures for their income (Lloyd and Burrows 1988). The gross contribution to the State's economy of production from native pastures is estimated at $1125 M annually (1983-84 data) (Lloyd and Burrows 1988).

Much of Queensland's native pastures lie in semi-arid, sub-tropical and tropical environments where climatic conditions and soil factors limit the potential for cropping and improved pasture development. The mulga zone fits this description with only limited areas successfully developed with improved pastures (predominantly Buffel grass - *Cenchrus ciliaris*).

Thus the better management of native pastures is likely to be of greater importance in the mulga region than further development with introduced species (Smith and Silcock 1986).

2.1.3 Climate

The climate of the mulga zone is characterised by a low and unreliable rainfall, high evaporation rates and extremes of temperature. Meigs (1953) described the climate of the zone as semi-arid with hot summers, cold winters and rain at any season. Climatic data for Charleville are presented in Table 2.1.

On average, summer months have a greater mean rainfall, higher intensity rainfall, and higher evaporation rates than winter months. Rainfall variability is high throughout the year, but is highest in summer months. Droughts or floods can occur at any time. Drought frequency and indices of rainfall variability for Charleville are compared with those for Gayndah and Hughenden (two centres located outside south-west Queensland) (Table 2.2). Drought frequency for nine south-west Queensland shires, as defined by the Queensland State Government (annual rainfall less than 60% of average) is illustrated in Figure 2.2. By this definition "droughts" are frequent. An alternative analysis by Clarkson and Owens (1991) indicates the frequency is slightly less.

Table 2.1 Monthly climatic data for Charleville (26° 25'S 146°16'E elevation 306 m) (Bureau of Meteorology)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)													
Mean	68	67	61	33	32	28	21	20	21	35	41	57	493
Median	47	50	30	19	22	21	16	10	8	22	25	45	468
Lowest	3	0	0	0	0	0	0	0	0	0	1	1	203
Highest	308	400	382	248	199	128	220	125	127	188	190	235	1202
Temperature (°C)													
Mean max.	34.6	34.0	31.7	28.4	22.9	20.1	19.5	21.7	25.7	29.8	33.0	34.5	28.0
Mean min.	21.5	21.2	18.5	13.8	8.6	5.1	3.5	5.5	9.4	14.3	17.7	20.0	13.3
Pan Evaporation (mm/day)	11.2	9.8	7.9	6.3	4.1	3.4	3.7	4.7	6.5	8.7	11.4	12.2	2730
Vapour Pressure Deficit (hPa)	31.3	27.0	21.1	16.1	9.3	7.2	8.1	11.1	16.9	23.6	31.8	34.2	19.8
Rainfall / Evaporation	0.20	0.24	0.25	0.17	0.25	0.27	0.18	0.14	0.11	0.13	0.12	0.15	0.18

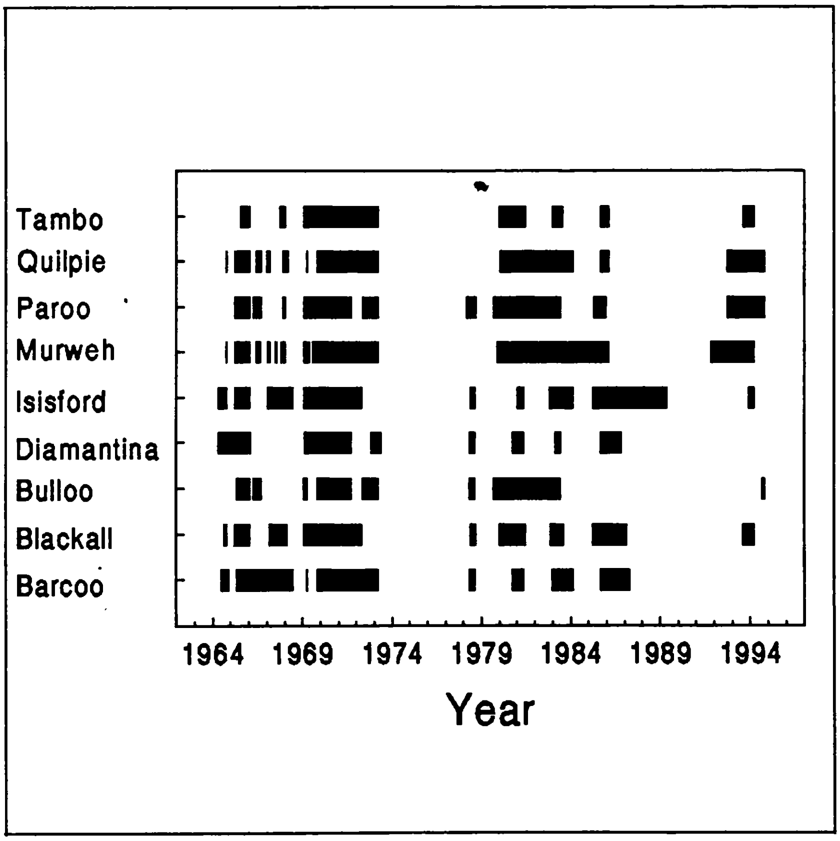


Figure 2.2 Declared drought periods for nine south-west Queensland shires from 1964 to 1994 (Queensland Department of Primary Industries).

Evaporation rates are high and vary from 2100 mm to 3000 mm annually at Charleville (four to five times the annual rainfall). December has the greatest evaporation (280 mm) and July the lowest (75 mm). The ratio of rainfall to evaporation does not exceed 0.3 for any month of the year indicating the high potential for moisture to limit plant growth (Table 2.1). This is supported by Fitzpatrick and Nix's (1970) average moisture index for Charleville not exceeding 0.4 throughout the year (Table 2.2).

Extremes of temperature are common. At Charleville, the hottest month is January with mean maximum and minimum temperatures of 34.6°C and 21.5°C respectively. In the coldest month, July, mean maximum and minimum temperatures are 19.5°C and 3.5°C respectively. Frosts are common in much of the region with Charleville averaging 50 to 100 frosts annually, occurring from mid-June to mid-August.

The mean monthly vapour pressure deficit at Charleville ranges from a maximum 34.2 hPa in December to a minimum of 7.2 hPa in June. The vapour pressure deficit, a measure of the dryness of the air, influences plant growth. Plant water use is less efficient when the vapour pressure deficit is high (Tanner and Sinclair 1983).

Failure to recognise the seasonal variability and potential interactions with economic variability may lead to land, livestock and financial management problems for grazing enterprises in this region.

Table 2.2 Comparison of indices for drought and climatic variability for three locations in Queensland.

Index*	Charleville	Gayndah	Hughenden	Reference
1.	2 - 3 in 10	1 in 10	1 -2 in 10	Daly and Dudgeon (1987)
2.	2.0 in 10	1.7 in 10	1.7 in 10	Clarkson and Owens (1991)
3.	1.8 in 10	1.4 in 10	1.3 in 10	Clarkson and Owens (1991)
4.	55	57	37	Clarkson and Owens (1991)
5.	1.09	0.71	1.07	
6.	0.95	1.03	0.99	
7.	0.42	0.27	0.42	
8.	0.2 - 0.4	0.6 - 0.8	0.2 - 0.4	Fitzpatrick and Nix (1970)
9.	0.2 - 0.4	0.4 - 0.6	< 0.2	Fitzpatrick and Nix (1970)
10.	< 0.2	0.2 - 0.4	< 0.1	Fitzpatrick and Nix (1970)
11.	0.18	0.37	0.17	

* Key to indices;

1. Drought frequency expressed as the number of drought years expected in every ten years. (Drought = Annual rainfall less than 60% of average, the index used by the Queensland Treasury Department).
2. Drought frequency expressed as the number of drought years expected in every ten years. (Drought = Driest 10% of calendar years).
3. Severe drought frequency expressed as the number of severe drought years expected in every ten years. (Severe drought = Driest 5% of calendar years).
4. Average proportion of time each drought spends as a severe drought (driest 5% of calendar years).
5. Index of rainfall variability (Decile 9 - Decile 1)/mean annual rain.
6. Index of rainfall variability (Median annual rain/Mean annual rain).
7. Index of rainfall variability (SD mean annual rain/Mean annual rain).
8. Soil moisture index, Summer (October - March).
9. Soil moisture index, Winter (April - September).
10. Soil moisture index, driest sixteen week period.
11. Ratio of Annual mean rainfall to Annual mean pan evaporation (Total).

2.1.4 Soils

The soils of the mulga zone are diverse, and have been described by Northcote *et al.* (1968), Dawson and Ahern (1973, 1974), Walker and Fogarty (1986) and Ahern and Mills (1990). Red earths predominate. These include loamy red earths (Gn2.11, Um1.43), sandy red earths (Uc1.23, Um5.51), earthy sands (Gn2.12), siliceous sands (Uc1.22) and lithosols (Uc1.43) (Ahern and Mills (1990)). Intermixed with the red soils are alluvial clay soils (Ug5.24), cracking clay soils (Ug5.34) and texture contrast soils (Dr2.53). These soils are mainly confined to water courses, and while only small in area, contribute significantly to the livestock production of the region.

The red earths, sands and lithosols of the mulga zone are structureless and prone to surface sealing and erosion by wind and water. Water holding capacity is low, with soil water held at field capacity ranging from 8 to 18% (mean 13%) and at wilting point ranging from 4 to 11% (mean 7%) (Dawson and Ahern 1973). Infiltration rates are variable and depend on the level of surface sealing. Levels of available phosphorus, total nitrogen and organic matter are low and decrease rapidly with depth. Greater than 95% of available soil nutrients are held within the surface 15mm of soil (Pressland and Cowan 1987). Soil depth varies considerably ranging from only a few centimetres on the lithosols, to several metres on the earthy sands. The soils are acidic in reaction, with iron and aluminium oxides responsible for the red colouring.

In contrast, the clay and texture contrast soils are alkaline to neutral in reaction, have greater water holding capacity and nutrient levels. The cracking clay soils are typically blocky with crumb, granular, platy or blocky structure. The texture contrast soils have predominantly a massive surface soil over-lying a more structured subsoil (Dawson and Ahern 1974). Calcium is present in many cracking clay soils and texture contrast soils. It is present as concretionary or soft lime and in some instances gypsum.

The diversity of soils in the region contribute to the complexity and variability of the environment with which management must contend.

2.1.5 Vegetation

The vegetation of the mulga zone has been described by several authors: Blake (1938), Beadle (1948), Everist (1949), Perry (1970), Specht (1981), Johnson and Burrows (1981), Boyland (1984) and Neldner (1984 and 1986). Trees and shrubs of the *Acacia* genus characterise much of the area. Mulga (*Acacia aneura*) is the most common species. Other tree species growing in association with mulga include *Eucalyptus populnea* (Poplar Box), *E. terminalis* (Western Bloodwood), *E. cambageana* (Blackbutt), *E. melanophloia* (Silver-leafed Ironbark), *E. thozetiana* (Mountain Yapunyah), *Grevillea striata* (Beefwood), *Atalaya hemiglauca* (Whitewood), *Hakea ivoryi* (Corkwood), *Geijera parviflora* (Wilga), *Alstonia constricta* (Bitter bark) and *Flindersia maculosa* (Leopardwood). Associated shrubs include *Cassia* spp., *Dodonaea* spp., and *Eremophila* spp..

Depending on the seasonality and amount of rainfall, mulga pastures can support a wide variety of herbage species. Grasses usually predominate after summer rainfall, and a range of forb species after winter rainfall (Purdie and McDonald 1990). Over half the total species in the area are ephemerals or short lived perennials, their presence determined by specific seasonal conditions.

Perennial grasses include *Amphipogon caricinis* (grey beard grass), *Aristida* spp. (wire grasses), *Chloris* spp., *Digitaria* spp., *Enneapogon* spp. (bottle washer grasses), *Eragrostis* spp. (love grasses), *Eriachne* spp. (Wanderrie grasses), *Monachather paradoxa* (mulga oats), *Panicum* spp., *Sporobolus* spp., *Thyridolepis mitchelliana* (mulga mitchell) and *Triodia* spp. (spinifex).

Under suitable seasonal conditions annual grasses such as *Dactyloctenium radulans* (button grass), *Paspalidium* spp., and *Tripogon lolliformis* (five-minute grass) proliferate. Annual forbs include *Ptilotus* spp. (foxtails), *Trachymene* spp., *Calotis* spp. (daisy burrs), *Helichrysum* spp. (everlastings), *Helipterum* spp. (paper daisies), *Atriplex* spp. (annual saltbushes), *Maireana* spp. (bluebushes), *Sida* spp., *Abutilon* spp. and *Velia* spp..

The variability in composition, quantity and quality of vegetation in the region needs to be acknowledged when managing for sustainable pasture and animal production. The challenge addressed in this thesis is how to manage with this variability to achieve sustainable grazing land management.

2.2 Grazing management, stocking theory and pasture utilisation

There is considerable debate in the literature over the definition, derivation, use and relevance of grazing capacity values (Bartels *et al.* 1993). Nevertheless, graziers, land administrators and financiers need to make strategic decisions on grazing capacity (20-30 years) and tactical decisions regarding stocking rate (seasonally or annually). While stocking rate theory (e.g. Jones and Sandland 1974, Hart 1978, 1986, Danckwerts 1984, White 1987, Turner and Tainton 1989, Vallentine 1990, Heitschmidt and Taylor 1991, Abel 1992, Behnke and Scoones 1993 and Holechek *et al.* 1995) and the impact of stocking rates on rangelands (Ash and Stafford Smith 1996) has been examined worldwide, there are few practical tools available to guide the estimation and implementation of sustainable grazing capacities. Most rely on 'gut' feeling, local knowledge and experience in determining appropriate livestock numbers despite the volume of science and theory directed at the issue. A similar conclusion was drawn by Holechek (1988) for rangelands in the USA. In contrast, Bartels *et al.* (1993) questions the validity of the carrying capacity concept in the communal rangelands in sub-Saharan Africa and recommends its application be stopped. In this thesis the carrying capacity concept as it applies to Western range management, where livestock are mostly confined by fences and the land owned or leased by individuals, is discussed.

Before continuing, some definitions of terms related to grazing land management are reviewed briefly.

2.2.1 Definitions

Grazing capacity (DSE/ha) is the number of animals that produces the greatest return without damage to the physical resources and in concert with other values received from the land (Heady 1975). In general terms it is the average number of animals that a particular pasture will sustain over time and in most cases is the figure determining the dollar value of properties being bought and sold (Holechek *et al.* 1995).

Carrying capacity (DSE/ha) is defined by The Macquarie Dictionary (1981) as the capacity of land or pasture to support livestock. It is also used synonymously with grazing capacity. However, it can be differentiated from grazing capacity to include harvested forages and other materials used in conjunction with grazing (Vallentine 1990a). It is therefore a means of summarising total property capacity. Heady (1975) stresses carrying capacity should not be confused with grazing capacity. He describes carrying capacity as the greatest return of combined products without damage to the physical resources. However, more recently Heady and Child (1994) equate carrying capacity with grazing capacity.

Stocking rate (DSE/ha) is the number of animals of a specified class, or animal units, per unit area of land over a specified period of time (Heitschmidt and Taylor 1991). Different classes of stock are converted to standard units or animal equivalents for comparison across classes. In this thesis, dry sheep equivalents (DSE) as defined by Anon. (1977) are used, and the stocking rate is expressed as DSE/ha or DSE/km^2.

Actual stocking rates may vary considerably between years due to fluctuating forage conditions. An average of the stocking rates possible year after year without damage to the land resource can define a carrying or grazing capacity (Holechek *et al.* 1995).

Grazing pressure is defined by Vallentine (1990b) as the animal demand for forage per unit weight of forage at any time. Cumulative or total grazing pressure relates the total animal demand (including feral and native animals) for forage to the amount of forage available. Grazing pressure fluctuates widely over time and space as a result of variations in forage quality and quantity caused by environmental factors such as rainfall, soil fertility, slope and aspect, and management factors, but chiefly stocking rate decisions (Heitschmidt and Taylor 1991).

Utilisation refers to the percentage of the current year's forage production that is consumed and/or destroyed by herbivores (Holechek *et al.* 1995 from Society for Range Management 1989). Quantitatively it is expressed as;

Utilisation % = [(Forage eaten + Forage trampled) / Forage grown] * 100

Utilisation measurements have many uses in grazing management. The most important are in assessing and adjusting stocking rates. The links between utilisation and stocking rates are explored later in this section.

The term "forage" has been used above to describe plant material consumed and destroyed by grazing animals. In section 2.3 the term "forage" and techniques for estimating forage production are described. From a practical point of view the quantity of material "trampled" is difficult to quantify whilst the amount "eaten" can at least be measured in pen studies. In this thesis the term utilisation will refer to the percentage of material eaten of what has grown unless otherwise specified. I.e.

Utilisation % = (Forage eaten) / (Forage grown) * 100

For semi-arid environments there are a number of limitations to these definitions:

1. They assume a single equilibrium is attainable between rainfall, forage growth and land condition on the one hand and the stocking and intake rates on the other. In semi-arid environments characterised by variable rainfall, non-equilibrium systems and multiple states are more applicable (Westoby *et al.* 1989). The attainment of one equilibrium (if any) is unlikely under these conditions.
2. They assume there is a threshold density of animals or level of forage utilisation above which degradation occurs and below which it does not.
3. The definitions do not clarify the "return", nor do they define the type or level of degradation resulting from grazing; and,
4. In south-west Queensland domestic livestock may only represent a portion of the total number of herbivores in the system. Other herbivores include kangaroos, feral goats and pigs, rabbits and insects. Studies in western New South Wales (Hacker *et al.* 1995 and Landsberg *et al.* 1996) and in south-west Queensland (L. Pahl, pers. comm.) have found that kangaroos and feral goats can contribute more than half the total grazing pressure.

The need for definitions relevant to semi-arid grazing lands is highlighted. Heady and Child (1994) recommend a careful choice of words when describing grazing capacities for specific situations. To avoid confusion definitions need to be quantitative and reflect non-equilibrium conditions.

In this thesis a temporal distinction is made between grazing capacity and stocking rate. Grazing capacity refers to livestock numbers in a long-term, strategic (20-30 year) time frame and stocking rate refers to a shorter term, or tactical (seasonal-annual) time frame.

2.2.2 Stocking theory

Determination of the appropriate stocking rate is the most important of all grazing management decisions from the standpoint of vegetation, livestock, wildlife and economic return (Holechek *et al.* 1989). Grazing pressure is the principal force, together with fire and cultivation, controlling species composition and forage production which the manager can manipulate (Heady 1975). The choice of stocking rate and the resulting grazing pressure also have a profound effect on both the immediate and the long-term animal productivity of the range. The immediate effect arises from changes in the quality and quantity of available forage at different levels of utilisation. The long-term effect on productivity arises from changes in the density and composition of the natural pasture community (Wilson *et al.* 1990).

The complex and highly variable relationships between stocking rate, production per animal, and unit of land have been reviewed by Jones and Sandland (1974), Hart (1978, 1986), Danckwerts (1984), White (1987), Holechek *et al.* (1989), Turner and Tainton (1989), Vallentine (1990b), Heitschmidt and Taylor (1991), Abel (1992), Behnke and Scoones (1993) and Holechek *et al.* (1995).

In general terms, at low stocking rates, individual animal performance is maximised as grazing pressure is low and forage quality is high. However, animal production per unit area is low as the number of animals per unit area is low. As stocking rate is increased individual animal performance declines because of restrictions imposed on nutrient intake by reductions in either quantity and quality of forage on offer, or increased energy use by animals. The stocking rate at which this decline begins is referred to as the critical stocking rate (Hart 1978). Production per unit area, however, continues to increase as stocking rate increases because of the increase in the number of animals. This increase continues to some maximum as stocking rate is increased, but eventually it too decreases as nutrient intake becomes progressively more restrictive (Heitschmidt and Taylor 1991).

Thus, for sustainable production from native pastures the links between grazing capacity and pasture utilisation are most important and will be explored here. However, animal productivity is not always a good indicator of pasture condition as animal production can be maintained for some time after pasture deterioration has occurred (Beale *et al.* 1984). Ash and McIvor (1995) indicate that diet quality may be higher (significant increase in in-vitro digestibility and nitrogen concentration) from pastures on land in poor condition. However, these authors warn that the large decrease in pasture productivity associated with declining land condition may more than offset the apparent improvement in feed quality. The role of supplements also distorts the links between animal production and pasture condition by enabling livestock to survive and produce on pastures in 'poor' condition (Gardener *et al.* 1990)

Hence, there is a need to balance the optimum stocking rate and resulting utilisation, with the grazing capacity of the pasture. Where animal production ($/ha) is maximised at a stocking rate lighter than the grazing capacity, over utilisation (overgrazing) and subsequent damage to the pasture resource is unlikely. Where the stocking rate for maximum animal production exceeds the grazing capacity the likelihood of overgrazing and pasture degradation increase. There is also a need to determine whether the grazing 'thresholds' thus established are biologically and/or socially acceptable.

This thesis does not aim to explore any further the relationships between stocking rate and animal production. However, at this point it is worth noting Abel's (1992) criticism of the conventional use of the terms overgrazing and degradation. He indicates successional theory describes degradation as a series of undesirable changes in land condition. Alternatively, Abel (1992) considers change in the net value of production as an indicator of degradation. Abel (1992) therefore adopts the definition of "overgrazing" as the result of a stocking density which causes a reversible decline in the net value of production, and "degradation" as an irreversible decline in the net value of production.

This is based on Abel and Blaikie's (1989) definition of range degradation as: "an effectively permanent decline in the rate at which land yields livestock products under a given system of management. In effect this means that natural processes will not rehabilitate the land within a time scale relevant to humans, and that capital or labour invested in rehabilitation are not justified. This definition excludes reversible vegetation changes even if these lead to temporary declines in secondary productivity. It includes irreversible changes in both soils and vegetation."

Determination of the grazing capacity of grazing lands and development of an understanding of the consequences are the most difficult tasks in grazing management (Vallentine 1990a). Several approaches are available for determining grazing capacity and appropriate stocking rates. Most are based on experience of "average" properties in "average" years (Wilson *et al.* 1990), and trial and error coupled with regular adjustments. Due to the variability in climate and base resources in south-west Queensland, the use of "district averages" is unlikely to yield appropriate grazing capacities for individual properties. Despite this, decisions on grazing capacity must be made, and Vallentine (1990a) lists seven methods for this. Briefly these are:

1. Initial stocking rate tables for various land and pasture types such as those reported by Mills and Purdie (1990) for south-west Queensland.
2. Known stocking rates adjusted for pasture condition and trend information. This is comparable to Condon *et al.* (1969) where known grazing capacity was corrected for factors such as precipitation, soil fertility, plant community type and topography.
3. Assessment of standing forage yield and calculation of stock numbers to use an appropriate quantity of that forage.
4. Percentage utilisation method where actual estimates of forage use or forage remaining are compared with appropriate levels of use or levels of residue for that forage.
5. Pasture comparison methods in which the grazing land under question is compared to a mental ideal or standard for that pasture.
6. Energy based methods requiring detailed quantification and matching of the energy content of pastures and requirements of grazing animals.
7. Forage density methods requiring estimates of forage density and quality to develop indices for appropriate stocking rates.

A number of these approaches require subjective judgment and some prior level of experience regarding the pastures in question. To remove this limitation a quantified approach to determining grazing capacity is required. Several authors propose the adoption of a utilisation approach in estimating grazing capacity. Heady (1975) and Vallentine (1990a) propose that estimates of forage production and utilisation will provide the basis for determining the correct amount of grazing, and the basis for further adjustments in stocking rates as the grazing season progresses. Holechek *et al.* (1989) indicates that most information regarding critical grazing intensities involves utilisation data, and these data can readily be used in stocking rate decisions. They add that a reasonable estimate of average forage production can be combined with the level of utilisation to estimate sustainable grazing capacities. Heady and Child (1994) generally support the utilisation approach in estimating grazing capacity but question whether the proportion of forage utilised or proportion remaining is the appropriate component to examine. They suggest the portion remaining can be measured directly while the portion utilised is only measurable by indirect methods. Scanlan *et al.* (1994) based their examination of "safe" carrying capacities for properties in the extensive cattle grazing region of north-eastern Australia on the portion utilised. This can be represented as:

"safe" grazing capacity(DSE/land system) = (**amount of forage which can be safely eaten** (kg/ha/year) / **amount eaten per dry sheep** (kg/DSE/year)) * **area of the land system** (ha)

where:

amount of forage which can be safely eaten (kg/ha/year) = (**"safe" level of forage utilisation (%) /** 100) * **average annual forage grown** (kg/ha/year)

An estimate of average forage production in semi-arid rangelands is not easy to determine. Forage production varies widely from year to year and from place to place. Up to four-fold variation in pasture yield was observed by Johnston and Carter (1986) from year to year. Consequently grazing pressure and utilisation will also vary. Regional statistics show up to two-fold variation in stock numbers among years (Mills and Lee 1990), which is a smaller variation than for pasture yield (Wilson and Harrington 1990). Vallentine (1990a) reported similar variations in forage production for semi-arid regions of the United States.

In the above discussion the term 'forage' has been used in its broadest sense to describe the vegetation within a system. As described in Section 2.1.5 the vegetation of south-west Queensland is composed of a mixture of perennial, annual and ephemeral species whose presence is largely determined by seasonal conditions. Each of these species, contributes differently to the quantity and quality of forage available and exhibits characteristic responses and tolerances to grazing.

The above discussion indicates the need for flexible stocking rates if appropriate levels of pasture utilisation are to be achieved. Otherwise, pastures will be under-utilised in above average years and over-utilised in below average years. In reality, such flexibility in adjusting stocking rate is impractical due to the inability of graziers to readily either dispose of or acquire large numbers of stock in short time periods. Despite this, Scanlan *et al.* (1994) reported a ±50% change in herd size was occurring on cattle properties in the semi-arid woodlands of north-eastern Australia over the three years 1986/87 to 1988/89.

There are several reasons for maintaining relatively "constant" stock numbers. These include: maintaining income stability (as demonstrated in south-west Queensland by Buxton *et al.* 1995), maintenance of the genetic resource for breeding operations, lack of infrastructure for rapid stock adjustment, avoidance of low prices when de-stocking is required and avoidance of high prices when re-stocking is possible. As a result, Wilson and Harrington (1990) and Reid and Thomas (1973) report short-term increases and decreases in livestock numbers lag behind rainfall variation by one to two years in south-west Queensland. Hence, it may be appropriate to calculate an average "safe" grazing capacity for individual properties at which a core flock or herd can be operated and variability in cash flow minimised. Under favourable seasonal conditions livestock numbers may increase above this 'target' and reduced in poorer seasons.

In practice, Heady's (1975) approach stipulates stocking rates that result in appropriate utilisation of the average forage yield, or more conservatively that result in appropriate utilisation when "about 70 percent" of the average yield is produced. Methods for estimating average pasture growth will therefore be valuable in establishing appropriate utilisation rates.

The question arises as to what approach (constant stock numbers or constant utilisation) is applicable for south-west Queensland. An examination of the broad pasture types found in rangeland Australia indicates a different approach based on pasture type (Table 2.3) although it is unclear as to exactly what was defined as 'low utilisation'.

Table 2.3 Stocking strategies on three main pasture types found in semi-arid Australian rangelands.

Pasture Type	Longevity (years)	Period when plants most susceptible	Stocking approach most suitable	Reference
Chenopod shrublands	30	Drought and fire	Low utilisation via moderate set stocking rates	Graetz and Wilson (1990)
Grasslands	2.5 - 30	Growing season	Low utilisation over growing season	Orr and Holmes (1990)
Ephemeral	0.3 - 0.6	Establishment and reproduction	Low utilisation year round	Wilson et al. (1990)

As the vegetation of south-west Queensland is predominantly a wooded grassland, a regime of moderate set stocking to achieve 'low' levels of forage utilisation during the growing season appears to be the most appropriate for making strategic decisions (20-30 years) on grazing capacity. Due to the variability in seasonal forage production it is unlikely that even low constant livestock numbers will regularly achieve low levels of forage utilisation. However, under such a strategy it is anticipated that both the frequency and duration of periods of over-utilisation is reduced such that plant health is adequate for resource maintenance and production goals. Over several seasons, the average level of forage utilisation could therefore be considered appropriate or "safe". From ecological viewpoint, "safe" levels of forage utilisation would assist in maintaining plant health (maintenance of photosynthetic tissue, root function and flowering and seeding potential), plant density and diversity and ground cover. From a functional viewpoint the level of forage utilisation deemed "safe" may vary across pasture communities and soil types.

In the United States Holechek (1988) reviewed a range of grazing intensity trials and reported positive relationships between average annual precipitation / pasture type and appropriate levels of pasture utilisation. Generally, as average annual precipitation increases, utilisation can be increased, with some exceptions (Holechek *et al.* 1989). They suggested that 25-35% utilisation is appropriate for desert shrublands in arid regions (under 300 mm mean annual precipitation), 35-45% for the semi-arid shortgrass prairie where shrub encroachment was not a problem, and 45-60% for the humid tallgrass and southern pine regions.

Stated in this way, these findings represent a simplification of potentially complex interactions between precipitation, pasture type and appropriate levels of pasture utilisation. As discussed in Chapter 1 the structure and composition of pastures is determined by a range of factors. A pasture community's resilience to grazing, expressed above as appropriate levels of utilisation is also influenced by a variety of factors (e.g. soil fertility, soil infiltration rates, soil surface characteristics, soil erodibility, species morphology, phenology, composition and palatability). Conversely, utilisation levels are integral to changes in species composition, plant density, forage yield and soil cover. While appearing simplified, the findings of Holechek *et al.* (1989) provide a useful guide for practitioners making strategic decisions (20-30 years) on grazing capacity in the absence of other information.

An examination of forage growth and "safe" / "low" levels of forage utilisation therefore appears appropriate to objectively estimate strategic grazing capacities of native pastures in south-west Queensland.

Such an approach requires an understanding of plant production in the region, and the effect utilisation has on these plant processes. This is reinforced with the statements of Harrington *et al.* (1990) that "management of rangeland ecosystems is ecological in nature, of a low energy input, and involves actions that seek to modify, rather than control, the natural forces operating on the land" and "that management is weak in proportion to the dominant climatic forces that control the ecosystem".

Plant growth in semi-arid areas is directly related to rainfall (Christie 1978, Le Houerou 1984, O'Connor 1985, Sala *et al.* 1988, Robertson 1988 and Scholes 1990), but on a non-linear scale depending on geographical location and pasture species present (Wilson and Harrington 1990). It follows that seasonality and amount of rainfall may be used to estimate pasture productivity and appropriate levels of pasture utilisation (Utilisation as defined earlier, is the proportion of the current year's forage production that is consumed by grazing animals.)

The timing of when to assess pastures and adjust stocking rate deserves attention. Holechek (1988) indicated that most decisions regarding stocking rates for perennial pastures are made at the end of the growing season when the quantity of forage available has peaked. Christie and Hughes (1983) supported this view for south-west Queensland and recommended that annual adjustment of livestock numbers be made at the end of each summer (October to March) growing period. This can lead to over estimates of grazing capacity as the peak standing crop usually does not last due to senescence, detachment and decay of material. However, this reduced forage availability may not reduce grazing capacity during winter, provided plants can tolerate closer utilisation during dormancy and forage intake relative to body weight is reduced as pasture quality deteriorates (Vallentine 1990a).

The important question is the stage at which perennial pastures become susceptible to over-utilisation. Adjustments to stocking rates at the end of summer may lead to over-utilisation at the start of the next growing season resulting in damage to individual plants and the pasture as a whole. Determination of stocking rates to achieve appropriate levels of utilisation at the start of the growing season when individual plants are susceptible to over-use may be a more appropriate goal. An understanding of plant growth responses is necessary to achieve this.

2.3 Plant growth and net primary productivity

The other component influencing grazing capacity is plant production. A multitude of terms in the literature describe plant production. These include:- forage production, pasture production, forage growth, standing crop, pasture yield, dry matter yield, peak yield, browse, and net primary production. In this thesis, plant production is confined to the grass and forb component of the pasture. It is the portion that directly determines grazing capacity. The contribution of browse (most commonly mulga leaf) where it is available is considered additional, and its inclusion as a component of the diet is described in Chapter 5.

The earliest reported measurements of pasture yield in western Queensland were made by Davies *et al.* (1938) and Roe and Allen (1945) on Astrebla spp. grasslands in central and south-western Queensland respectively. Hulett (1970) recorded basal cover, standing crop (green material, standing dead material and litter), root yield and soil moisture in order to examine the net productivity and biomass transfer on a mitchell grass (*Astrebla* spp.) community near Charleville. The first observations of pasture yields in mulga country were reported by Ebersohn (1970). He compared presentation yields from a range of native and sown pastures throughout the mulga zone and showed that greater dry matter yields could be achieved from introduced pastures under favourable conditions.

Numerous authors have since examined many aspects influencing native pasture growth in the mulga zone of Queensland. Brown (1982, 1985 and 1986) reported the effects of defoliation, burning and fertilising on the growth of a number of native grass species. The water use of native and exotic species was examined by Christie (1975a,1978 and 1981) and by Pressland (1982). Growth response to nutrients and temperature was studied by Christie (1975b and 1979) and Silcock *et al.* (1976). The effects of soil loss on pasture production was examined by Pressland and Cowan (1987) and Miles (1993). Beale (1973) described a decrease in pasture yield under increasing densities of mulga trees at two locations, and Carter and Johnston (1986) reported similar relationships for the effects of *Eremophila gilesii* on pasture yield at one location.

In the majority of these studies, presentation yields were recorded and were an adequate measure for the issue in question. However, presentation yields do not indicate the dynamics of pasture production. They reflect what is in a pasture at a given point in time and not what has been produced. Alternatively net primary productivity describes the rates of plant production from a unit area. It integrates the duration of active growth, and rates of litter production and decomposition. Knowledge of net primary production is more meaningful for interpretation of grazed situations than presentation yields taken two or three times a year (Burrows and Beale 1976). Absolute net primary production refers to both the above and below ground pasture components. However, above ground or aerial primary production is the most common measure where large vertebrates are the principal herbivores (Milner and Hughes 1968).

Primary production experiments from around the world are illustrated by Singh *et al.* (1975), Le Houerou and Hoste (1977), Webb *et al.* (1978), O'Connor (1985), Biddiscombe (1987), Redman (1992) and Milchunas *et al.* (1994). In a similar fashion to these authors, Sala *et al.* (1988) summarised data from 9500 sites in the central grassland region of the United States and demonstrated a strong relationship between above ground net primary production, the amount and distribution of annual precipitation and the effect of soil type.

Slatyer (1961) and Christie (1978, 1979) laid the foundations for primary production studies in the mulga zone, the former author working in central Australia, and the latter in south-west Queensland. Christie (1978) related water use, primary production, litter production and decomposition and nutrient dynamics over a twelve month period for a native pasture in the mulga zone near Charleville. In further studies, Christie and Hughes (1983) explored the interrelationships between net primary productivity and the grazing capacity of the mulga lands using systems analysis and computer simulation.

In conclusion, net primary production data from the dominant land systems of south-west Queensland would be crucial to estimating sustainable grazing capacities for individual properties. Using systems analysis and simulation, these data can be extrapolated over time and space to estimate probabilities of plant production and "safe" long-term grazing capacities.

2.4 Role of systems analysis and computer modelling in understanding pasture productivity, grazing theory and decision making processes

The terms "systems analysis", "systems approach" and "computer modelling" can be ambiguous. Weiss and Robb (1986) highlighted this problem and called for consistency in the use and definition of the term "systems". Abel (1977) defined a "system" as a set of interrelated elements which behave interactively and collectively. It enables the synthesis of those attributes of a system which may be useful, and the description of these attributes in a manner which is amenable to manipulation and analysis. This procedure is called model building, and Abel (1977) provided two main reasons for this approach. Firstly, by constructing a model and studying its behaviour we may learn something about the "real-world" system. Secondly, we may be able to use the model to predict the behaviour of the "real-world" system.

The method of describing a system is also important. It must be flexible and capable of being modified to reflect changes and the development of ideas. That is, it must be graphical or numerical in nature (Abel 1977). In order to accommodate the complex interactions and relationships found in biological systems, computers are commonly used for model construction and evaluation. When described mathematically the components of a system are linked within a computer program to form a computer model. Ross (1977a) pointed out that a computer is not essential to modelling, and suggested that many of the benefits of computer modelling projects are dependent on the model building process rather than on the computer.

The field of systems analysis and computer modelling is rapidly growing in all aspects of human endeavour. Originating within the physical sciences, the methods of systems analysis are now widely applied to the biological systems found within agriculture. Van Dyne (1970) described a systems approach to grassland problems which would include (i) compiling, condensing and synthesising much information concerning the system components, (ii) detailed examination of the system structure, (iii) translating knowledge of components, function and structure into models, and (iv) using models to derive new insights about management and utilisation. Two major roles therefore exist for systems analysis and computer modelling in agriculture. The first is describing and understanding how various systems work, and the second is evaluating management decisions made within those systems. The two roles are often linked.

Examples of the first role are models describing beef cattle growth (McCown 1980, Oltjen *et al.* 1986 and McCaskill 1991), lamb and wool production (Pepper and McMeniman (1980)), runoff from catchments (Littleboy *et al.* 1992 and Wilcox *et al.* 1990), cropping systems (DeJong and Zentner 1985, Berndt and White 1976, Hammer *et al.* 1983, Hammer 1984) and grazing and forage systems (Freer and Christian 1980, Caughley 1982, McKeon *et al.* 1982b., Coughenour *et al.* 1984, Smith *et al.* 1985, Clewett 1985, Hanson *et al.* 1988, Stout *et al.* 1990, Hacker *et al.* 1991).

In the role of decision making, McKeon *et al.* (1982a) indicated five main reasons for mathematical modelling:

(i) Modelling allows the decision maker to calculate the outcome of processes operating in opposite directions. For example, increased stocking may increase production per hectare, but decrease individual animal performance and increase the risk of pasture degradation. Similarly, with a management practice such as burning, the likely increased accessibility and diet quality have to be balanced against the increased risk of a forage shortfall.

(ii) Computer modelling allows the decision maker to respond quickly to changing economic situations. Field experiments to explore the best decisions take time and may be out of date before they are completed. Models can be re-run quickly with different inputs.

(iii) Models allow "what if" type questions to be answered without the expense of carrying these out in the real world. If the answers look promising then they can be tested in the field. This allows the decision maker to expand their horizons.

(iv) Modelling allows extrapolation of research results collected over limited time periods (a few years) to a greater range of weather and management possibilities.

(v) Modelling complements experimental work to provide a methodology for investigation of the efficient integration of forage options. Physical models of production systems with native pasture, sown pasture, forage and grain crops require large resources in time and space. Computer modelling is probably the only way the range of possibilities can be tested.

Examples of models used as decision making tools in the field of grazing and forage systems are reported by Swartzmann and Van Dyne (1972), White (1978), McKeon and Scattini (1980), Danckwerts (1982), Maden and Thatcher (1984), Christie and Hughes (1983), Freeman and Benyon (1983), Wight *et al.* (1984), Johnson and Parsons (1985), Tharel *et al.* (1985), Loehle (1985), Walker *et al.* (1989) and Meppem and Johnston (1990). Only two of these models tackle the topic of estimating sustainable grazing capacity. Christie and Hughes (1983) describe the theory within a modeling approach, but only Danckwerts (1982) puts this into practice, and favourably compares model results to actual grazing management.

Examples of the role of modelling in western Queensland are reviewed by Johnston (1992). In this environment, modelling methodology has proved to be a valuable tool in terms of handling year to year climate and production variability.

It is apparent from the above that computer modelling is not an end in itself, but aims to complement experimentation in the solution of management problems (McKeon *et al.* 1982a).

2.5 Modelling pasture productivity using the GRASP model

GRASP (GRASs Production) is a computer model that combines two successful approaches in modelling plant growth, viz., those of McCown *et al.* (1974) and Fitzpatrick and Nix (1970) (McKeon *et al.* 1990). GRASP was chosen for the following reasons:

1. it was available;
2. it was developed for native pastures of northern Australia;
3. it has been well tested on a range of native pasture communities (McKeon *et al.* 1990);
4. it is physiologically sound;
5. it has been peer reviewed in a week long workshop (Littleboy and McKeon 1996); and
6. it is supported by a network of other users.

It uses two basic biological concepts to describe forage growth and is written in the FORTRAN computer language.

The first concept is the soil water balance where changes in soil moisture are calculated as the difference between inputs and outputs of water to the soil profile. Inputs are rainfall, and outputs are soil evaporation, plant transpiration, runoff and drainage. A daily timestep and three soil layers are used, so that the separate processes of soil evaporation and transpiration can be simulated.

The soil water balance component of GRASP was first developed by Rickert (1975) using data from wheat crops in Western Australia. The model was subsequently validated with independent data for native and sown pastures at Gayndah in south-east Queensland (Rickert and McKeon 1982). The methodology of estimating processes in the water balance were reviewed by Rickert (1984) and the different approaches used to link soil water to plant production are described by McKeon (1984) and Clewett (1985).

The second basic concept in the GRASP model is that plant growth is proportional to transpiration (kg/ha/mm of transpired water or transpiration efficiency). This concept has provided a simple yet robust method of estimating forage growth in the Queensland environment. The transpiration efficiency is adjusted to account for forage type and soil fertility (nitrogen). The relationship is modified for temperature as described by Fitzpatrick and Nix (1970). Transpiration is calculated from soil moisture supply, evaporative demand and green cover. When green cover is very low (for example after severe drought or burning), growth is calculated from the potential regrowth rate which is characteristic of the forage. Three forage pools (green, standing dead and litter) are used and modified by growth, death decay and grazing. Details of the forage production model and it's applications are described by McKeon *et al.* (1982b), Carter and Johnston (1986), McKeon *et al.* (1990), Day *et al.* (1993), Scanlan and McKeon (1993), Littleboy and McKeon (1996) and Day *et al.* (1996).

2.6 Conclusions

The above review has described the environmental factors (climate, soils and vegetation) influencing pastoral production in south-west Queensland. The review has aimed to highlight the fact that the rangelands of south-west Queensland are semi-natural ecosystems in which pastoralism seeks to obtain a productive output by simply adding domestic stock to a natural landscape (Harrington *et al.* 1990). Management is dwarfed by the complexity of the landscape and community ecology of the region with manipulation of grazing pressure being the main management tool available to land managers.

Concerns regarding the level of land degradation within this landscape were raised by a number of authors. The processes and extent of land degradation were described by others with excessive grazing pressure regularly identified as a cause of degradation. Yet few authors suggested tangible means of addressing the issue of excessive grazing pressures. However, the Warrego Graziers Association (1988), Mills *et al.* (1989), Miles (1989) and Anon. (1993) suggested a need to review "carrying capacities" / "stocking rates" (grazing capacities) was central to reducing land degradation through a greater appreciation of the capability of the land resource. In addition, Anon. (1993) (Department of Lands publication) recommended these reviews should be done on a property-by-property basis and the revised estimates of grazing capacities should be publicly available.

To examine grazing capacities in the semi-arid rangelands of south-west Queensland an ecologically based approach is therefore warranted. Due to the complexity of ecological systems the potential role of modelling was examined. The end product of these models are decision-support-systems (DSS) which allow research information/knowledge to be used by individual ecosystem managers (McKeon *et al.* 1990). Unlike herd dynamic and economic models (Stafford Smith and Foran (1988), Stafford Smith and Foran 1990 and W.E. Holmes (pers. comm.), many of these grazing system models have not been actively extended and their use in managing native pastures has been limited. This is largely due to (i) the level of generality at which the models have been developed, (ii) the failure of model builders to design models which address the information needs of individual graziers (Cox 1996 and Humphreys 1997) and (iii) apparent failure of modellers to commit to a particular region and application. These issues are addressed in this thesis.

While capable of handling the year to year variability in productivity, current models are incapable of accommodating spatial variability. Such models are unlikely to contribute to the management of native pastures unless they address the variability in soil and vegetation at the individual property scale. The resources of individual properties need to be described within a modelling context so that the calculation of sustainable grazing capacities can be made.

In this thesis the role of modelling at a level useful for managing native pastures is described. An approach based on ecological principles is developed to estimate sustainable "safe" grazing capacities for individual properties in south-west Queensland. This then provided the basis for a quantitative review of grazing capacities on individual properties across the region in a joint Department of Lands and Department of Primary Industries program. The methodology using systems analysis and modelling entails:

1. Collection of net primary production data from the dominant land systems in south-west Queensland (Chapter 3).
2. Calibration of the forage production model GRASP for each of these land systems using these data (Chapter 4).
3. Validation of the forage production model GRASP using independent data from south-west Queensland (Chapter 4).
4. Linking model outputs and resource inventories for individual land systems on "benchmark" properties to estimate average forage growth and "safe" levels of forage utilisation for any location in south-west Queensland (Chapter 5).
5. Examination of real-time forage utilisation on 46 properties over the period 1986 to 1988 (Chapter 5).
6. Development and application of a method for use by land managers and administrators for the estimation of "safe" grazing capacities for individual properties (Chapter 5 and 6).

The hypothesis formulated is that through the measurement of key plant production relationships, and extrapolation of these over time and space, that grazing capacities for individual properties can be estimated, and related to sustainable levels of forage utilisation.

3.0 PRIMARY PRODUCTIVITY OF NATIVE PASTURES

3.1 Introduction

The above review and system analysis established a need for measuring net primary production from the major land systems found in south-west Queensland. This chapter describes the collection of those data from eight land systems over the period 1986 to 1990. An approach examining soil-plant-water relations similar to that of Christie (1978 and 1979) and McKeon *et al.* (1982b and 1990) was employed. The spatial and temporal variability in production is highlighted.

In Chapter 4, the data were used to adapt the GRASP computer model (McKeon *et al.* 1982b and 1990) to south-west Queensland pasture types. The role of this model in estimating sustainable grazing capacities for native pastures in the region is then explored in Chapter 5.

3.2 Materials and methods

Nine sites (Figure 3.1, Table 3.1) representative of eight land units found in south-west Queensland were selected for primary productivity measurements. Each of these units represented between 55% to 90% of the area of eight land systems with one exception. The land unit on which site 4 was located represented only 5% of the B1 land system but was chosen for the uniformity across the site. Sites were located on areas of uniform vegetation and soil and were fenced to exclude all grazing animals. Level sites were chosen to minimise the effects of rainfall run-on and run-off. There was no replication of sites due to time constraints. The technique for productivity measurements for sites 1 and 2 varied slightly from the remaining sites in terms of plot layout and sampling frequency and intensity. Sites 1 and 2 were observed over the period October 1986 to December 1987 (First observation period). Sites 3 to 9 were observed within the period October 1988 to November 1990 (Second observation period). Other variations are detailed below.

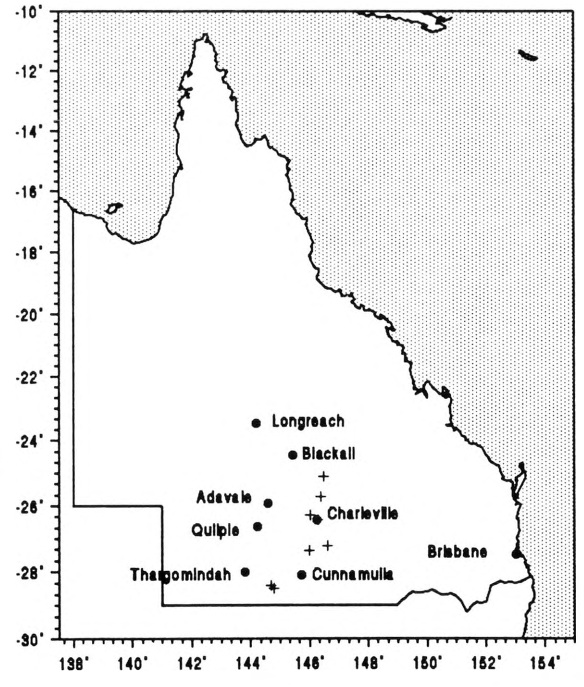


Figure 3.1 Location (+) of the nine sites for primary productivity measurements on native pastures in south-west Queensland during the period October 1986 to November 1990.

For sites 1 and 2, three plots (8m x 15m) were selected within the enclosure aiming to avoid micro-site variation. The three plots were mown at the start of the growing season (October) to a grass tussock height of 5cm with a lawn mower. Detached plant material was then removed from the site. At three week intervals, pasture data were collected from four quadrats (1.0 x 0.5m) in each plot. Quadrats were placed along a sampling front in each plot. The sampling front moved in a different direction for each plot to avoid possible edge effects. Soil moisture to 1m was measured from two hand augured cores in each plot. Quadrat and core placement were designed to avoid trampling of material awaiting future observation. (See Appendix 1 for site and plot layout and direction of sampling fronts.)

For sites 3 to 9, four plots (4 x 10m) were selected within enclosures. The four plots were mown at the start of the growing season (October) to a tussock height of 5cm with a whipper snipper mounted with a brush cutting blade. This method gave better control over cutting height and reduced tussock "trauma" compared to the lawn mower. Detached material was removed. At six week intervals, pasture data were collected from two quadrats (1.0 x 0.5m) in each plot. Quadrats were placed along a sampling front in each plot. Only one soil core to 1m was sampled for soil moisture in each plot. (See Appendix 2 for site and plot layout and direction of sampling fronts.)

3.2.1 Plant sampling and analysis

At each sampling the following parameters were recorded for each quadrat:

- visual estimate of species composition (by dry biomass yield);
- visual estimate of green cover %;
- visual estimate of bare soil %;
- plant height (cm) using a ruler and constant weight;
- slide photograph from above quadrat for additional estimates of bare soil %, green cover %, dead cover % and litter cover % using a point quadrat on projected slide image in laboratory; and,
- dry matter yield of grass and herbage (kg/ha) clipped to 5cm using hand-shears and oven dried at 80°C.

The visual estimates were made as a backup for the other recordings.

For sites one and two, sub-samples of harvested material were separated into green leaf, dead leaf, green stem, dead stem, inflorescence, and dicotyledons (forbs). Nitrogen concentration of grasses was determined for entire plant tops using the technique of Kerr and von Steiglitz (1938). Perennial grass basal area (%) was recorded once at the end of the growing season at each site using a point frame (Brown 1954). Tree basal area (m^2/ha) was also measured at the same time using a Bitterlich gauge.

A mean and standard deviation for each parameter at each sampling event was calculated. Plots were analysed as replicates to examine the degree of site variability. A one way analysis of variance was used to test for significant ($P<0.05$) changes in yield and green cover over time. Transformations were performed to normalise the yield data (ln yield) and green cover data (arc sin SQRT(green cover/100) prior to analysis in order that the assumptions for an analysis of variance were met (normal distribution of data) (Goulden 1952).

Table 3.1 Site descriptions for primary productivity measurements in south-west Queensland.

No.	Site	Latitude	Longitude	Land Zone WARLUS	Land System WARLUS*	Land Unit WARLUS*	Prop. of Land System (%)	Soil Type	Perennial Grasses	ppf
1	Biddenham	25°43′	146°24′	Undulating Downs	IV F1	IV 1	80	Grey/brown cracking clay	Astrebla spp.	Ug 5.21
2	Charleville	26°25′	146°18′	Mulga Sandplains	III S1	III 45	85	Sandy red earth	Mulga grasses #	Uc 1.43
3	Airlie	27°21′	146°0′	Alluvial Plains Open	III A2	III 16	55	Grey cracking clay	Astrebla spp.	Ug 5.24
4	Lisnalee	25°5′	146°30′	Undulating Brigalow	IV B1	IV 20	5	Loamy red earth	Cenchrus ciliaris	Gn 2.12
5	Maxvale	26°16′	146°3′	Soft Mulga Lands	III M3	III 52	85	Loamy red earth	Mulga grasses#	Um 1.43
6	Turn Turn	28°29′	144°49′	Mulga Sandplains	I S2	I 61	70	Sandy red earth	Mulga grasses#	Gn 2.12
7	Wittenburra Open	28°29′	144°42′	Hard Mulga Lands	I H2	I 51	70	Loamy red earth	Mulga grasses#	Gn 2.11
8	Wittenburra Enclosed	28°29′	144°42′	Hard Mulga Lands	I H2	I 51	70	Loamy red earth	Mulga grasses#	Gn 2.11
9	Wongalee	27°12′	146°37′	Spinifex Sandplains	III N1	III 64	90	Yellow earthy sand	Triodia spp.	Uc 1.23

* Western Arid Region Land Use Studies, (Dawson 1974, Turner 1978 and Mills *et al.* 1990)

\# *Thyridolepis mitchelliana, Monachather paradoxa, Digitaria* spp., *Eragrostis* spp. and *Aristida* spp.

3.2.2 Soil sampling, analysis and additional data sources

Soil moisture was measured in 10cm intervals to a depth of 1m at each sampling. Samples were oven dried (100°C) and gravimetric moisture content calculated. Results were converted to volumetric values using bulk density data for each soil type. A one way analysis of variance was used to test for significant ($P<0.05$) changes in soil moisture over time. Bulk density at 10 cm increments down the profile was measured at sites 1 and 2 by pressing tobacco tins of known volume into the side of a freshly excavated pit. The bulk density for other sites was estimated from site 1 and 2. Total soil nitrogen (N%), total soil phosphorus (P%), soil pH, organic carbon (OrC%), coarse sand (CS%), fine sand (FS%), silt (SI%) and clay (CL%) data were obtained from profile descriptions of the main land units comprising each land system in the Western Arid Region Land Use Studies (WARLUS) (Dawson 1974, Turner 1978 and Mills *et al.* 1990).

3.2.3 Climatic data

Daily rainfall was measured at each site or at a near-by homestead. As no weather station was located ate each site the following daily climatic data for Charleville were used:

- 9am dry bulb temperature (°C)
- 9am wet bulb temperature (°C)
- 3pm dry bulb temperature (°C)
- 3pm wet bulb temperature (°C)
- Daily maximum temperature (°C)
- Daily minimum temperature (°C)
- Daily terrestrial minimum temperature (°C)
- Daily pan evaporation (mm)
- Daily vapour pressure deficit (hPa)*

*The average daily vapour pressure deficit was calculated after Tanner and Sinclair (1983) as:

$$\mathbf{VPD=Vpsat_{(tmin)}+(Vpsat_{(tmax)}-Vpsat_{(tmin)})*0.75-Vpactual}$$

3.3 Results of primary productivity experiments

3.3.1 Weather conditions during observation periods

Rainfall varied considerably among sites and observation periods. For sites one and two, monthly rainfall was generally equivalent to or above the long-term median monthly rainfall (Figure 3.2). The seasonality of the rainfall during the first observation period approximated the distribution of median rainfall. For the second observation period, rainfall was erratic and unseasonal, with monthly totals either well below or above the long-term median (Figure 3.3). Over the entire measurement period at each site, observed rainfall totals varied +/- 25% from the long-term median (Table 3.2).

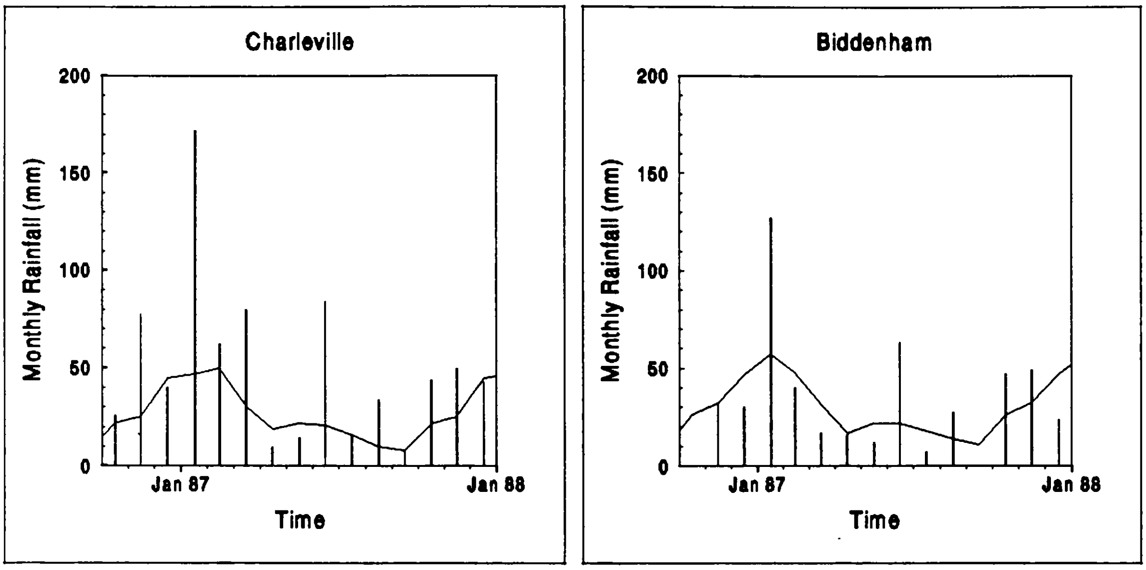


Figure 3.2 Monthly (vertical lines) and long-term median monthly (continuous line) rainfall at the Biddenham and Charleville native pasture primary productivity sites for the first observation period October 1986 to December 1987.

Table 3.2 Comparison of rainfall totals (mm) for each site over the observation periods with average and median values for corresponding periods from the nearest long-term recording stations. Deviation from median shown.

Site	Period	Observed	Average	Median	Deviation (%)
Biddenham	14 months	480	594	574	-16
Charleville	14 months	640	576	542	+18
Airlie	17 months	698	620	575	+21
Lisnalee	23 months	967	992	930	+4
Maxvale	18 months	594	723	672	-12
Turn Turn	18 months	358	514	475	-25
Wittenburra Open	13 months	281	345	314	-11
Wittenburra Enclosed	15 months	303	392	363	-17
Wongalee	18 months	537	626	527	+2

Air temperature, pan evaporation and vapour pressure deficit data for Charleville are presented in Figure 3.4 for both observation periods. Generally the summers were hotter than average, with both daily maximum and minimum temperatures above average. The winters were milder with daily maximum temperatures either approximating or below the long-term average, while daily minimum temperatures were generally warmer than average. The deviations from the long-term average for these parameters are shown in Figure 3.5.

Pan evaporation approximated the long-term average over both observation periods, while the vapour pressure deficit was greater than average (Figure 3.5), especially during the summers.

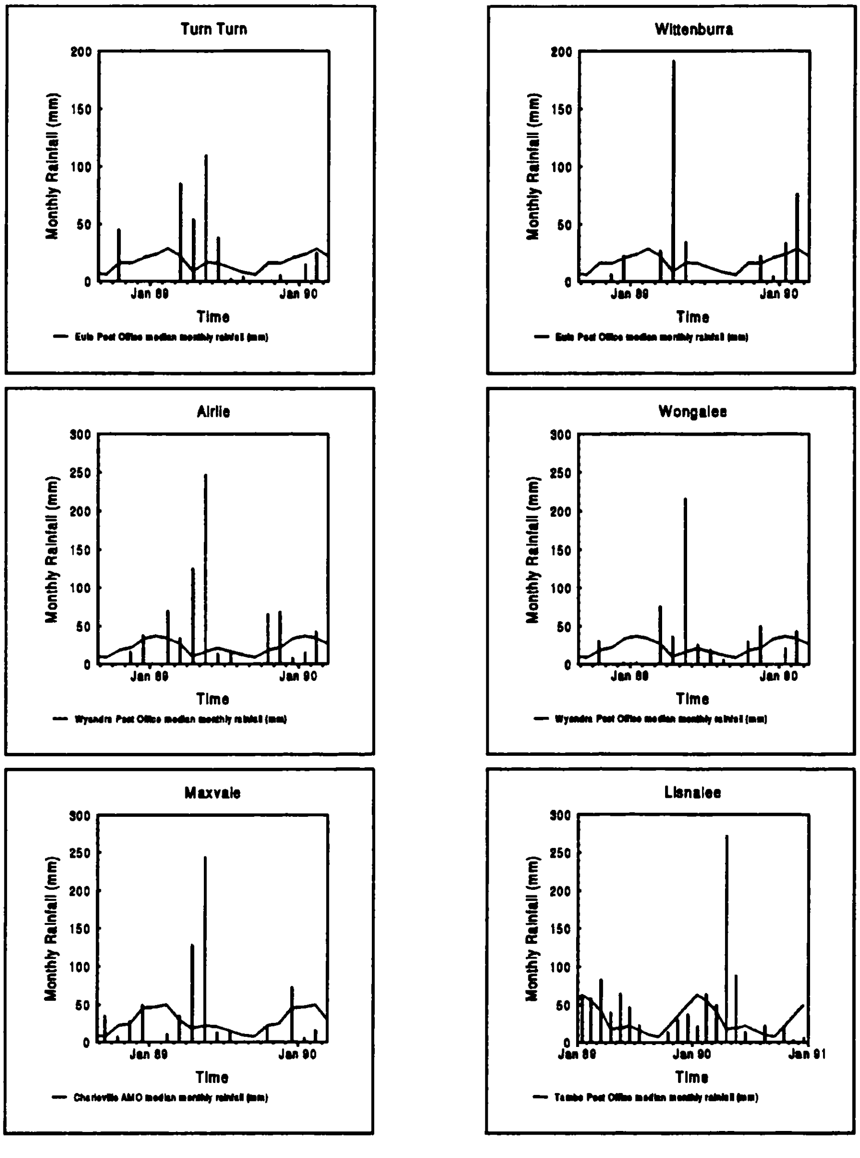


Figure 3.3 Monthly (vertical lines) and long-term median monthly (continuous line) rainfall for the Turn Turn, Wittenburra, Airlie, Wongalee, Maxvale and Lisnalee pasture primary productivity sites in south-west Queensland for the second observation period October 1988 to November 1990 (median rainfall from nearest long-term station).

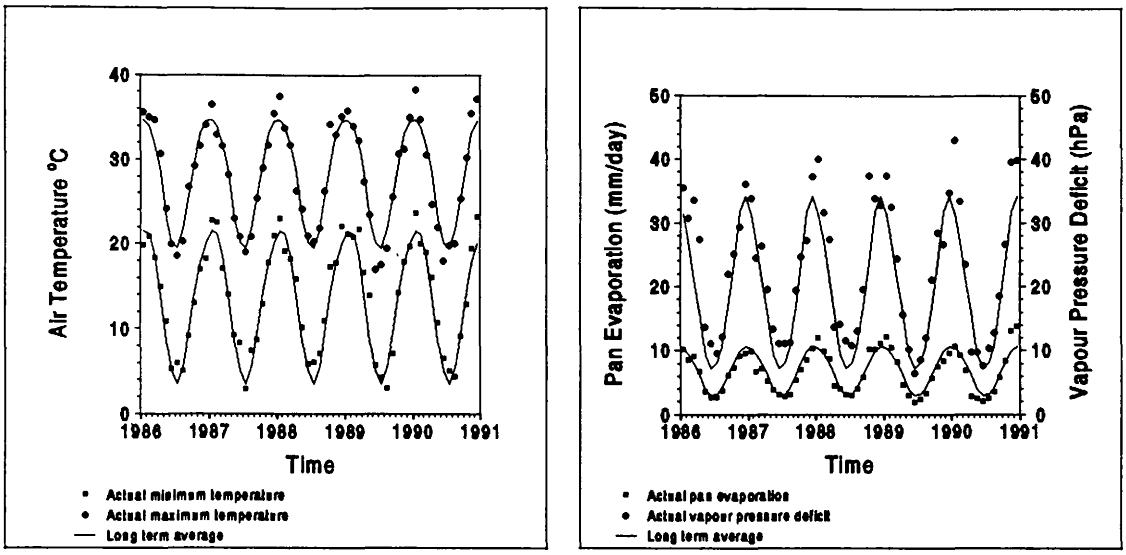


Figure 3.4 Temperature, pan evaporation and vapour pressure deficit over both observation periods at Charleville, October 1986 to November 1990. (Bureau of Meteorology).

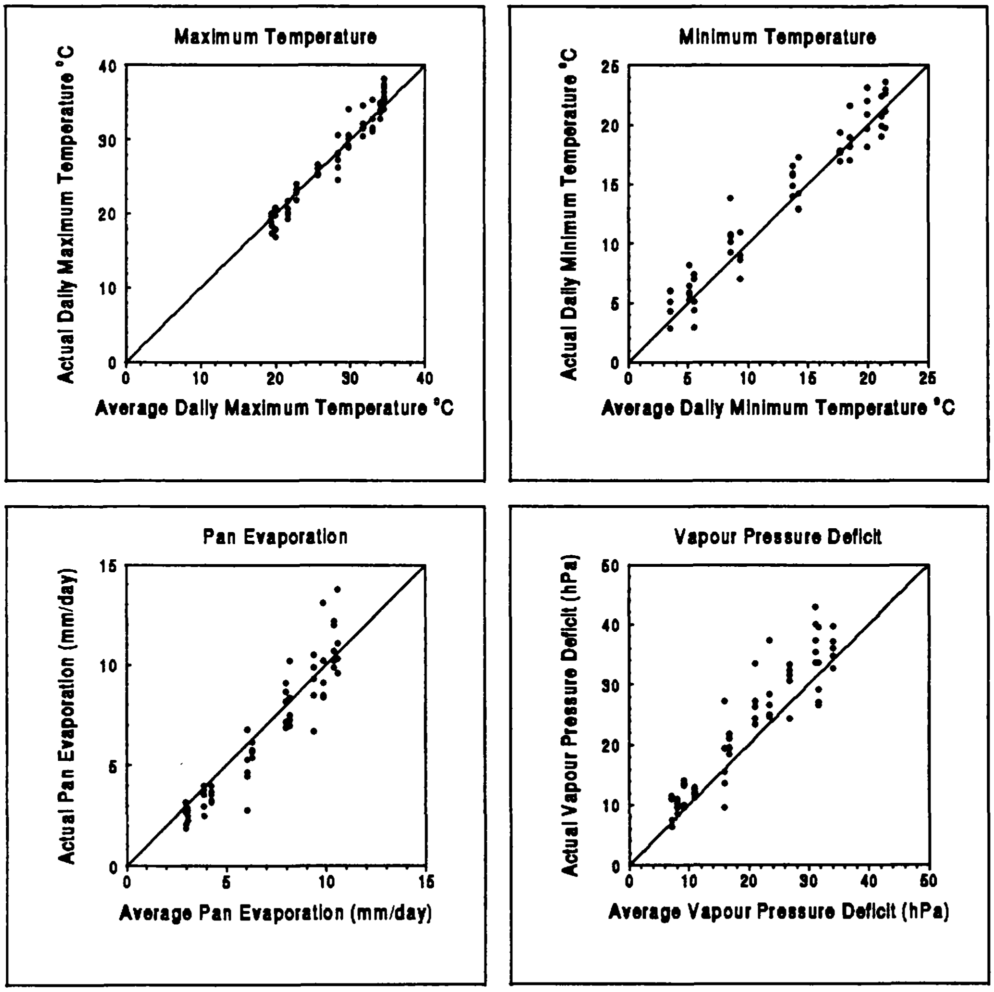


Figure 3.5 Deviations from average climatic conditions for Charleville over both observation periods October 1986 to November 1990. (Bureau of Meteorology).

3.3.2 Pasture yields and growth patterns

This section describes (1) the time course of pasture yield, green cover and nitrogen uptake; and (2) the relationships between yield, evapo-transpiration and site characteristics.

Basal area of perennial grasses ranged from 0.5% on the hard Mulga land system at Wittenburra to 6.2% on the Buffel grass on the undulating Brigalow and Gidyea land system at Lisnalee (Table 3.3).

Table 3.3 Perennial grass basal area (%) and tree basal area (m^2/ha) of sites measured once at the end of the growing season.

Site	Grass Basal Area (%)	Tree Basal Area (m^2/ha)
Biddenham	4.0	0.0
Charleville site	4.3	0.5
Airlie	4.0	0.0
Lisnalee	6.2	0.0
Maxvale	2.7	0.8
Turn Turn	1.6	2.0
Wittenburra Open	0.5	0.0
Wittenburra Enclosed	0.5	1.5
Wongalee	2.7	0.5

Primary productivity data are summarised in Table 3.4. Detailed data are presented in Appendix 3. Volumetric soil moisture was calculated for the full depth of the profile (0-100cm) using the bulk densities measured (Table 3.5). A significant variation ($P<0.05$) in soil moisture between plots was only observed at the Airlie site (cracking clay soil). At some sampling dates for most sites, when dry conditions prevailed, lower layers in the profile could not be sampled as the auger failed to retain the dry soil. Moisture content for these layers was extrapolated in order to present a complete data set for analysis. The extrapolation assumed the top half of the profile contained a proportion of the total moisture in the entire profile. Although the proportion of soil moisture in this half varied with each site, variation among sampling times was small (Appendix 4), allowing total soil moisture to be estimated when the whole profile was not able to be sampled. This approach allowed the calculation of evapo-transpiration for all sampling times. Evapo-transpiration was calculated as follows;

$$\mathbf{ET = SMt_1 - SMt_2 + RAIN}$$

where:

- ET = Evapo-transpiration (mm)
- SM = Soil Moisture (mm)
- RAIN = Rainfall (mm) between Time_1 and Time_2 (t_1 and t_2)

The loss or gain in soil moisture due to run-off, run-on and drainage below 1m and lateral movement was unable to be estimated and was not included the calculation of ET.

Standing dry matter yields varied among sites, reflecting differences in basal area (Table 3.3), species of perennial grasses, rainfall and soil type. Yields increased with time from initial mowing (Figure 3.6a and b). At the Charleville and Wongalee sites the dry matter yield varied significantly across plots ($P<0.01$ and $P<0.05$ respectively) reflecting possible problems of sampling on fronts and micro-site variation. A significant variation ($P<0.01$) in green cover(%) across plots was observed at the Charleville site only.

Table 3.4 Summary of primary productivity results, rainfall, soil moisture and calculated evapotranspiration (ET Cum.) (calculated between sample dates) for nine sites in south-west Queensland from October 1986 to November 1990 (Legend at the end of Table 3.4).

Site and Date	Dry matter Yield (kg/ha)		Green Cover (%)		N Conc. (%)	Rain Cum. (mm)	Total Soil Water (mm)		ET Cum. (mm)
Biddenham							0-85cm		
21.11.86						0.0	175.4	+	0.0
17.12.86	86	a	13.1	fg	2.57	62.0	215.8	ef	21.7
07.01.87	187	b	16.5	g	2.12	103.5	194.9	ac	84.1
26.02.87	1144	c-f	44.9	h	1.23	228.5	196.6	bc	207.4
18.03.87	1633	ef	16.8	g	0.82	228.5	179.5	a	224.5
08.04.87	950	c	6.8	d-f	0.66	245.5	D		NC
29.04.87	1238	c-f	4.1	b-e	M	269.5	184.3	ab	260.7
21.05.87	1129	c-e	2.9	a-d	0.59	273.2	183.6	ab	265.1
12.06.87	1040	c	0.6	a	0.64	273.2	178.0	a	270.6
24.06.87	1289	c-f	2.0	a-c	0.74	336.2	229.6	g	282.0
16.07.87	1463	d-f	1.2	ab	0.64	336.2	181.6	a-c	330.1
11.08.87	*1678	f	3.9	bc	0.64	343.2	201.5	c-e	317.1
26.08.87	1177	c-e	7.9	ef	0.63	370.2	D		NC
18.09.87	1127	c-e	5.5	c-e	0.65	370.2	D		NC
08.10.87	1093	cd	5.3	b-e	0.63	420.0	215.9	d-f	379.5
29.10.87	1405	c-f	7.0	d-f	0.65	426.2	188.5	bc	413.2
25.11.87 #						476.2	226.3	fg	425.4
10.12.87 #						479.7	D		NC
Charleville							0-100cm		
24.10.86						0.0	50.1	bc	0.0
05.12.86	206	a	16.7	de	2.46	120.4	68.1	+	102.3
31.12.86	243	a	9.1	bc	1.79	125.4	38.4	a	137.1
21.01.87	195	a	8.9	bc	1.77	145.4	41.2	ab	154.3
11.02.87	275	a	19.6	e	2.08	276.4	53.1	c	273.1
04.03.87	703	b	29.3	f	2.42	338.4	64.5	de	323.8
26.03.87	645	b	17.1	de	1.20	395.4	84.1	g	361.4
16.04.87	799	bc	18.4	de	1.26	395.9	44.9	a-c	400.5
20.05.87	720	bc	6.6	b	1.04	416.9	49.9	bc	417.1
11.06.87	847	bc	0.0	a	1.02	416.9	43.5	a-c	423.5
01.07.87	612	bc	10.4	b-d	1.45	495.9	76.5	fg	469.5
29.07.87	834	bc	11.3	b-e	1.38	503.3	71.9	ef	481.4
19.08.87	905	bc	12.5	c-e	1.67	536.9	79.7	fg	507.2
02.09.87	943	bc	16.3	de	1.72	536.9	65.5	de	521.5
23.09.87	*1190	e	16.6	de	1.24	545.4	45.7	a-c	549.7
15.10.87	985	bc	8.9	bc	0.83	595.9	45.8	a-c	600.5
05.11.87 #						605.4	44.7	a-c	610.7
26.11.87 #						640.4	45.0	a-c	645.4

Table 3.4 Continued

Site and Date	Dry Matter Yield (kg/ha)	Green Cover (%)	Rain Cum. (mm)	Total Soil Water (mm)	ET Cum. (mm)
Airlie				0-100cm	
10.11.88			0.0	86.5 +	0.0
16.01.89	53 a	2.3 a	53.3	88.6 +	51.2
27.02.89	80 a	2.6 a	122.3	87.6 +	121.2
10.04.89	45 a	6.8 b	183.5	132.9 +	137.1
03.07.89	388 b	12.2 c	543.3	274.7 +	355.1
14.08.89	411 b	14.5 cd	560.1	M	NC
25.09.89	560 b	21.3 d	560.1	40.8 +	605.8
28.11.89	*1216 c	33.6 e	694.1	146.9 +	633.7
12.02.90 #			698.1	69.3 +	715.3
Lisnalee				0-100cm	
13.01.89				95.5 +	0.0
02.03.89	648 a	24.2 c	31.5	43.6 +	83.4
14.04.89	1137 b-e	59.1 e	174.5	101.3 +	168.7
23.05.89	1052 b-d	43.0 d	228.5	93.2 +	230.8
06.07.89	1092 b-d	0.0 a	308.5	112.8 b	291.2
17.08.89	976 b-c	2.1 a	331.5	97.7 a	329.3
28.09.89	*1385 e	7.5 b	331.5	111.6 ab	315.4
01.12.89	1163 c-e	10.2 b	375.5	47.9 +	423.1
20.02.90	782 a	0.2 a	483.0	110.8 +	467.7
11.05.90	2009 f	81.6 f	816.0	134.6 c	777.7
22.11.90	1267 de	M	966.8	79.7 +	982.6
Maxvale				0-100cm	
14.09.88			0.0	95.7 a	0.0
09.12.88	20 a	0.3 ab	35.4	M	NC
19.01.89	72 b	2.6 cd	84.2	28.7 +	151.2
01.03.89	54 ab	0.2 a	90.4	25.3 +	160.8
13.04.89	85 b	7.0 d	140.5	69.8 +	166.4
22.05.89	278 c	M	333.9	181.0 d	248.5
05.07.89	444 de	26.7 f	410.3	149.8 c	356.2
17.08.89	495 c-e	19.6 ef	426.0	113.1 b	408.6
28.09.89	*742 e	16.7 e	429.0	81.3 +	443.4
01.12.89	399 cd	3.1 bc	483.7	38.6 +	540.8
20.02.90 #			593.9	42.7 +	646.9
Turn Turn				0-100cm	
20.09.88			0.0	43.6 +	0.0
07.12.88	11 a	0.2 a	45.0	24.0 +	64.6
17.01.89	11 a	0.5 a	46.0	24.0 +	65.6
28.02.89	11 a	1.1 a	46.0	21.6 +	68.0
11.04.89	17 a	1.6 ab	139.0	61.8 +	120.8
04.07.89	302 b	21.4 d	334.0	67.5 +	310.2
15.08.89	370 b	18.2 d	338.0	M	NC
26.09.89	*371 b	7.0 c	338.0	29.1 +	352.6
29.11.89	259 b	5.0 bc	343.0	33.8 +	352.8
13.02.90 #			358.0	12.6 +	389.0

Table 3.4 Continued

Site and Date	Dry Matter Yield (kg/ha)		Green Cover (%)		Rain Cum. (mm)	Total Soil Water (mm)		ET Cum. (mm)
Wittenburra Open						0-50cm		
21.09.88					0.0	33.0	+	0.0
07.12.88	9	a	0.3	a	6.0	19.7	+	19.3
17.01.89	61	b	3.4	b	28.0	27.1	+	33.9
28.02.89	16	a	0.3	a	28.0	22.8	+	38.1
11.04.89	7	a	0.5	a	105.0	34.4	+	103.6
04.07.89	64	b	6.7	bc	281.0	59.4	+	254.5
15.08.89	178	c	10.7	c	281.0	M		NC
26.09.89	*260	c	5.9	bc	281.0	25.2	+	288.7
Wittenburra Enclosed						0-50cm		
21.09.88					0.0	36.4	+	0.0
07.12.88	4	a	0.0	a	6.0	20.5	+	21.8
17.01.89	19	a	1.1	a	28.0	21.8	+	42.6
28.02.89	7	a	0.3	a	28.0	18.7	+	45.7
11.04.89	0	a	0.7	a	105.0	34.7	+	106.7
04.07.89	157	b	16.4	b	281.0	59.0	+	258.5
15.08.89	228	b	10.4	b	281.0	M		NC
26.09.89	*192	b	0.5	a	281.0	28.5	+	288.9
29.11.89 #					303.0	29.6	+	309.8
Wongalee						0-100cm		
22.09.88					0.0	82.1	a	0.0
07.12.88	83	a	4.5	a	31.5	M		NC
16.01.89	225	ab	6.0	a	33.5	25.4	+	90.2
27.02.89	395	bc	8.5	a	33.5	20.8	+	94.8
10.04.89	443	bc	4.9	a	112.5	106.8	b	87.9
22.05.89	648	c	M		309.5	231.0	+	160.6
03.07.89	426	bc	8.9	a	388.5	185.7	d	284.9
14.08.89	288	bc	9.4	a	406.5	M		NC
25.09.89	295	bc	13.6	ab	413.0	151.5	c	343.5
28.11.89	*621	bc	27.3	b	493.0	80.2	a	494.8
12.02.90 #					536.5	18.4	+	600.2

Legend for **Table 3.4**

- M Missing value
- NC Not Calculated due to missing value
- D Profile too dry to sample by hand auger
- W Profile too wet to auger
- SD Based on 12 quadrats for Biddenham and Charleville (0.5*1.0m), based on 8 quadrats for remaining sites (0.5*1.0m)
- * Peak yield used to calculate water use efficiency (WUE)
- WUE Peak yield / Cumulative evapo-transpiration to peak yield
- \+ Insufficient samples to calculate LSD
- a Values followed by the same letter are not significantly different at P<0.05
- # Yield and green cover measurements not made.

Table 3.5 Bulk densities (g/cm^3) for the Biddenham (cracking clay) and Charleville (sandy red earth) sites at 10cm increments to a depth of 1m.

Layer	Biddenham	Charleville
0-10cm	1.33	1.21
10-20cm	1.35	1.23
20-30cm	1.39	1.24
30-40cm	1.39	1.23
40-50cm	1.40	1.22
50-60cm	1.40	1.22
60-70cm	1.40	1.21
70-80cm	1.20	1.20
80-90cm	1.20	1.18
90-100cm	1.20	1.10

The fluctuations in yield and green cover were examined in detail to determine periods of significant increase and decrease in yield. Significant changes in yield would be expected to be associated with changes in green cover. However, decline in green cover could occur through plant senescence or after frost without significant change in yield.

At Biddenham, there were two periods of significant increase in yield, each followed by a significant decline in yield. The first increase was rapid, occurring over a nine week period in summer at a calculated rate of 17.0 kg/ha/day (from 17.12.86 to 18.03.87). The second was more gradual, occurring over 18 weeks in winter at the rate of 5.8 kg/ha/day (between 08.04.87 and 11.08.87). Both these periods corresponded to significant increases in green cover of pasture (from 07.01.87 to 26.02.87, and 12.06.87 to 11.08.87).

However, the yield fluctuations in winter between each observation during this second period were not significantly different. This highlights the difficulty of measuring small changes in yield in highly variable tussock grasslands. Both these periods were followed by sharp significant declines in yield. A significant decline in yield of 42% (32.5 kg/ha/day or 2%/day) occurred in autumn between 18.03.87 and 08.04.87. A second significant yield decline of 30% (33.4 kg/ha/day or 2%/day) occurred in late winter between 11.08.87 and 26.08.87. Fluctuations in yield after 26.08.87 were not significant. Significant decline in green cover occurred in early autumn (26.02.87 to 08.04.87).

At the Charleville site, two significant periods of yield increase were observed. The first was rapid, over three weeks in late summer at a rate of 20.4 kg/ha/day between 11.02.87 and 04.03.87 (15 weeks since initial cutting back). The second, during winter was more gradual at 2.4 kg/ha/day over 29 weeks between 04.03.87 and 23.09.87. Fluctuations in yield between progressive observations were not significant. Yield declines measured after each of these periods of increase were not significant.

Significant changes in green cover at the Charleville site occurred more frequently than significant changes in yield (Figure 3.6a and Table 3.4). Both periods of significant yield increase corresponded to periods of significant increase in green cover. However, there were five periods of significant decline in green cover occurring in both summer and winter. These were not related to a significant decline in yield.

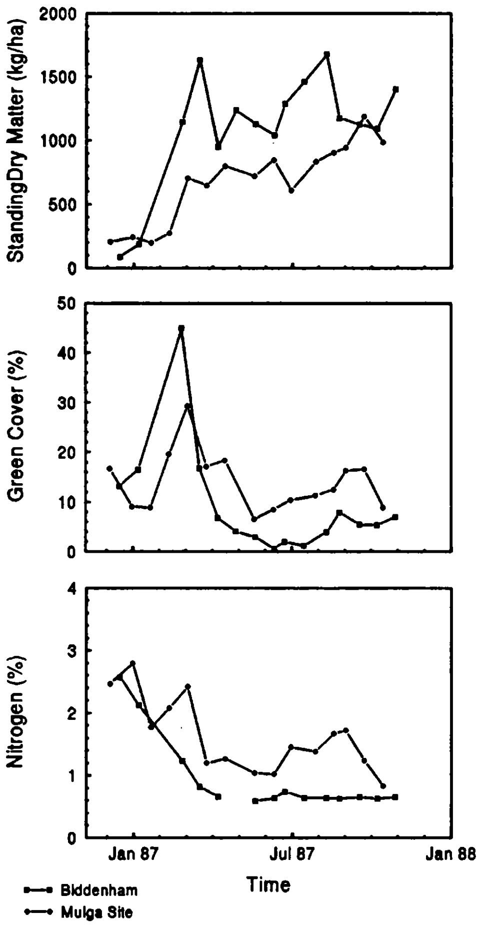


Figure 3.6a Change in standing dry matter yield (kg/ha), green cover (%) and nitrogen concentration of plant tops (%) at Biddenham and Charleville during the period November 1986 to December 1987.

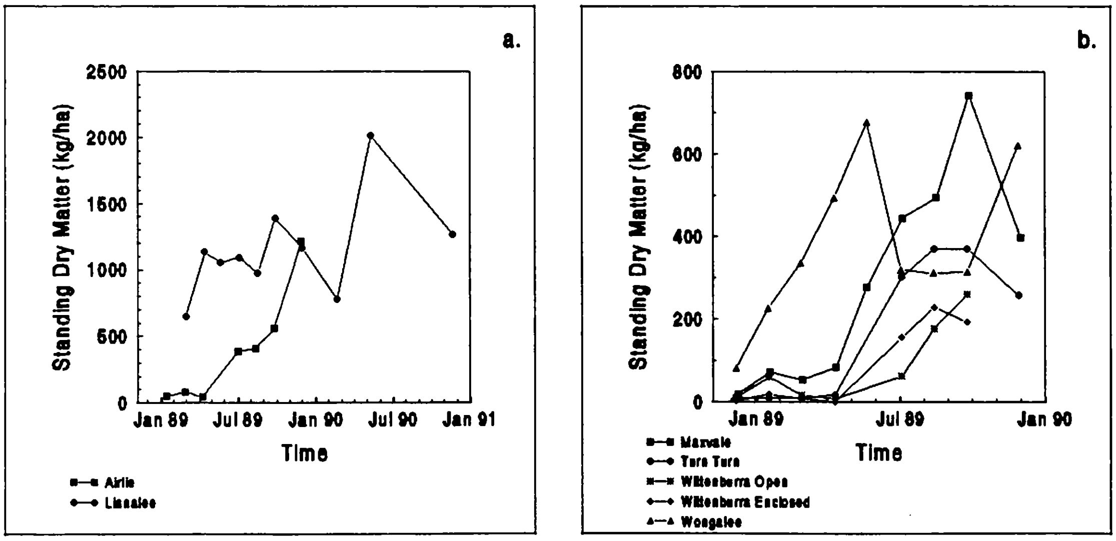


Figure 3.6b Change in standing dry matter yield (kg/ha) at (a) sites 3 and 4 and (b) sites 5 to 9 during the period September 1988 to November 1990.

At Airlie, a significant increase in yield occurred over 12 weeks during autumn and early winter at a rate of 4.1 kg/ha/day between 10.04.89 and 03.07.89 following 360 mm of rain (33 weeks since initial cutting back). A second significant yield increase occurred over nine weeks in spring, between 25.09.89 and 28.11.89 at a rate of 10.3 kg/ha/day. Three periods of significant increase in green cover were observed at Airlie. The second and third of these matched significant increases in yield. A decline in yield in early autumn prior to the main growth period (44% over six weeks from 27.02.89 to 10.04.89 at a rate of 0.8 kg/ha/day or 1%/day) was not significant.

Observations at Lisnalee spanned 23 months. During this period there were three periods of significant yield increase, and two periods of significant decline in yield. The first significant yield increase occurred over six weeks in the first summer between 02.03.89 and 14.04.89 at a rate of 11.4 kg/ha/day. The second significant increase in yield occurred over six weeks in the following spring between 17.08.89 and 28.09.89 at a rate of 9.7 kg/ha/day. This was closely followed by a significant decline in yield of 33% (4.7 kg/ha/day or 0.4%/day) in the latter half of the following summer (between the 01.12.89 and 20.02.90). Unseasonal rain in April 1990 (widespread flooding) resulted in the third significant increase in yield observed at Lisnalee. This occurred over 11 weeks in late autumn at a rate of 15.3 kg/ha/day between 20.02.90 and 11.05.90. A significant decline in yield (37%) followed at a rate of 3.8 kg/ha/day or 0.2%/day between 11.05.90 and 22.11.90.

Each of the three periods of significant increase in yield at Lisnalee corresponded with a significant increase in green cover. Three periods of significant decline in green cover were observed. However, only one of these (between 01.12.89 and 20.02.90) in mid-summer corresponded with a significant decline in yield.

At Maxvale, there were three periods of significant increase in yield. The first occurred over six weeks in summer between 09.12.88 and 19.01.89 at a rate of 1.3 kg/ha/day. The second occurred over six weeks in late autumn between 13.04.89 and 22.05.89 at a rate of 4.5 kg/ha/day. The third occurred over six weeks in winter between 22.05.89 and 05/07/89 at a rate of 3.9 kg/ha/day. A significant decline in yield of 46% occurred over nine weeks in early summer between 28.09.89 and 01.12.89 at a rate of 5.4 kg/ha/day or 0.7%/day.

Only the first two periods of significant increase in yield at Maxvale correspond with a significant increase in green cover. Two periods of significant decline in green cover were observed. However, only one of these (between 28.09.89 and 01.12.89) corresponded to a significant decline in yield.

At Turn Turn and the enclosed site at Wittenburra, a significant increase in yield was measured over 12 weeks in autumn and early winter from 11.04.89 to 04.07.89. At Turn Turn yield increased at a rate of 3.4 kg/ha/day, while at the enclosed Wittenburra site the rate was 1.9 kg/ha/day. Subsequent fluctuations in yield were not significant at either site. At both these sites the significant yield increase was matched by significant increases in green cover. However, the significant decline in green cover between 15.08.89 and 26.09.89 at both sites did not correspond to a significant decline in yield.

At the open (not enclosed) Wittenburra site, three periods of significant increase and one period of significant decrease in yield were observed. The first significant yield increase occurred over six weeks in summer between 07.12.88 and 17.01.89 at a rate of 1.3 kg/ha/day. This was followed immediately by a significant decline in yield of 74% between 17.01.89 and 28.02.89 at a rate of 1.1 kg/ha/day or 1.8%/day. This corresponded to a significant decline in green cover. The second period of significant yield increase was over 12 weeks in autumn (11.04.87 to 04.07.89) and early winter at a rate of 0.7 kg/ha/day. The third period of significant yield increase was over six weeks in late winter (04.07.89 to

15.08.89) at a rate of 2.7 kg/ha/day. While the first two periods of significant yield increase corresponded to significant increases in green cover there was no change in green cover during winter.

At Wongalee, yields fluctuated considerably. Yield increased significantly over 24 weeks in summer between 07.12.88 and 22.05.89 at a rate of 3.8 kg/ha/day. Over the next 38 weeks to the end of sampling, fluctuations in yield were not significant. This may be partly due to the difficulty in sampling *Triodia spp.* due to its large tussock habit, sampling on a front and the variability across plots. Only one period of significant increase in green cover was observed over the spring of 1989 (14/08/89 to 28/11/89). Increases in green cover corresponded to increased yield.

To better understand the variation in growth patterns identified above, the following section explores the relationships between growth and site characteristics.

3.3.3 Comparisons between sites

Standing biomass accumulated over approximately twelve months was used to compare productivity among sites. While short periods of rapid yield decline were observed at some sites (Section 3.3.2), the standing biomass at the end of a twelve month period represented the available forage production that is most relevant in rangeland grazing systems (Heady 1975, Holechek *et al.* 1990). Peak biomass yields in the first twelve months following mowing ranged from 193 kg/ha (Mulga grasses in the enclosure at Wittenburra) to 1678 kg/ha (Mitchell grass at Biddenham) (Table 3.6).

In Table 3.6, standing biomass is represented as net growth rate (kg/ha/day) and is presented with:

(1) other growth measures (water use efficiency (WUE kg/ha/mm) and perennial grass basal area measured at end of growth period (BA%));

(2) site characteristics (tree basal area (TBA m^2/ha), total soil nitrogen (N%), total soil phosphorus (P%), soil organic carbon (OrC %), soil particle size distribution (coarse sand (CS%), fine sand (FS%), silt (SI%) and clay (CL%)) and the available water range estimated from the wettest and driest profiles (AWR mm)); and,

(3) climatic variables (a moisture index calculated as the ratio of evapo-transpiration/ pan evaporation (ETP) and vapour pressure deficit (VPD hPa)).

Linear regression analysis indicated net growth rate was significantly correlated with basal area of perennial grasses, tree basal area, soil pH, the fine sand and clay content of the soil and the moisture index for the sites examined (Table 3.7, Figure 3.7). A correlation between net growth rate and water use efficiency (Table 3.7) is not biologically significant in this comparison as they are mathematically related. Latitude and longitude are also inappropriate variables to correlate with net growth rate as they indirectly reflect climatic (represented here as the ratio of calculated evapo-transpiration to pan evaporation (ETP)).

Multiple regression analysis indicated that a combination of soil, vegetative and climatic variables explained greater than 93% of the variation in annual net growth rates (Table 3.8).

Table 3.6 Comparison of peak yield (kg/ha) and net growth rate (kg/ha/day) to other growth measures, site characteristics and climatic variables.

Site No	Peak Yield (kg/ha)	Month of Peak Yield	Net Growth Rate (kg/ha/day)	Cum. ET (mm)	WUE at Peak Yield (kg/ha/mm)	ET/Pan To Peak Yield	Basal Area (%)	Tree Basal Area (m^2/ha)	Total* Soil N%	Total* Soil P%	AWR (mm)	Soil* ph	Organic* Carbon %	Coarse* Sand %	Fine* Sand %	Silt* %	Clay* %
			GRO	ETP	WUE	ETP	BA%	TBA	N%	P%	AWR	pH	OrC	CS	FS	SI	CL
1	1678	08/87	6.4	317	5.3	0.198	4.0	0.0	0.078	0.058	137	8.1	0.80	3	24	16	57
2	1190	09/87	3.6	548	2.2	0.271	4.3	0.5	0.053	0.023	51	5.2	0.78	51	30	5	14
3	1216	11/89	3.2	634	1.9	0.246	4.0	0.0	0.045	0.038	178	8.3	0.46	20	30	5	49
4	1385	09/89	5.4	315	4.4	0.225	6.2	0.0	0.040	0.068	73	5.8	0.50	38	34	7	23
5	742	09/89	2.0	443	1.7	0.169	2.7	0.8	0.050	0.033	85	5.6	0.81	23	47	11	19
6	371	09/89	1.0	353	1.1	0.137	1.6	2.0	0.045	0.059	66	6.1	0.55	28	49	7	20
7	260	09/89	0.7	289	0.9	0.112	0.5	0.0	0.055	0.049	39	5.1	0.63	15	51	8	28
8	193	08/89	0.5	289	0.7	0.112	0.5	1.5	0.055	0.049	40	5.1	0.63	15	51	8	28
9	621	11/89	1.4	495	1.3	0.162	2.7	0.5	0.026	0.013	160	5.9	0.54	59	29	4	9

* Data from profile descriptions of the main land units comprising each land system in Western Arid Region Land Use Studies, (Dawson 1974, Turner 1978 and Mills *et al.* 1990)

Table 3.7 Correlation matrix presenting Correlation Coefficients (R values) between net growth and other measures of growth, site characteristics and climatic variables. (Legend shown in Table 3.6)

** $P<0.01$ (0.6055)

* $P<0.05$ (0.4821)

	GRO	WUE	BA	TBA	pH	N%	P%	OrC	CS	FS	SI	CL	Lat	Lon	ETP	AWR	VPD
GRO	1.00																
WUE	0.97a	1.00															
BA	0.86**	0.77**	1.00														
TBA	0.60*	0.54*	0.54*	1.00													
pH	0.56*	0.51*	0.39	0.37	1.00												
N%	0.40	0.44	0.08	0.14	0.29	1.00											
P%	0.31	0.43	0.09	0.06	0.16	0.41	1.00										
OrC	0.20	0.22	0.07	0.00	0.15	0.66**	0.17	1.00									
CS	0.10	0.18	0.30	0.03	0.39	0.77**	0.60*	0.23	1.00								
FS	0.76**	0.67**	0.76**	0.60**	0.61**	0.04	0.25	0.01	0.30	1.00							
SI	0.44	0.56*	0.01	0.12	0.32	0.82**	0.46	0.64**	0.73**	0.02	1.00						
CL	0.51*	0.50*	0.15	0.40	0.82**	0.68**	0.45	0.04	0.79**	0.32	0.58*	1.00					
Lat	0.87**	0.85**	0.89**	0.56*	0.27	0.12	0.08	0.28	0.17	0.66**	0.32	0.13	1.00				
Lon	0.71**	0.64**	0.84**	0.57*	0.37	0.17	0.34	0.12	0.46*	0.86**	0.02	0.01	0.86**	1.00			
ETP	0.71**	0.53*	0.87**	0.50*	0.41	0.00	0.19	0.04	0.34	0.77**	0.17	0.16	0.69**	0.74**	1.00		
AWR	0.34	0.28	0.37	0.40	0.80**	0.19	0.32	0.28	0.07	0.70**	0.01	0.41	0.26	0.60*	0.37	1.00	
VPD	0.06	0.13	0.34	0.03	0.42	0.59*	0.13	0.51*	0.45	0.19	0.63**	0.47	0.14	0.02	0.25	0.33	1.00

a = GRO and WUE are mathematically related, therefore not compared.

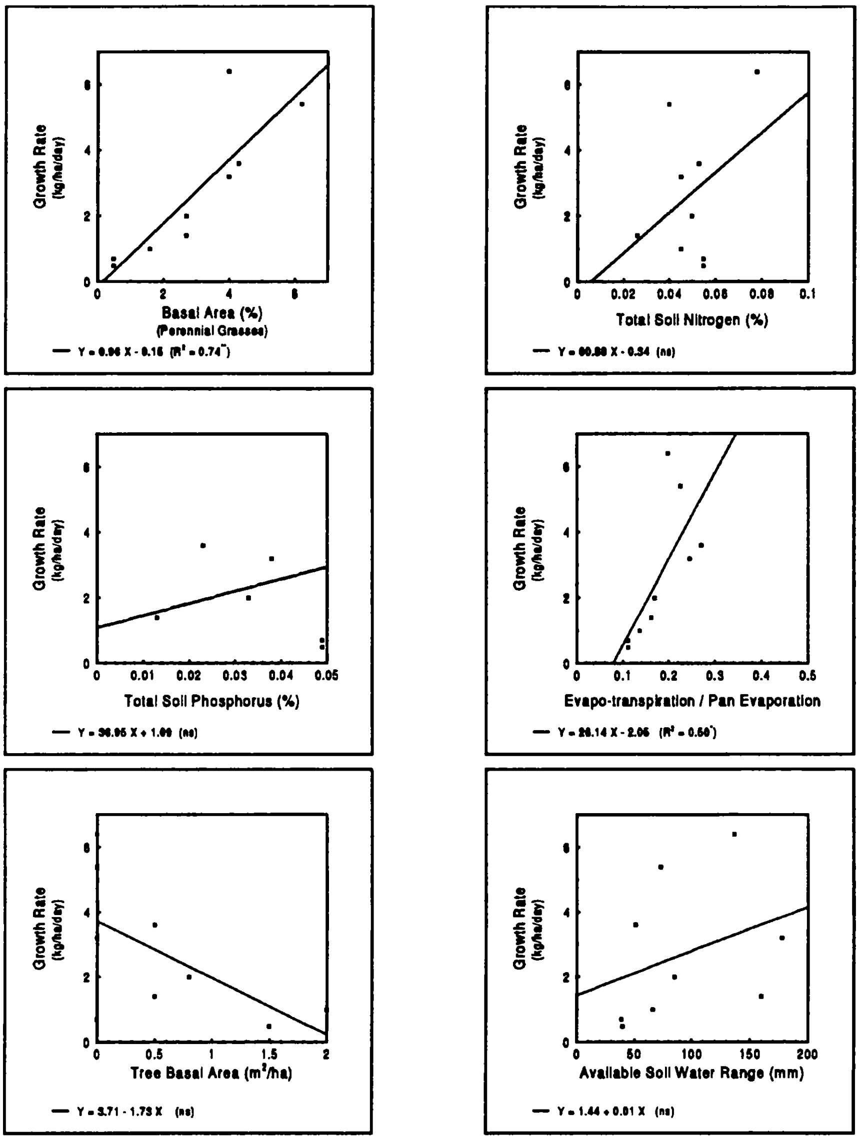


Figure 3.7 Relationship between net growth rate (kg/ha/day) and basal area of perennial grasses (%), total soil nitrogen (%), total soil phosphorus (%), a moisture index (calculated evapo-transpiration/pan evaporation), tree basal area (m^2/ha) and the available soil water range (mm) at nine sites in south-west Queensland from October 1986 to November 1990.

Table 3.8 Regression equations relating net growth rate to soil, vegetative and climatic variables.

	^{a}ADJ R^2	$^{b}C_p$
Soil variables		
$GRO = 6.60 + 63.79 * P - 0.17 * FS^{\#}$	0.81	0.6
$GRO = 5.92 + 50.95 * P - 0.17 * FS + 0.13 * SI$	0.83	1.7
$GRO = 9.00 + 57.41 * P - 0.20 * FS + 0.15 * SI - 0.40 * PH$	0.84	3.0
$GRO = 8.87 + 57.18 * P - 0.20 * FS + 0.14 * SI - 0.40 * PH + 5.59 * N$	0.79	5.0
$GRO = 7.99 + 58.70 * P - 0.20 * FS + 0.13 * SI - 0.27 * PH + 13.28 * N - 0.01 * C$	0.68	7.0
Vegetation and climatic variables		
$GRO = -0.15 + 0.96 * BA$	0.70	5.8
$GRO = -8.14 + 1.12 * BA + 0.33 * VPD^{\#}$	0.84	1.8
$GRO = -7.52 + 1.34 * BA + 0.34 * VPD - 8.29 * ETP$	0.83	3.3
$GRO = -6.76 + 1.28 * BA + 0.33 * VPD - 8.56 * ETP - 0.30 * TBA$	0.80	5.0
Soil, vegetation and climatic variables		
$GRO = -10.17 + 33.67 * P + 1.10 * BA + 0.36 * VPD^{\#}$	0.94	3.0
$GRO = - 9.57 + 34.73 * P + 1.07 * BA + 0.35 * VPD - 0.01 * FS$	0.93	5.0
$GRO = - 3.80 + 71.16 * N + 1.00 * BA$	0.94	12.0
$GRO = - 6.33 + 56.85 * N + 1.06 * BA + 0.14 * VPD$	0.95	8.7
$GRO = - 8.08 + 37.91 * N + 1.07 * BA + 0.22 * VPD + 19.09 * P$	0.97	6.0

Legend

#	Best subset model following stepwise regression.
^{A}	The adjusted R^2 was used to accommodate for the varying number of independent variables in the models.
^{B}	Mallows'C_p index of model bias. (Good models have C_p values near to or less than the number of parameters in the model (A.M. Kelly pers. comm.)).
GRO	Net growth rate (kg/ha/day)
N	Total Nitrogen (%)
P	Total Phosphorus (%)
FS	Fine Sand (%)
SI	Silt (%)
C	Clay (%)
PH	Soil pH
ETP	Moisture index (Cumulative evapo-transpiration / pan evaporation)
BA	Perennial grass basal area (%)
TBA	Tree basal (m^2/ha)
VPD	Vapour pressure deficit (hPa)

3.4 Nitrogen uptake

The nitrogen content of plant tops was measured at the Biddenham and Charleville sites. The concentration of nitrogen declined with time (Figure 3.6a). Towards the end of the growing season, lower concentrations were observed in the C4 mitchell grass plants at Biddenham than in C3 mulga grasses at the Charleville site.

3.3.5 Soil moisture, evapo-transpiration and water use efficiency

The above section has described the change in yield over time and has highlighted the variability among sites in terms of peak yield. The timing of the peak yield varied among sites, indicating differences in the patterns of growth. Seasonal distribution of rainfall and temperature were the most likely influences on growth patterns in south-west Queensland. Species composition (ratio of C3 to C4 species) may also have influenced the response at individual sites. To better understand growth patterns, net growth rates and water use efficiencies were compared (Table 3.9) with site characteristics and climatic variables over summer (November to April) and winter (May to October). At Airlie and Lisnalee significant growth periods during the second summer period were also examined.

Table 3.9 Comparison of standing dry matter yield (kg/ha) and net growth rates (kg/ha/day) with cumulative evapo-transpiration (ET)(mm), water use efficiency (WUE) (kg/ha/mm evapo-transpired water), a moisture index (ET/Pan) (cumulative evapo-transpiration/cumulative pan evaporation) and vapour pressure deficit (VPD) (hPa) over summer and winter at nine sites in south-west Queensland from October 1986 to November 1990.

	Summer						Winter					
Site No	Yield *	Net growth rate	ET	WUE	ET/ Pan	VPD	Yield +	Net growth rate	ET	WUE	ET/ Pan	VPD
1	1238	7.8	261	4.7	0.207	30.9	167	0.9	153	1.1	0.201	15.0
2	799	4.6	401	2.0	0.278	29.4	186	1.0	200	0.9	0.271	14.6
3	45	0.3	137	0.3	0.090	31.2	515	3.1	469	1.1	0.839	11.8
4	1137	12.5	169	6.7	0.199	28.3	248	1.5	147	1.7	0.266	11.9
5	85	0.4	166	0.5	0.081	31.4	657	3.9	277	2.4	0.489	11.9
6	17	0.1	121	0.1	0.060	31.9	354	2.1	232	1.5	0.416	11.8
7	7	0.0	104	0.1	0.052	31.9	253	1.5	185	1.4	0.332	11.8
8	0	0.0	107	0.0	0.053	31.9	193	1.1	182	1.1	0.326	11.8
9	492	2.5	88	5.6	0.044	32.5	0	0.0	256	0.0	0.459	11.8
3a.#	656	10.3	104	6.3	0.208	23.4						
4a.!	1227	15.3	310	4.0	0.799	19.5						
Long Term Average						26.9						12.7

- * Yield at the end of April
- \+ Change in yield from the end of April to the end of October
- \# Change in yield in Spring 1989 at Airlie (25.09.89 - 28.11.89)
- ! Change in yield in Autumn 1990 at Lisnalee (20.02.90 - 11.05.90)

The proportion of annual evapo-transpiration occurring in summer ranged from 23% to 67% (Table 3.9). Net growth rates over summer were significantly correlated with basal area of perennial grasses, the fine sand fraction, the moisture index and vapour pressure deficit (Table 3.10). Water use efficiency over summer was significantly correlated with basal area of perennial grasses, the fine sand fraction, latitude and longitude. During winter, net growth was significantly correlated with the moisture index only.

Table 3.10 Correlations between measures of growth over summer and winter of native pastures in south-west Queensland to site characteristics and climatic variables (Correlation Coefficient R shown).

Site Variable	SUMMER		WINTER	
	Net growth rate (kg/ha/day)	WUE (kg/ha/mm)	Net growth rate (kg/ha/day)	WUE (kg/ha/mm)
BA%	0.82**	0.68**	0.02	0.04
TBA	0.49	0.47	0.08	0.11
pH	0.16	0.16	0.19	0.12
N%	0.11	0.19	0.04	0.27
P%	0.39	0.05	0.12	0.50
OrC	0.02	0.11	0.05	0.27
CS	0.17	0.42	0.36	0.46
FS	0.58**	0.68**	0.34	0.50
SI	0.23	0.07	0.13	0.42
CL	0.12	0.06	0.17	0.08
Lat	0.84**	0.73**	0.02	0.19
Lon	0.64*	0.76**	0.14	0.23
ETP	0.73**	0.44	0.58*	0.02
AWR	0.06	0.35	0.03	0.41
VPD	0.81**	0.47	0.33	0.19

** $P<0.01$ (0.6411)

* $P<0.05$ (0.5139)

3.4 Discussion

3.4.1 Pasture yield

The range of peak annual dry matter yields of 193-1678 kg/ha approximated those reported elsewhere for semi-arid environments. Following abundant summer rain, Ebersohn (1970) recorded air dry pasture yields of 1333 kg/ha from cleared Mulga pastures and 2222 kg/ha from Mitchell grass pastures in south-west Queensland. Christie (1978) recorded peak yields of 1220 and 1540 kg/ha for Mulga pastures and Buffel grass respectively in western Queensland. A peak yield on Mitchell grass of 1960 kg/ha was reported by Christie (1981) while Hulet (1970) reported a net primary shoot production of 719 kg/ha on a Mitchell grass community near Charleville. Ross (1977b) observed a peak yield of 1230 kg/ha for native pasture in central Australia, and in the United States, Redman (1975) recorded yields in the range 176-3518 kg/ha from semi-arid grassland communities. Sims and Singh (1978) observed yields of 840-3360 kg/ha and Webb *et al.* (1978) yields of 800-3800 kg/ha for similar north American grasslands.

The systematic analysis of the time course of yield indicated that: (1) measurement accuracy was sufficient to detect major trends in pasture yield relative to short term fluctuations; and, (2) that most sites displayed two to three periods of significant growth separated by periods of no growth. However, a common growth pattern could not be derived due to the differences in the timing and magnitude of the changes in yield (Figure 3.6a and 3.6b). Growth rates during these periods varied within and across sites, ranging from 0.7 to 20.4 kg/ha/day. Rates of yield decline also varied, ranging from 0.8 to 32.5 kg/ha/day or 0.2 to 2% of total yield per day. Across all sites, growth pulses matched significant increases in green cover. However, decline in green cover rarely was associated with decline in yield. This indicated that "non-green" or senesced plant material was often a substantial proportion of presentation yield. This result has implications for remote sensing where estimates of yield and ground cover are made using indices of greenness e.g. (NDVI in (Danaher *et al.* 1992) and MSS visible green-visible red in Pickup (1995).

Net growth rate over summer was low when the moisture index was below 0.1 (Table 3.9, Figure 3.8). Six of the eleven site/year combinations had an index of less than 0.1 over summer. At five of these six site/year combinations with an index of less than 0.1, net growth rates of less than 0.4 kg/ha/day were measured. Wongalee was an exception with a net growth rate over summer of 2.5 kg/ha/day in conjunction with a low (0.044) moisture index. The presence of sub-surface moisture at this site indicated rainfall was not the sole source of moisture for growth, possibly explaining the yield increases measured during periods of perceived low moisture supply.

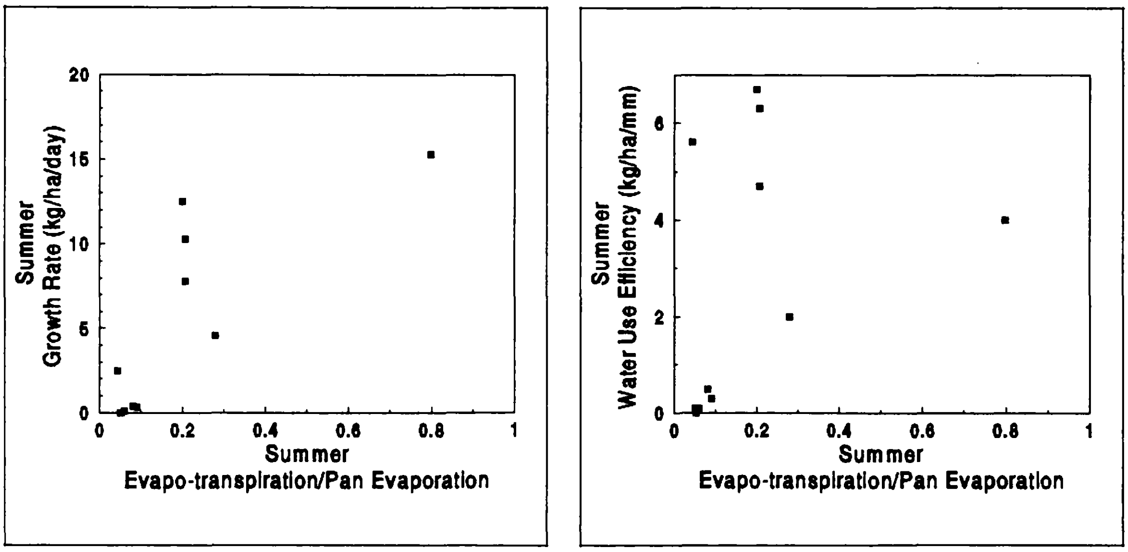


Figure 3.8 The relationship between the moisture index (ratio of evapo-transpiration to pan evaporation) and net growth rate and water use efficiency over summer for nine sites in south-west Queensland from October 1986 to November 1990.

The results indicated that a number of soil variables and vegetative and climatic variables were significantly correlated with annual net growth rate for the sites examined. Combination of these variables improved the prediction of annual net growth rate. This section has identified a number of these factors to be significantly correlated with summer growth. Vapour pressure deficit was also significantly related to summer growth and indicated the importance of this factor in describing growth over this period. For example, rapid growth at Lisnalee occurred during early autumn 1990, a period of relatively low VPD (VPD = 19.5 Table 3.9) compared to peak summer values of 35 hPa. A lack of correlation between net growth rate and total soil nitrogen, total soil phosphorus and soil organic carbon may be biologically significant or a chance result of the distribution of these values across the sites examined.

This indicates that limited insight was gained into the productivity of pastures from individual year data as indicated in the review of literature. The effects of climate, soils and species on pasture growth rates need to be separated. For example, in this study, annual net growth rate was significantly correlated with several parameters characteristic to each site (Table 3.7), with the major effects in summer (Table 3.10). A possible approach for comparison of sites would be to use water use efficiencies to remove the major source of year to year variability due to rainfall.

3.4.2 Water use efficiency

The range of water use efficiencies (WUE) calculated approximate those reported elsewhere for semi-arid environments. The term approximate is used, as considerable confusion arises as to exactly how these values were defined and calculated. Noy-Meir (1973) proposed a range of 5-20 kg/ha/mm of precipitation, Ripley (1992) reported a mean world grassland value of 12 kg/ha/mm of water used; and Webb *et al.*,(1978) indicated 1-3 kg/ha/mm of transpired water for hot desert systems; and Sala *et al.* (1988) reported 6 kg/ha/mm of precipitation for the central grasslands of the United States.

In this discussion, water use efficiency is defined as the ratio of above ground dry matter production (kg/ha) to water used (soil evaporation + transpiration) (mm). This chapter has calculated water use efficiencies for a number of pasture types in south-west Queensland. This is distinct to the transpiration efficiency which is the ratio of above ground dry matter production to water transpired through plants (mm). Calculating the transpiration efficiency requires separating soil evaporation and transpiration empirically in the absence of large equipment such as lysimeters.

At each site where C4 species predominated, summer water use efficiencies were greater than both the annual and winter values. This corresponded with rapid summer growth and attainment of a peak yield towards the end of the first summer (13 to 17 weeks since initial mowing back). This reflects the temperature response of these species. An exception was the first summer at Airlie, when rainfall was low.

At sites dominated by C3 species (Charleville site, Maxvale, Turn Turn, and Wittenburra), winter water use efficiencies were generally greater than summer and annual values. This corresponded with significant yield increases occurring later during the year, and attainment of the peak yield towards the end of winter (47 to 54 weeks since initial mowing back).

In western Queensland, Christie (1978) measured a "mean" summer water use efficiency of 3.9 kg/ha/mm of "stored" moisture for a native Mulga pasture, and 6.9 kg/ha/mm for a Buffel grass pasture. Christie (1981) later reported a "mean" summer water use efficiency of 2.6 kg/ha/mm for the same native Mulga pasture and 3.8 kg/ha/mm for a Mitchell grass pasture. Summer values recorded in this work were 2.0 kg/ha/mm of stored moisture for native Mulga pasture at the Charleville site, 6.7 kg/ha/mm for Buffel grass at Lisnalee and 4.7 kg/ha/mm for Mitchell grass at Biddenham.

Differences in water use efficiency between studies at similar sites can be due to several factors:

(1) Variation on the definition of the amount of "water used", precipitation, evapo-transpiration, transpired water, or stored moisture. These measures are not usually clearly defined making comparisons difficult.

(2) The growth period and technique for estimating growth are not well defined. It is often unclear whether yields represent seasonal or annual growth, or whether yields are presentation yields or true values of primary production. Table 3.10 highlighted the variation in water use efficiency when comparing different growth periods, for example summer and winter. If water use efficiency is to reflect true net primary production, estimates of detachment rates need to be made.

(3) Water use efficiencies vary with plant species, soil type and most importantly with vapour pressure deficit (Tanner and Sinclair 1983). These workers showed from both theoretical analysis and field experimentation, that transpiration efficiency (TE) (kg/ha/mm of transpired water) was inversely proportional to daytime vapour pressure deficit (VPD), i.e. TE=K/VPD where K is constant for a given species / nutrient combination. This approach has proved successful in crop modelling (e.g. Hammer and Muchow 1991).

To clarify the differing water use efficiencies of 3.6 kg/ha/mm or 2.6 kg/ha/mm reported by Christie (1978 and 1981 respectively) for Mulga pastures, his results were re-calculated and compared to water use efficiencies measured in this study. The value of 3.6 kg/ha/mm of evapo-transpired water reported by Christie (1978) was confirmed correct. The average daytime VPD for the period (01/12/73 to 21/02/74) was 23.1 hPa. For a similar period (04/12/86 to 03/03/87) in this study, a water use efficiency of 2.1 kg/ha/mm evapo-transpired water was measured at the Charleville site. The average daytime VPD however was higher at 31.5 hPa. The K (i.e. TE * VPD) value for Christie (1978) was 83 compared to 66 in this study. The relative range from 66 to 83 is similar to the range reported by Tanner and Sinclair (1983) for maize, and McKeon *et al.* (1990) for *Heteropogon spp.* pastures, and is within the range of errors in estimating average daytime VPD and approximating TE by using WUE.

A similar difference occurred between Christie's (1981) water use efficiency of 3.8 kg/ha/mm for Mitchell grass pasture measured over 1975/76 and the annual value of 3.4 kg/ha/mm for the Biddenham Mitchell grass site in this trial. After re-calculating Christie's (1981) data, a water use efficiency of 4.2 kg/ha/mm resulted. The average daytime VPD for this period was 17.0 hPa compared to 21.3 hPa for the Biddenham site. The K value of 71 for Christie's (1981) sampling and 72 for the Biddenham site suggested in this case that the different water use efficiencies can be explained in terms of different VPD during the relative sampling periods.

The significant correlation between summer growth and VPD in this experiment in conjunction with the above results, confirm the importance of vapour pressure deficit in understanding water use efficiency and plant growth, as shown by Tanner and Sinclair (1983), McKeon *et al.* (1990), Day *et al.* (1993) and Hammer and Muchow (1991).

Water use efficiencies and net growth rates over summer were also influenced by low moisture indices. Low net growth rates (< 4 kg/ha/day) and low water use efficiencies (< 0.5 kg/ha/mm) were associated with indices less than 0.1. This indicates the importance of the moisture index as one of the factors influencing growth.

3.4.3 Nitrogen uptake and dilution

The peak nitrogen uptake of the Mitchell grass at Biddenham (14 kgN/ha) approximated the 16 kgN/ha reported for Mitchell grass by Christie (1981). However, the range of nitrogen concentrations in this work was wider than that of Christie (1981) (0.59 to 2.57 %N vs. 0.92 to 2.00 %N respectively). Christie (1981) reported a decline in N concentration from 2.00 to 0.92% over the summer growing period. The decline in this work for a similar period (17/12/86 to 18/03/87) was 2.57 to 0.82%. However, N concentrations as low as 0.59% were measured in this work.

Peak nitrogen yield for Mulga pastures in this trial (16 kgN/ha) was below that reported by Christie (1979) for similar species (22 kgN/ha). However, nitrogen concentrations were similar.

Differences between these two pasture communities in terms of nitrogen use exist. The C4 Mitchell grass pasture diluted nitrogen in plant tops to a lower level than the C3 Mulga pastures resulting in an improved efficiency of nitrogen use. Estimates of pasture productivity on a property or regional scale need to accommodate such differences between broad pasture types (C3 vs C4). Christie (1981) suggested that mineral nutrients (including phosphorus limitations) may be more significant than water as an external factor influencing the distribution of pasture types. This study supports that suggestion. Thus for the same amount of nitrogen uptake, C4 grasslands can produce more yield than C3 grasslands. Grasslands with a mix of C3 and C4 species such as in the Mulga lands would exhibit varying patterns of nitrogen use depending on relative species composition.

The efficiency of nitrogen use is also likely to influence forage quality for grazing animals as dietary nitrogen is important component of ruminant nutrition. At the end of the growing season pastures with predominantly C4 species with lower nitrogen concentrations are likely to be of a lower quality than C3 dominated communities with higher nitrogen concentrations.

3.4.4 Conclusion

In this Chapter the collation and analysis of native pasture primary productivity data from sites representative of 8 land systems from south-west Queensland were described. As there was no replication of sites the data can only be interpreted as point-based information. While representing only a small sample of the diversity of land systems found in the region these results provide a basic level of understanding of the productive capacity of the resources in the region. Such an understanding is central to a review of grazing capacity based on ecological principles.

In summary, this section demonstrated that primary production could be measured and related to water use (evapo-transpiration) over short periods of time. The impact of VPD on water use efficiency and subsequent estimates of pasture growth was highlighted. The effects of tree basal area, total soil nitrogen and phosphorus, soil texture, a moisture index and species composition (C3 vs C4) on pasture productivity and nitrogen utilisation were also indicated. Regression analysis using simple multiplicative indices of these factors explained up to 97% of the variation in the data for the time period and sites under observation. However, the effect of topography was not examined as relatively level sites were selected to minimise the effects of rainfall run-on and run-off. A method for reviewing grazing capacities on a regional scale requires extrapolation of this point-based production information temporally and spatially. The spatial component would need to include climatic and topographical variability that exists at a regional scale. To achieve this Lauenroth *et al.* (1986) and Redman (1992) suggested that simulation modeling was the most promising procedure to estimate and extrapolate above-ground net primary production due to the complexity of interrelationships. Such an approach using the above data is described in Chapter 4.

4.0 MODELLING PRIMARY PRODUCTIVITY USING THE GRASP MODEL

4.1 Introduction

The preceding chapter has demonstrated that primary production can be measured and related to water use (evapo-transpiration) over short periods of time for particular locations. Estimation of "safe" grazing capacities for individual properties requires extrapolation of these "point" results over time and space. The previous chapter suggests that simulation modelling offers the most promising procedure to do this, due to the complexity of the interrelationships governing plant growth.

In this chapter, modification of the GRASP (GRASs Production) computer model to south-west Queensland is described. Data collected and analysed in Chapter 3 are used to calibrate the model. Calibration results are presented and the model is validated with independent yield data collected in south-west Queensland. Historical rainfall records for twenty locations across the region are then used to extrapolate modelling results over time and space. These results are used in Chapter 5 for the estimation of sustainable grazing capacities for native pastures in south-west Queensland.

4.2 Materials and methods

4.2.1 Description of the GRASP model

The GRASP model uses a series of mathematical equations in a computer program to describe the biological processes of forage growth. The biology within the model is outlined in Section 2.5. It is written in the FORTRAN computer language and consists of a main program and a series of modules or sub-routines. The modules perform specific tasks and are called from the main program in a logical sequence. Many of the modules transfer information within the program while others describe the actual biology of forage growth. The roles of the main program and subroutines are described in Appendix 5.

4.2.2 Calibrating the GRASP model to south-west Queensland

The GRASP model calculates transpiration and soil evaporation on a daily basis. Transpiration efficiencies and rates of soil evaporation vary with different species/soil combinations. To facilitate calibration of the model to a range of sites, GRASP uses parameters to describe these and other factors (Appendix 6) e.g. the water use efficiency of a site can be measured directly as described in Chapter 3. However, the transpiration efficiency (parameter 7 in Appendix 6) needs to be estimated in a manual calibration. This is due to the dynamic nature of changing green cover of the forage and subsequent changes in soil evaporation.

Thus calibrating the GRASP model to a particular site requires the development of a parameter file containing parameters describing that site. Three steps are involved.

(1) Beginning with a default parameter file (best estimates derived from Johnston and Carter (1986) (Appendix 6), as many parameters as possible are derived from the field data (Chapter 3). These include depth of soil layers, maximum and minimum soil moistures, plant density, temperature response, timing of detachment of plant material, maximum N content, rate of decline of N in plant material and nearest climatic station. The methodology for formally measuring these parameters has been described by Day and Philp (1997).

(2) A number of parameters are derived from the literature. These include relationships describing runoff (Miles 1993), screen temperature at which plant material is frosted, detachment rates and maximum N uptake (Christie 1978, 1981).

(3) The third step is running the model and calculating additional selected parameters from model output. Examples of parameters derived this way are potential daily regrowth rate and transpiration efficiency. Due to the interaction between these parameters, factorial sensitivity analyses were performed to determine the appropriate combination. In calibration, particular attention was given to these parameters as they have a major impact on production (e.g. water use efficiency).

Regression analysis and the simultaneous F-test of unit slope and zero intercept (H_0 regression slope=1.0 and H_0 regression intercept=0.0) were used to compare modelled (simulated) and observed values as described by Mayer and Butler (1993) and Mayer *et al.* (1994). This form of calibration was used to obtain the best fit to all data placing emphasis on how well the model simulated the pattern of growth, rather than being biased towards prediction of peak yield. Results are presented graphically in conjunction with regression analyses.

Diaries describing model calibration for Biddenham and the Charleville site are presented in Appendix 7. Remaining sites were calibrated with the same approach. Parameter files for each site are also presented in Appendix 7. A critical appraisal of this calibration methodology is given in the discussion (Section 4.4).

4.2.3 Validation of the GRASP model with independent data from south-west Queensland

Validation tests using data independent of calibration examine the robustness of the model. Observed data from different time periods and locations were used in the model and comparisons of simulated and observed results made.

In south-west Queensland several independent data sets exist in the form of grazing trials or experiments examining forage growth. Data from the four treatments (20%,35%,50% and 80% utilisation) in the Arabella grazing trial (Beale 1985) and experiments measuring forage yield (Christie 1978,1981) for mulga and mitchell grass pastures were used to validate the GRASP model in south-west Queensland. Availability of validation data is presented in Table 4.1.

From data reported in the above papers, final reports and unpublished raw data, validation parameter and management files were compiled describing each data set. Parameter files derived during calibration for comparable forage types, were used as the basis for this compilation (Table 4.1). Validation parameter files were then used in the model with climatic records corresponding to the periods of field observations. Regression analysis and the Student's t tests (H_0 regression slope=1.0 and H_0 regression intercept=0.0) were used to compare simulated and observed values.

4.2.4 Extrapolation of model results over time and space

A series of simulations were conducted to examine the spatial and temporal variation in water use efficiency for each of the land systems examined in Chapter 3.

In these simulations, daily rainfall data for twenty locations in south-west Queensland from 1960 to 1992 were used (Table 4.2). Daily climatic data were only available for Charleville, and were used in preference to AUSTCLIM climatic averages (Keig and McAlpine (1969) due to the high correlation between pan evaporation, vapour pressure deficit and rainfall.

Table 4.1 Availability of data and appropriate calibration parameter data for validation of the GRASP model to south-west Queensland (y=data was available, n=no data available).

Site and reference	Parameter data set	Yields	Plant parameters	Soil moistures	Soil parameters	Green cover (%)	N (%)
Mulga pasture Arabella all treatments (Beale 1985)	Charleville site	y	n	n	n	n	n
Mulga pasture Charleville (Christie 1978)	Charleville site	y	y	y	y	n	n
Mulga pasture Louth (J. Noble pers. comm.)	Turn Turn site	y	n	y	n	y	n
Mitchell Grass Charleville (Christie 1981)	Biddenham site	y	y	y	y	n	n
Mitchell Grass Burenda (Christie 1981)	Biddenham site	y	y	n	n	n	n
Mitchell Grass Burenda (Beale 1985)	Biddenham site	y	y	n	n	n	n

Table 4.2 The 20 daily rainfall stations used in simulation studies examining the spatial and temporal variability of water use efficiencies for eight land systems in south-west Queensland.

Station Number	Daily Rainfall Station	Latitude	Longitude	Elevation (m)
44002	AUGATHELLA	25°48’	146°35’	328
44168	BAYRICK	25°28’	146°01’	350
36143	BLACKALL POST OFFICE	24°26’	145°28’	283
44009	BOATMAN	27°16’	146°55’	269
44010	BOLLON POST OFFICE	28°02’	147°29’	183
44021	CHARLEVILLE AMO	26°25’	146°16’	306
44004	CHEEPIE (BEECHAL)	27°08’	144°44’	Not available
44026	CUNNAMULLA POST OFFICE	28°04’	145°45’	189
45006	EROMANGA	26°40’	143°16’	152
44032	EULO POST OFFICE	28°10’	145°03’	137
44040	GUMBARDO	26°07’	144°52’	300
44042	HEBEL POST OFFICE	28°58’	147°48’	150
44181	HUNGERFORD POST OFFICE	29°00’	144°24’	130
44050	MORVEN POST OFFICE	26°25’	147°06’	423
44054	MULGA DOWNS	28°47’	146°54’	130
45003	QUILPIE (SOUTH COMONGIN)	26°54’	144°20’	183
35069	TAMBO POST OFFICE	24°53’	146°15’	395
45017	THARGOMINDAH POST OFFICE	28°00’	143°49’	125
38024	WINDORAH POST OFFICE	25°26’	142°39’	126
44076	WYANDRA POST OFFICE	27°15’	145°59’	237

A simulation consisted of each calibrated and validated parameter file being run across all 20 rainfall locations for the 32 years of available climatic data. Simulation results were analysed using regression analysis to examine the variation in water use efficiency over time and space (rainfall and evapo-transpiration), and to simplify the relationships between rainfall, evapo-transpiration and predicted growth. Temporal and spatial variability in annual, summer and winter water use efficiencies were then examined with the objective of determining a method to estimate an average annual water use efficiency (ARUE kg/ha/mm) for the eight land systems at any location in south-west Queensland. Latitude and longitude were chosen as proxies for rainfall in order to estimate water use efficiencies beyond the limited (20) number of available rainfall stations. These values were compared to corresponding values calculated in Chapter 3 (Tables 3.5 and 3.8).

4.3 Results

Each site is examined in detail to document performance of the model. As correlation coefficients (R^2) are not always appropriate for comparing accumulating yields, results of a simultaneous F-test of unit slope and zero intercept between predicted and observed data are also presented.

4.3.1 Calibration

Comparing the simulated (predicted) and observed total soil moistures across all sites and sampling times (Figure 4.1a), indicated the GRASP model overestimated soil moisture in "dry" profiles (for some sites up to 40 mm) and underestimated soil moisture in "wet" profiles (for some sites by up to 50 mm). Statistical analysis of the regression between predicted and observed values indicated the slope was significantly different to one, and the intercept was significantly different to zero. Despite this, seventy-four percent of simulated total soil moistures were within $\pm$ 20% of observed total soil moistures (Figure 4.2a).

A significant relationship between predicted and observed standing dry matter indicated the GRASP model successfully described forage growth when all nine sites from south-west Queensland were analysed together (a slope not significantly different to 1.0 and an intercept not significantly different to 0.0 ($P<0.05$) (Figure 4.1b). Fifty percent of simulated values were within $\pm$ 20% of observed values (Figure 4.2b).

Closer examination of the results was thus warranted (Table 4.3 and Figures 4.3 to 4.11). Each site is described in detail to document performance of the model.

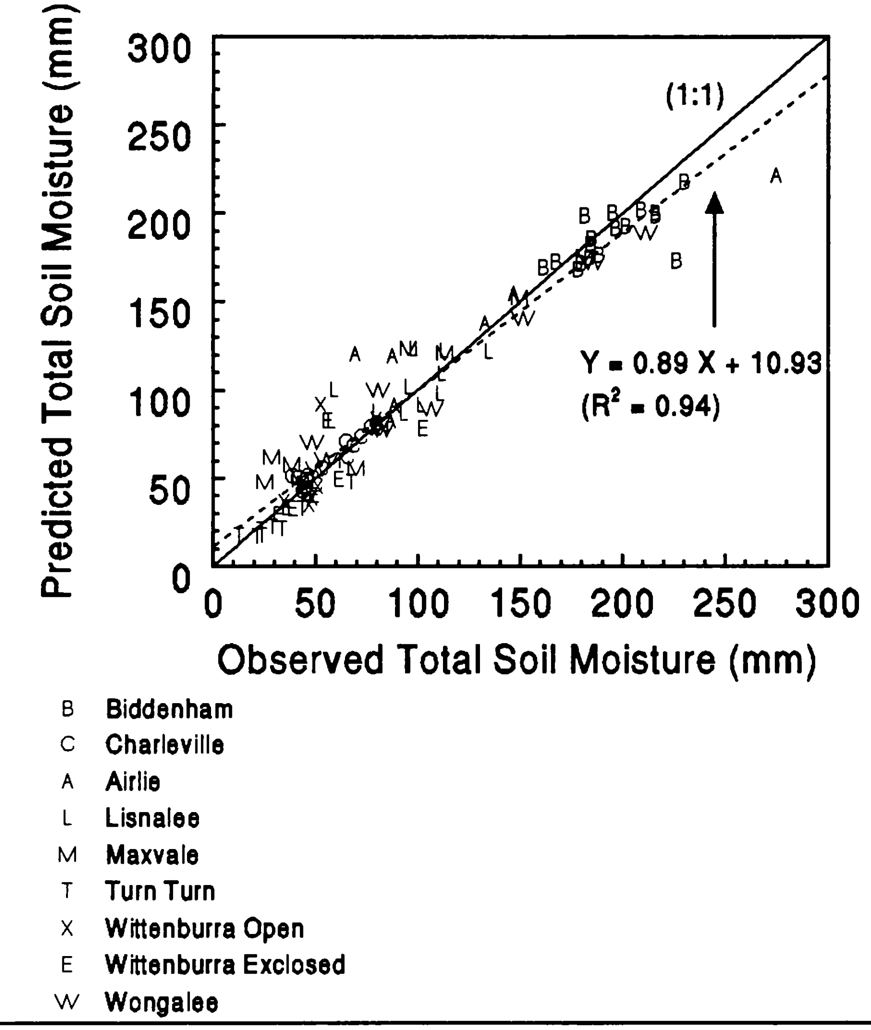


Figure 4.1a Comparison between predicted and observed total soil moisture (mm) following calibration of the GRASP model to nine sites in south-west Queensland during the period November 1986 to November 1990.

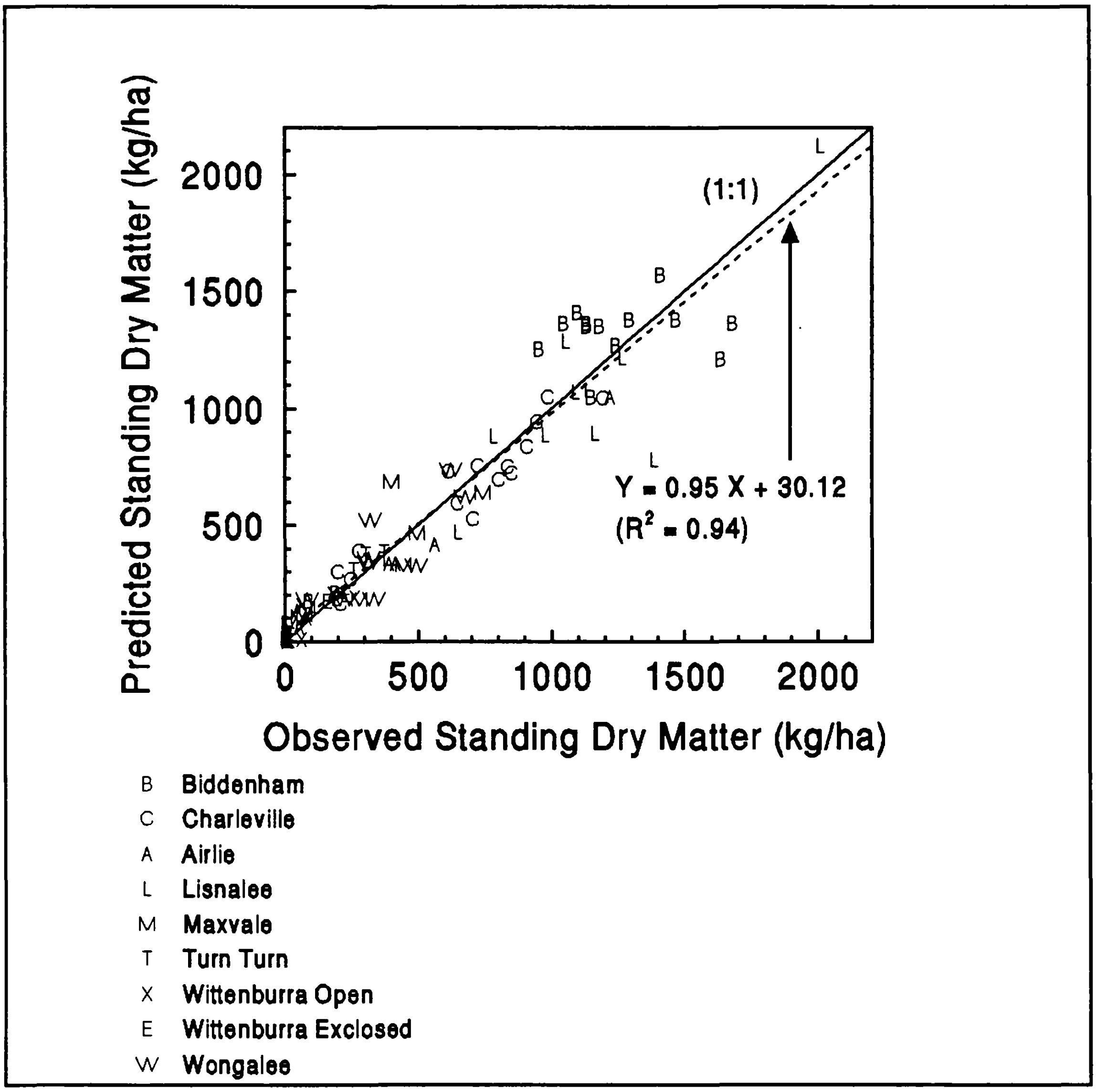


Figure 4.1b Comparison between predicted and observed standing dry matter (kg/ha) following calibration of the GRASP model to nine sites in south-west Queensland during the period November 1986 to November 1990.

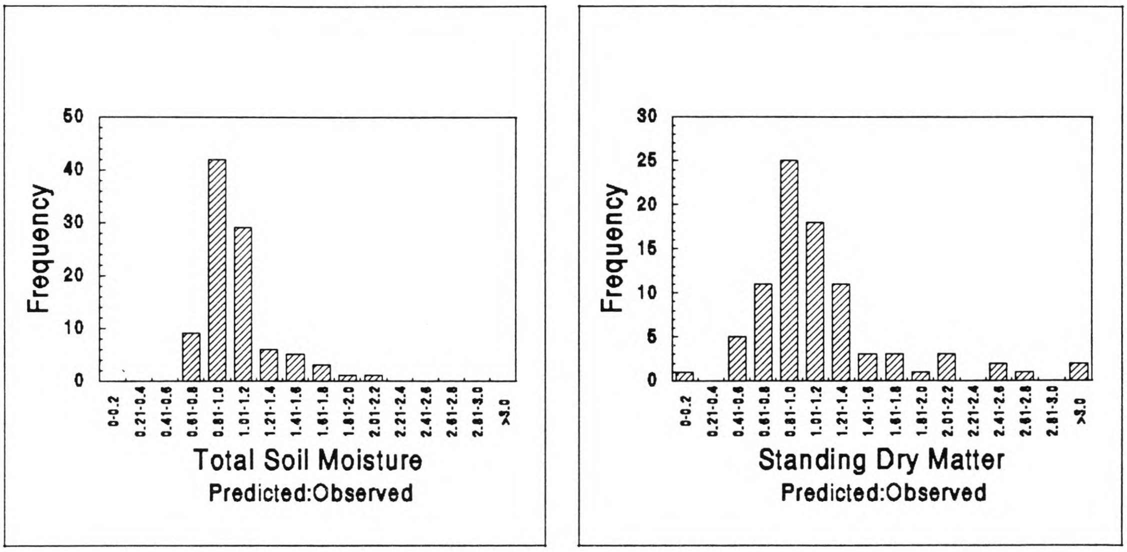


Figure 4.2 Frequency distribution of the ratio between (a) predicted and observed total soil moisture and (b) predicted and observed standing dry matter following calibration of the GRASP model to nine sites in south-west Queensland during the period October 1986 to November 1990.

4.3.1.1 Biddenham - Mitchell Grass

The time course of simulated total soil moisture at Biddenham generally followed observed values, (Figure 4.3a). Ninety-four percent (16 out of 17) of simulated values were within 10% of the observed (average sampling variation of 2.7% in the field). However, one observation (25/11/87) resulted in a low correlation between observed and predicted (slope significantly different to 1.0 and an intercept significantly different to 0.0) (Table 4.3). On this occasion, an observed rapid wetting of the profile was underestimated by the model. Evapo-transpiration from late October to November was low (0.5 mm/day or 5% of pan evaporation) despite high soil water. For this period the model simulated 2 mm/day of evapo-transpiration (24% of pan evaporation). The results suggest the sward was dormant and not transpiring. However, simulated evapo-transpiration for the entire period of observation was within 3% of observed evapo-transpiration.

At Biddenham, the GRASP model and parameters describing plant growth resulted in a significant comparison between simulated and observed standing dry matter (kg/ha) (Figure 4.3d and Table 4.3).

However, caution is required when interpreting these results as the majority of yield observations at Biddenham were clustered in the range 1000-1500 kg/ha. A cluster of low values and a cluster of high values can produce a significant regression when comparing simulated and observed values. Closer examination of the time course of simulated yield is therefore warranted, and indicated only 53% of simulated values were within one standard error either side of the observed values.

The observed pattern of growth at Biddenham showed three bursts of growth and rapid detachment of some yield components (e.g. inflorescence and leaf). The calibrated model showed only two growth periods (Figure 4.3c). The chosen temperature response for C4 grass (Christie 1978, McCown 1980 and McKeon *et al.* 1988) suggested that temperatures were too low for growth to occur in winter (June to

August) (Figure 4.3c). However, during this period an observed yield increase occurred in green stem but not in forbs or green leaf. This dry matter growth disappeared in spring possibly due to translocation, detachment and/or consumption by insects.

As the transitory components of yield do not contribute to end of season standing crop or dry season carry over feed, the failure of the model to simulate these components is not regarded as a major limitation. Implications for future model development are detailed later (Chapter 6).

Table 4.3 Regressions of predicted (Y) and observed (X) standing dry matter yields and total soil moistures from the GRASP grass production model for nine sites in south-west Queensland from October 1986 to November 1990. Student's t test calculated to determine whether slope nsd 1.0 (y or n) and intercept nsd 0.0 (y or n) at the 5% and 1% level.

Site	Regression	R^2	Slope $P<0.05$	Slope $P<0.01$	Intercept $P<0.05$	Intercept $P<0.01$
Standing Dry Matter						
Biddenham	Y = 0.81 X + 282.60	0.75	y	y	y	y
Charleville	Y = 0.84 X + 84.55	0.91	n	y	y	y
Airlie	Y = 0.81 X + 30.91	0.98	n	y	y	y
Lisnalee	Y = 0.94 X + 141.45	0.65	y	y	y	y
Maxvale	Y = 0.83 X + 69.96	0.76	y	y	y	y
Turn Turn	Y = 1.05 X + 13.52	0.97	y	y	y	y
Wittenburra open	Y = 0.82 X + 15.06	0.72	y	y	y	y
Wittenburra enclosed	Y = 0.94 X + 4.75	0.98	y	y	y	y
Wongalee	Y = 0.93 X + 31.00		y	y	y	y
Total Soil Moisture						
Biddenham	Y = 0.49 X + 91.92	0.44	n	n	n	n
Charleville	Y = 0.87 X + 9.64	0.91	y	y	n	y
Airlie	Y = 0.61 X + 55.94	0.87	n	y	n	y
Lisnalee	Y = 0.31 X + 55.47	0.27	n	y	n	y
Maxvale	Y = 0.85 X + 22.53	0.92	y	y	n	y
Turn Turn	Y = 0.76 X + 2.12	0.87	y	y	y	y
Wittenburra open	Y = 1.16 X - 4.49	0.47	y	y	y	y
Wittenburra enclosed	Y = 0.72 X + 10.87	0.61	y	y	y	y
Wongalee	Y = 0.80 X + 20.31	0.96	n	y	n	y

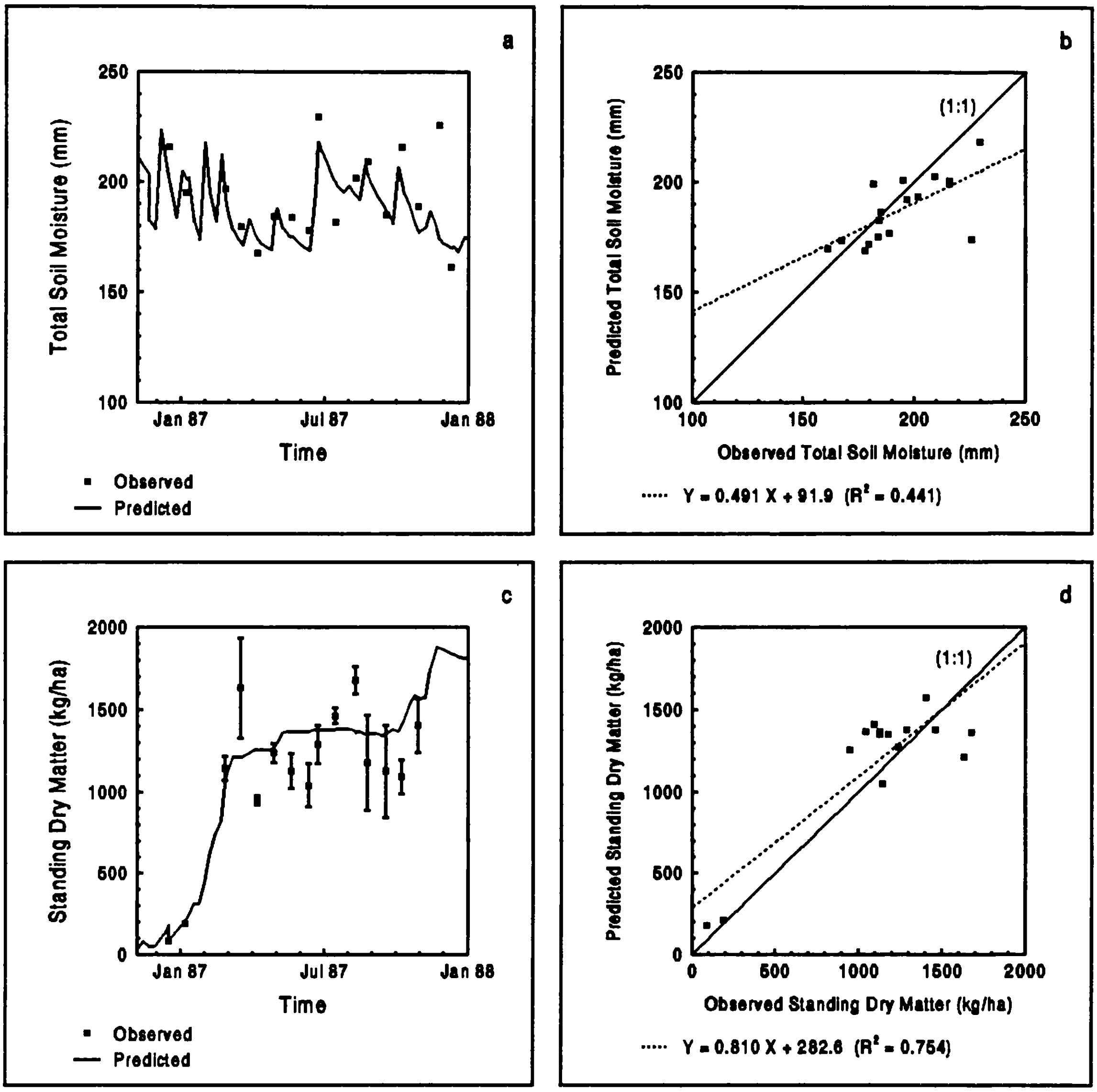


Figure 4.3 Predicted and observed standing dry matter and total soil moisture at the Biddenham undulating downs site during the period November 1986 to December 1987. Error bars indicate ± one SE.

4.3.1.2 Charleville site - Mulga Grasses

The simulated time course of total soil moisture at the Charleville site was comparable to observed values (Slope nsd 1.0 (5% level)) (Figure 4.4 a&b and Table 4.3). Eighty-three percent (15 out of 18) of simulated values were within 10% of observed (average sampling variation of 4.5%). However, the intercept was significantly greater than 0.0 (5% level) indicating the model was overestimating soil moisture (by up to 13mm or 34%) when dry conditions prevailed.

At the Charleville site the slope of the regression between simulated and observed standing dry matter was significantly comparable to 1.0 only at the 1% level (Figure 4.4c and Table 4.3). However, the intercept was not significantly different to 0.0. Sixty-seven percent of simulated dry matter yields were within one standard error of observed yields.

The simulated time course of dry matter yield at the Charleville site corresponded to the two periods of significant observed increase in yield (between 11.02.87 and 04.03.87, and between 04.03.87 and 23.09.87). During each of these periods, significant increases in green cover (Chapter 3) corresponded to simulated increases in green cover (Appendix 8). However, the loss of material observed was not simulated by GRASP. As for Biddenham the calibration procedure underestimated the observed peak yield at the end of both growth phases (by 176 kg/ha or 25% and by 145 kg/ha or 12% respectively).

4.3.1.3 Airlie - Mitchell Grass

The time course of simulated total soil moisture at Airlie generally followed observed values (Figure 4.5a). However, the regression between simulated and observed soil moisture was only significant at $P<0.01$ (Figure 4.5b and Table 4.3). Fifty-seven percent (4 out of 7) of simulated values were within 10% of observed (average sampling variation of 8.3%). The GRASP model underestimated the moisture content of wet profiles (by 53 mm or 19%) and overestimated the moisture content in dry profiles (by 42 mm or 56%). This indicates the model did not simulate the apparent rapid drying or wetting of the profile. This may be the result of large cracks developing in this soil and subsequent spatial variability in soil water over short distances (<1m) which was not adequately described by GRASP or observed in the field (little variation in soil moisture between cores >5m apart (Appendix 3, Table 8.2)). A greater sampling density with improved methods for estimating dry profiles (e.g. neutron moisture meter) would assist in describing the soil water relationships for these soils.

The observed pattern of growth at Airlie showed two bursts of growth (between 10.04.89 and 03.07.89, and between 25.09.89 and 28.11.89). Both were simulated by the model (Figure 4.5c). As for Biddenham and the Charleville site, GRASP model (GVT74) underestimated the peak yield and the end of each of these periods (Table 4.4). However, the simulated first peak yield was within one standard error of the observed peak yield.

A significant decline in observed dry matter yield at Airlie in early Autumn (between 27.02.89 and 10.04.89 at 1%/day) was not simulated by GRASP. This was due to a decline in grass yield, possibly through detachment. No attempt was made to calibrate variable timing of detachment in GRASP.

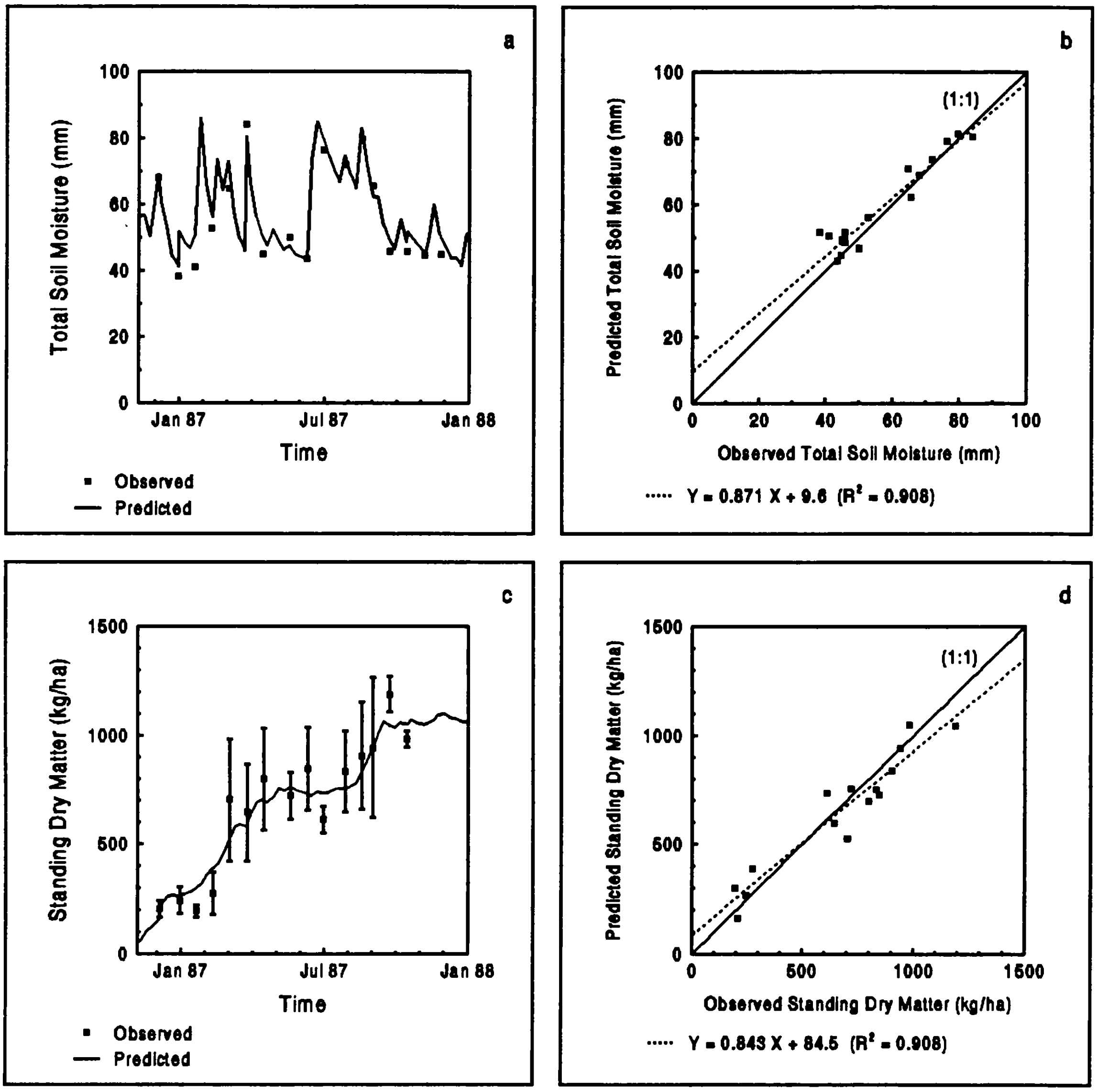


Figure 4.4 Predicted and observed standing dry matter and total soil moisture at the Charleville mulga sandplain site during the period November 1986 to December 1987. Error bars indicate ± one SE.

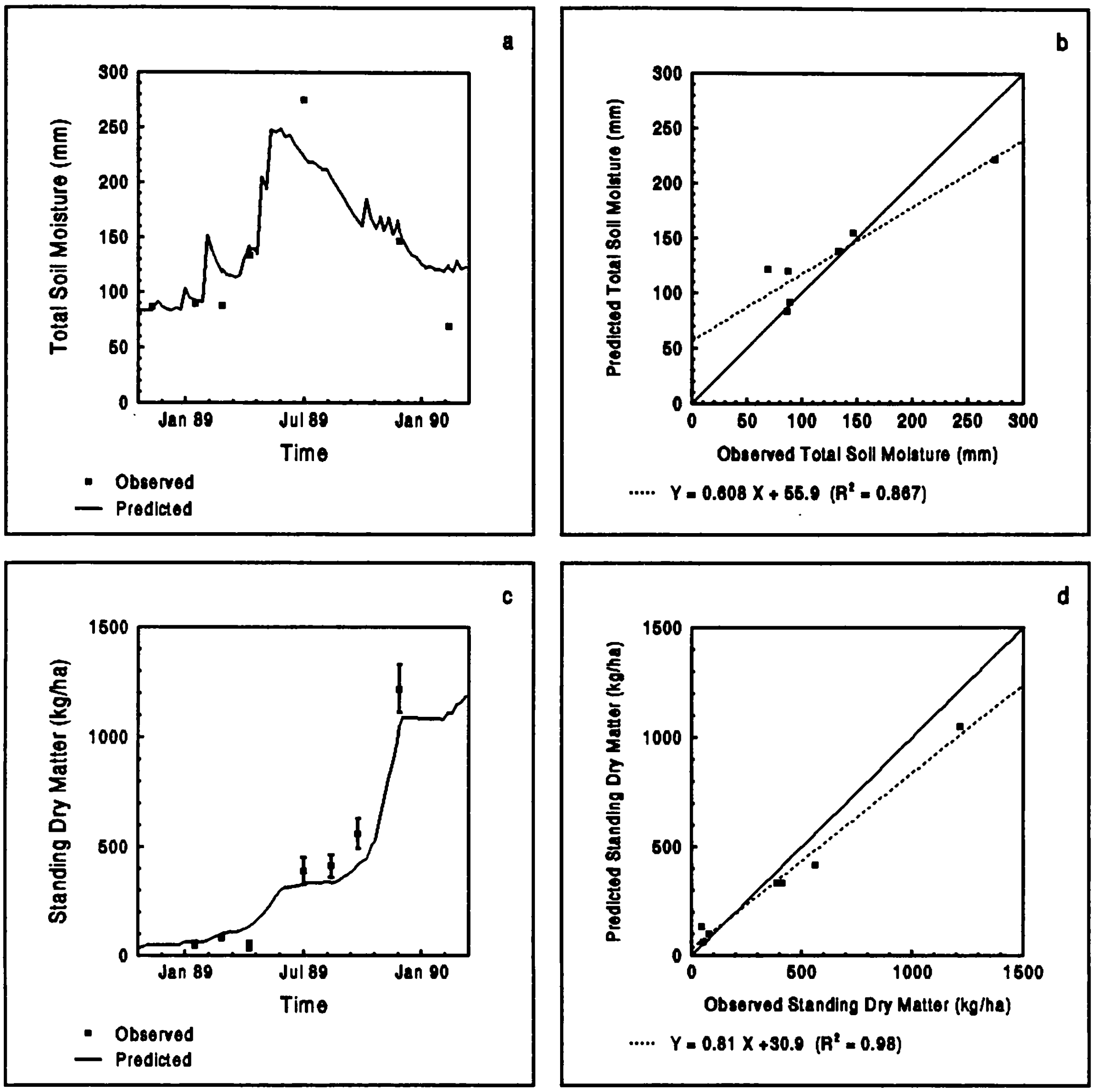


Figure 4.5 Predicted and observed standing dry matter and total soil moisture at the Airlie alluvial plains site during the period November 1988 to February 1990. Error bars indicate ± one SE.

4.3.1.4 Lisnalee - Buffel Grass

The time course of total soil moisture at Lisnalee generally followed observed values (Figure 4.6a). Seventy-three percent (8 out of 11) of simulated values were within 15% of observed soil moistures (average sampling variation of 5.2%). However, the regression was only significant at the 1% level (Figure 4.6b and Table 4.3). As for other sites on clay to clay-loam soils in this study (Biddenham and Airlie), GRASP overestimated the moisture content of dry soils (by up to 41 mm or 70%) and underestimated moisture in wet soils (by up to 12mm or 9%) at Lisnalee.

The observed pattern of growth at Lisnalee showed three bursts of growth (between 02.03.89 and 14.04.89, between 17.08.89 and 28.09.89 and between 20.02.90 and 11.05.90). The time course of simulated yield corresponded with the first and third of these (Figure 4.6c). The second growth phase (early spring) not simulated by the model was associated with an increase in observed green cover. It is possible this was the result of the growth of green stems as described for the Biddenham site, as the C4 temperature response used in calibration suggests temperatures were too low for leaf growth. As for Biddenham this material disappeared over late spring and summer possibly through translocation, detachment and/or consumption by insects.

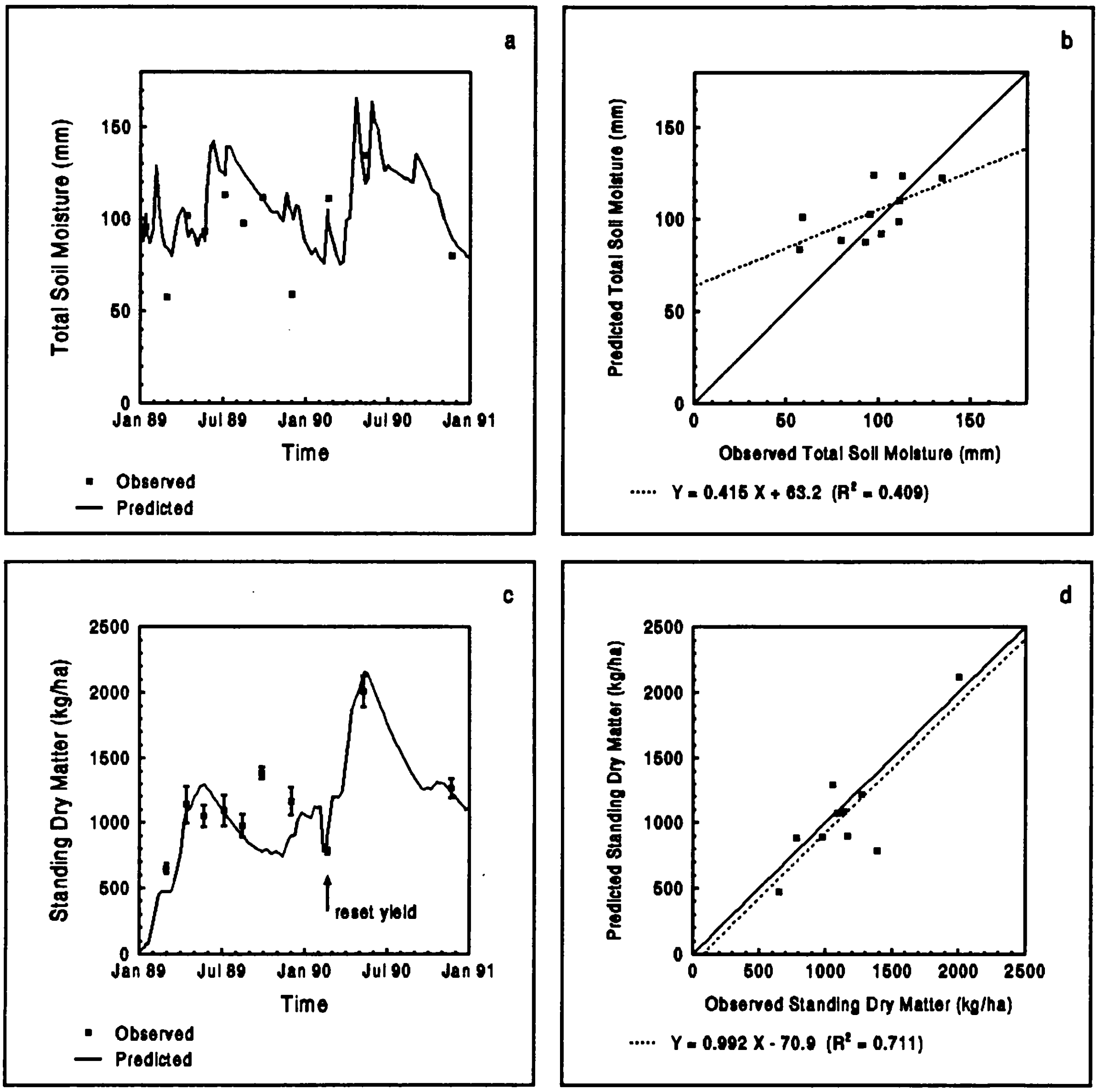


Figure 4.6 Predicted and observed standing dry matter and total soil moisture at the Lisnalee buffel grass site during the period January 1989 to November 1990. Error bars indicate ± one SE.

4.3.1.5 Maxvale - Mulga Grasses

The simulated time course of total soil moisture at Maxvale was comparable to observed values (Figure 4.7a and Table 4.3). However, the model failed to simulate the early period of drying when there were low yields and covers. Due to the lack of grass cover, water use at this stage was most likely evaporation from soil and transpiration from trees (one *Eucalyptus populnea* tree located outside the enclosure may have had roots in the plot). When grass cover was present simulated soil moisture was comparable to observed values.

The observed pattern of growth at Maxvale showed two periods of growth (between 09.12.88 and 19.01.89 and between 13.04.89 and 22.05.89) and a period of yield decline (possibly through detachment) (between 28.09.89 and 01.12.89). The calibrated model simulated these growth periods but did not simulate the loss of material during spring (Figure 4.7c). No attempt was made during the calibration to account for detachment occurring in spring. Green cover was overestimated by the model during late winter, and an observed significant decline in green cover during spring (between 28.09.89 and 01.12.89) (again possibly via detachment) was not simulated by the model (Appendix 8).

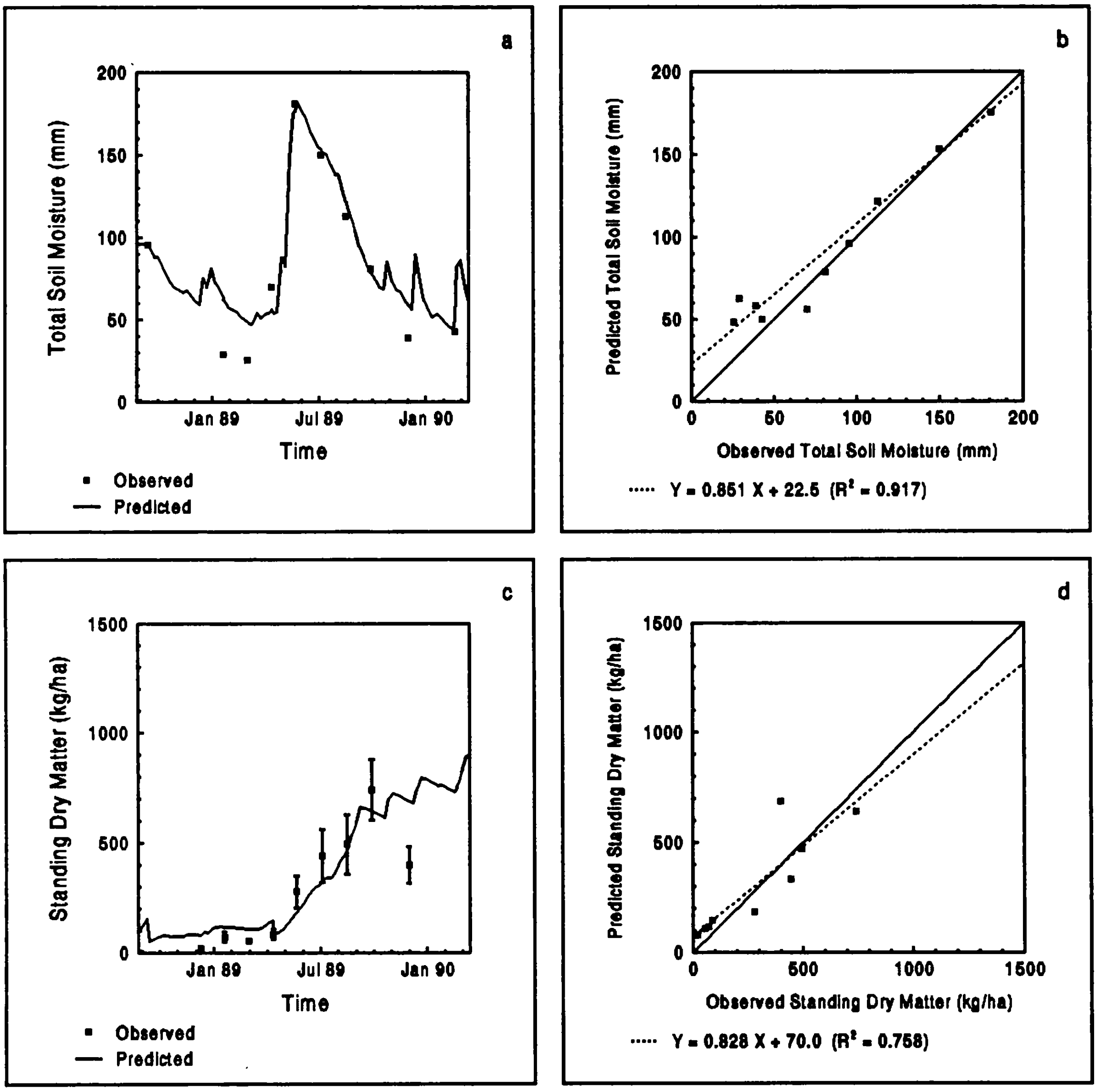


Figure 4.7 Predicted and observed standing dry matter and total soil moisture at the Maxvale soft mulga site during the period September 1988 to February 1990. Error bars indicate ± one SE.

4.3.1.6 Turn Turn - Mulga Grasses

The simulated time course of total soil moisture at Turn Turn was comparable to observed values (Figure 4.8a and Table 4.3). In contrast to the Maxvale site, the calibration of GRASP adequately simulated the drying of the soil profile over the summer of 1988/89. However, the simulated timing of drying in winter was 26 days too early in comparison to that observed in the field.

The observed pattern of growth at Turn Turn showed one major growth phase with material disappearing (predominantly forbs) shortly after the peak yield was attained. The calibrated model matched the observed yields with 88% of simulated values within one standard error of observed values (Figure 4.8c).

Simulated green covers at Turn Turn corresponded to those observed in the field (Appendix 8).

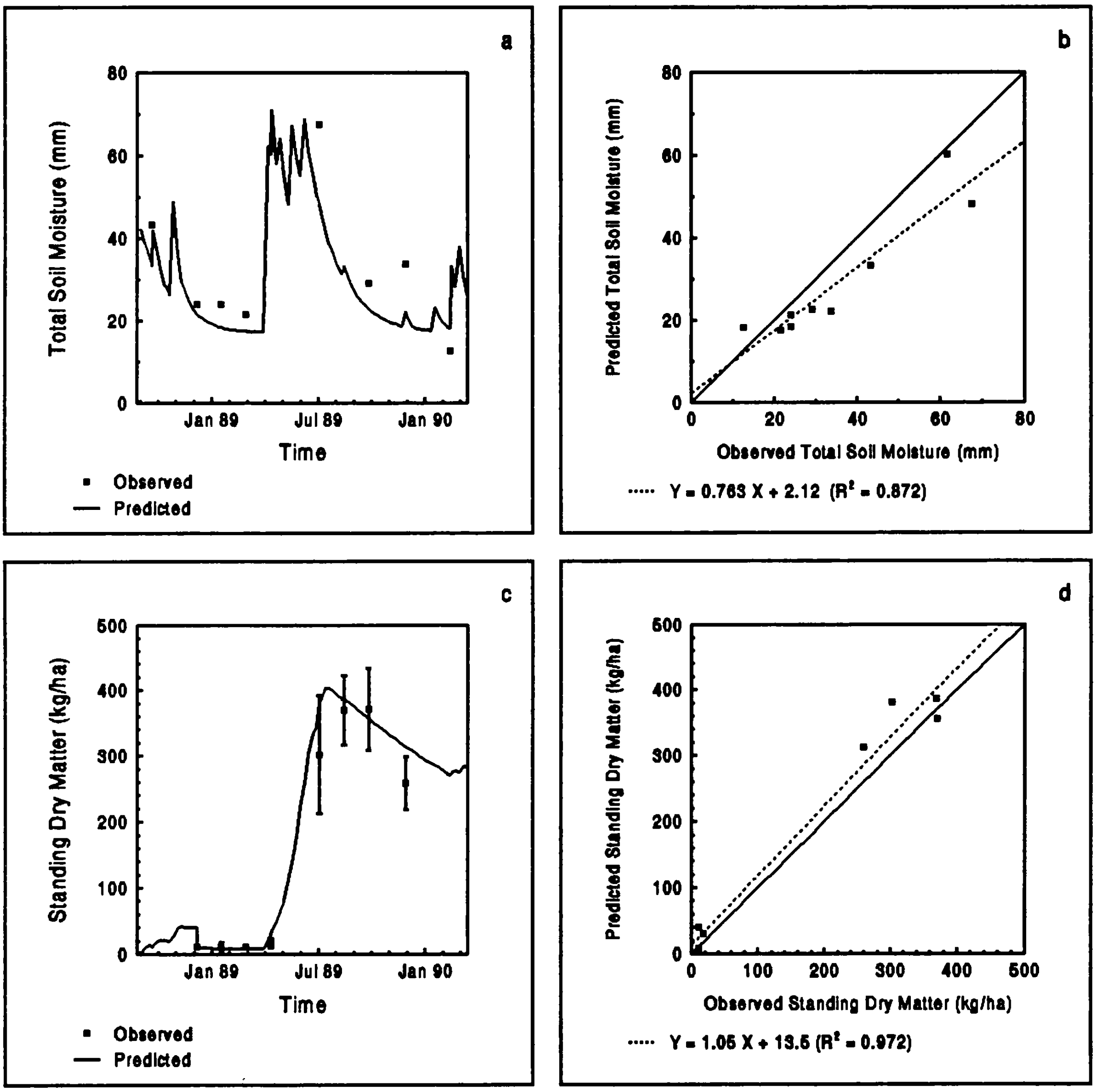


Figure 4.8 Predicted and observed standing dry matter and total soil moisture at the Turn Turn mulga sandplain site during the period September 1988 to February 1990. Error bars indicate ± one SE.

4.3.1.7 Wittenburra - Mulga Grasses

At each of the Wittenburra sites, the time course of simulated total soil moistures was similar and comparable to observed values (Figures 4.9a and 4.10a). However, there was one major outlier on 11/04/89 when the predicted value was greater than the observed (40 mm at the open site and 27 mm at the enclosed site). This may be explained by a possible mis-timing of the rainfall event (localised storm or shower) leading to the increased soil moisture near this date. As accurate daily rainfall was unavailable at the site, the timing of rainfall was estimated from nearby rainfall stations (Eulo and Hungerford). Soil moistures in the enclosed site were generally lower than those in the open site (due to the presence of trees in the enclosure).

At each of the Wittenburra sites, regression analysis indicated a significant relationship between observed and simulated dry matter yield (Figures 4.9c and 4.10c and Table 4.3). As for Biddenham, caution is required when interpreting these data due to the clustering of low and high values and the magnitude of the standard errors.

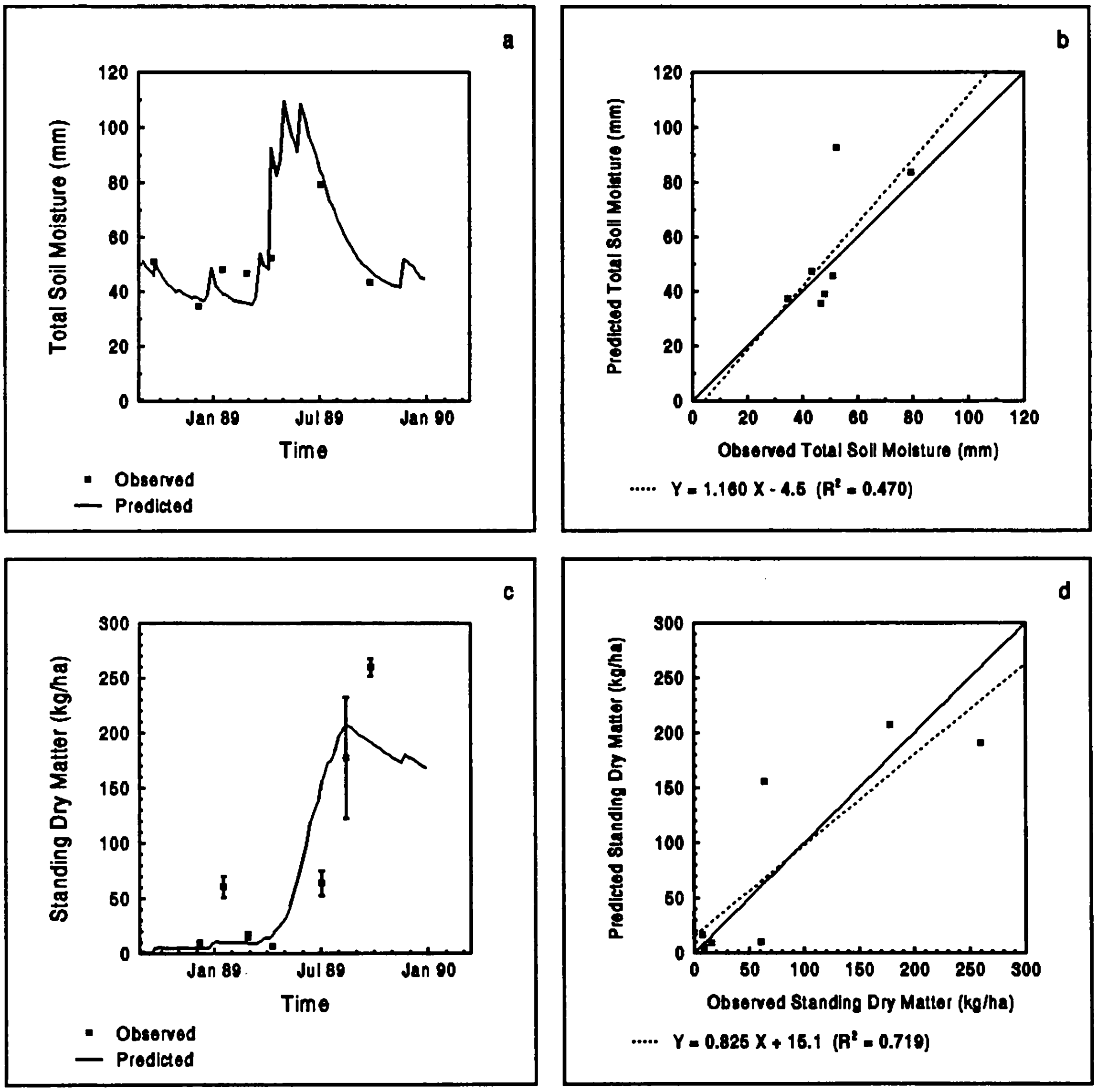


Figure 4.9 Predicted and observed standing dry matter and total soil moisture at the Wittenburra Open hard mulga site during the period September 1988 to September 1989. Error bars indicate ± one SE.

The observed pattern of growth at Wittenburra Open showed two bursts of growth. The first peak in summer was followed by a rapid loss of some yield component (e.g. inflorescence and leaf). The calibrated model did not show this growth phase (Figure 4.9c). The forage at this stage was dominated by ephemeral grasses which characteristically disappear rapidly on completion of flowering and seeding. As these species make only a short term contribution to animal nutrition, the inability of GRASP to simulate these species was not considered a major limitation. The second and larger growth phase over autumn and winter was simulated by the calibrated model. However, the peak yield was not simulated as the model predicted a loss of material in August 1989 not observed in the field. As for other sites, the calibration procedure did not concentrate on tuning on the time of detachment, occasionally resulting in differences between simulated and observed yields late in the sampling period.

At the enclosed Wittenburra site the pattern of growth was simulated by the calibrated model (Figure 4.10c and Table 4.3). The simulated peak yield (188 kg/ha) was within one standard error of the observed peak yield (193 kg/ha) (Table 4.4). Simulated green cover values were comparable to those observed in the field (Appendix 8).

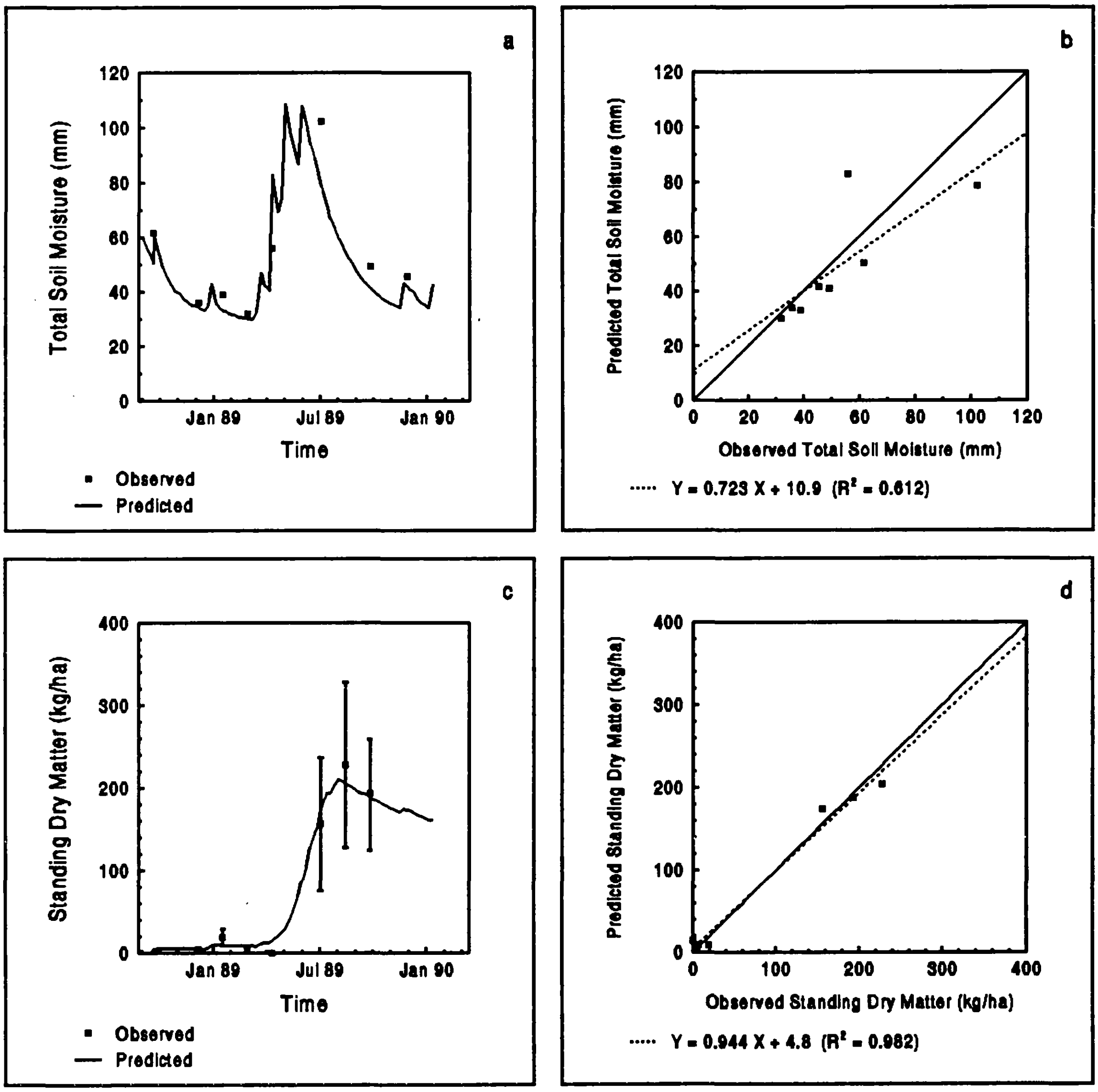


Figure 4.10 Predicted and observed standing dry matter and total soil moisture at the Wittenburra Enclosed hard mulga site during the period September 1988 to November 1989. Error bars indicate ± one SE.

4.3.1.8 Wongalee - Spinifex

The simulated time course of soil moisture at Wongalee appeared to correspond well to observed values (Figure 4.11a). However, regression analysis of simulated and observed values indicated the slope and intercept were significantly different to 1.0 and 0.0 respectively, despite a high correlation (R^2 0.96) (Figure 4.11b and Table 4.3). As for other sites in this study the GRASP model overestimated soil moisture in dry profiles and underestimated the moisture content of wet profiles.

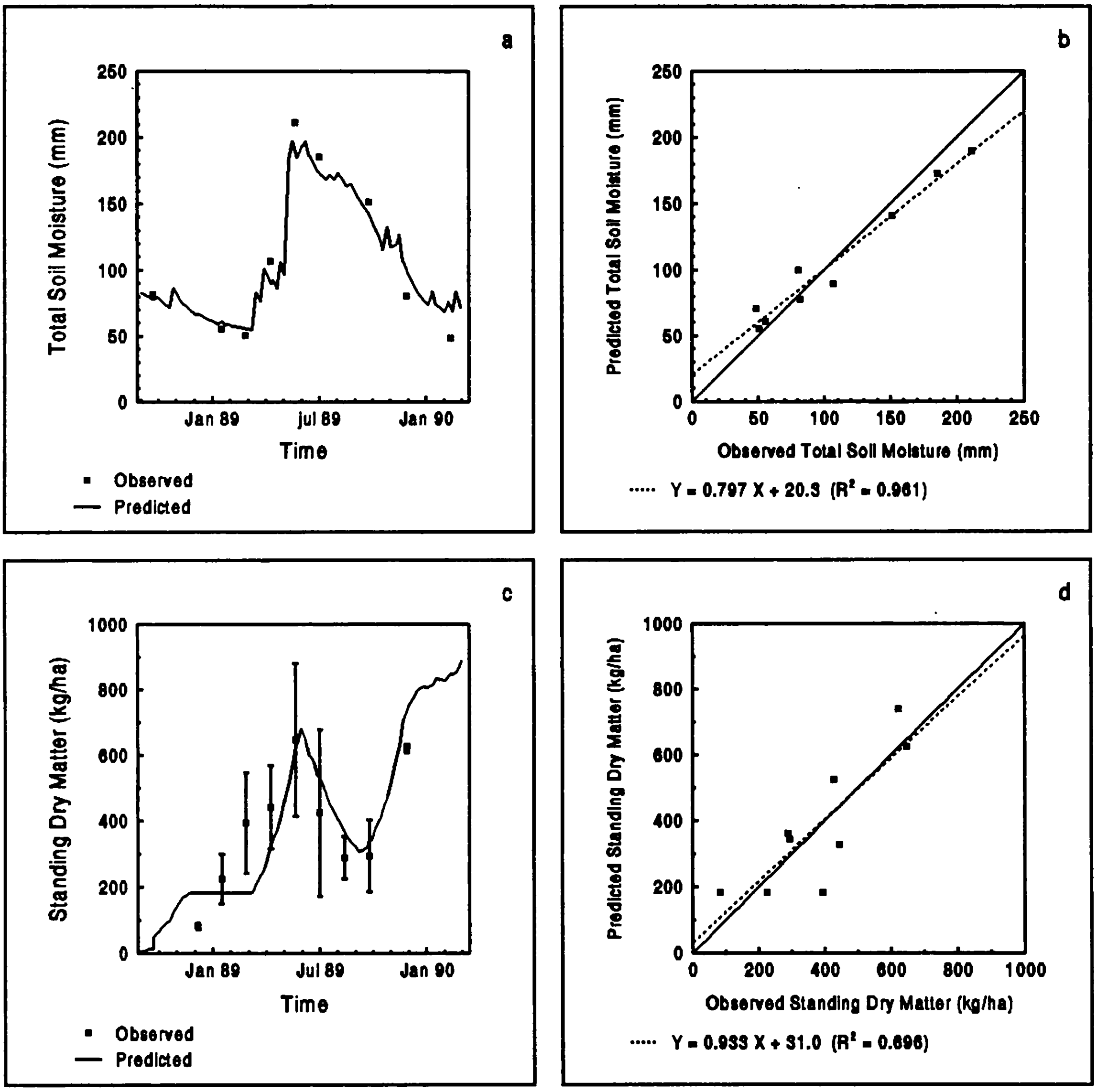


Figure 4.11 Predicted and observed standing dry matter and total soil moisture at the Wongalee spinifex heathland site during the period September 1988 to February 1990. Error bars indicate ± one SE.

The pattern of growth at Wongalee showed two, almost linear bursts of growth (Figure 4.11c). The first (between 07.12.88 and 22.05.89) at 3.6 kg/ha/day and the second (between 25.09.89 and 28.11.89) at 4.8 kg/ha/day. The calibrated model showed each of these growth periods. The commencement of both growth phases occurred during periods of either low or declining soil moisture (Figure 4.11a). Spinifex growth at Wongalee therefore appears independent of moisture availability in the surface 100cm. Either moisture for spinifex growth is being supplied from below 100cm (possible on this land system) or spinifex growth can occur at low moisture potentials and is more influenced by the C4 temperature response chosen for calibration. In contrast to relating spinifex growth to soil moisture, Griffin and Allen (1984) used spinifex cover (%) and cover (%) of other plants to predict the yield of spinifex communities in relation to fuel loads and fire management in central Australia.

Following the first growth phase, a rapid loss of material (8.5 kg/ha/day or 1.26%/day) was observed (between 22.05.89 and 03.07.89). For model calibration detachment was estimated at 1%/day. These high rates of loss are explained by the loss of the tall and heavy seed heads and stalks of spinifex.

Table 4.4 Predicted and observed peak yields for nine sites in south-west Queensland from October 1986 to November 1990. (Observed peak yields from Table 3.5 in Chapter 3.)

Site	Predicted Peak Yield (kg/ha)	Observed Peak Yield (kg/ha)	Difference (%)
Biddenham	1364	1678	19
Charleville	1045	1190	12
Airlie	1049	1216	14
Lisnalee	1073	1092	2
Maxvale	643	742	13
Turn Turn	356	371	4
Wittenburra open	191	260	27
Wittenburra enclosed	188	193	3
Wongalee	739	621	-19

4.3.2 Validation

At sites where soil moisture data were available for validation (estimated from published figures) there was a poor correlation between simulated and observed values (Table 4.5 and Figures 4.14a and 4.16a).

The observed pattern of growth at each of the validation sites was adequately simulated by GRASP (slope nsd 1.0 and intercept nsd 0.0 at 5% level) (Table 4.5 and Figures 4.12 to 4.17).

Each site will be described individually to document performance of the model.

4.3.2.1 Arabella - Mulga pasture (Beale 1985)

At Arabella, stocking rates and estimates of tree density (m^2/ha) in each of the treatments were included in the parameter file. The observed pattern of growth in each treatment was adequately simulated by GRASP (slope nsd 1.0 and intercept nsd 0.0 1%) (Figures 4.12 and 4.13). The highest correlations between simulated and observed yields (r^2 0.78 and 0.74) were recorded in the treatments receiving the lowest and highest grazing pressures (20% and 80% utilisation respectively) (Table 4.5). In the 35%, 50% and 80% treatments simulated yields were consistently less than observed values over the three years 1984 to 1986. In each of these treatments Orr *et al.* (1993) reported an increase in the basal area of *Aristida* spp. from 1982. By 1984 approximately half the basal area in the 50% and 80% treatments comprised *Aristida* spp. This suggests the chosen C3 temperature response for Arabella was too low to simulate the observed growth of the increasing density of the C4 *Aristida* spp. in these treatments.

The simulated utilisation (eaten/grown*100) of average growth was 15.5, 27.6, 27.9 and 39.1% for the 20, 35, 50 and 80% treatments respectively.

Table 4.5 Regressions of predicted (Y) and observed (X) standing dry matter yields and total soil moistures from the GRASP grass production model for five sites in south-west Queensland where data was available for validation of the model. Student's t test calculated to determine whether slope nsd 1.0 (y or n) and intercept nsd 0.0 (y or n) at the 5% and 1% level.

Site and reference	Regression	R^2	Slope nsd 1.0		Intercept nsd 0.0	
			$P<0.05$	$P<0.01$	$P<0.05$	$P<0.01$
Standing Dry Matter						
Mulga pasture Arabella all (Beale 1985)	Y = 0.81 X + 26.13	0.66	y	y	y	y
Mulga pasture Arabella 20% (Beale 1985)	Y = 0.74 X + 159.98	0.78	y	y	y	y
Mulga pasture Arabella 35% (Beale 1985)	Y = 0.47 X + 105.02	0.33	y	y	y	y
Mulga pasture Arabella 50% (Beale 1985)	Y = 0.59 X + 64.46	0.31	y	y	y	y
Mulga pasture Arabella 80% (Beale 1985)	Y = 0.86 X - 26.62	0.74	y	y	y	y
Mulga pasture Charleville (Christie 1978)	Y = 1.33 X - 86.53	0.88	n	n	y	y
Mulga pasture Louth (J.Noble pers. comm.)	Y = 0.81 X + 39.16	0.91	y	y	y	y
Mitchell Grass Charleville (Christie 1981)	Y = 0.94 X - 0.46	0.62	y	y	y	y
Mitchell Grass Burenda (Christie 1981)	Y = 1.23 X - 292.8	0.83	y	y	y	y
Mitchell Grass Burenda (Beale 1985)	Y = 0.28 X +1033.09	0.15	n	n	n	n
Soil moisture						
Mulga pasture Charleville (Christie 1978)	Y = 0.18 X + 44.46	0.11	n	n	n	n
Mitchell Grass Charleville (Christie 1981)	Y = 0.44 X + 155.91	0.63	n	n	n	n

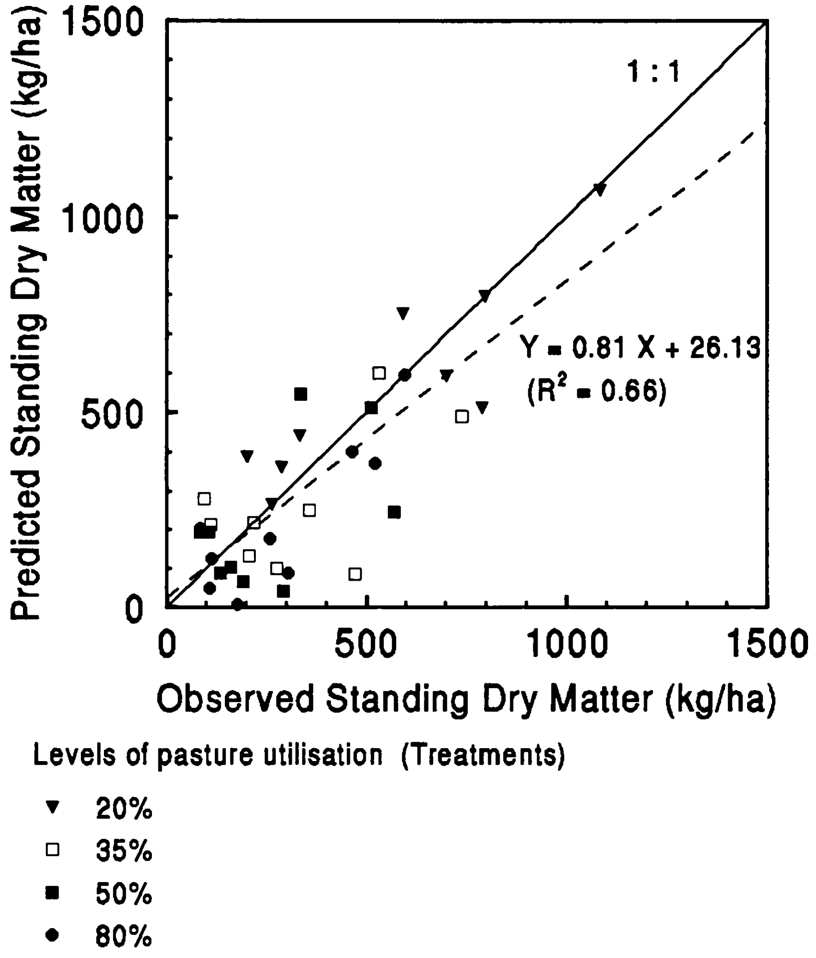


Figure 4.12 Comparison of predicted and observed standing dry matter yields (kg/ha) from validation of the GRASP model with data from all of the treatments in the Arabella grazing trial (Beale 1985) on mulga pastures near Charleville in south-west Queensland.

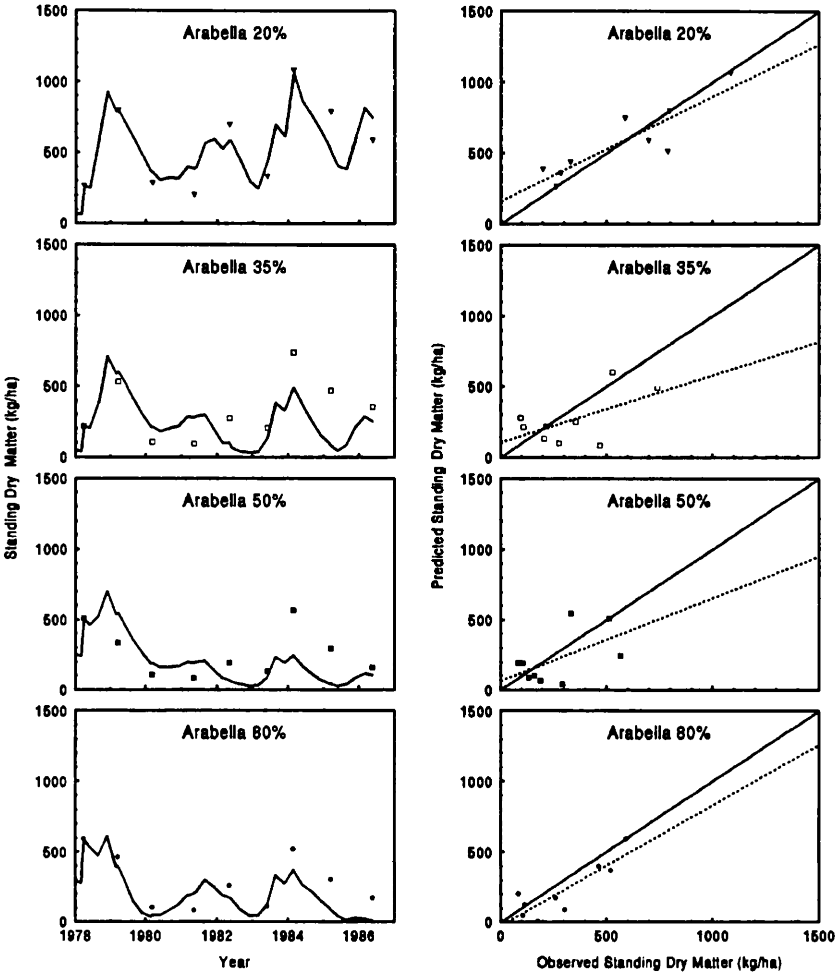


Figure 4.13 Comparison of predicted and observed standing dry matter yields (kg/ha) from validation of the GRASP model with data from each of the grazing utilisation treatments in the Arabella grazing trial (Beale 1985) on mulga pastures near Charleville in south-west Queensland.

4.3.2.2 Charleville - Mulga pasture (Christie 1978)

The time course of simulated soil moisture at this site differed significantly from that reported by Christie (1978) (slope sd 1.0 and intercept sd 0.0) (Figure 4.14a and Table 4.5). Variance was most noticeable from May to November 1974 when simulated soil moistures were consistently 13 to 28 mm greater than reported values. Over this period evapo-transpiration averaged 23% of pan evaporation, with most of the moisture losses occurring from the 10-75cm layer in the soil profile. This indicates high rates of soil evaporation were occurring over this winter period which was not simulated by the GRASP model. The density of trees at this site was unknown. Trees if present would influence the soil water balance and may explain some of the variation between observed and simulated.

The pattern of growth reported by Christie (1978) showed three bursts of growth and two periods of rapid loss of some yield components. The calibrated model showed each of these periods of growth (Figure 4.14c). However, the first growth period was over predicted by the model by 400 kg/ha. With good summer rain in 1974, soil moisture was not limiting and high yields were simulated by GRASP despite a limit on nitrogen uptake by mulga grasses to 21 kg N/ha in the model. For C3 mulga pastures Christie (1981) suggests phosphorus is the major limiting nutrient. The inclusion of Christie's (1978) ceiling on phosphorus uptake for this pasture of 1.1 kg/ha in the model may constrain the over prediction of yield.

The rapid loss of material in April 1974 and August 1974 was not simulated by the model. As a result of this, successful simulation of the growth bursts required the resetting of yields to levels reported at the start of each growth phase. Subsequent simulated peak yields at the end of the second and third growth periods were comparable to the observed values.

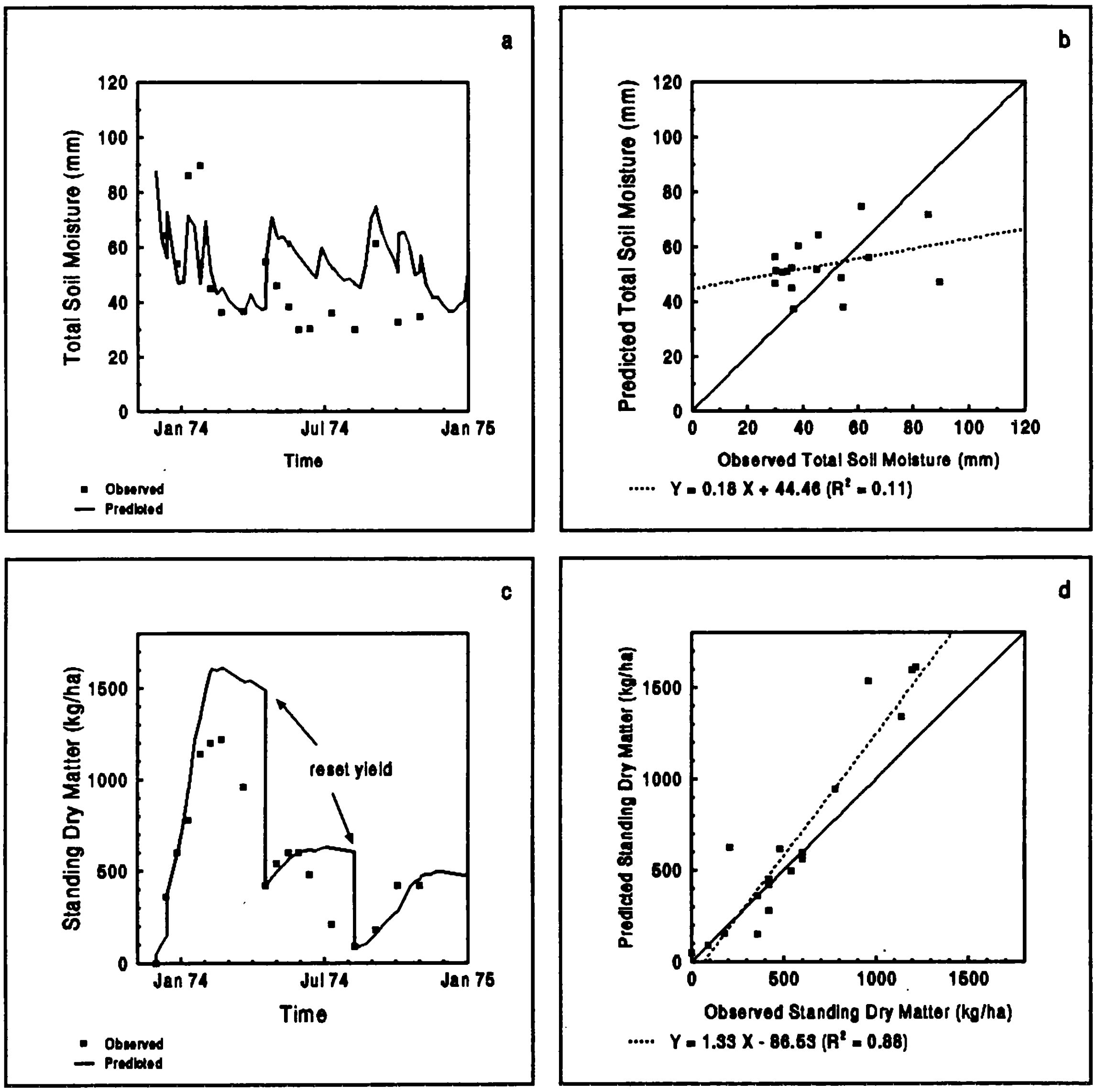


Figure 4.14 Predicted and observed standing dry matter and total soil moisture using the data of Christie (1978) to validate the GRASP model to mulga pastures near Charleville in south-west Queensland.

4.3.2.3 Louth - Mulga pasture (Noble pers. comm.)

The pattern of growth at the Louth site (Noble pers comm) showed a period of gradual growth over summer 1989 with a burst of growth in late winter 1989 (Figure 4.15). The calibrated model based on parameters from Turn Turn adequately simulated both periods of growth (slope nsd 1.0 and intercept nsd 0.0) (Table 4.5).

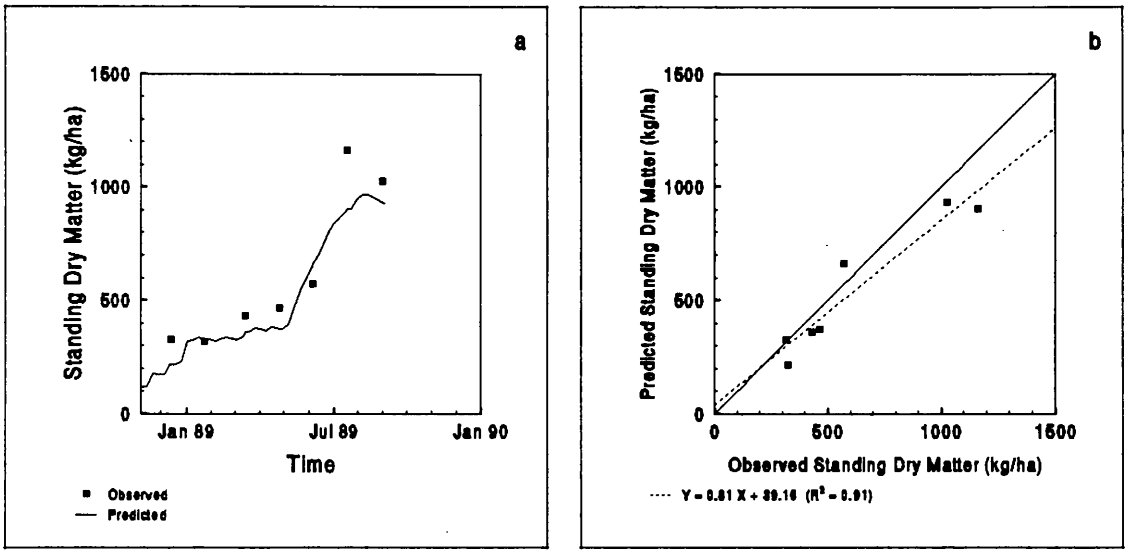


Figure 4.15 Predicted and observed standing dry matter using the data of Noble (1992) (pers. comm.) to validate the GRASP model to mulga pastures near Louth in north-west New South Wales.

4.3.2.4 Charleville - Mitchell grass (Christie 1981)

The time course of simulated soil moisture at Christie's (1981) Charleville mitchell grass site generally followed reported values (Figure 4.16a). The available water range reported by Christie (1981) was used in validation. Despite this, GRASP underestimated the soil moisture content by an average 30 mm during January 1976. Most of these errors were noted in the 50-100cm layer where rapid wetting of the profile could occur via large cracks in the soil.

The observed pattern of growth reported by Christie (1981) at his Charleville mitchell grass site showed one burst of growth followed by a rapid loss of material (Figure 4.16c). Initial validation using these data (using parameters from the Biddenham site) over estimated yield by 365 kg/ha as the maximum nitrogen uptake was calibrated at 21 kg/ha. Using the nitrogen uptake of 16 kg/ha reported by Christie (1981) for this site, a closer estimation of peak yield was simulated (within 5% of the observed value). However, the rapid loss of material (e.g. inflorescence and leaf) was not simulated by the model.

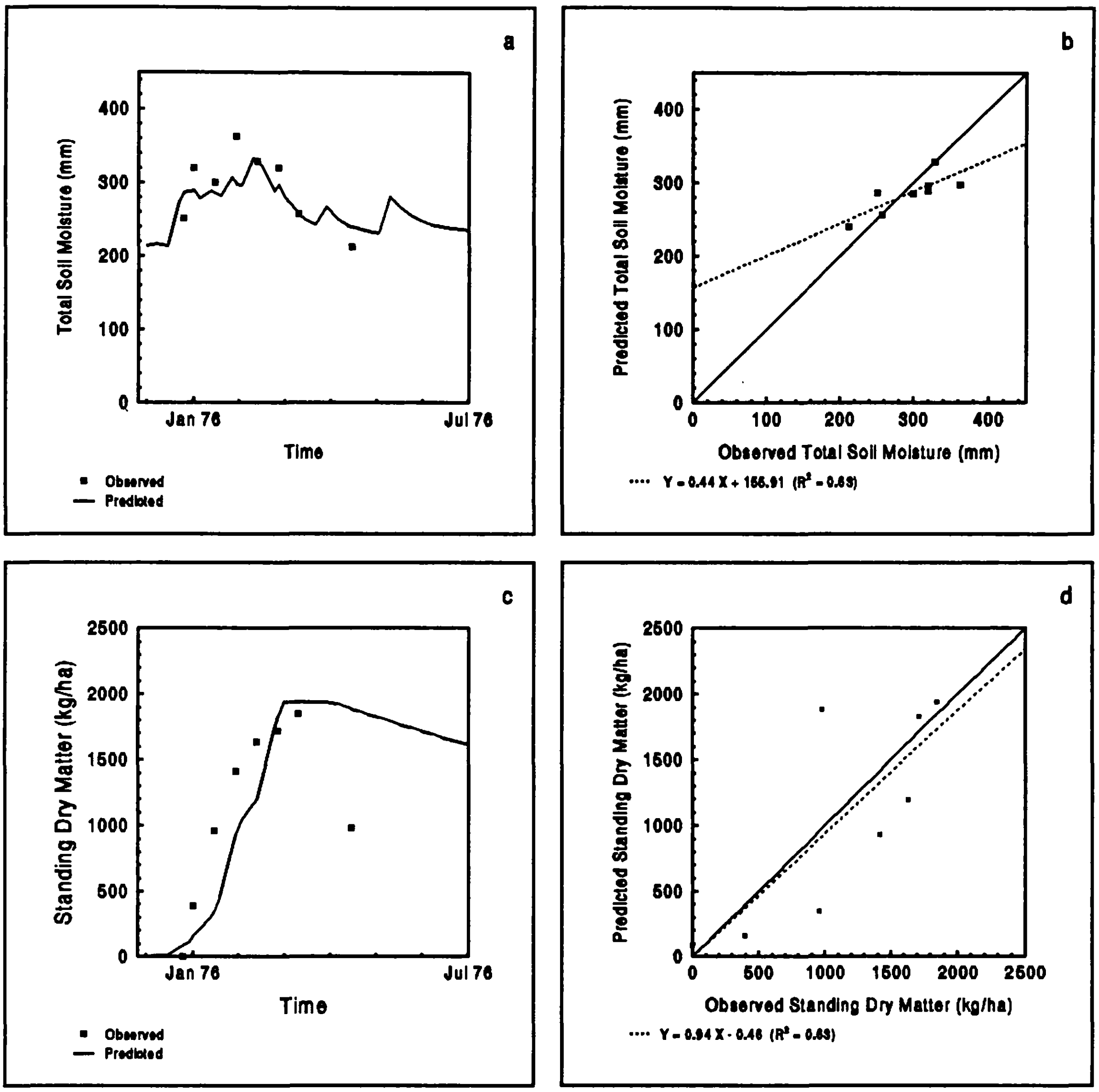


Figure 4.16 Predicted and observed standing dry matter and total soil moisture using the data of Christie (1981) to validate the GRASP model to mitchell grass pastures near Charleville in south-west Queensland.

4.3.2.5 Burenda - Mitchell grass (Christie 1981)

At Burenda, Christie (1981) reported end of season yields from October 1974 to March 1977 for the grass and forb component of the forage. Yields reported were end of summer and winter season "peak live biomass" following mowing back at the start of each growing season. Only the grass component was used in the validation exercise, where yields were reset to 100 kg/ha at the end of each summer and winter growing season to simulate the mowing back. The validated model showed each of these growth phases but over estimated yields at each observation (Figure 4.17a). Actual dates for yield observations and mowing back were not reported making it difficult to draw further conclusions.

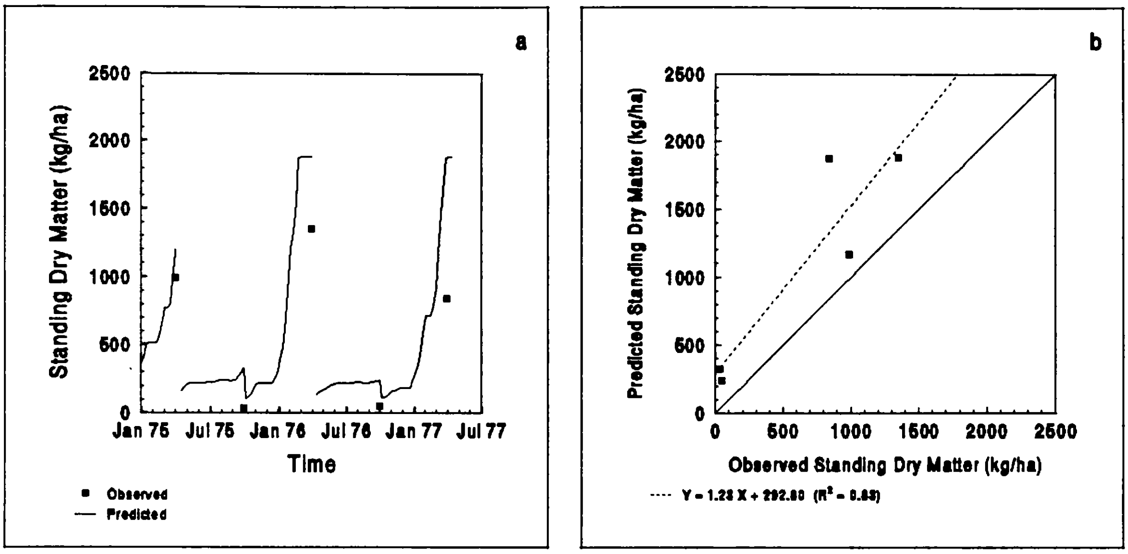


Figure 4.17 Predicted and observed standing dry matter using the data of Christie (1981) to validate the GRASP model to mitchell grass pastures on Burenda near Augathella in south-west Queensland.

4.3.2.6 Burenda - Mitchell grass (Beale 1985)

The reported pattern of growth in the 10% treatment of the Burenda grazing trial (Beale 1985) was characterised by marked fluctuations in end of summer yield (five fold variation between 1982 and 1983) (Figure 4.18). The calibrated model (based on Biddenham parameters) adequately simulated end of summer yield in eleven of the fourteen years of the trial. Each year is described to document performance of the model under a dynamic grazing regime.

In 1976 the simulated yield was 23% greater than the observed value (observed-predicted/observed*100). Examination of Figure 4.18 at this time indicates the quantity of simulated dry matter was declining. An excess of material at this time indicates the simulated rate of detachment was too low to meet the observed yield (i.e. too much material (e.g. leaf, inflorescence and stem) was retained in the simulated forage). Without data on the various yield components it is difficult to determine what material was being lost. However, the above average rainfall in 1976 (Figure 4.19) contributing to this yield was due to above average summer rainfall. Following these conditions it was likely most tussocks flowered and seeded profusely. The rapid loss of inflorescence would result in a sharp decline in yield. This suggests detachment rates were perhaps too low either during or shortly following the wet summer.

In 1977 the simulated yield closely matched the observed value.

In 1978 the simulated yield was 18% below the observed value. Both the annual and summer rainfall for the periods associated with this yield were below average (Figure 4.19). The growth simulated by the model never approached the observed yield indicating there was insufficient retention of material by the end of the previous growing season. This suggests over the dry summer either the simulated detachment rates were too high or the simulated uptake of nitrogen was too low.

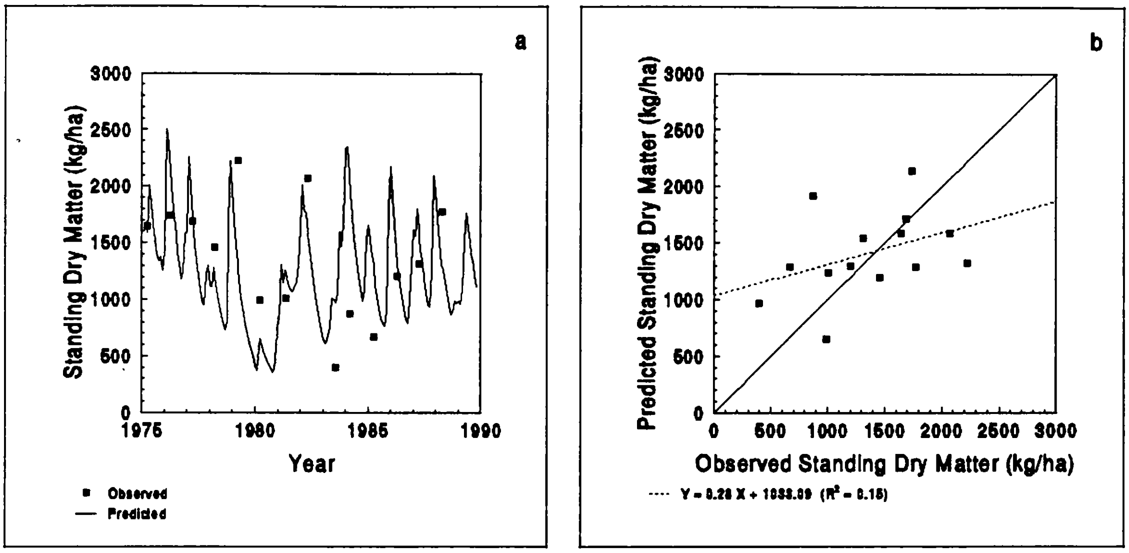


Figure 4.18 Predicted and observed standing dry matter using the data reported by Beale (1985) to validate the GRASP model to mitchell grass pastures in the grazing utilisation trial on Burenda near Augathella in south-west Queensland.

Yield was again under predicted in 1979 (by 40%). Above average rainfall in winter 1978 (Figure 4.19) resulted in a simulated yield at the end of November 1978 comparable to that observed at the end of March 1979 (Figure 4.18). However, the rapid loss of material simulated by the model over the dry summer of 1979 resulted in the under prediction of the observed yield.

In 1980 the simulated yield was 35% below the observed value. Insufficient carry over of material from the previous year (detachment too high) associated with below average summer rainfall in 1980 contributed to the under prediction of yield.

In 1981 the simulated yield closely matched the observed value.

Yield was again under predicted in 1982 (by 23%). With the above average rainfall in winter 1981 and summer 1982 and potentially greater quantity of nitrogen available after the drought of 1980 and 1981 simulated yields could have been greater. This indicates the need for a more dynamic nitrogen model as a component of GRASP. However, the simulated yield at the end of November 1981 was comparable to that observed at the end of March 1982. Again the rapid loss of material simulated by the model over the summer of 1982 resulted in the under prediction of the observed yield.

The model over predicted yields by 144%, 119% and 93% in the years 1983,1984 and 1985 respectively (Figure 4.18). Between 1982 and 1983 a five fold reduction in yield was reported. Below average summer rainfall in 1983 and below average winter rainfall in 1982 (Figure 4.19) and an observed reduction in perennial grass basal area (Beale 1985) would have contributed to the low observed yield. Despite the high detachment rates and dynamic basal area model within GRASP, the model could not match the observed yield decline.

In 1984 the biggest over prediction of yield was observed (Figure 4.18). This followed a very wet winter in 1983 and good summer rain in 1984 (Figure 4.19). The low basal areas reported for 1984 in combination with a potential lack of nitrogen (due to profuse forb growth in winter 1983) may explain the low observed yield. Again a more dynamic nitrogen model may have resulted in a simulated yield closer to the observed.

In 1985 yield was again over predicted (Figure 4.18). The above average rainfall in winter 1984 and low summer rainfall in 1985 (Figure 4.19) may again have resulted in a lack of available nitrogen for grass growth. The basal area of grasses may also have still been low (due to low summer rainfall), contributing to low observed yields.

In 1986 and 1987 simulated yields were comparable to observed values (Figure 4.18).

Yield was again under predicted in 1988 (by 27%) (Figure 4.18). Above average rainfall in winter 1987 (Figure 4.19) resulted in a simulated yield at the end of November 1987 comparable to that observed at the end of March 1988. However, the rapid loss of material simulated by the model over the dry summer of 1988 resulted in the under prediction of the observed yield.

The simulated utilisation (eaten/grown*100) of average growth was 11.9, 19.5, 29.9, 37.1 and 36.8% for the 10, 20, 30, 50 and 80% treatments respectively.

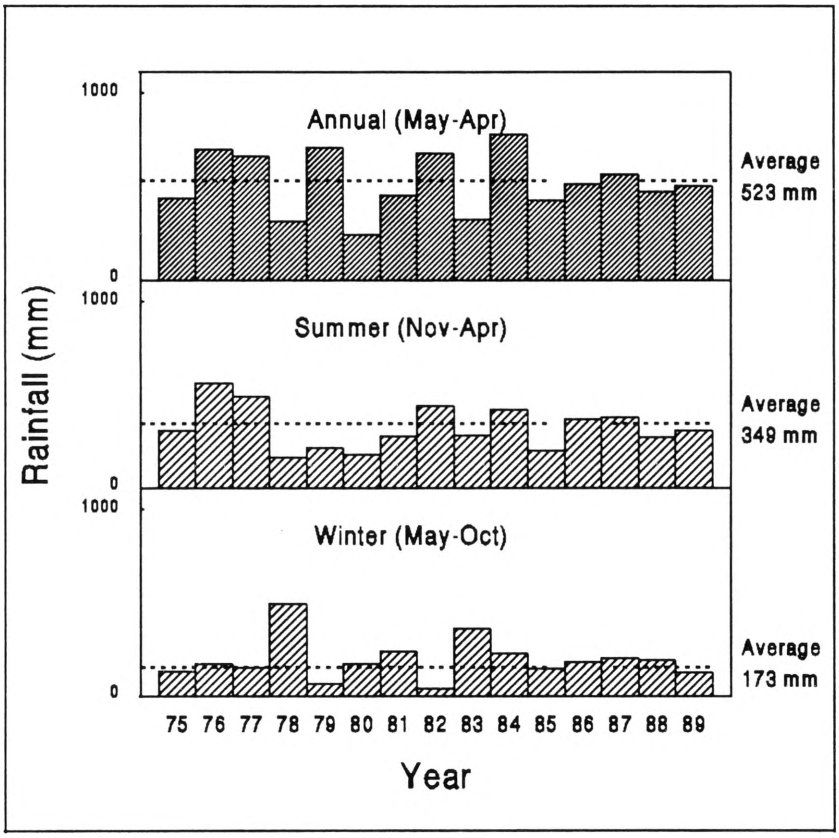


Figure 4.19 Annual, summer and winter rainfall between 1975 and 1989 and long-term average rainfall for Burenda (25°46' S 146°44' E) near Augathella in south-west Queensland.

4.3.3 Extrapolation over time and space

Simulated forage growth during the thirty-two years 1960 to 1992 reflected the rainfall sequence for the corresponding period (Figure 4.20). Only the results for one site are presented graphically (Charleville site). The remaining sites displayed a similar pattern. Marked fluctuations in growth were observed, with three periods of substantial growth (early 1960's, early 1970's and the late 1980's) separated by three periods of low yields (mid to late 1960's, early 1980's, and early 1990's). Yield observations reported for May 1963 by Ebersohn (1970), February 1972 by Beale (1975) and end of summer 1974-77 by Christie (1978b) are in close agreement with those simulated by the model (Figure 4.20 b). At this stage of model development, GRASP does not predict growth of annual and ephemeral species.

In simplifying the simulation results there was a positive relationship between evapo-transpiration and rainfall and simulated growth for each of the thirty-two years and twenty rainfall locations (Charleville site data presented in Figure 4.21). However, the correlation between cumulative evapo-transpiration and simulated growth was greater than that between cumulative rainfall and simulated growth (Table 4.6). The slope of the regression using these data represents an average annual water use efficiency (growth per unit of water used) for the Charleville site for the geographical area covered by the twenty rainfall locations, and for the thirty-two years 1960 to 1992. However, the scatter of points in Figure 4.21 and correlation coefficients in Table 4.6 indicated variability in water use efficiencies (water used per unit of growth).

Examination of this relationship at only one rainfall location (Charleville) also indicated a range of water use efficiencies (Figure 4.22 and Table 4.7). Water use efficiency varied from year to year (Figure 4.23). The range of annual, summer and winter water use efficiencies were 4.0-0.2, 3.8-0.2 and 6.4-0.2 (kg/ha/mm) respectively. From these data an "average" water use efficiency for one location (Charleville) was estimated (slope of regressions in Table 4.7).

Average water use efficiencies for the thirty-two years were compared across the twenty rainfall locations (Charleville site results presented in Figure 4.24 as an example). There was a positive relationship between annual water use efficiency (growth per unit rainfall) and longitude and latitude (proxies for rainfall) for all parameter sites except Maxvale (Table 4.8). At Maxvale the relationship between annual water use efficiency and latitude was not significant.

When conducted for the other sites these analyses have simplified the variability in water use efficiency for the eight land systems examined in Chapter 3 based on the temporal and spatial variability in rainfall across the twenty locations used. The regressions in Table 4.8 enable the estimation of an average rainfall use efficiency for the eight land systems at any location in south-west Queensland. However, these regressions have not accounted for the spatial variability in vapour pressure deficit across the region as only vapour pressure deficit data for Charleville was used for each of the simulations.

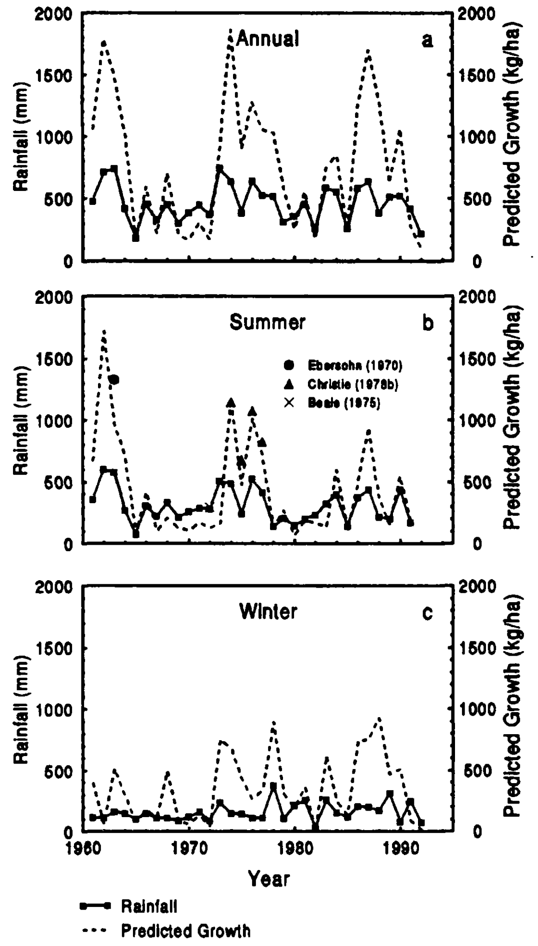


Figure 4.20 Rainfall and predicted growth from the GRASP forage production model for the Charleville site between 1960 and 1992 using climatic data for Charleville. Data reported by Ebersohn (1970), Beale (1975) and Christie (1978b) are shown for validation.

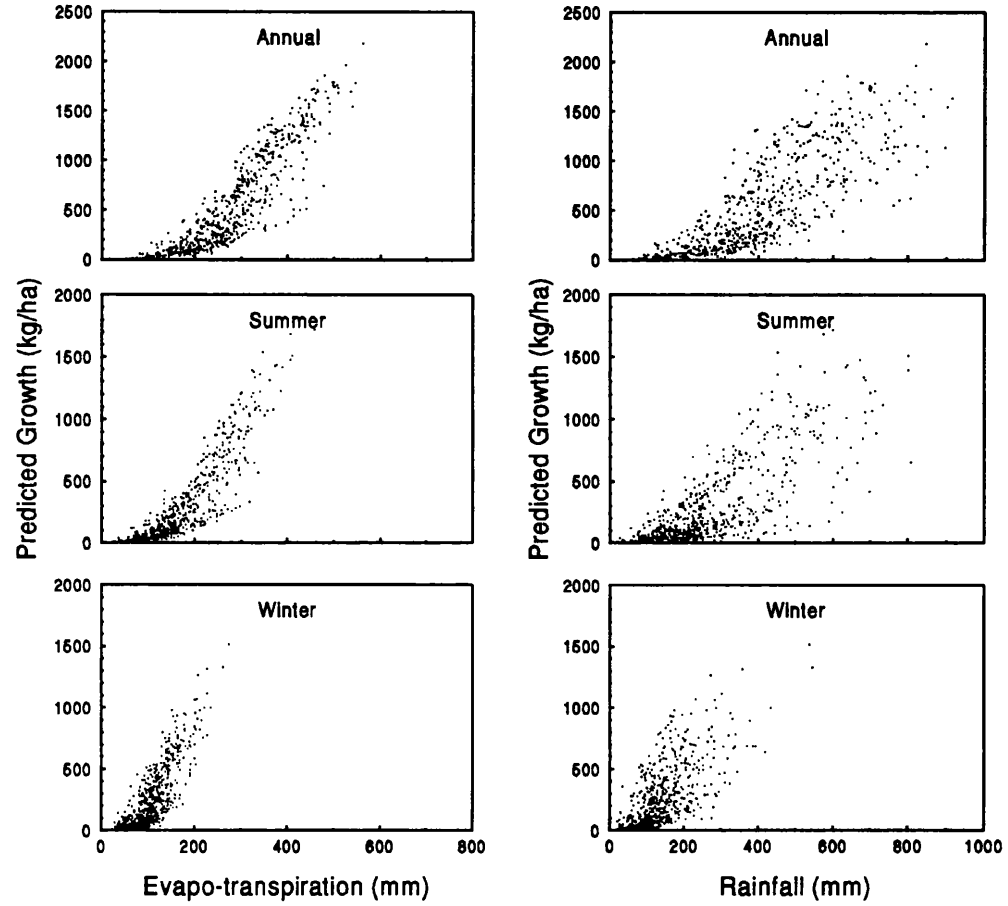


Figure 4.21 The relationship between predicted growth and cumulative evapo-transpiration and rainfall for twenty rainfall locations for the years 1960 to 1992 for parameters describing the Charleville site from simulations using the GRASP forage production model.

Table 4.6 Spatial regressions using data for twenty rainfall locations between growth (kg/ha)(G) simulated by the GRASP model and cumulative rainfall (Ra) and evapo-transpiration (ET) in south-west Queensland for 32 years (1960-92) using parameters describing the Charleville site.

Season	Regression (Ra)	R^2	Regression (ET)	R^2
Annual	G = 2.24 * RA - 360.27	0.65	G = 4.25 * ET - 627.00	0.79
Summer	G = 1.73 * Ra - 172.91	0.57	G = 3.79 * ET - 351.79	0.77
Winter	G = 2.39 * Ra - 71.37	0.50	G = 4.78 * ET - 251.80	0.68

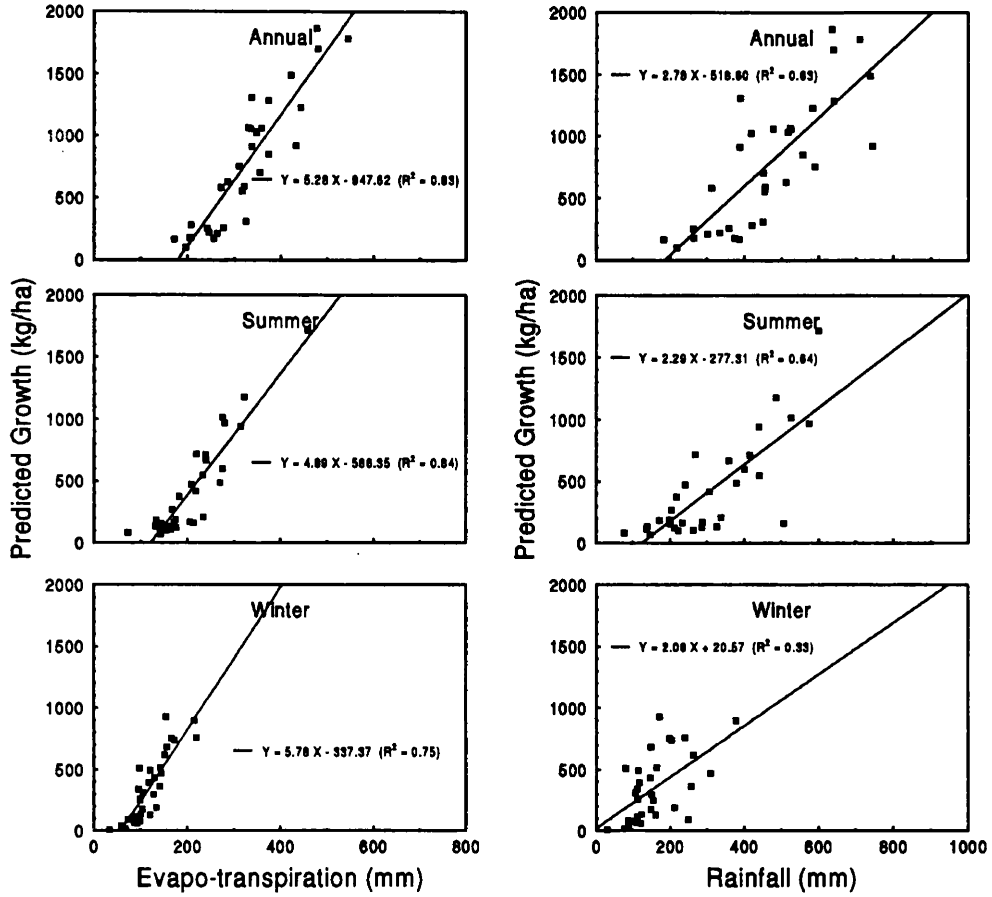


Figure 4.22 The relationship between growth simulated by the GRASP forage production model for the 32 years 1960 to 1992 and cumulative evapo-transpiration and cumulative rainfall using the Charleville rainfall location and parameters describing the Charleville site.

Table 4.7 Temporal regressions for 32 years (1960-92) at one location (Charleville) between growth (kg/ha)(G) simulated by the GRASP model and cumulative rainfall (Ra) and evapo-transpiration (ET) using parameters describing the Charleville site.

Season	Regression (Ra)	R^2	Regression (ET)	R^2
Annual	G = 2.78 * RA - 518.60	0.63	G = 5.28 * ET - 947.62	0.83
Summer	G = 2.29 * Ra - 277.31	0.64	G = 4.89 * ET - 586.35	0.84
Winter	G = 2.09 * Ra - 20.57	0.33	G = 5.78 * ET - 337.37	0.75

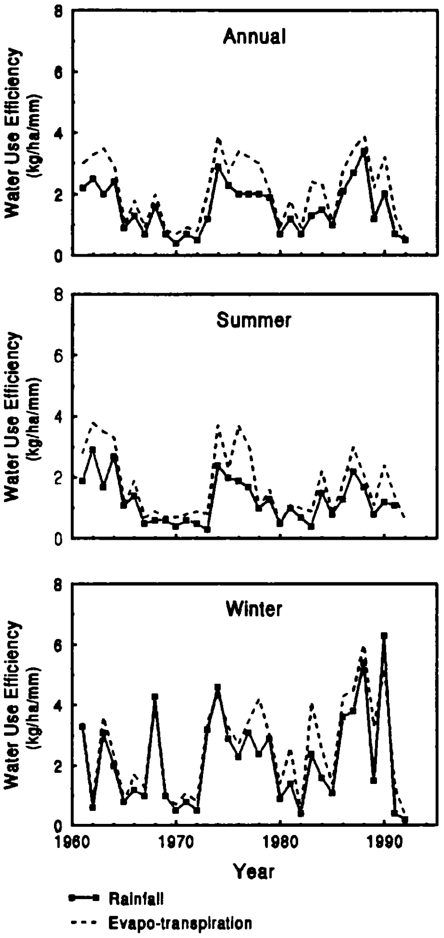


Figure 4.23 The temporal variation in water use efficiency (kg/ha/mm) (evapo-transpiration and rainfall) calculated from output from the GRASP forage production model over the period 1960 to 1992 using the Charleville rainfall location and parameters describing the Charleville site.

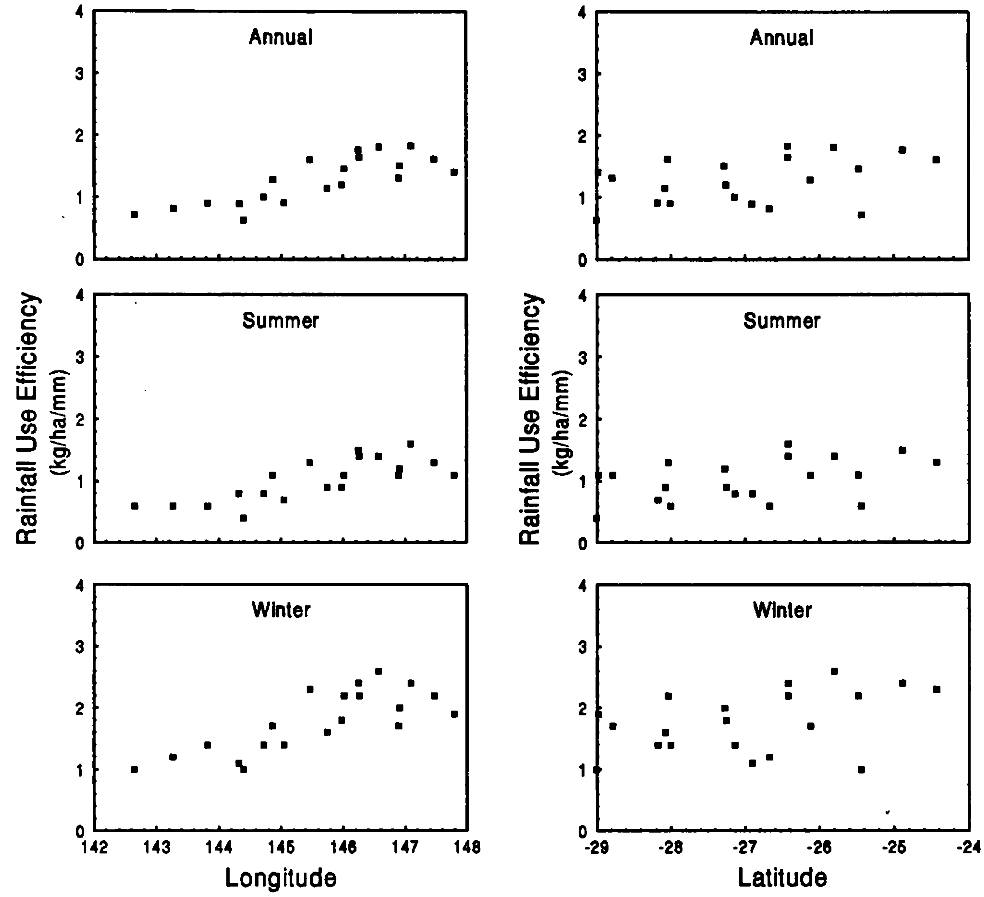


Figure 4.24 The spatial variation in rainfall use efficiency over the study region in south-west Queensland using growth simulated by the GRASP model for twenty locations for the 32 years 1960 to 1992 using parameters describing the Charleville site.

Table 4.8 Regressions between Longitude (Long), Latitude (Lat) and average rainfall use efficiencies (RUE) (kg/ha/mm) for the 32 years 1960-92 derived from simulation studies using the GRASP model with rainfall data from twenty locations in south-west Queensland and regional overall average rainfall use efficiency (ARUE).

Site and Season	Regression	R^2	ARUE (kg/ha/mm)
Annual			
Biddenham	RUE = 0.414*Long - 0.265*Lat - 50.17	0.93	2.94
Charleville	RUE = 0.242*Long - 0.154*Lat - 29.74	0.94	1.28
Airlie	RUE = 0.295*Long - 0.234*Lat - 34.55	0.92	2.10
Lisnalee	RUE = 0.325*Long - 0.299*Lat - 36.32	0.93	3.00
Maxvale	RUE = 0.082*Long - 10.28	0.71	1.63
Turn Turn	RUE = 0.138*Long - 0.073*Lat - 16.84	0.89	1.23
Witten Open	RUE = 0.160*Long - 0.049*Lat - 19.85	0.83	2.16
Witten Enc.	RUE = 0.221*Long - 0.120*Lat - 27.36	0.93	1.65
Wongalee	RUE = 0.078*Long - 0.039*Lat - 8.22	0.70	2.17
Summer			
Biddenham	RUE = 0.526*Long - 0.310*Lat - 64.76	0.93	3.49
Charleville	RUE = 0.209*Long - 0.145*Lat - 25.56	0.91	1.02
Airlie	RUE = 0.410*Long - 0.268*Lat - 49.92	0.90	2.56
Lisnalee	RUE = 0.466*Long - 0.366*Lat - 54.00	0.95	3.96
Maxvale	RUE = 0.136*Long - 0.057*Lat - 16.87	0.77	1.42
Turn Turn	RUE = 0.147*Long - 0.110*Lat - 17.47	0.92	1.00
Witten Open	RUE = 0.205*Long - 0.120*Lat - 24.78	0.93	1.83
Witten Enc.	RUE = 0.226*Long - 0.168*Lat - 26.98	0.95	1.35
Wongalee	RUE = 0.086*Long - 10.02	0.57	2.45
Winter			
Biddenham	RUE = 0.275*Long + 0.077*Lat - 36.23	0.81	1.79
Charleville	RUE = 0.309*Long - 0.211*Lat - 37.52	0.91	1.78
Airlie	RUE = 0.114*Long - 0.106*Lat - 12.51	0.78	1.28
Lisnalee	RUE = 0.128*Long - 0.097*Lat - 14.99	0.81	1.02
Maxvale	RUE =-0.035*Long + 0.096*Lat + 4.45	0.30	2.00
Turn Turn	RUE = 0.098*Long - 12.53	0.43	1.69
Witten Open	RUE = 0.072*Long - 7.67	0.16	2.87
Witten Enc	RUE = 0.192*Long - 25.63	0.65	2.28
Wongalee	RUE = 0.111*Long - 0.061*Lat - 12.95	0.79	1.55

4.4 Discussion

4.4.1 Calibration of the GRASP model

In general, the GRASP model adequately described the broad seasonal pattern of annual forage growth, in terms of reflecting the significant increases in yield described in Chapter 3. In semi-arid regions forage production is characterised by marked fluctuations in response to large variations in seasonal rainfall (Orr *et al.* 1993). Results from this Chapter indicate the GRASP model was capable of describing the rapid increases in forage production but had difficulty simulating high rates of detachment. As the calibration procedure did not concentrate on either the timing or rate of detachment the model cannot be critically assessed in this area. To achieve this, closer examination of the timing and rates of detachment of various plant components (leaf, stem and inflorescence) would be required. This would vary between species and depend on climatic factors. Under grazing, detachment rates would also be dependent on grazing pressure.

Simulated peak yields were comparable to observed peak yields (Table 4.4). During calibration, the GRASP model tended to underestimate yields late in the growing season, while overestimating yield early in the growing season. This indicates the GRASP model was conservative when estimating forage production on an annual or longer term basis. In some instances the GRASP model failed to describe some short term (less than 6 months) but still significant yield fluctuations. This was most notable on sites characterised by large tussock C4 grasses (*Astrebla* spp. at Biddenham and Airlie, and *Triodia* spp. at Wongalee).

At these sites, inter-tussock grasses and herbs can contribute to the dry matter yield of the forage depending on season. During winters receiving above average rainfall, these species can contribute in excess of 10% of annual forage production (Silcock *et al.* 1985). In the form used here, the GRASP model (version GVT74) was based on parameters describing a mono-specific sward (e.g. only one temperature response and one rate of nitrogen uptake). As a result it was not possible to predict the growth of annuals and ephemerals. If the model was capable of describing a mixed sward (C3/C4), short term yield fluctuations due to growth of less dominant species could be potentially estimated.

For most sites the simulated time course of soil moisture reflected observed values. For all sites except Wittenburra enclosed, the GRASP model overestimated soil moisture in dry profiles and underestimated moisture in wet profiles. The GRASP model had greatest difficulty predicting soil moisture at sites with cracking clay soils (Biddenham, Airlie and Lisnalee). The cracking nature of these soils may explain the rapid wetting and drying of the soils observed. Under dry conditions cracks would allow water to wet the profile at depth at the same time as surface layers. Cracks would also allow air to dry the soil at depth to low levels. Further application of the model to cracking clay soils will require modification of soil evaporation functions and also allow infiltration to lower soil layers (for example Clewett 1985).

However, in this study, the GRASP model was not used in the expectation of describing either the detailed pattern of forage growth or the daily fluctuations in soil water at each location. The objective of calibrating and using GRASP was to extrapolate data reported in Chapter 3 over time and space to examine the key plant production relationships (e.g. water use efficiency, impact of trees, basal area and N uptake). If the traditional scientific model was followed, further research would be conducted to refine the model used. The major criteria in determining success of this operation was whether the broad pattern of growth was described. The calibration procedure chosen, and the results presented above indicate this objective was achieved. This enabled the necessary validation and extrapolation steps to proceed in order to meet the objective of estimating grazing capacities of individual properties through the examination of these key plant production relationships.

4.4.2 Validation of the GRASP model

Validation results support the conclusion above with reasonable agreement between simulated forage yields and those reported by a variety of authors. The ability of the GRASP model to describe patterns of forage production in general terms, from treatments and locations external to data used in calibration indicates the robustness of the GRASP model.

However, the model again underestimated dry matter yields observed late in the growing season. As in the calibration stage, the GRASP model was conservative when estimating forage production on an annual or longer term basis. Where soil moisture data were available for validation, simulated soil water was not significantly correlated to observed values, though the simulated time course of soil moisture generally followed the observed. The model tended to underestimate and overestimate the moisture content of wet and dry profiles respectively. This may be largely due to the quality of soil moisture data, as it was estimated directly from figures in the papers of Christie (1978 and 1981) and was not actual data. In addition, the published description of soil parameters in these papers was insufficient to satisfactorily describe soil characteristics required for the GRASP model.

Refinements to the GRASP model subsequent to the work described in this Chapter have resulted in an improved prediction of the data of Christie (1981) (Figure 4.14) and validation against an additional two grazing trials conducted in south-west Queensland ('Eastwood' on Buffel grass on cleared gidyea (Orr et al. *in prep.) and 'Gilruth Plains' on mitchell grass (Roe and Allen (1945, 1993)) (See Appendix 10). At the time of writing, refinement of the GRASP model continues. Improvements to the model largely derive from its application to a wide range of native pasture communities across Australia in exercises similar to that described in this Chapter (G.M. McKeon pers. comm.).*

The capability of the GRASP model to account for removal of forage by grazing animals was supported by the validation results from the Arabella grazing trial. At light grazing pressure (20% removal of end of growing season standing dry matter by sheep) and heavy grazing pressure (80% removal of end of growing season standing dry matter by sheep) simulated yields were well correlated with those observed in the paddocks, despite fluctuations in basal area and species composition of perennial grasses described by Orr *et al.* (1993).

However, the yields observed in the paddocks are a combination of current seasons growth and carry over material from the previous year. From this data it is difficult to determine whether the desired levels of forage utilisation were achieved due to the growth occurring during the year. While it was an objective of these grazing trials to treat this additional forage production as a bonus, an understanding of the utilisation of this growth would be valuable in comparing treatments. Using the GRASP model an examination of the actual utilisation of current years forage growth was possible. In the highest grazing pressure treatments (80% removal of end of growing season standing dry matter by sheep) at Arabella and Burenda, average utilisation of growth in the trial period did not exceed 40% (39.1 and 36.8% respectively).

4.4.3 Extrapolation of the GRASP model

Chapter 3 demonstrated that primary production could be measured and related to water use (growth per unit of evapo-transpiration or unit of rainfall) over short periods of time. This concept is not new. Le Houerou (1984) documents over 100 similar attempts to relate range production to rainfall either on a seasonal or an annual basis. In these attempts, significant to very highly significant correlations have been found in arid and semi-arid zones of the world. Under comparable management situations, throughout the various arid zones of the world, with totally different floras and vegetation types Le Houerou (1984) reports surprising consistency in rainfall use efficiencies in the range 0.5 to 10 kg/ha/mm of rain. However, most of these relate to one site and one range type or to a very limited number of sites (Le Houerou *et al.* 1988). Lauenroth and Sala (1992) highlight the need to recognise the impact of spatial and temporal variability when estimating long term forage production.

This was examined in this study using simulations based on the successful calibration and validation of the GRASP model using data from nine sites. Extrapolation results indicated the difficulty in determining an "average" water use efficiency for a forage type due to the variation in water use efficiency over time and space (Table 4.8). Spatial and temporal variation in rainfall, influenced both evapo-transpiration use efficiency and rainfall use efficiency. However, as climatic data from only one location (Charleville) were used in these simulations the spatial effect of a variable vapour pressure deficit on rainfall use efficiencies has not been included. The impact of the VPD on growth was described in Chapter 3 and would need to be included in a method for examining forage growth across south-west Queensland. The annual range reported in Table 4.8 (1.23 - 3.00 kg/ha/mm) approximates that originally proposed by Noy-Meir (1973) (0.5-2.0 kg/ha/mm) and fits within the range summarised by Le Houerou (1984) (0.5-10 kg/ha/mm).

Water use efficiencies would also be expected to vary with landscape factors not included in the analyses in this Chapter. Topography, groving of vegetation, soil type, soil surface characteristics, soil depth and the proportions of run-on and run-off areas are examples of landscape characteristics that are likely to influence water use efficiencies.

Water use efficiencies calculated as unit growth per unit of water used (either evapo-transpiration or rainfall) indicate forage growth would be expected on even the smallest amounts of water used. Examination of Figure 4.22 indicate 186 mm of rain or 179 mm of evapo-transpiration was required before any yield was simulated. This "ineffective" rainfall is greater than that reported by Noy-Meir (1973) (25-75 mm/year) and by Sala *et al.* (1988) (56 mm/year). For different seasons and different forage types, analysis of simulation results reported in this Chapter indicates varying levels of water are required before growth occurs. Therefore, in calculating forage production based on water used (either evapo-transpiration or rainfall) it would be more appropriate to use the estimated regressions rather than one water use efficiency value.

The question also arises as to which water use efficiency best describes growth. The discussion in Chapter 3 alluded to the variation in definition and interpretation of water use efficiencies. Chapter 3 also estimated several water use efficiencies for each site based on these definitions. Analysis of simulation results in this Chapter has identified a degree of temporal and spatial variability in water use efficiencies, yielding a range of water use efficiencies for each site (Table 4.9).

Table 4.9 Comparison of annual, summer and winter water use efficiencies (evapo-transpiration) for the Charleville site derived from (1) experimental data from Chapter 3 (Tables 3.5 and 3.8), (2) simulation using 32 years of Charleville daily climate (1960 to 1992), (3) average from twenty locations in south-west Queensland (Table 4.2) over 32 years (1960 to 1992), (4) slope of the regression between growth and evapo-transpiration at Charleville (Table 4.7) and (5) slope of the regression between growth and evapo-transpiration for twenty locations in south-west Queensland over 32 years (1960 to 1992) (Table 4.6).

Site	(1)			(2)			(3)			(4)			(5)		
	An	Su	Wi	An	Su	Wi	An	Su	Wi	An	Su	Wi	An	Su	Wi
Charleville	2.2	2.0	0.9	2.3	2.0	2.9	1.0	0.9	2.1	5.3	4.9	5.8	4.3	3.8	4.8

In order to estimate long term "safe" grazing capacities of properties in south-west Queensland, it would be appropriate to use a model which predicts forage growth based on the spatial and temporal rainfall and vapour pressure deficit variability experienced in the region. Lauenroth and Sala (1992) highlight the variation between existing spatial and temporal models for North American grasslands. The variation is based on differences in vegetation structure ("reflected in abundance of life forms and species and in the density of seeds and tillers") and the impact these differences have on estimates of long term forage production. The spatial model described by these authors utilises the primary production of an ecosystem with a different vegetation structure at each value of precipitation. Conversely the temporal model relates annual rainfall to primary production for the same vegetation structure through time.

In GRASP, a dynamic grass basal area model partially addresses this issue. Grass basal area is calculated at the end of each summer growing season and is then used in the calculation of potential regrowth for the next growing season (Littleboy and McKeon 1996). The vegetation structure for each of the nine sites used in the extrapolation exercise fluctuates (in terms of basal area) as rainfall varies both spatially and temporally. The regressions predicting rainfall use efficiency in Table 4.8 integrate the spatial and temporal factors influencing production based on the years 1960 to 1992. However, these regressions represent an estimate of rainfall use efficiency for only 8 of the 180 land systems found in south-west Queensland. Estimating grazing capacities on individual properties with a wider range of land systems than sampled in Chapter 3 will require estimates of rainfall use efficiencies for these land systems. This is examined in Chapter 5.

4.4.4 Conclusions or, "Were the modelling objectives met"?

The preceding chapter suggested that simulation modelling was the most promising procedure to estimate above-ground net primary production due to the complexity of interrelationships between factors governing forage growth (Lauenroth *et al.* (1986) and Redman (1992)). When calibrated to and validated against a range of pasture communities across south-west Queensland the GRASP model (version GVT74) adequately described the pattern of annual forage production for communities dominated by C3 or C4 species. For a number of sites where annual/ephemeral species contributed to the pasture community (e.g. the mulga pastures at the Wittenburra outside site and the Burenda mitchell grass sites of Christie (1981) and Beale (1985)) or where the proportions of C3 and C4 species changed over time (e.g. the 35%, 50% and 80% treatments of the Arabella grazing trial (Beale 1985)) the GRASP model did not predict the pattern of forage production as well. This may limit the application of the current GRASP model (version GVT74) to other pasture communities (e.g. chenopod shrublands and annual pastures).

With a number of limitations in the GRASP model identified, the question arises as to what level of accuracy is required. Singh *et al.* (1975) indicates one must choose methods for sampling and calculating above-ground net primary production which are at a similar level of resolution as the objectives of the study. In order to estimate long term "safe" grazing capacities of properties in south-west Queensland to review carrying capacities and guide strategic (20-30 years) stocking decisions, it is desirable to predict the long term fluctuations in forage production. While short term fluctuations in forage production are important for tactical (annual or seasonal) stocking rate decisions they are less important for examining long term resource capability required for a review of grazing capacities.

Calibration, validation and extrapolation results presented in this Chapter indicate that the GRASP model is appropriate for predicting long term patterns of forage production in south-west Queensland. Simulations using the calibrated GRASP model enabled the estimation of parameters describing growth (water use efficiencies) on a regional scale for selected land systems. However, the approach is still confined to the selected land systems for which primary production data was collected. To review grazing capacities on individual properties requires extrapolation of parameters estimating average growth to other land systems. In the following Chapter these predictors of growth were derived and used to estimate the grazing capacities of native pastures for individual properties in south-west Queensland.

5.0 A QUANTITATIVE APPROACH TO ESTIMATING "SAFE" GRAZING CAPACITIES

5.1 Introduction

Determining the grazing capacity of grazing lands, and understanding the consequences, is one of the most difficult tasks in grazing management (Vallentine 1990a). A "safe" grazing capacity is defined here as the number of dry sheep equivalents that can be carried on a land system, paddock or property in the long-term (20-30 years) without any decrease in pasture condition and without accelerated soil erosion (after Scanlan *et al.* 1994). In this thesis it differs from a "safe" 'stocking rate' which is a tactical or shorter term (seasonal or annual) calculation of "safe" stock numbers.

Several approaches are available for determining grazing capacity and appropriate stocking rates. Most are based on experience of "average" properties in "average" years (Wilson *et al.* 1990), and trial and error, coupled with regular adjustments. Due to the variability in climate and land types in south-west Queensland, the use of district averages is unlikely to yield appropriate grazing capacities for individual properties. Despite this, decisions on grazing capacities must be made and Vallentine (1990a) lists seven methods for this. Briefly these were:

1. Initial stocking rate tables for various land and pasture types such as those reported for south-west Queensland by Mills and Purdie (1990);

2. Known or historical stocking rates adjusted for land condition and trend information. This is comparable to Condon *et al.* (1969) where known grazing capacity was corrected for factors such as precipitation, soil fertility, plant community type and topography;

3. Estimates of standing forage yield and conversion to stock numbers using appropriate levels of use for that forage;

4. Percentage utilisation methods where actual estimates of forage utilisation are compared with appropriate levels of use for that forage;

5. Forage comparison methods in which the grazing land under question is compared to a mental ideal or standard for that forage;

6. Energy based methods requiring detailed measurements matching the energy content of forages to the requirements of grazing animals; and

7. Forage density methods requiring laborious estimates of forage density and quality to develop indices for appropriate stocking rates.

A number of these approaches requires subjective judgment and some prior level of experience regarding the forages in question. To remove this limitation, a quantitative approach to estimating grazing capacity linking ecological principles with local knowledge and experience was examined.

This chapter describes the development of such an approach building on the primary productivity and simulation results from Chapters 3 and 4. It is equivalent to the third method listed above by Vallentine (1990a) except it is based on calculated annual forage growth rather than standing forage yield.

In this Chapter, selected results are presented in the materials and methods section as they were integral to further development of the method for estimating grazing capacities.

5.2 Model development

A quantified approach to estimating "safe" long-term grazing capacities was developed based on primary productivity and simulation studies described in Chapters 3 and 4. The method is comparable to that developed by Scanlan *et al.* (1994) for resource units and properties in northern Australia. In place of the resource units of Scanlan *et al.* (1994), land systems (Mills and Lee 1990) were chosen in this study as the base unit for estimating the amount of forage grown, the "safe" level of use of that forage and the grazing capacity. Land systems have been defined by Christian and Stewart (1968) as 'an area or group of areas throughout which there is a recurring pattern of topography, soils and vegetation'. These have been mapped for south-west Queensland by Dawson (1974) and Mills and Lee (1990). Using this mapping, land systems can be readily identified and mapped at the paddock and property scale.

A "safe" grazing capacity is defined here as the number of dry sheep equivalents (DSE) that can be carried on a land system, paddock or property in the long-term without any decrease in pasture condition and without accelerated soil erosion (after Scanlan *et al.* 1994).

Mathematically a "safe" grazing capacity can be represented as:

"safe" grazing capacity(DSE/land system) = **(amount of forage which can be safely eaten** (kg/ha/year) **/ amount eaten per dry sheep** (kg/DSE/year)) * **area of the land system** (ha)

where:

amount of forage which can be safely eaten (kg/ha/year) = (**"safe" level of forage utilisation** (%) / 100) * **average annual forage grown** (kg/ha/year)

The above relationship differs from other concepts of forage utilisation (e.g. Beale *et al.* (1986), Orr *et al.* (1993), Anderson *et al.* (1994)). These authors expressed utilisation as a proportion of standing dry matter either measured or observed in the field at some point in time. Standing dry matter measured or observed in the field may include dry matter carried over from the previous 12 months and is thus distinct from average annual forage grown. The latter is difficult to measure but can be estimated using primary productivity studies linked with computer simulation. Estimates of average annual forage grown and utilisation of this material over a 12 month period (May to April) are used in this chapter. These estimates do not include carry-over material.

Thus the four factors which need to be determined were:

- land system areas of a property (ha);
- amount eaten (intake) per dry sheep (kg/DSE/year);
- average forage grown (kg/ha/year) for each land system and property; and
- "safe" level of forage utilisation (%) for each land system.

5.2.1 Land system area

The land system area was estimated by overlaying 1:250,000 scale cadastral maps with 1:250,000 scale land system maps and measuring land system area per property with a planimeter.

5.2.2 Intake

While daily intake varies with the type and quantity of pasture and the type and physiological age of an animal, an average annual amount of forage eaten (intake) was assumed to be 400 kg/DSE/year (McMeniman *et al.* 1986). While a dynamic intake model relating intake to the quantity of forage available would be applicable for estimating short term stocking decisions an average annual intake was chosen to match the calculation of average annual forage grown. The intake of leaf from the mulga tree (*Acacia aneura*) is also considered in this study and its estimation is described later in Section 5.2.3.4.

The remaining two factors, average annual forage grown and "safe" level of utilisation of this forage, are more difficult to estimate. Thus the key to calculating "safe" grazing capacities for land systems and properties in south-west Queensland was to develop a methodology for determining average annual forage grown and a "safe" level of utilisation of this forage.

5.2.3 Forage grown

Individual grazing properties in south-west Queensland have a unique mix of land systems and occur across a range of climate (rainfall and vapour pressure deficit, Chapter 1). To examine the grazing capacities of these properties required an estimate of average annual forage grown for each of the land systems found on a property. As long-term primary productivity data for many of these land systems were not available, a method for estimating average annual forage growth for any land system in south-west Queensland was required.

In Chapter 4 the forage production model GRASP was successfully calibrated to 9 sites representing 8 land systems. This enabled the examination of long-term forage growth on these sites. Without calibration data and climatic records for the remaining 172 land systems it would be difficult to use the GRASP model to estimate growth on these land systems.

An alternative was to explore a rainfall use efficiency (RUE) (kg/ha/mm) approach and apply it to individual land systems on individual properties. This approach assumes a linear relationship between forage growth (FG) and rainfall (RAIN) (e.g. Le Houerou and Hoste (1977), and Milchunas *et al.* 1994).

The method attempted to account for:

- the variation in productivity between land systems;
- the temporal and spatial variation in the vapour pressure deficit (VPD); and
- the impact of trees and shrubs (spatial but not temporal).

Average annual forage grown (FG) for a land system was calculated as the product of potential forage grown (PFG), an index describing the impact of woody species (WI) and an empirically derived multiplier accounting for the spatial distribution of woody species (Section 5.2.3.3.1):

$$\mathbf{FG\ (kg) = PFG\ (kg) * WI * 1.168}$$

where the potential forage grown (PFG) for a land system was the product of the standard rainfall use efficiency for the land system (SRUE), a vapour pressure deficit index (VPDI), long-term average annual rainfall (RAIN) and the area (AREA) of the land system:

$$\mathbf{PFG\ (kg) = SRUE\ (kg/ha/mm) * VPDI * RAIN\ (mm) * AREA\ (ha)}$$

5.2.3.1 Estimation of standard rainfall use efficiencies for land systems

To apply a rainfall use efficiency to any land system at any location in the study region, a method for predicting rainfall use efficiencies using site data was established as follows.

For each of the 8 land systems (9 sites) analysed in Chapters 3 and 4 a standard rainfall use efficiency (SRUE) at Charleville (146°15' east and 26°24' south) was estimated using the regressions from Table 4.8. This point was chosen as a standard reference, as the simulations conducted in Chapter 4 used daily climatic data from Charleville. The objective was to remove spatial variability in rainfall allowing examination of the relationship between standard rainfall use efficiencies and site data. In addition, the regressions in Table 4.8 did not account for the spatial variability in the vapour pressure deficit as climatic data from only one location (Charleville) was used in the simulation studies of Chapter 4.

Site data describing chemical and physical soil properties (Bulk 0-10cm) from the Western Arid Region Land Use Studies (WARLUS) (Dawson and Ahern 1974, Turner and Ahern 1978, Mills and Ahern 1980 and Ahern and Mills 1990) were used (Table 5.1) in a best subset multiple regression to examine the relationships between site data and standard rainfall use efficiencies. These site data were used as they were available for 78% of the land systems in south-west Queensland. For the nine sites examined standard rainfall use efficiency was best correlated to a combination of soil pH, total phosphorus (TotP) and the fine sand fraction (FS).

To estimate a standard rainfall use efficiency for each land system in south-west Queensland (Table 5.2 and summarised in Table 5.3) this regression was applied to the site data representative of each land system:

$$\mathbf{SRUE\ (kg/ha/mm) = 0.2970 * pH + 22.1169 * TotP(\%) - 0.0149 * FS(\%)} \quad (R^2=0.93\ \ n=9)$$

While the range of data representing the nine sites did not cover the diversity reported in the WARLUS site descriptions (Table 5.1) the resultant range of calculated SRUE (1.3 - 5.6 kg/ha/mm) (Table 5.2) was comparable to the range reported in Chapter 3 (1.28 - 3.00 kg/ha/mm) and by Le Houerou (1984) (0.5 - 10 kg/ha/mm) in Chapter 4.

Table 5.1 Site data from the Western Arid Region Land Use Studies (WARLUS) Parts I-IV (Dawson and Ahern 1974, Turner and Ahern 1978, Mills and Ahern 1980 and Ahern and Mills 1990) for comparison with rainfall use efficiencies standardised to Charleville's location and climate (SRUE (kg/ha/mm)). Maximum and minimum values across WARLUS shown.

SRUE*	pH	Organic Carbon (%)	Tot. N (%)	Tot. P (%)	Coarse Sand (%)	Fine Sand (%)	Silt (%)	Clay (%)	Soil Water at -33 kPa (%)	Soil Water at -1500 kPa (%)	Avail. Soil Water (%)
3.37	8.1	0.80	0.08	0.058	3	24	16	57	38	20	17
1.53	5.2	0.78	0.05	0.023	51	30	5	14	8	4	4
2.42	8.3	0.46	0.05	0.038	20	30	5	45	31	18	13
3.39	5.8	0.50	0.04	0.068	38	34	7	23	10	6	5
1.68	5.6	0.81	0.05	0.033	23	47	11	19	12	6	6
1.36	6.1	0.55	0.05	0.059	28	49	7	20	11	4	7
2.29	5.1	0.63	0.06	0.049	15	51	8	28	17	8	9
1.86	5.1	0.63	0.06	0.049	15	51	8	28	17	8	9
2.24	5.9	0.54	0.03	0.013	59	29	4	9	5	3	2
Max	9.2	2.0	0.10	0.170	73	69	25	66	39	27	24
Min	4.2	0.1	0.01	0.009	1	14	0	3	2	1	1

Table 5.2 Calculated standard rainfall use efficiencies (SRUE kg/ha/mm) for the WARLUS land systems of Dawson and Ahern 1974 (Part I), Turner and Ahern 1978 (Part II), Mills and Ahern 1980 (Part IV) and Ahern and Mills 1990 (Part III).

Land Zone	Land System	Part 1	Part 2	Part 3	Part 4	Land Zone	Land System	Part 1	Part 2	Part 3	Part 4
Alluvial	A1	1.9	2.5	2.4	2.5	Hard	H1	2.1	*	1.8	2.3
Plains Open	A2	*	2.4	*		Mulga	H2	1.8	1.9	1.6	
	A3	2.0	2.5	2.1		Lands	H3	2.2	*	1.7	
	A4	2.5	1.8				H4	1.3	1.6	1.4	
	A5	*	2.1				H5	1.6	1.6		
	A6	2.1	2.4			Claypans /	L1	2.3	*	2.4	*
Undulating	B1				*	Lakes	L2	2.5		*	*
Brigalow	B2				2.8	Soft	M1	2.0	2.2	1.7	1.9
Lands	B3				2.6	Mulga	M2	1.9	1.8	1.7	*
	B4				2.9	Lands	M3	*	1.6	1.7	
	B5				5.6		M4	*	*	1.7	
Channel	C1	2.8	2.3				M5	2.1		1.8	
Country	C2	2.4	2.5			Spinifex	N1			1.6	
	C3	2.3	2.6			Dissected	R1	1.3	*	*	*
Dunefields	D1	*	1.7	1.9		Residuals	R2	*	1.8	*	*
	D2	1.6	1.8	2.5			R3	*	*	1.7	1.7
	D3	*	2.1	2.2			R4	*	1.5		
	D4	2.0	1.9				R5	*	*		
	D5	1.7					R6	1.5	1.6		
	D6	*					R7		*		
	D7	2.1					R8		1.9		
	D8	*				Mulga	S1	1.8	1.4	1.6	1.8
Poplar Box	E1			1.8	1.7	Sandplains	S2	2.4	1.8	1.6	
Lands	E2			2.3	1.7		S3		1.7	2.0	
	E3			2.1	3.8		S4		1.7		
	E4			2.1	2.1		S5		2.0		
	E5				2.3		S6		1.7		
	E6				1.8	Wooded	T1		2.4		*
	E7				1.8	Downs	T2		2.7		*
Mitchell	F1	*	2.2	2.6	3.3		T3		2.9		
Grass	F2	2.4	2.2		3.0		T4		2.6		
Downs	F3	2.7	3.1		3.1		T5		2.5		
	F4	2.2	*			Alluvial	W1	2.4	2.5	2.0	*
	F5		2.8			Plains	W2	2.6	*	*	2.0
	F6		*			Woodland	W3	2.9	2.5	2.5	2.6
	F7		2.8				W4	2.1	2.3	*	2.4
	F8		2.1				W5	*	2.8	2.7	2.8
Gidyea	G1	2.1	3.0	3.4	3.0		W6	2.5	2.3	*	
Lands	G2	2.0	3.2	2.3	5.6		W7	2.7	2.5	*	
	G3	2.5	2.4	2.6	3.8		W8			2.7	
	G4	2.5	2.5								
	G5	*									

* Insufficient site data to calculate a rainfall use efficiency for that land system

A blank indicates the absence of that land system from that part of WARLUS.

Table 5.3 Estimated average standard rainfall use efficiencies (SRUE kg/ha/mm) for the 15 land zones from WARLUS Parts I-IV. (* denotes land zone with observations from Chapters 3 and 4).

Land Zone	SRUE (kg/ha/mm)
Alluvial Plains Open (A) *	2.3
Brigalow (B) *	3.5
Channel Country (C)	2.5
Dunefields / Sandhills (D)	1.9
Poplar Box Lands (E)	2.1
Downs (F) *	2.7
Gidgee Lands (G)	2.9
Hard Mulga Lands (H) *	1.8
Claypans / Lakes (L)	2.4
Soft Mulga Lands (M) *	1.8
Spinifex Sandplains (N) *	1.6
Dissected Residuals (R)	1.6
Mulga Sandplains (S) *	1.8
Wooded Downs (T)	2.6
Alluvial Plains Wooded (W)	2.5

5.2.3.2 Estimating the spatial variability in VPD

As rainfall use efficiencies for forages have been shown to be inversely proportional to VPD (Day *et al.* 1993, Scanlan *et al.* 1994), a VPD index (VPDI) was developed to account for the spatial variability in the VPD. The temporal and spatial variability in RUE for a particular land system was examined in Chapter 4. This variation was attributed to seasonal differences in the atmospheric vapour pressure deficit (VPD). However, the impact of spatial variability in VPD was not examined in Chapter 4. An examination of average annual VPD calculated from AUSTCLIM climatic averages of Keig and McAlpine 1969 indicates that in south-west Queensland the annual average VPD increases when moving west and decreases with increasing annual rainfall.

Since the standard rainfall use efficiencies listed in Tables 5.2 and 5.3 were derived using 32 years of Charleville climatic data, the seasonal effect of the VPD on rainfall use efficiency has already been accounted for. To account for the effect of geographical location on the vapour pressure deficit, data for 12 locations from the AUSTCLIM climatic averages (Keig and McAlpine 1969) (Table 5.4) were used to estimate a Vapour Pressure Deficit Index (VPDI) using latitude and longitude (Figure 5.1). As Charleville climatic data were used in simulations, the VPDI was 1.0 at this location.

$$\mathbf{VPDI = 22.997/(190.024+0.2270*Latitude-1.1068*Longitude)\quad R^2=0.96\quad n=12}$$

Table 5.4 Average annual vapour pressure deficits (hPa) from AUSTCLIM for 12 stations used to estimate the VPD index.

Station	Station Number	Latitude	Longitude	VPD (hPa)
Bollon	44010	-28° 2’	147° 29’	20.0
Mitchell	43020	-26° 29’	146° 58’	19.3
Goodooga	48046	-29° 7’	147° 27’	20.4
Tambo	35069	-24° 53’	146° 15’	22.6
Cunnamulla	44026	-28° 4’	145° 41’	22.4
Charleville	44021	-26° 24’	146° 15’	23.1
Thargomindah	45017	-28° 0’	143° 49’	24.9
Blackall	36143	-24° 25’	145° 28’	23.5
Adavale	45043	-25° 55’	144° 36’	24.9
Isisford	36026	-24° 15’	144° 26’	24.8
Quilpie	45015	-26° 37’	144° 16’	24.8
Birdsville	38002	-25° 55’	139° 22’	29.3

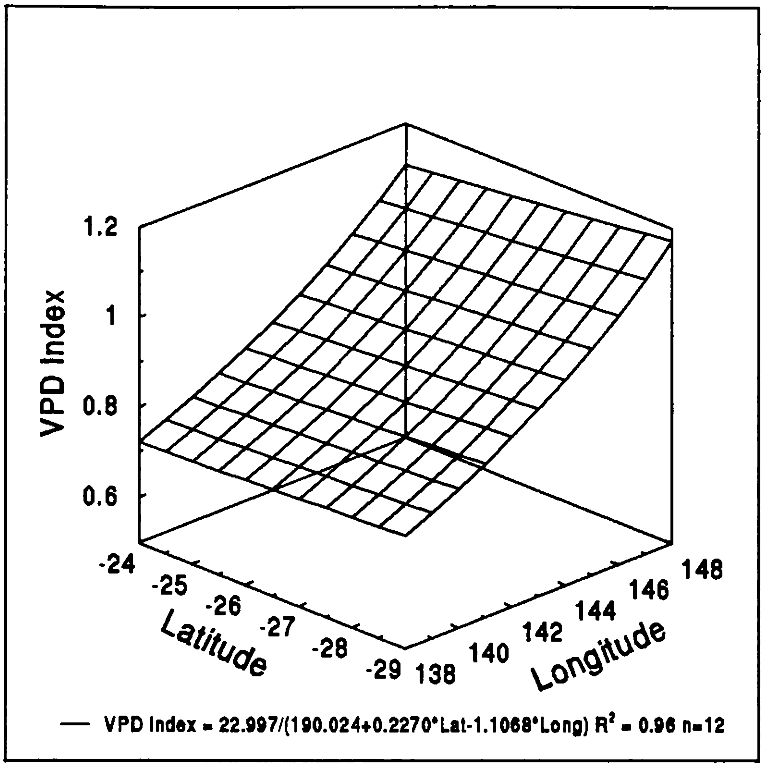


Figure 5.1 A vapour pressure deficit index (VPDI) as a function of latitude and longitude developed from AUSTCLIM average climatic data for 12 locations across south-west Queensland.

5.2.3.3 Estimating the impact of trees and shrubs

Factors such as tree and shrub density and tree and shrub canopy cover, soil erosion, the amount of bare soil and the density of annual and perennial grasses and forbs potentially influence forage production. The impact of tree and shrub density is the well documented (Walker *et al.* (1972), Beale (1973), Scanlan and Burrows (1990), and Scanlan (1991)) and readily assessable in the field. For the estimation of long-term average forage production in south-west Queensland tree and shrub cover was chosen as an indicator of land condition reflecting many of the factors listed above. Areas with high tree and / or shrub cover generally have low soil surface cover and low densities and yield of perennial and annual grasses and forbs. With low levels of soil surface cover they are susceptible to soil loss via water and wind erosion (Miles 1993).

Using step point methodology (Evans and Love 1957), the presence or absence of either a tree or shrub canopy (using a periscope device similar to Buell and Cantlon 1950) was noted at each step to estimate tree and shrub canopy foliage projected cover (FPC (%)) along a transect. The distribution of sampling points across a property was proportional to the areas of the land systems comprising each property. The FPC for each land system was then expressed as woody index (WI).

A number of methods for estimating a woody index existed. These were:

1. Beale's (1971) study examining the effect of different mulga (*Acacia aneura*) densities on forage production at two sites in south-west Queensland and using a site potential of 1000 kg/ha (Figure 5.2).
2. Scanlan's (1984) more general relationship between tree density and forage production established for a range of species (Figure 5.2).

3. Beale's (unpublished) relationship between foliage projected canopy cover and yield potential collected at 97 south-west Queensland sites at the end of the 1994 growing season (Figure 5.3). The major species at these sites were mulga (*Acacia aneura*), poplar box (*Eucalyptus populnea*), green turkey bush (*Eremophila gilesii*), and false sandalwood (*Eremophila mitchellii*). The sites were located on four land systems characterised by sandy-loam red earths. This relationship was comparable to that described by Jameson (1967) based on the sigmoid relationships of Grosenbaugh (1965).
4. Tuning the k value in Scanlan's (1984) more specific relationship to western Queensland conditions. However, the value of k value is a function of site potential and it's applicability to south-west Queensland has not been examined.
5. Using the GRASP model to examine the effects of trees for each site. As the tree component in GRASP was not yet fully validated, this method was not used. The validation of the tree component in GRASP in south-west Queensland has so far been restricted to mulga data (Beale 1971). Further application and validation of GRASP can proceed once all available data have been analysed (e.g. using the first three methods). Whilst it is expected that a process-based model would have greater extrapolation power, such a level of complexity may be unnecessary to achieve the objective of estimating property grazing capacity. Validation using Beale's 97 locations would also require intensive field sampling to estimate parameters for GRASP.

The first three methods were compared to determine the appropriate tree/forage production relationship for estimating forage growth and utilisation across south-west Queensland.

Scanlan's (1984) general relationship did not require extensive testing and validation with specific data for south-west Queensland. It was comparable to results from Beale (1971) when a site production potential of 1000 kg/ha was used (Figure 5.2).

Both authors measured tree density as "tree basal area" (TBA) (m^2/ha). As tree density on the properties used in model development were measured as foliage projected canopy cover (FPC) (%) using a step point and periscope technique, a conversion to TBA was required. To do this, estimates of TBA using a Bitterlich gauge and FPC using the step point technique were made at 14 sites near Charleville. Mulga was the dominant tree species at each site. At each site 100 points were sampled using the periscope to estimate FPC in an area 100m by 100m. Tree basal area was measured using a Bitterlich gauge at five locations within each site. An inverse power relationship between TBA and FPC was estimated (Figure 5.4). This was used to convert Scanlan's (1984) potential yield*TBA relationship to a potential yield*FPC relationship (Figure 5.5).

Examination of these relationships indicate that for mulga communities around Charleville low canopy covers (10%-20%) were associated with tree basal areas in the range 1-5 m^2/ha (Figure 5.4). Within this range a 90% reduction in potential forage was predicted when Scanlan's (1984) general relationship between tree density and forage production was used (Figures 5.5). This relationship may vary for other species and land system combinations.

In comparison, potential yield (WI) was less sensitive to the relationship described by Beale (Figure 5.3). This may be due to the short time period of data collection (end of summer 1994) and the range of tree species/land system/location combinations comprising the FPC data (as opposed to data collected from mulga dominated communities). Regrettably, an analysis of these data for individual species/land system/location combinations has not been made. Such an analysis may remove some of the noise in the data presented by Beale (Figure 5.3) and offer a series of yield/cover relationships for different species/land system/location combinations. Despite this, Beale's "broader" relationship was used as it was considered more appropriate to apply at the paddock and property scale where a range of species are most commonly found. This relationship was also derived using FPC data and did not require a conversion to tree basal area (Figure 5.5) for comparison with forage yield.

$$\mathbf{WI = 1.008 - 0.945 * (1 - e^{(-0.105 * FPC)})^{(0.611 + 1.0)}} \quad (R^2=0.47 \ n=97)$$

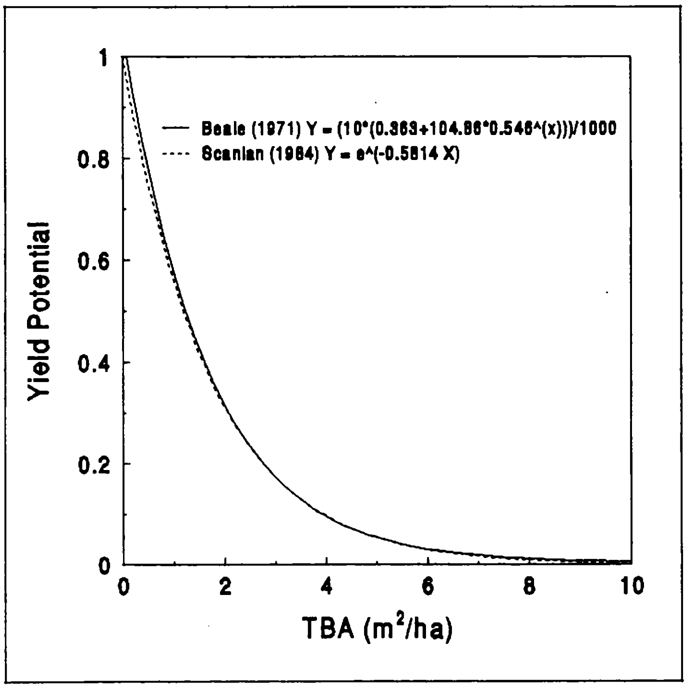


Figure 5.2 Comparison between Scanlan's (1984) and Beale's (1971) relationships between tree basal area (m^2/ha) and forage yield potential.

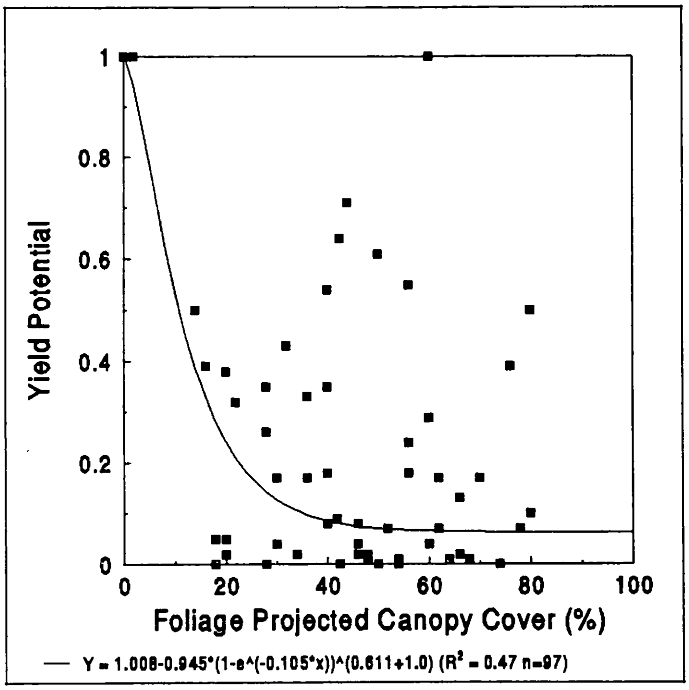


Figure 5.3 The relationship between forage yield potential and foliage projected canopy cover (FPC%) for a range of tree and shrub species on a range of land systems in south-west Queensland (I.F. Beale pers. comm.).

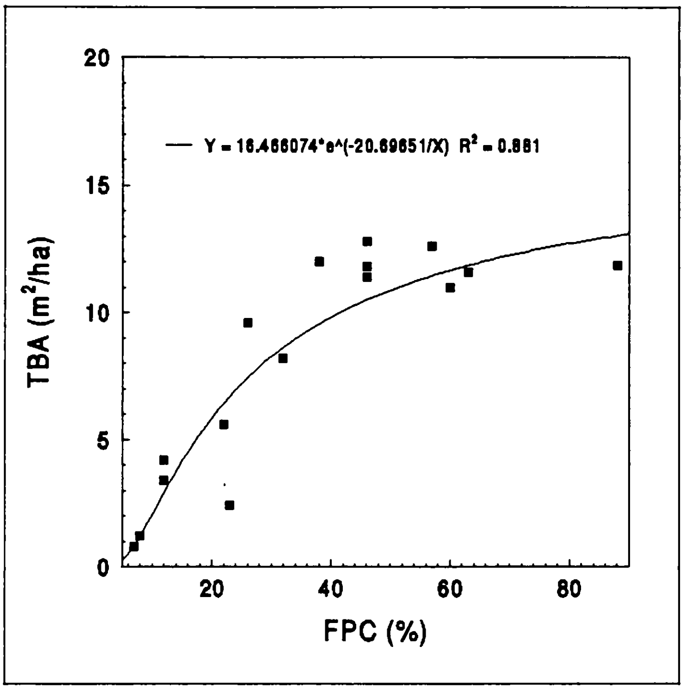


Figure 5.4 The relationship between foliage projected canopy cover (FPC%) of mulga (*Acacia aneura*) and tree basal area (TBA m^2/ha).

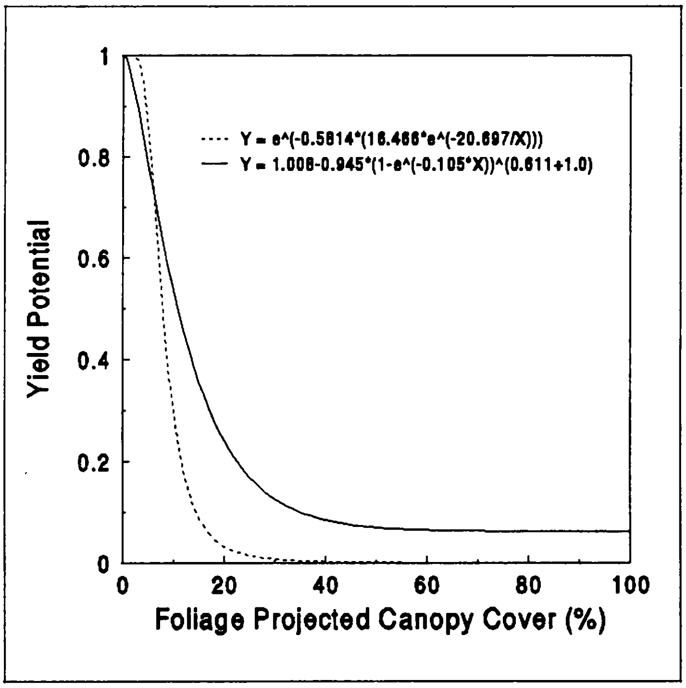


Figure 5.5 A comparison of relationships predicting forage yield potential as a function of foliage projected canopy cover (I.F. Beale pers. comm.___ and Scanlan (1984) ---).

5.2.3.3.1 Estimating the spatial distribution of trees

When estimating forage yield, direct application of each of these relationships assumes an even distribution of trees and shrubs across the landscape. Field observations indicate that trees and shrubs are not evenly distributed across the landscape and that a degree of "patchiness" occurs. Therefore it would be incorrect to apply the relationships derived above evenly over the whole landscape. To examine the spatial distribution of trees, land condition data collected on discrete land systems during an economic survey in south-west Queensland were re-analysed. The results were used to determine the appropriate method to accommodate for patchiness when estimating forage growth at the paddock scale.

The point-based land condition data were originally collected along transects of varying lengths and recorded on field sheets. Each sheet contained the results from 50 points covering an approximate distance of 50m. An average total tree cover (ATC) for each land system was originally estimated as:

ATC (%) = No. points with cover / Total points*100

These data were re-analysed to estimate a segment tree cover (STC) for each of the 50m segments as follows:

STC (%) = No. points with cover in each segment / 50*100

Forage growth was then estimated for each land system using two approaches: (i) using the average tree cover applied evenly across the entire area of the land system; and (ii) calculating the growth on each segment using the tree cover for that segment and then summing the growth from all segments. The growth estimated by the second approach was assumed to represent a "true" growth accounting for the spatial distribution of trees.

The "true" growth was 1.168 times that of yield estimated from an average cover evenly applied across the landscape (Figure 5.6) (R^2=0.97 n=19). These results indicate that for the land systems examined, trees and shrubs were not evenly distributed across the landscape and that a multiplier of 1.168 was appropriate to use to estimate "true" average growth for the mulga woodlands of south-west Queensland. Similar relationships may exist for other communities. However, the application of this multiplier to specific land systems requires caution as it was developed using data from a range of land systems.

Actual annual forage growth (AAG) for a land system was therefore estimated as:

AAG (kg) = SRUE (kg/ha/mm) * VPDI * RAIN (mm) * WI * 1.168 * Area (ha)

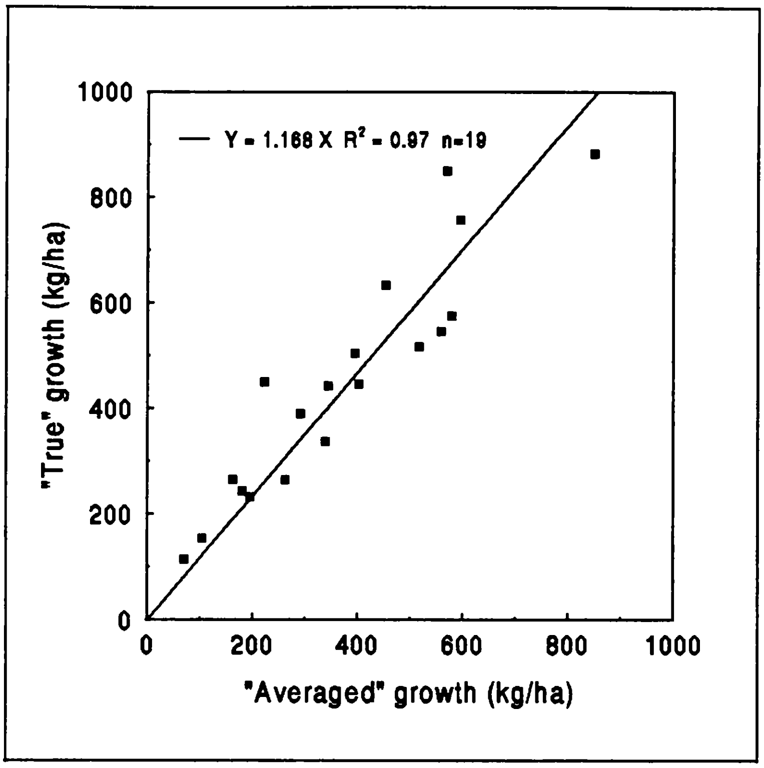


Figure 5.6 The relationship between the forage growth for a land system calculated (i) using an average of the growths estimated from each 50m segment using STC data from each segment and (ii) using ATC data from all transects representing a land system to estimate a singular growth value.

5.2.3.4 Estimating dietary mulga leaf

In mulga woodlands livestock eat a portion of mulga leaf throughout the year (Beale 1975) and as such, the number of livestock supported by leaf fall (DSE_LEAF) has been included in the calculation of grazing capacity. A quantity of mulga leaf litter (LEAF) was calculated based on rates of leaf fall described by Beale (1971). It was estimated that 5% of average annual leaf fall was utilised by livestock (LUTIL). This was based on a long term average proportion of mulga in the diet of 2% (8 kg/DSE/year) and an average annual leaf fall of 150 kg/ha from a stand of mulga with an average FPC of 10%. An annual intake of 600 kg/DSE (LI) for sheep consuming solely mulga was estimated based on voluntary intake of rates of mulga leaf ranging from 500 to 800 kg/DSE/year in pen trials (Miller pers. comm.).

$$\text{LEAF (kg/ha)} = 16.466 * e^{(-20.697/\text{FPC } (\%))} * 50.0$$

$$\text{DSE\_LEAF} = (\text{LEAF(kg/ha)} * \text{LUTIL } (\%) * \text{Area (ha)}) / (\text{LI (kg/DSE)} * 100)$$

This method does not account for the browsing of mulga leaf still attached to trees. Such an estimate would require the estimation of the quantity of browsable mulga which varies with the species grazing and the density and structure of the mulga community.

5.2.4 "Safe" level of forage utilisation

In contrast to other approaches to estimating "safe" grazing capacities (e.g. Scanlan *et al.* 1994), three options were explored in this thesis for calculating "safe" utilisation levels of forage grown. Each option relied on the comparison of pasture condition with known levels of utilisation. The first option involved findings from grazing trials which were designed to examine and demonstrate the effects of differences in grazing management on soil, pasture and animal condition. Although grazing trials are "data rich" they have only been conducted on a limited number of land systems. Graziers have experience of a much wider range of land types. Thus, the second option was to use a structured group discussion where the experience of local graziers, researchers and land administrators was pooled to derive a consensus of "safe" forage utilisation for the 15 land zones in south-west Queensland. Land zones represent a grouping of land systems (Dawson 1974). A third option was to examine utilisation levels on selected "benchmark" properties using producer experience to define relative grazing capacities of different land types. The third option only became available during application of the model in the field (Described in Chapter 6). As it complemented the first and second options it has been reported here.

5.2.4.1 Analysis of grazing trials

Five grazing trials from western Queensland were re-analysed using the GRASP model to examine the relationships between the simulated average annual pasture grown and the stocking rates considered safe by the researchers who conducted the trials. The five grazing trials considered (Table 5.5) were relevant to three pasture communities found in south-west Queensland i.e. mulga, mitchell grass and sown gidgee communities. "Safe" levels of utilisation of average annual forage grown thus calculated ranged from 11.7% to 26.4 % (Table 5.5).

In the 20% treatment of the unreplicated Arabella grazing trial, sheep numbers were adjusted to eat 20% of end of summer (April) standing dry matter (kg/ha). Orr *et al.* (1993) reported that reasonable wool production (average 1.245 kg/ha/year greasy wool production) and maintenance of good pasture condition (increased proportions of desirable species, perennial grass basal area > 2% and sufficient dry matter yield to maintain soil cover) was achieved in this treatment. When this grazing trial was analysed using the forage production model GRASP, 20% utilisation of end of summer standing dry matter equated to 15.5% utilisation of simulated average annual forage grown (kg/ha/year over 7 years) (Table 5.5).

Table 5.5 "Safe" treatments in five grazing trials conducted on three western Queensland native pasture communities* used to examine the relationship between utilisation (Util) of average annual forage grown (FG), average annual forage eaten (Eaten) and the maximum observed nitrogen uptake (Nup) as an indicator of site fertility.

Trial Site	Pasture Community *	"safe" Treatment	Reference	FG kg/ha	Eaten kg/ha	Util %	Nup kg/ha
Toorak	Mitchell grass	30% utilisation	Phelps *et al.* (1994)	1608	299	18.6	30.4
Eastwood (Buffel grass)	Gidgee pastures	0.4 ha/DSE	D.M. Orr (pers. comm.)	3222	851	26.4	26.9
Burenda	Mitchell grass	30% utilisation	Beale (1985)	1510	347	23.0	16.0
Arabella	Mulga pastures	20% utilisation	Beale (1985)	580	90	15.5	17.0
Gilruth Plains	Mitchell grass	1 DSE/2ha	Roe and Allen (1945,1993)	1435	168	11.7	16.7

* Native pasture communities as described by Weston *et al.* (1981)

At the Gilruth Plains mitchell grass site it appears the treatment which resulted in an average 11.7% utilisation of forage grown was favoured by the investigators due more for reasons of variability in production than due to evidence of damage to pastures. From the perspective of resource maintenance, the heavier stocking treatment which equates to a calculated 23.4% utilisation appeared to be a "safe" treatment. If this is a correct interpretation of the findings of these trials, "safe" utilisation levels (as defined in this thesis) ranged from 15.5% to 26.6 % of average annual forage grown with an average of 22.4% across these trials.

5.2.4.2 Consensus data

A group consisting of two experienced graziers, two Department of Primary Industries staff and a Department of Lands officer, reached a consensus on their estimates of a "safe" level of utilisation for each of the 15 land zones in south west Queensland (Table 5.6). The range of 15% to 20% utilisation considered safe by consensus was similar to the range found for grazing trials (above). Whether the utilisation levels for each land type may be related to the productivity of the land types as reflected in the SRUE was then investigated. A linear regression between an index of SRUE and utilisation proved significant ($P<0.05$) but accounted for only 59% of the variability in utilisation (Figure 5.7).

Table 5.6 Estimates of "safe" levels of utilisation of average annual forage grown using a consensus approach for 15 land zones (Dawson 1974, Mills and Lee 1990) in south-west Queensland.

Land Zone	"Safe" Utilisation (%)
Alluvial Plains Open (A)	20.0
Brigalow (B)	20.0
Channel Country (C)	17.5
Dunefields / Sandhills (D)	15.0
Poplar Box Lands (E)	15.0
Downs (F)	20.0
Gidgee Lands (G)	17.5
Hard Mulga Lands (H)	15.0
Claypans / Lakes (L)	15.0
Soft Mulga Lands (M)	15.0
Spinifex Sandplains (N)	15.0
Dissected Residuals (R)	15.0
Mulga Sandplains (S)	15.0
Wooded Downs (T)	20.0
Alluvial Plains Wooded (W)	17.5

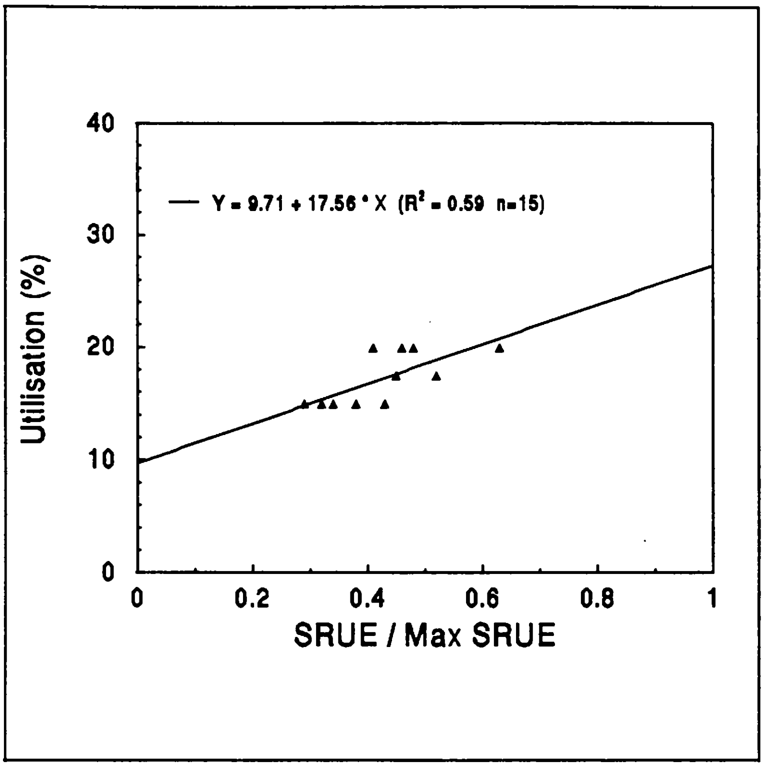


Figure 5.7 The linear relationship between "safe" levels of forage utilisation derived from consensus data and an index of land system fertility (ratio of land zone rainfall use efficiency to maximum standard rainfall use efficiency (SRUE)).

5.2.4.3 Selected benchmark properties and grazier experience

Following discussions with experienced graziers, Department of Lands and Department of Primary Industries staff, three "benchmark" properties were chosen to examine "safe" levels of forage utilisation on the assumption that the grazing strategies on these properties were "safe" (Figure 5.8). These properties were considered to be in "good condition" with relatively stable livestock numbers (27, 19 and 21 DSE/km^2 respectively). The selection of properties was necessarily subjective. Detailed surveys of the land and pasture condition on these properties have not been conducted (apart from tree and shrub FPC %). Had such data been available it still would not have been possible to quantitatively compare the condition of the properties with others in south-west Queensland due to the lack of regular regional scale monitoring in the region.

Actual average livestock numbers for each "benchmark" property were obtained from the graziers. However, these data were only available at the property level. As land systems provide the basis for extrapolating resource and management information from one property to another it was necessary to convert this property level livestock data to a land system level. The grazier's experience was used as a basis to rate the relative grazing capacity of each land system on the property. The average livestock numbers were then apportioned to land systems based on these grazier ratings. Average annual forage grown and the FPC % of trees and shrubs was calculated for each land system on each property by using the approach described above.

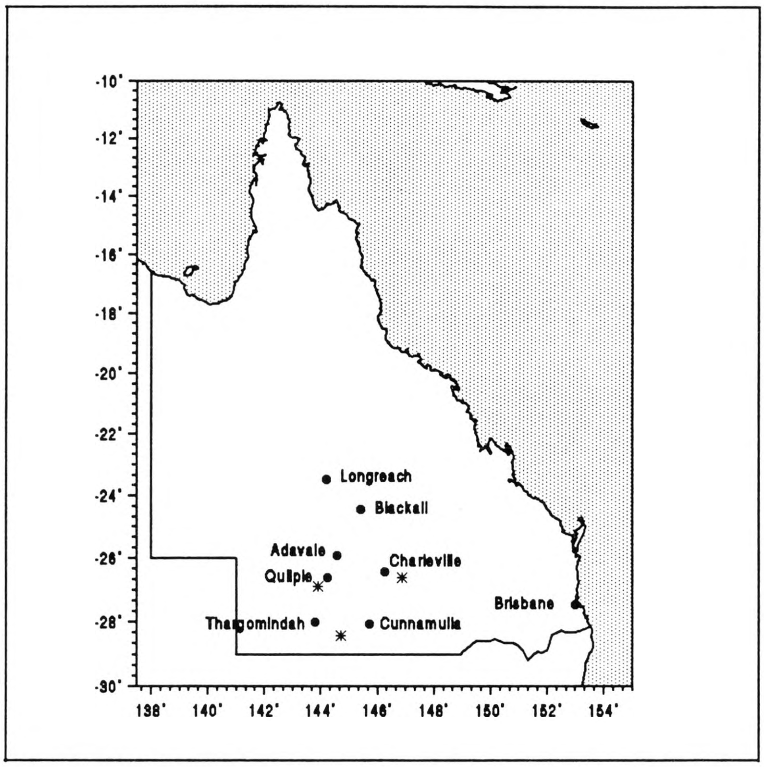


Figure 5.8 Location of the three benchmark properties (*) used to estimate "safe" levels of utilisation of estimated average annual forage grown in south-west Queensland.

Thus with an estimate of average annual forage grown and average livestock numbers for each land system (Figure 9a), utilisation was calculated (Figure 9b). As the properties were considered to be in good condition, it was assumed that the utilisation (SUTIL) of average annual forage grown (FG) on these properties and land systems was "safe":

SUTIL (%) = ((DSE * Intake (kg/DSE)) / FG (kg)) * 100

The average utilisation of average annual forage grown across all land systems and properties was 21.3% (n=38, range = 8.4%-41.7%, SE = 1.7). This average agreed with that for consensus data and grazing trials. However the range in utilisation was wider. This higher variation is to be expected given (1) the greater number of observations and (2) the estimates were made by individual graziers and, as such, were not "averaged" by consensus.

An alternative examination of the above equation using a linear regression forced through the origin indicated a slope of 0.172 ($R^2 = 0.93$ n=38) between total intake (kg/ha) and average annual forage grown (kg/ha) (Figure 9b). This equates to a utilisation level of 17.2%.

In an attempt to further account for the observed variation in utilisation levels across land systems, as with the consensus data presented above, the relationship between SRUE and utilisation was examined. In this case a significant ($P<0.05$) negative relationship was found between utilisation and SRUE:

SUTIL (%) = 19.832 - 1.193 * SRUE (kg/ha/mm) ($R^2 = 0.56$ n = 38)

However, this relationship described the pattern of estimated utilisation across the land systems on the three benchmark properties. It was based on the individual grazier's perception of the grazing capacity for each land system and not what actually was grazing each land system. It indicates less fertile land systems with smaller SRUE's experienced higher levels of utilisation. This may be due to greater quantities of browse being available on these land systems thereby contributing to a perceived greater grazing capacity. The actual grazing derived from each land system is also difficult to determine due to different grazing preferences exhibited by livestock across the landscape in relation to water location, wind direction and vegetation preference (Landsberg *et al.* 1992).

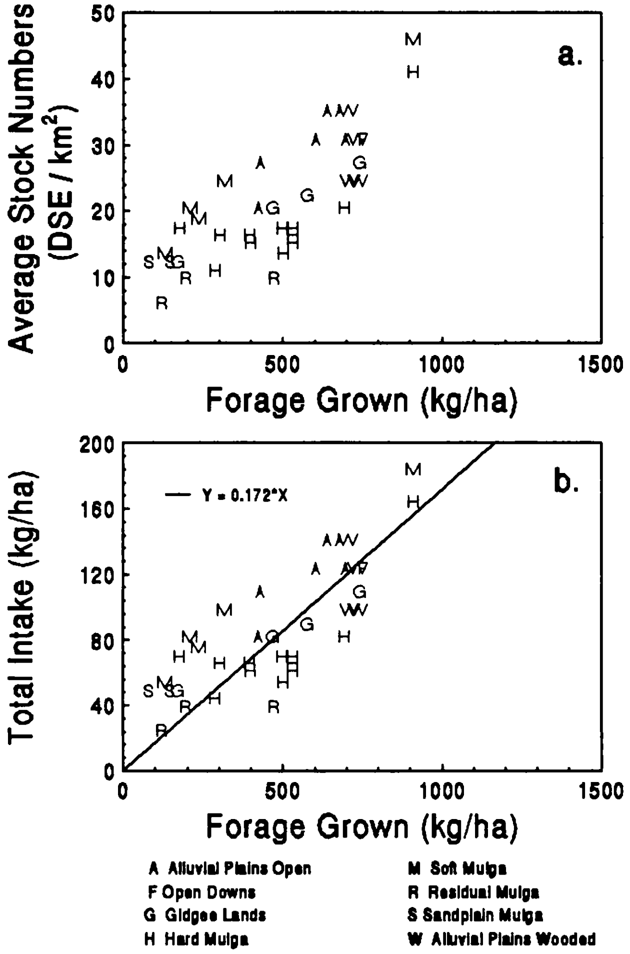


Figure 5.9 The relationship between (a) average livestock numbers (DSE/km^2) and average annual forage grown (kg/ha) and (b) average annual total intake (kg/ha) and average annual forage grown (kg/ha) on the 38 land systems on the 3 benchmark properties used to estimate 'safe' levels of utilisation of forage grown in south-west Queensland (Letters denote land zones described by Dawson (1974, Mills and Lee 1990)).

5.3 Estimating a grazing capacity

The three sources of information examined (grazing trial, consensus and "benchmark" property) point to a "safe" "average" level of utilisation of approximately 17% but, depending on individual perceptions and land type, "safe" utilisation might expect to range from 15% to 25%. For the purpose of deriving a single figure or relationship for inclusion in the carrying capacity calculation the consensus data were chosen. This choice was made on the basis that this best represented a shared and, an assumed, fair and balanced view. Rather than take an average utilisation value (17%) it was assumed that a hypothetical relationship existed between pasture fertility (as measured by SRUE) and a "safe" level of utilisation. A linear relationship between "safe" utilisation and an index of SRUE was significant (Figure 5.7). While this was true over the range of SRUE values examined, the methodology described in this thesis is likely to be used and evaluated beyond this range of fertility (SRUE). Given that such extrapolation is likely, a choice was made to err on the side of caution in calculating safe utilisation levels at extreme (high and low) values of SRUE. Thus the function fitted to the consensus data (Figure 5.10) was:

SUTIL (%) = (SRUE/Max SRUE)/(0.0340*(SRUE/Max SRUE) + 0.0102) (R^2=0.57 n=15)

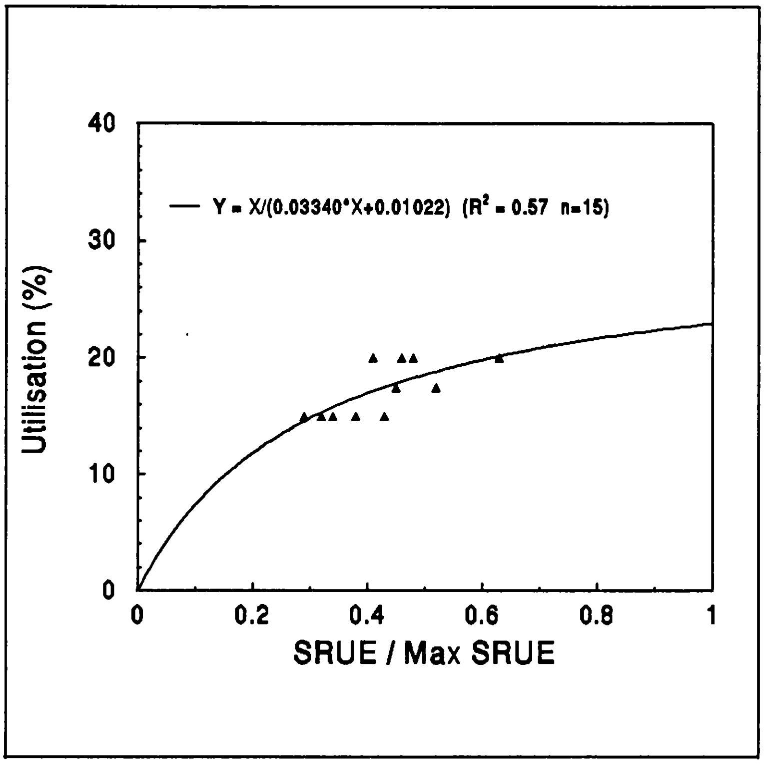


Figure 5.10 The hypothesised curvilinear relationship between 'safe' levels of forage utilisation derived from consensus data and an index of land system fertility (ratio of land zone rainfall use efficiency to maximum standard rainfall use efficiency (SRUE)) used in the calculation of 'safe' grazing capacities for individual properties in south-west Queensland.

For extremely infertile sites the view was taken that grazing should only be conducted with very careful attention to stock numbers. The relationship therefore chosen was one which reduces safe utilisation to zero as SRUE approaches zero. In choosing this relationship it is emphasised that there is no "biological" implication in choice of this function and no supporting data is presented. As such this choice of function simply reflects a conservative attitude to risk taken in this thesis.

For extremely fertile sites it is likely that other factors (e.g. rainfall variability) are likely to limit safe levels of utilisation. The plateau in the above relationship (Figure 5.10) reflects this assumption and, as such, provides a conservative safe utilisation level at high SRUE.

5.4 Sensitivity analysis

A sensitivity analysis was performed to assess the reliability and sensitivity of different components of the model. Each coefficient in each of the above relationships was varied by ± 10% and the resulting variation in grazing capacity expressed as a percentage.

The grazing capacity estimate was most sensitive to the second and fourth coefficients describing the vapour pressure deficit index (VPDI) (>10% change in grazing capacity with a 10% variation in any one coefficient) (Table 5.7). This indicates the VPDI needs to be estimated most reliably and that application of the approach outside south-west Queensland (based on the 12 AUSTCLIM stations from Table 5.4) requires caution. The grazing capacity estimate was also sensitive to the first coefficient describing the woody index (1.008). This coefficient defines the slope of the negative exponential where it is most sensitive to change in the FPC (0-30%) and places importance on the analysis of the data conducted by Beale (pers. comm.) illustrated in Figure 5.3. The sensitivity to this coefficient supports further analysis of these data as indicated in Section 5.2.3.3 to establish a series of relationships for different species, land system combinations. For other coefficients and input values a ± 10% change resulted in a less than 10% variation in the grazing capacity.

Table 5.7 Sensitivity analysis examining change in grazing capacity (%) for individual land systems following a ± 10% variation in coefficients and selected input data in the equations used to estimate a grazing capacity.

Equation	Coefficient	Change (%) resulting from: +10%	-10%
Equation coefficients			
VPDI	22.997	9.50	-9.50
	190.024	-43.93	650.00
	0.2270	1.39	1.35
	1.1068	289.04	-40.58
WI	1.008	10.23	-121.08
	0.945	-3.80	3.80
	0.105	-6.35	6.60
	0.611	2.46	-2.72
SUTIL	0.03340	-4.35	4.81
	0.01022	-4.68	5.22
	5.6	-4.68	5.22
LEAF	16.466	0.50	-0.50
	20.697	-0.71	0.85
	50.0	0.50	-0.50
Input data and equation results			
SRUE		9.50	-9.50
VPDI		9.50	-9.50
SUTIL (%)		9.50	-9.50
LEAF (kg)		0.50	-0.50
RAIN (mm)		9.50	-9.50
Tree FPC (%)		-3.94	3.97
Shrub FPC (%)		-2.24	2.36

5.5 Estimating grazing capacities on 46 individual properties

For 46 properties surveyed in south-west Queensland in 1989 (Passmore 1990) (Figure 5.11), actual forage growth was calculated for the years in which livestock data were available using the method described above. Land condition was estimated from December 1989 to January 1990 using the step point method (Evans and Love 1957). The 2000 step points per property were stratified in proportion to the areas of different land systems. A grazing capacity was then estimated for each property and compared to actual stocking rates over the survey period (sheep and cattle numbers expressed as DSE). The calculated grazing capacity and actual stocking rates were also compared to the Department of Lands rated carrying capacities. These values were obtained from the Charleville and Cunnamulla district offices. They were determined from settlement up to the 1940's and 1950's through local experience, early stock returns and what stock the properties carried over that period (P.R. Tannock pers. comm.)

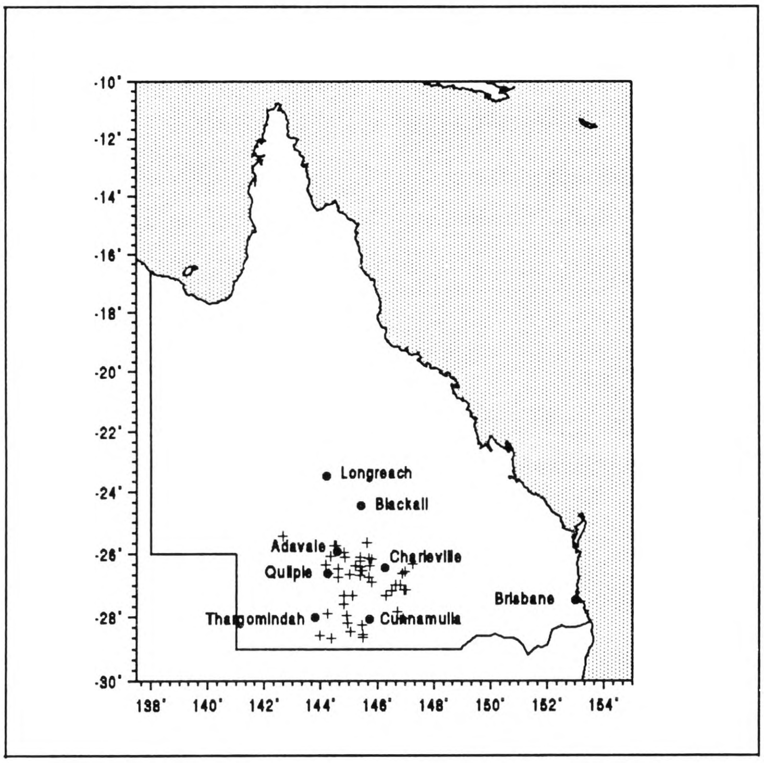


Figure 5.11 Location of the 46 properties of Passmore (1990) for comparison of actual stocking rates and calculated grazing capacities for the years 1986 to 1988 in south-west Queensland.

5.5.1 Forage utilisation in south-west Queensland

For the 46 properties utilisation of average annual forage growth (April to March) by domestic stock was 33.5% for the years 1986 to 1988 (Figure 5.12). There was little variation between years (32.4% to 34.6%). This reflects the small variation in rainfall (average 385mm, range 375-402mm, long-term average 400mm) and subsequent calculated forage growth (average 542 kg/ha) for this period.

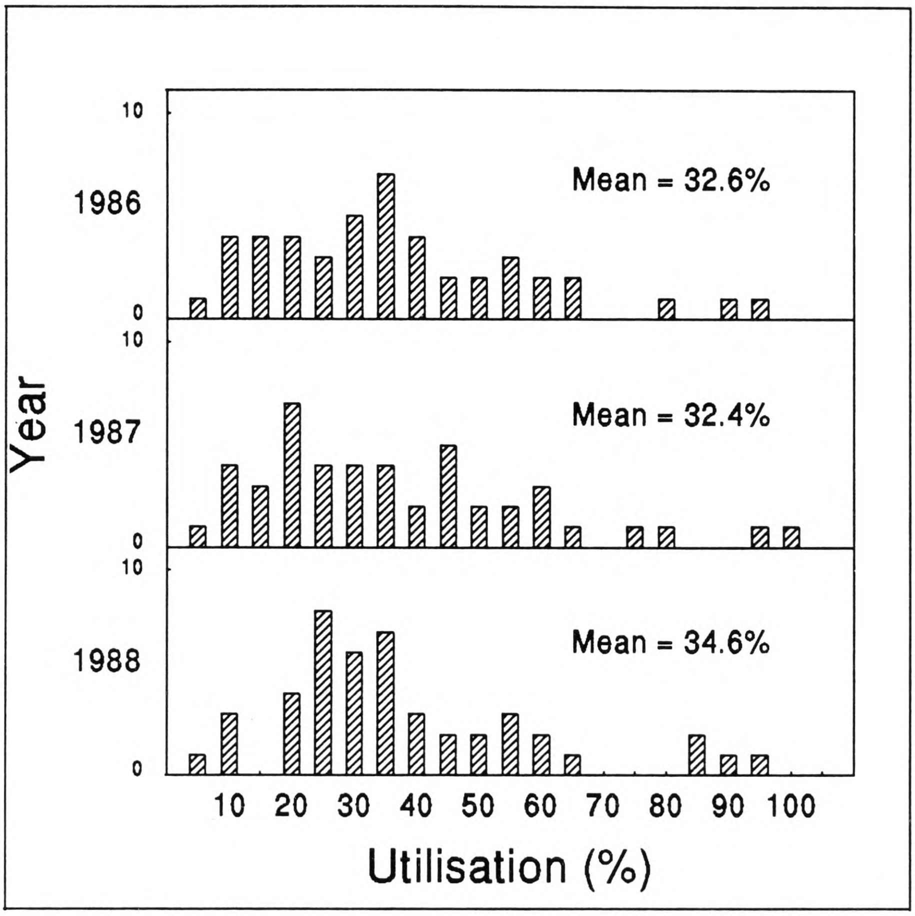


Figure 5.12 Frequency distribution of forage utilisation for the years 1986 to 1988 across the 46 properties of Passmore (1990) in south-west Queensland using actual rainfall and livestock numbers.

An examination of utilisation of calculated average regional forage growth masks the high degree of variability in utilisation between properties. Utilisation of annual (April to March) forage growth ranged from 5 to 100% for the years 1986 to 1988 with 86% of properties exceeding 17.2% utilisation (Figure 5.12).

Using the average stock numbers for the 1986 to 1988 period and long-term average rainfall, 17.2% utilisation was exceeded on 83% of properties and 20% utilisation exceeded on 78% of properties (Figure 5.13a). Using the Department of Lands rated carrying capacities and long-term average rainfall, 17.2% utilisation was exceeded on 91% of properties while only 72% of properties exceeded 20% utilisation (Figure 5.13b).

The majority of flocks increased in size from 1986 to 1987 and from 1987 to 1988 (Figure 5.14). However, change in flock size was not significantly correlated to forage utilisation in the preceding year (R^2=0.025, n=92, P<0.05) (Figure 5.14).

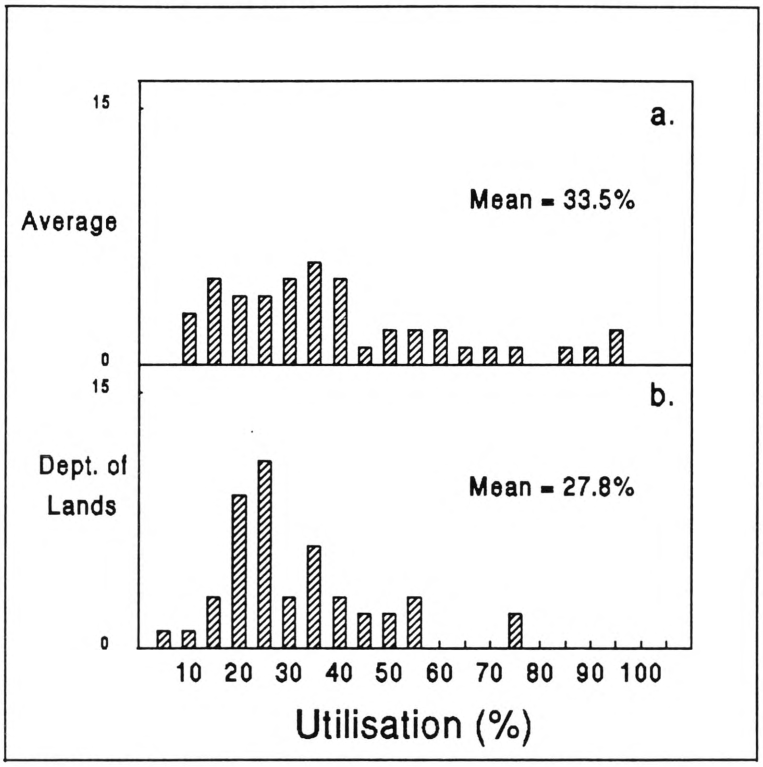


Figure 5.13 Frequency distribution of forage utilisation for 46 properties in south-west Queensland using long-term average rainfall and average livestock numbers for each property for the period 1986 to 1987 (a.), and Department of Lands rated livestock numbers (b.).

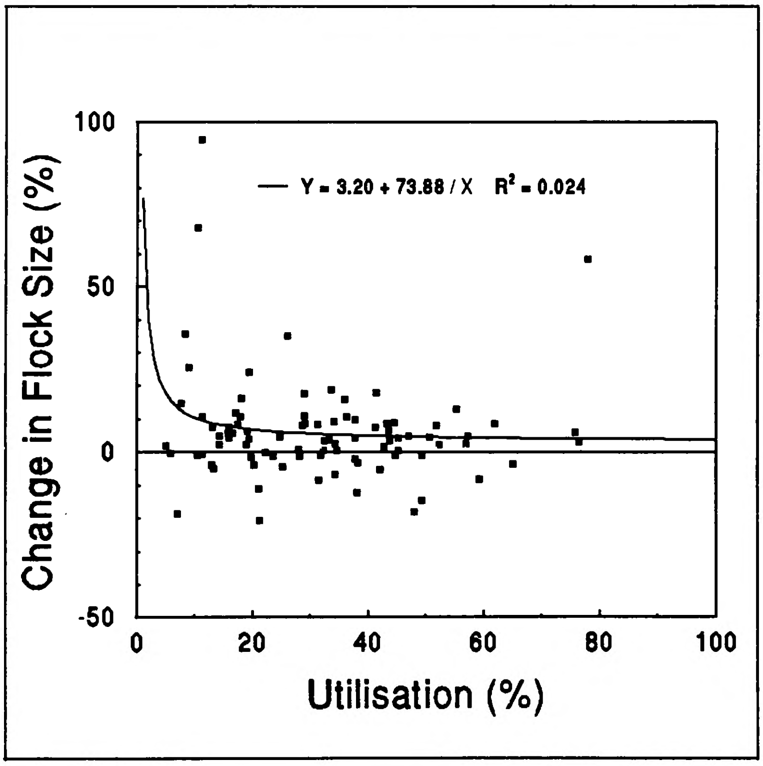


Figure 5.14 Annual change in flock size (%) in relation to forage utilisation (%) for 1986 to 1987 and 1987 to 1988 for 46 properties of Passmore (1990) in south-west Queensland. There was no significant relationship between change in flock size and utilisation.

5.5.2 Comparison of stocking rate and calculated grazing capacity

The ratio of actual average stocking rate to calculated grazing capacity (0.6 to 9.6) was not significantly correlated to property size (Figure 5.15a) or flock size (Figure 5.15b). Five of the 46 properties in the 1986 to 1988 period were stocked at the calculated grazing capacity or below it (ratio < 1.0).

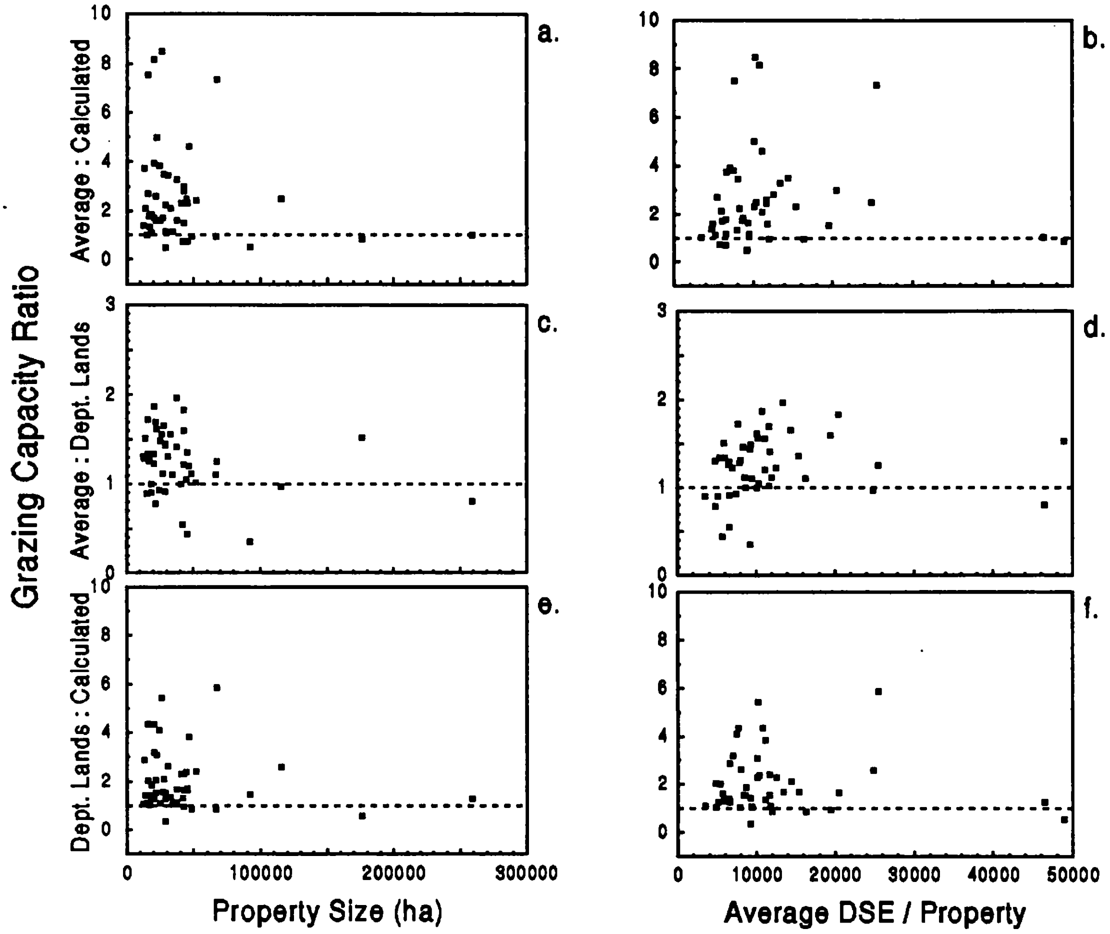


Figure 5.15 Comparison of livestock ratios (a) owner livestock numbers : calculated grazing capacity and property size, (b) owner livestock numbers : calculated grazing capacity and flock size, (c) owner livestock numbers : Department of Lands rated carrying capacities and property size, (d) owner livestock numbers : Department of Lands rated carrying capacities and flock size, (e) Department of Lands rated carrying capacities : calculated grazing capacity and property size and (f) Department of Lands rated carrying capacities : calculated grazing capacity and flock size for 46 grazing properties in south-west Queensland during the period 1986 to 1988.

The ratio of actual average stocking rate to the Department of Lands rated carrying capacity (0.4 to 2.0) was not significantly correlated to property size (Figure 5.15c) or flock size (Figure 5.15d). Twelve of the 46 properties in the 1986 to 1988 period were stocked at or below the Department of Lands rated carrying capacity (Figure 5.15c and 5.15d).

The ratio of Department of Lands rated carrying capacity to calculated grazing capacity (0.4 to 6.2) was not significantly correlated to property size (Figure 5.15e) or flock size (Figure 5.15f). On four of the 46 properties the Department of Lands rated carrying capacity was at or below the calculated grazing capacity (Figure 5.15e and 5.15f).

The ratio of actual average stocking rate to calculated grazing capacity (0.6 to 9.6) was not significantly correlated to the proportion of bare ground, litter cover, presence of soil erosion, perennial grass cover or forb cover as estimated in the step point survey of land condition (Figure 5.16). Shrub and mulga cover were not compared as they were mathematically related to the calculated grazing capacity.

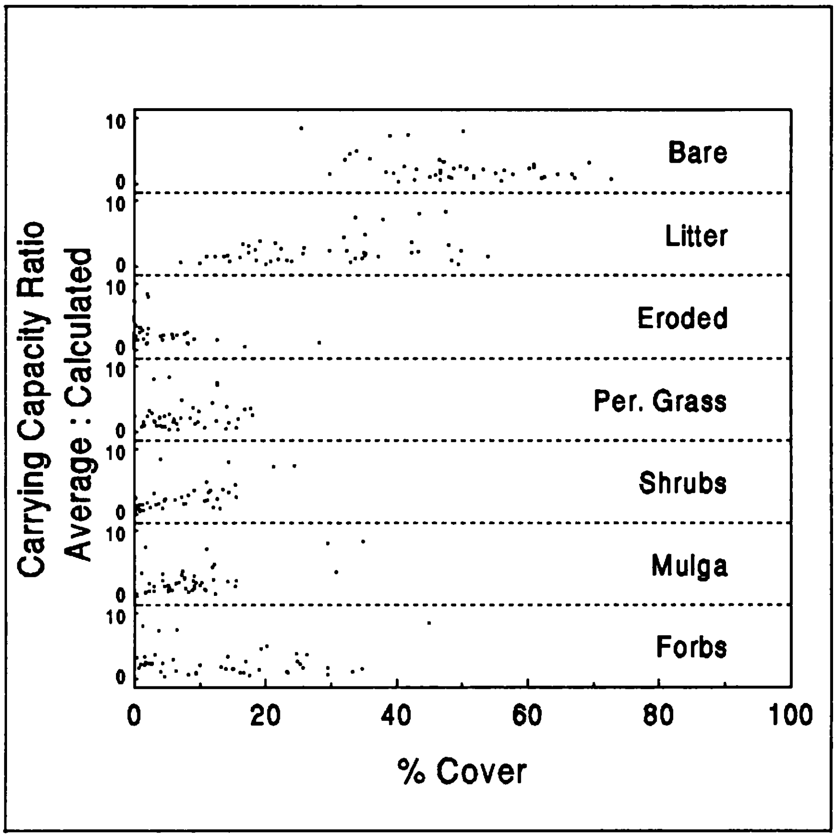


Figure 5.16 The ratio of average livestock numbers to calculated "safe" livestock numbers in relation to 7 measures of land condition (cover %) on the 46 properties of Passmore (1990) in south-west Queensland during the period 1986 to 1988.

5.6 Discussion

Estimation of average annual forage growth using rainfall use efficiencies, coupled with independent estimates of "safe" levels of forage utilisation (grazing trials, consensus data and 'benchmark' properties), provided an ecological basis for examining grazing capacities on individual properties in south-west Queensland. This Chapter has developed links between science, "benchmark" grazing practice and local experience within an ecological framework to derive a method for estimating grazing capacities of individual properties. Such links are necessary if grazing lands are going to meet the increasing variety of needs society places upon it (Walker 1995).

The approach to estimating grazing capacities enabled a preliminary examination of the 46 properties for which production and land condition data were available (Passmore 1990). The correlation between calculated grazing capacities and actual stocking rates may be improved by refinements identified by Scanlan *et al.* (1994) which include; accounting for spatial variability in resource use by grazing animals, complete accounting for the effects of land condition on forage growth, accounting for the forage consumed by native and feral herbivores, better estimates of "safe" levels of utilisation for different land systems, and improved methods to estimate potential forage growth. As "benchmark" properties were used, the methodology is considered sound even if these factors were not fully accounted for. The key is that the level of influence of these factors is considered the same on the "benchmark" properties as on the other 46 properties.

For the period 1986 to 1988 (a period of average rainfall), livestock numbers on 34 of the 46 properties exceeded the Department of Lands ratings at that time. This indicates the consensus that Department of Lands rated carrying capacities for the mulga zone are higher than those practiced by graziers does not hold. The Department of Lands rated carrying capacities in the mulga zone have been under review since 1989 and results here indicate that current rated capacities are more conservative than actual stocking rates. However, the Department of Lands values were higher than those calculated, and in the long-term could result in 91% of properties exceeding 17.2% utilisation of average growth. As there was no relationship between the Department of Lands values and either the actual or calculated capacities, a review of these values may be warranted if these values are to be used in the administration of leasehold properties (Scanlan *et al.* 1994), or as a guide for the purchase or disposal of properties. This has major implications for the economy of the region as the value of a property is largely determined by its grazing capacity (Holechek *et al.* 1995). For south-west Queensland in the mid 1990's this ranges from $27-$40 per sheep area.

The methodology proposed in this chapter to estimate "safe" long-term grazing capacities assumes average annual utilisation of average annual growth by domestic livestock should not exceed 15%-25%. This was supported by grazing trials in which term wool production and resource stability was achieved at 20% rather than higher levels of utilisation of end of summer standing dry matter (Orr *et al.* 1993) (equating to an average 15.5% utilisation of annual growth). If grazing management used forage utilisation concepts in stocking rate decisions then flock sizes would increase as forage utilisation declined and decrease when forage utilisation increased. In an ideal scenario, a compromise between a "safe" constant stocking policy and a flexible policy based on utilisation as described by Wilson *et al.* (1990) could be achieved. Under such a scenario a long-term average of the flexible policy would approximate that of the "safe" constant policy.

However, it is possible that, under a flexible stock management policy, a higher level of utilisation may be "safe" than if stock numbers were kept constant. This could occur if the stocking rate (in the short term) matched pasture growth, thereby avoiding critical periods of pasture damage. This is an area requiring further research for land systems in south-west Queensland.

For the larger group of 46 properties there was no significant relationship between change in flock size and level of forage utilisation. This indicates stock numbers fluctuated with little regard for the level of forage utilisation and that high levels of utilisation were practiced by most of the grazing industry in south-west Queensland over the 1986 to 1988 period.

The ability of livestock to survive at such high levels of utilisation is most likely due to the availability of mulga as browse. Without browse high livestock losses would be anticipated. However, the exact contribution of mulga to the diet of stock over the study period was unknown. It is also unclear as to what level of forage utilisation that stock begin to rely on mulga as a food source. In a grazing trial conducted near Charleville (Beale 1985), where sheep numbers were adjusted annually at the end of summer (April) to eat 80% of the available forage, calculated average utilisation of growth did not exceed 39% (Figure 5.17). In this trial, mulga was only available as browse (not felled for livestock) and sheep were removed from the trial based on liveweight to avoid deaths. However, as a result of heavy grazing (39% utilisation) in this treatment a detrimental change in pasture composition and grass density was observed (Orr *et al.* 1993). In paddocks on properties where reliance on mulga (either as browse or felled) results in prolonged periods of high utilisation detrimental changes to pasture composition would therefore be expected. Orr *et al.* (1993) indicate this has important implications for pasture recovery following heavy grazing. Experimental evidence (Brown 1986 and 1987) indicates that any recovery of desirable species may be difficult to achieve and the chances of woody weed invasion are more likely. On the properties experiencing high levels of forage utilisation it was unknown whether mulga was being fed to livestock, whether deaths were above average and whether pasture deterioration was occurring (lack of correlation between the ratio of actual average stocking rate to calculated grazing capacity and land condition (Figure 5.16)). However, the land condition data presented here was from a single survey. It would be desirable to compare the calculated ratio to change in land condition or more importantly to change in livestock productivity as described by Abel and Blaikie (1989). However, regional surveys of land and pasture condition (Mills *et al.* 1989) indicate pasture deterioration and woody weed invasion was occurring. The availability of mulga as browse can therefore be considered a factor contributing to land and pasture degradation in south west Queensland.

Similarly, dietary supplements used in the beef industry to sustain livestock production have also contributed to land and pasture degradation in the dry tropics of northern Australia (Gardener *et al.* 1990).

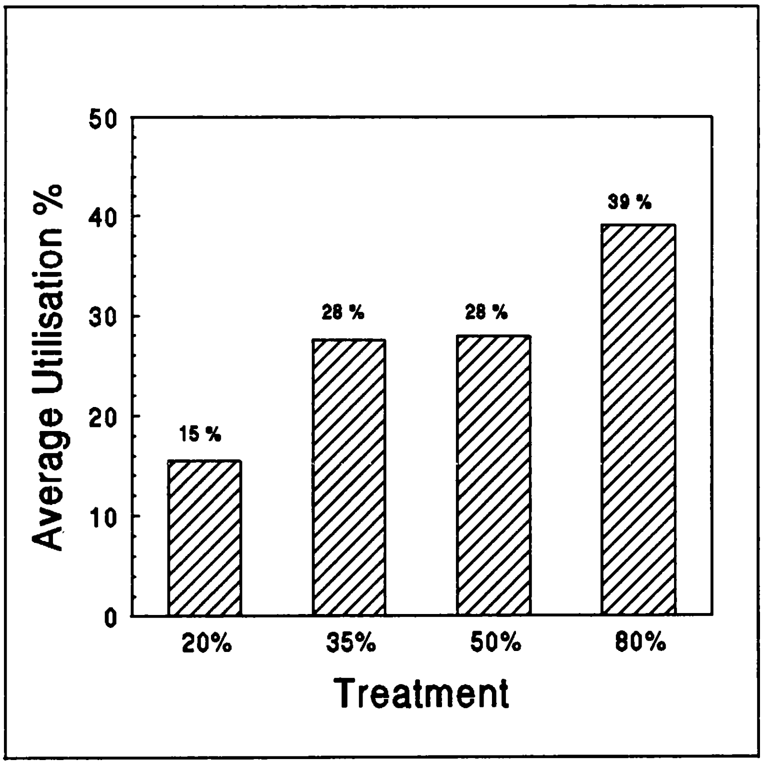


Figure 5.17 Utilisation (%) of calculated average forage growth (kg/ha) in the four treatments (20%, 35%, 50% and 80% utilisation of end of summer standing dry matter) in the Arabella grazing trial (Beale 1985) conducted near Charleville.

A potential factor contributing to increasing flock sizes, and high levels of utilisation during the study period was the rapid increase in the value of wool over this time (Figure 5.18). It would be worthwhile to compare the costs and benefits associated with the increased wool prices and risks of land and pasture degradation. This would require detailed economic analyses linking the costs of pasture degradation to future productivity and is beyond the scope of this thesis.

In contrast to Scanlan *et al.* (1994) there was no relationship between property size and the ratio of actual stocking rate to "safe" grazing capacity. The smaller properties sampled (< 20000 ha) were both heavily and lightly stocked (ratio range 1.1-8.2). The larger properties (> 40000 ha) also experienced heavy and light stocking regimes (ratio range 0.5-7.8). However, only five of the 46 properties were stocked more conservatively than the calculated capacity. This included both small and large properties, indicating that potential problems associated with high grazing pressures and ensuing land degradation were not confined to the smaller properties. This suggests the problems of land degradation will not be solved by merely increasing average property size while current stocking practices exist. Many factors determine a stocking policy for a particular property. These include commodity prices, debt level, lifestyle preferred, attitude to risk, off farm income, rainfall and suitability of resources. However, if potential problems regarding land degradation are to be addressed, the concept of applying "safe" levels of forage utilisation is central to grazing capacity decision making regardless of property size.

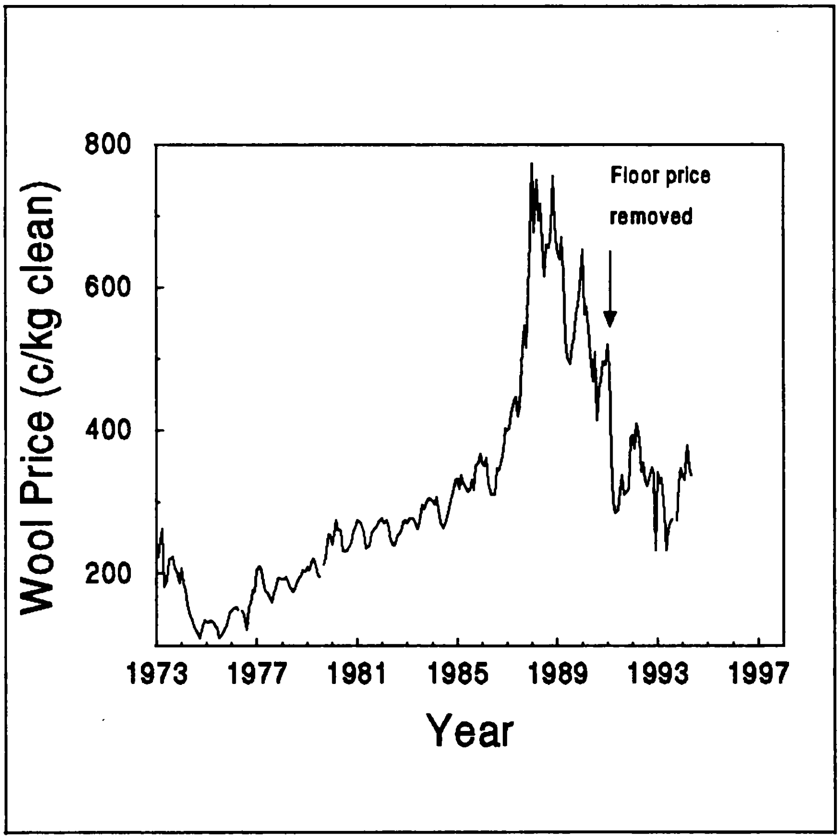


Figure 5.18 The fluctuation in wool prices (c/kg clean) from 1973 to 1994. (Source: The National Council of Wool Selling Brokers of Australia).

5.7 Conclusions

The methodology developed to estimate "safe" grazing capacities was based on ecological principles. It is repeatable and can be applied to any property in south-west Queensland or to other regions of the state where rainfall is the major factor influencing forage production and appropriate data are available. The repeatability of the method enables it to be applied to individual properties to provide an individual "safe" grazing capacity for that property. This alleviates the problems of inaccurate estimates of a grazing capacity for a property when based on district average capacities. The repeatability of the method also enables the review of "safe" grazing capacities if changes in land condition (tree and shrub density at this stage) or forage production occur for a particular property or land system on the property. Other factors such as the impact of soil loss or change in botanical condition could be include in the methodology as the relationships between these factors and forage production are defined.

If land managers and land administrators used the approach developed here to assess grazing capacity, improved land management practices may follow as a result of better informed decision making. Coupled with financial and economic analyses for aggregations, improved estimates of appropriate property size could be examined using the methodology. The determination of "living areas" would then have a quantifiable basis. Definition and implementation of drought assistance policies could also be improved with use of the methodology. Instances where disregard for resource capability and seasonal conditions inducing early "droughts" could be better identified. The method would also enable the assessment of the financial impacts and risk flowing from changes in commodity prices and cost structures associated with rural industry.

There is room for further refinement of the methodology requiring a commitment from researchers and funding bodies. At this stage the methodology provides a framework for examining long-term or 'strategic' decisions regarding domestic livestock numbers. Native and feral grazing animals have not been included in the estimation of grazing capacity. The methodology focuses on 15% to 25% utilisation of average annual forage growth by domestic livestock as being "safe" and assumes an average long term (20-30 years) uniform distribution of feral and native herbivores. However, the inclusion of native and feral grazing animals in the methodology would facilitate the examination of total grazing pressure. From a land stability viewpoint total grazing pressure and its management is critical. However, any improvements must adhere to the ecological principles developed and focus on utilisation as the measure of sustainability. With such an approach, our understanding of the production variability associated with grazing in south-west Queensland, and our ability to "safely" use the resource will be improved.

6.0 APPLICATION AND EVALUATION OF A "SAFE" GRAZING CAPACITY MODEL

6.1 Introduction

Concern over the decline in agricultural productivity of south-west Queensland has been expressed by a number of authors e.g., Ratcliffe (1937), Burrows and Beale (1969), Pressland (1976, 1984), Mills (1986), WGA (1988), Mills *et al.* (1989), Miles (1989), Passmore and Brown (1992) and Anon (1993). Reliance on feed from browse trees and maintenance of inappropriate stocking rates at critical times have reportedly caused pasture degradation and productivity losses in the region. The processes and extent of degradation have been described by Beale (1986), Burrows (1973), Brown (1981), Pressland and Cowan (1987), Mills (1986), Mills *et al.* (1989), and Miles (1993). The most common forms of degradation reported by these authors are the lack of ground cover, accompanied by increases in sheet erosion and woody shrub cover. Mills (1989) estimated that the gross value of wool production from the "Paroo" Mulga area (3M ha bounded by Charleville, Quilpie, Thargomindah and Cunnamulla) had been reduced by $4.4m (4.2%) per annum through the effects of erosion and woody shrub cover.

In focussing on these concerns a review of "carrying capacities" / "stocking rates" was suggested by WGA (1988), Mills *et al.* (1989), Miles (1989) and Anon. (1993). At the same time the Department of Lands was concerned that its traditional long-term carrying capacities generally represented an over-estimation of the ability of land types in the Mulga region to sustainably carry stock in the long-term (P.R. Tannock, pers. comm.). The majority of these capacities were based on subjective judgments during the 1940's and 1950's and were no longer considered appropriate by local land managers and administrators. In 1989 the Department of Lands reviewed the carrying capacities on a number of properties in south-west Queensland based on personal assessment and "gut" feeling. While this review generally reduced carrying capacities the process remained a subjective one.

Determining the number of animals or grazing capacity of grazing lands, and understanding the consequences are the most difficult tasks in grazing management (Vallentine 1990a). Several approaches are available for determining grazing capacity and appropriate stocking rates. Most are based on experience of "average" properties in "average" years (Wilson *et al.* 1990), and trial and error coupled with regular adjustments. Due to the variability in climate and base resources in south-west Queensland, the use of "district averages" is unlikely to yield appropriate grazing capacities for individual properties.

To review grazing capacities of individual properties in south-west Queensland an objective assessment was required. As grazing capacities largely determine the value of land bought and sold (Holechek *et al.* 1989) any review of these values directly affects the livelihood of individuals. Examination and discussion of grazing capacities are therefore sensitive issues. Due to these sensitivities the methodology developed to review grazing capacities needed to be rigorous, defendable and most importantly respected in the grazing community.

To remove the subjectivity and perceived inaccuracies in carrying capacity values, the Department of Lands appointed three experienced graziers from the region as consultants in February 1994. Their role was to apply and evaluate a methodology for objectively assessing long-term carrying capacities on a number of selected properties. The development of an objective assessment of carrying capacity for individual properties was considered important for several reasons:

1. A general review of grazing capacities in south-west Queensland required a more open and defendable review process;
2. The method for review needed to account for the condition of the land resource;

3. Specific reviews of carrying capacities for properties being amalgamated under an integrated regional adjustment and recovery program (Williams 1995) required open and defendable means of conducting assessments;
4. The method needed to recognise and accommodate the unique combination of land systems comprising individual properties in south-west Queensland;
5. To avoid the intellectual loss of local information as industry and government personnel leave the region; and,
6. Better communicate basic resource information to those unfamiliar with the region.

The method chosen to estimate long-term grazing capacities of individual properties needed to:

(i) be quantitative;
(ii) be based on ecological principles;
(iii) be defendable;
(iv) be transparent;
(v) have resolution at a practical scale (individual property or paddock);
(vi) use appropriate terminology (acres/dry sheep equivalent);
(vii) complement existing property management; and,
(viii) build on existing community knowledge.

These characteristics were important to facilitate the training of the grazier consultants and to ensure the consultants could convey the methodology among the grazing community. Omission of several of these factors from modelling efforts in the dryland cropping area has lead to "communication errors" between farmers and scientists (Ridge and Cox 1995).

This Chapter describes my role in: (1) packaging an appropriate methodology; (2) the selection and training of three grazier consultants; and, (3) application of the method to selected properties. It describes an attempt to utilise a participatory approach to technology transfer, where partnerships among researchers, extensionists, graziers, financiers and administrators (grazing community) were developed (Jiggins 1993). The industry and community benefits and the scientific insights gained from the analysis of individual property data are described with a focus on outcomes (improved grazing land management in south-west Queensland) rather than outputs (computer packages). This is in contrast to Cox (1996) who suggests similar modelling exercises in broadacre agriculture have focussed on the production and adoption of decision support systems rather than the improved management of agricultural production systems.

6.2 Materials and methods

6.2.1 Selection of appropriate methodology

The method for estimating grazing capacities developed in Chapter 5 was chosen. It met each of the criteria above. Briefly, the method entailed estimating the potential annual average forage growth (kg/ha) of the different land systems on each property. This estimate was based on the product of average annual rainfall use efficiencies for each land system and long-term average rainfall. Actual forage growth was estimated after accounting for the effect of tree and shrub cover. An estimate of the number of livestock to utilise a "safe" portion of the actual forage grown was then calculated. The level of "safe" forage utilisation was based on utilisation levels observed in grazing trials conducted in northern Australia, utilisation levels estimated on three "benchmark" properties and on consensus data of utilisation levels considered "safe" by a group of experienced graziers, land administrators and researchers. Summing the livestock numbers for each land system on a property produced an estimate of the "safe" long-term grazing capacity for that property. The term "safe" implies conservative levels of forage utilisation by domestic livestock and subsequent sustainable resource use. The derivation of these conservative levels of forage utilisation was conducted without quantification of the grazing pressure attributed to other herbivores such as kangaroos, goats and insects (Chapter 5). The ability to manage populations of other herbivores and estimate their contribution to total grazing pressure would result in a different levels of "safe" forage utilisation.

6.2.2 Selection and roles of grazier consultants

The Department of Lands placed advertisements in January 1994 seeking to employ three experienced graziers as grazing capacity consultants. Their role was to apply and evaluate the above methodology (Chapter 5 and Chapter 6.2.1) as a means to estimating "safe" long-term grazing capacities on selected properties in the Mulga lands of south-west Queensland. They were appointed in February 1994 and training in the methodology conducted by myself commenced in March 1994. A consultant was chosen from each of three broad bio-geographical regions (eastern Mulga lands (Booringa, Balonne and Warroo shires), central Mulga lands (Paroo and Murweh shires - east of the Warrego river) and western Mulga lands (Paroo, Bulloo and Quilpie shires - west of the Warrego river).

The duties of the consultant were to:

(1) Undertake training in the concepts and techniques behind the methodology,

(2) Trial the model and techniques on the consultant's own property. This entailed:

(a) a detailed inspection of the property,

(b) refinement of the land system mapping where necessary to reflect actual country types,

(c) estimating tree and woody weed density using step point methodology, and

(d) calculating a long-term grazing capacity for each land system and the property overall.

(3) Contact selected receptive graziers in their regions willing to have their properties assessed and arrange inspection times,

(4) Arrange for relevant maps to be prepared prior to property inspections,

(5) Visit each property to discuss the methodology, refine the land system maps (if necessary), assess the condition of each land system and estimate a "safe" long-term grazing capacity,

(6) Prepare a report for each property for the benefit of each landholder, and

(7) Prepare a public report for the Department of Lands summarising the findings from all properties.

The technical component in each of the above steps was closely supervised by myself to ensure the methodology developed in Chapter 5 was adhered to, and to solve difficulties in application should they arise.

6.2.3 Packaging the methodology and consultant training

A "user-friendly" manual was compiled by myself to summarise the concepts and steps in estimating "safe" grazing capacities as described in Chapter 5. Apart from the land system maps for each property, the manual provided the necessary formulae, data and working sheets to estimate a "safe" grazing capacity for any property in south-west Queensland. Maps for each property surveyed in this exercise were supplied by the Department of Lands. The maps consisted of cadastral and land system boundaries overlain on recent satellite imagery for the property. The working sheets were designed to enable grazing capacity calculations to be performed either by hand or with a calculator.

In March 1994, a three day training session lead by myself was held to introduce the grazier consultants and Department of Lands staff to the background and steps involved in estimating grazing capacities for individual properties. The three grazier consultants, and a number of staff from the Department of Lands and Department of Primary Industries district offices participated in the training session. The session included sections on the ecological principles behind the methodology, techniques for sampling foliage projected cover of trees and woody weeds using the step point methodology of Evans and Love (1957) and sighting tube of Buell and Cantlon (1950) and performing the calculations.

As a case study, I lead an exercise where the method was applied to the 5362 ha Department of Primary Industries research station "Croxdale" (26°27' South, 146°09' East) located 12 km from Charleville. The land system mapping for "Croxdale" was examined and representative locations within the various land systems sampled for tree and woody weed cover. The calculations to estimate a "safe" long-term grazing capacity for "Croxdale" were performed and discussed as a group.

Following the initial training, each of the consultants assessed their own properties as a team. The objective of this was to resolve any problems and consolidate the approach to be used. Following these assessments the grazier consultants approached an additional 20 properties, offering to conduct an assessment and evaluate the methodology (Figure 6.1). The selection of properties was determined by the grazier consultants and aimed to cover their respective regions. The confidentiality of individual property information was assured for each of the 20 properties selected.

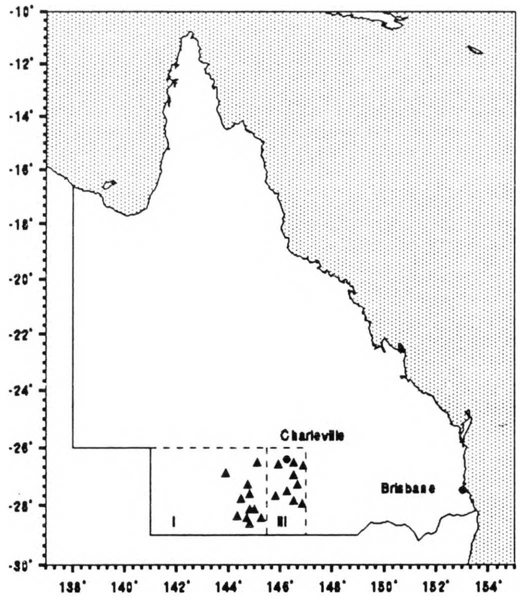


Figure 6.1 Location of 20 grazing properties in south-west Queensland selected by two grazier consultants to apply and evaluate a model for calculating "safe" long-term grazing capacities of individual properties. The WARLUS land system map areas of (I) Dawson (1974) and (III) Mills and Lee (1990) are shown dotted.

6.3 Results

6.3.1 Training evaluation

No formal evaluation of the training session was conducted. The following are qualitative observations regarding the learning process and grazier perceptions of the methodology.

6.3.1.1 The learning process

Each of the grazier consultants rapidly grasped the issues relating to the grazing capacities in south-west Queensland and the need to review these values using a rigorous, quantifiable and defendable method. When presented with the basic ecological principles behind the approach to estimating grazing capacities it was difficult initially to determine the depth of understanding. However, in the field at "Croxdale" the graziers rapidly developed an understanding of the principles and techniques for recognising different land systems and sampling tree and woody weed cover. They became conversant with the terminology quickly and began using it regularly when discussing the work.

However, due to the unavailability of the land system mapping used in model development east of 147°, only two of the consultants were able to fully proceed with application of the model. The land system mapping of Mills and Lee (1990) ends at 147° East.

During the property assessments a number of aspects in the methodology required clarification and or modification. The questioning and identification of these aspects indicated the consultants had developed a sound understanding of the components of the methodology. Issues regarding the methodology were solved as they arose. However, no change was made to the methodology until the final workshop held in June 1995. This was to ensure consistency in applying the methodology among properties.

In June 1995 I lead a workshop where the consultants presented their findings for discussion. Modifications to the methodology based on issues they identified were discussed. A "safe" long-term grazing capacity for each of the twenty properties was then calculated using the refined methodology and the data collected by the grazier consultants.

6.3.1.2 Grazier observations regarding the methodology

Regarding the methodology the two remaining consultants (Cooney (1995) and Crichton (1995)) reported:

1. More research should be conducted into all aspects of the methodology, particularly the rainfall use efficiencies and the effect of tree and shrub cover on pasture growth.
2. The methodology should not be set in concrete and should be reviewed and refined at regular intervals to account for the findings of new research. These reviews would also cater for improving satellite technology and other techniques as they arise.
3. Continual upgrading of the WARLUS land system mapping on a property by property basis would improve the accuracy of the grazing capacity estimation. Eventually, every property should be done separately.
4. Most landholders have a deep suspicion that this exercise is the first step towards controlled stocking and greater government control in how they run their properties. Security of tenure and property size of an adequate "living area" were two issues identified as being closely linked with "safe" grazing capacities.
5. The presentation of grazing capacities should be re-thought. Rather than hectares per DSE the land's capacity should be expressed as "units of production" per hectare. Everything leaving the property

would have a "unit of production value" which can be related to the current components of the grazing capacity estimation (land system, rainfall, tree and woody weed cover).

6. Various relevant bodies and particularly the grazing industry accept the methodology for estimating the grazing capacities in the Mulga lands of south-west Queensland.
7. Grazing capacities must be looked at in the full context of land care, and not simply how many animals the land resource can support.
8. The impact of less palatable forage species (e.g. *Aristida* spp. (Wire grasses)) on the level of forage utilisation needs to be examined.

6.3.1.3 Scientific insights gained through grazier participation

Following discussion with the grazier consultants, use of a variable level of "safe" forage utilisation as a function of site fertility (Figure 5.9) was confirmed. Early testing of the methodology on the case study property 'Croxdale' and the consultants own properties also prompted a close examination of the derivation of the rainfall use efficiencies for land systems outside of those examined in Chapters 3 and 4. This lead to the development of the relationship between rainfall use efficiency and site characteristics. A factor to accommodate the frequency of flooding on regularly flooded land systems (alluvial plains (A) and wooded alluvial plains (W)) was also developed. Annual rainfall was increased by 30% and 15% for land systems experiencing flooding every 1 in 3 years and 1 in every 4 to 10 years respectively. The estimation of the quantity of mulga leaf available as browse was considered an important component of the methodology. While only 5% of this material was available to livestock, the fact that it was a component was important for the credibility and acceptance of the methodology amongst graziers.

Components of the methodology identified by the grazier consultants requiring further refinement

included:

(i) the relationships between different woody species and forage production across different land systems and rainfall gradients (e.g. comparable to Scanlan (1984) on brigalow and eucalypt communities in central Queensland);

(ii) examination of the long-term utilisation of browse across different land systems, density of mulga, forms of mulga and management of mulga;

(iii) examination of the degree of complementarity between sheep and cattle across different land systems;

(iv) inclusion of a measure of grass density as an additional indicator of land condition; and,

(v) comparison of domestic livestock numbers to total herbivore grazing pressure at the paddock and property scale.

6.3.2 Property assessments

Twenty grazing properties in south-west Queensland (average size 32916 ha) were assessed by the grazier consultants during the period March 1994 to June 1995 (Cooney 1995 and Crichton 1995) (Figure 6.1). Properties were not assessed in the eastern region due to unavailability of the mapping on which the method was developed (McLean 1995). The land system mapping of Mills and Lee (1990) ends at 147^{o} East. The next two sections summarise the data collected by two of the grazier consultants (Cooney 1995 and Crichton 1995).

6.3.2.1 Land systems and land condition

A total of 6583 km^2 was assessed covering 77 different land system combinations described by Dawson (1974) (WARLUS Part I) and Mills and Lee (1990) (WARLUS part III). The average annual rainfall for the twenty properties was 357 mm. Sixty-one percent of the area assessed was either the Soft Mulga land zone (2065 km^2 or 31%) or the Hard Mulga land zone (1966 km^2 or 30%). The average foliage projected canopy cover of trees on the twenty properties was 9.6% (range 0.0% to 30.6%) and the average foliage projected canopy cover of woody weeds was 6.5 % (range 0.0% to 38.3%) (Appendix 9). The Soft Mulga land zone supported the highest density of trees (13.6%) and the Open Downs the lowest (0.0%) (Table 6.1). The Sandplain land zone had the highest density of woody weeds (21.6%) and the Open Downs the lowest (0.0%) (Table 6.1). The Sandplain land zone also had the highest total woody vegetative cover (28.1%) and the Open Downs the lowest (0.0%) (Table 6.1).

Table 6.1 Total area, average rainfall, average foliage projected cover (FPC%) of trees and shrubs and total cover for the 13 of the 15 land zones (Dawson (1974) and Mills and Lee (1990)) encountered in the assessment of 77 land systems on 20 grazing properties in south-west Queensland. (Detailed data for the 77 land systems presented in Appendix 9)

Land Zone	Area (ha)	Rainfall (mm)	Tree (FPC%)	Shrub (FPC%)	Total (FPC%)
Alluvial Plains Open (A)+	33340	327	3.5	1.2	4.7
Brigalow (B)*	0				
Channel Country (C)	718	303	5.0	0.0	5.0
Dunefields (D)	13614	338	5.3	15.6	20.0
Poplar Box Lands (E)	18528	434	10.8	4.6	14.9
Downs (F)	247	325	0.0	0.0	0.0
Gidgee Lands (G)	40546	328	8.4	4.8	12.8
Hard Mulga Lands (H)	196626	354	8.1	5.0	12.6
Claypans (L)	11542	376	5.2	1.4	6.5
Soft Mulga Lands (M)	206512	372	13.6	4.8	17.7
Spinifex Sandplains (N)	18204	423	9.3	17.6	25.3
Dissected Residuals (R)	37309	360	9.8	12.2	20.8
Mulga Sandplains (S)	39856	344	8.3	21.6	28.1
Wooded Downs (T) *	0				
Alluvial Plains Wooded (W)	41283	338	5.9	3.0	8.7
Mean	43888	308	6.2	6.1	11.8

+ Code letter for land zones used by Dawson (1974) and Mills and Lee (1990).

* Land zones not encountered on the properties assessed.

6.3.2.2 Grazing capacity comparisons

The average pre-1989 Department of Lands rated carrying capacity (3.31 ha/DSE) was 40% heavier than the owner assessed capacities (4.62 ha/DSE) which was 7% heavier than the "safe" long-term grazing capacity (4.95 ha/DSE) calculated using the model described in Chapter 5 (Table 6.2).

Seventy-five percent of the owner's average grazing capacities were within ± 10% of the calculated grazing capacity (Table 6.2). There was a significant relationship (slope nsd 1.0 and intercept nsd 0.0 at $P<0.05$) between the calculated grazing capacity and the owners average livestock numbers (Figure 6.2) when two outliers were removed on recommendation of one of the consultants (more livestock were run on these properties due to a greater use of mulga leaf as a source of forage due to the regular pushing and feeding of mulga for pasture development). The ratio of owner grazing capacities to those calculated (average 1.08, range 1.39 to 0.95) was neither related to property nor flock size (Figures 6.3a and 6.3b). Six of the twenty properties on average ran less livestock than the calculated "safe" grazing capacity.

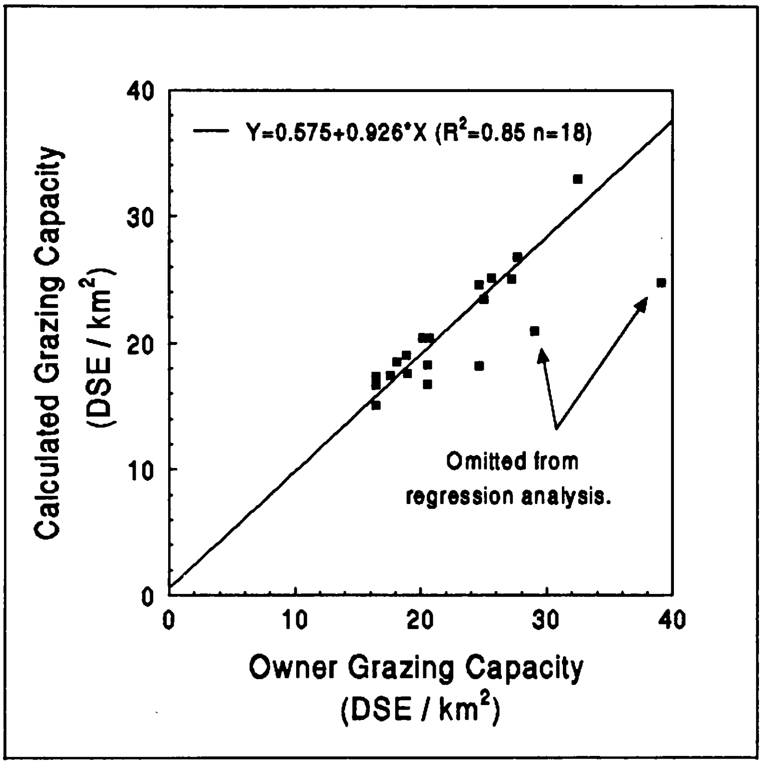


Figure 6.2 Comparison between calculated "safe" grazing capacities and average livestock numbers on 18 grazing properties in south-west Queensland selected by two grazier consultants applying and evaluating a methodology for estimating "safe" long-term grazing capacities of individual properties (slope nsd 1.0, intercept nsd 0.0 $P<0.05$).

Similarly there was no relationship between the ratio of owner grazing capacities to the pre-1989 Department of Lands rated grazing capacities (average 0.73, range 1.00 to 0.50) and property or flock size (Figures 6.3c and 6.3d). All twenty properties supported fewer livestock than that rated by the pre-1989 Department of Lands values (Table 6.2).

The ratio of Department of Lands capacities to those calculated (average 1.51, range 2.18 to 1.15) was not related to property or flock size (Figures 6.3e and 6.3f). On all twenty properties the pre-1989 Department of Lands rated capacities were heavier than the calculated "safe" grazing capacity (average 50% heavier) (Table 6.2).

Table 6.2 Pre-1989 Department of Lands (DOL) rated carrying capacities, average owner grazing capacities, calculated "safe" grazing capacities and grazing capacity ratios for twenty properties in south-west Queensland assessed by grazier consultants.

Property	Owner (DSE/km^2)	Calculated (DSE/km^2)	DOL (DSE/km^2)	Owner: Calculated	Owner: DOL	DOL: Calculated
A	17.6	17.5	33.9	1.01	0.52	1.94
B	20.7	20.4	29.1	1.02	0.71	1.42
C	19.0	17.6	31.6	1.08	0.60	1.80
D	20.6	16.8	26.6	1.22	0.78	1.58
E	16.5	16.7	22.5	0.99	0.73	1.35
F	16.5	17.4	22.5	0.95	0.73	1.29
G	20.6	18.3	27.5	1.12	0.75	1.50
H	18.9	19.0	29.1	0.99	0.65	1.53
I	16.5	15.1	32.9	1.09	0.50	2.18
J	18.1	18.6	24.7	0.98	0.73	1.33
K	24.7	24.6	33.9	1.01	0.73	1.38
L	27.2	25.1	30.9	1.09	0.88	1.23
M	32.5	33.0	38.0	0.99	0.86	1.15
N	29.1	21.0	29.1	1.39	1.00	1.39
O	20.2	20.4	30.9	0.99	0.68	1.51
P	25.6	25.1	41.2	1.02	0.62	1.64
Q	27.8	26.8	35.3	1.03	0.79	1.32
R	24.7	18.2	35.3	1.35	0.70	1.93
S	31.5	24.8	32.9	1.27	0.96	1.33
T	25.1	23.5	31.6	1.07	0.79	1.35
Mean	22.7	21.0	31.0	1.08	0.73	1.51
SE	1.1	1.0	1.1	0.03	0.03	0.06
Lightest	16.5	15.1	22.5	1.39	1.00	2.18
Heaviest	32.5	33.0	41.2	0.95	0.50	1.15

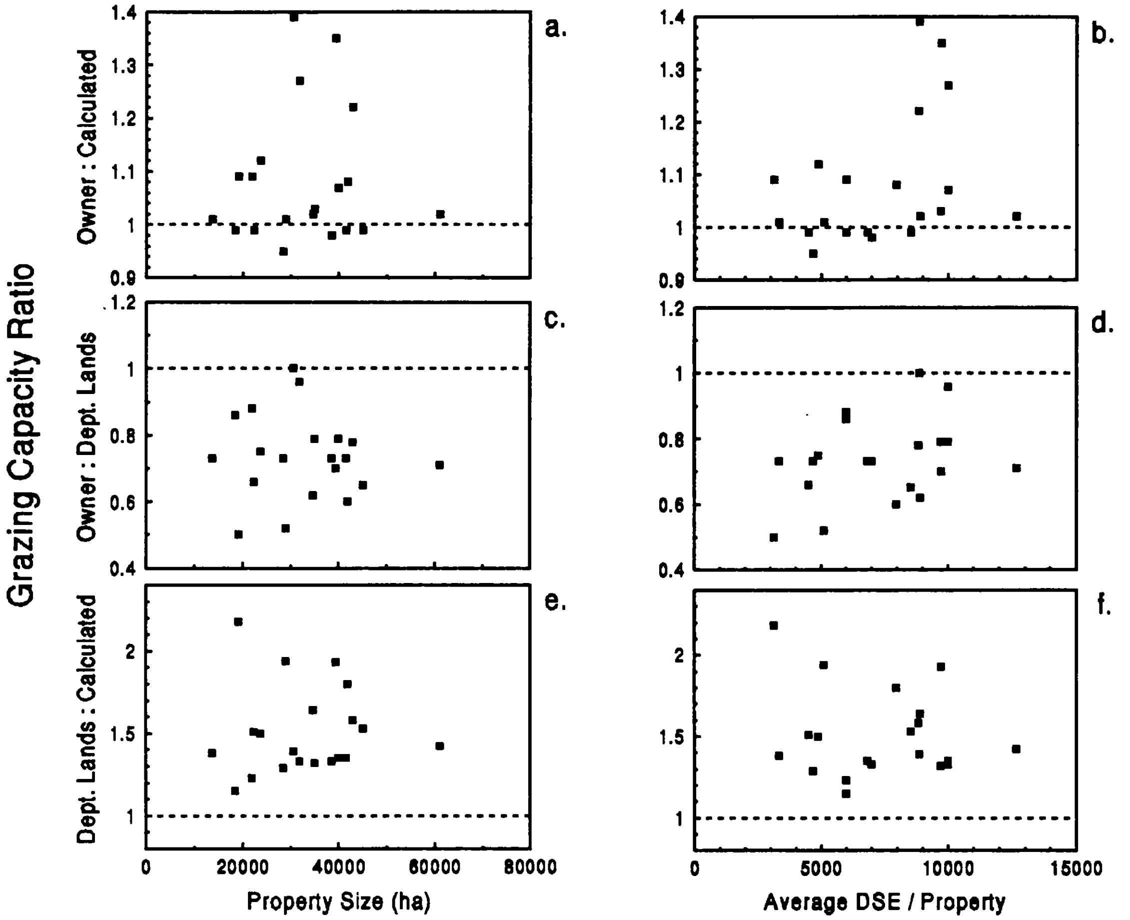


Figure 6.3 Comparison of livestock ratios (a) owner assessed grazing capacities : calculated grazing capacity and property size, (b) owner assessed grazing capacities : calculated grazing capacity and flock size, (c) owner assessed grazing capacities : Department of Lands rated carrying capacities and property size, (d) owner assessed grazing capacities : Department of Lands rated carrying capacities and flock size, (e) Department of Lands rated carrying capacities : calculated grazing capacity and property size and (f) Department of Lands rated carrying capacities : calculated grazing capacity and flock size for 20 grazing properties in south-west Queensland selected by two grazier consultants applying and evaluating a model for estimating 'safe' long-term grazing capacities of individual properties.

6.4 Discussion

6.4.1 Graziers as consultants and the scientific insights gained

Employing experienced graziers as consultants to test and help refine a methodology for objectively estimating grazing capacities was a positive step towards gaining community confidence in the process. However, in failing to include all the clients from the outset the approach described in this Chapter did not conform entirely to the participatory model of technology transfer as described by Jiggins (1993). Despite this, the employment of the grazier consultants was considered appropriate and useful in developing partnerships among researchers, extensionists, graziers, financiers and administrators. As experienced graziers, the consultants had long established links within the grazing community. Using these links and assurance of confidentiality, the consultants were able to build confidence and discuss concerns regarding the methodology using their own personal "grazier" terminology.

Feedback from the consultants and the scientific insights gained, led to a more rapid development and refinement of the methodology than would have been possible under conventional evaluation. As a form of action-research, the training sessions, case study and follow-up meetings provided the consultants with the background ecological principles and understanding of the terminology necessary for examining grazing capacities. For the researchers, valuable insight into the practicalities regarding the estimate of grazing capacities at the property scale were gained (refinement of rainfall use efficiencies, inclusion of flooding, mulga as browse, variable forage utilisation and the need to work at the paddock scale). For both the grazier consultants and researchers, use of a common terminology expedited discussion and identification of problems in the methodology as they arose.

Insight was also gained into areas requiring further refinement from a grazier's perspective (tree/grass relationships, use of browse, sheep/cattle ratios, grass density/land condition relationships and the impact of other herbivores). Of these, a closer examination of the role of browse may not have been a priority from a researchers viewpoint. However, for the methodology to gain recognition in the wider grazing community improvements to the browse component may be critical. Humphreys (1997) in examining the work of Jones Q.R. suggests some of the difficulties in determining the importance of components on which to focus is due to basic differences in personality types between graziers and researchers.

These insights have highlighted the valuable and innovative role that can be played by experienced graziers in linking science and practice. In tackling sensitive issues such as grazing capacities the approach described here may serve as a model for dealing with other issues in other regions. Cox (1996) in discussing the role of decision support systems in cropping areas also highlights the need for participation and communication between the producers and the users of decision support systems. A comparable approach is currently being proposed to investigate long-term property grazing capacities in the Dessert Uplands region of central Queensland (Edwards and Caltabiano pers. comm.).

Use of the methodology by the grazier consultants provided an independent evaluation of the method for estimating grazing capacities. From their documented observations (section 6.3.1.2) and personal communication their was general support for and acceptance of the methodology on the 20 properties assessed. This indicates that wider application of this methodology for estimating grazing capacities of individual properties could proceed. This is currently happening as a project under the resource management component of a regional reconstruction initiative termed "The South West Strategy" (Williams 1995). Funding for this initiative is provided jointly by the Queensland state government and the federal government (National Landcare Program).

6.4.2 Land Condition

The methodology assessed only tree and shrub cover as an indicator of land condition. Surveys at a regional scale where these or other forms of land condition data are recorded in south-west Queensland are rare. In three previous regional scale surveys, Dawson and Boyland (1974), Mills *et al.* (1989) and Passmore (1990) used different techniques to those used by the grazier consultants. This makes it difficult to compare the present results with earlier surveys (Table 6.3) and highlights a need for regular regional scale surveys using techniques that are comparable over time.

Some land condition data for selected land zones were reported in WARLUS Part I (Dawson and Boyland 1974). The Alluvial Plains and Wooded Alluvial Plains land zones were surveyed with 85% of the area recorded as having less than 3% cover of shrubs. This approximated values of 1.2% and 3.0% respectively reported by the grazier consultants. For the Soft Mulga land zone, Dawson and Boyland (1974) reported 35% of the area had a shrub canopy cover greater than 6%, and 15% of the area had a cover of greater than 10%. This compared to a shrub cover of 4.8% observed by the grazier consultants. However, caution is required when making these comparisons, as survey techniques, sample size and sample regions varied between land zone surveys.

Table 6.3 Comparison of tree, shrub and total woody cover from regional scale surveys of land condition in south-west Queensland.

Survey	Method	Tree Cover (%)	Shrub Cover (%)	Total Cover (%)
Crichton (1995) and Cooney (1995)	sighting tube from step points (fpc%)	9.6	6.5	15.5
Passmore (1990)	visual from step points	9.9	7.1	16.3
Mills et al. (1989)	step point and photo standards	4.4	5.0	9.4

6.4.3 Grazing capacity comparisons

6.4.3.1 Ratio of owner assessed grazing capacity to calculated "safe" grazing capacities

A significant relationship between the owner's assessed grazing capacity and the calculated grazing capacity indicated the model was capable of estimating a long-term "safe" grazing capacity for these "participants" properties. However, this was only and small sample of south west Queensland properties and may have been biased towards producers with more conservative grazing practices. It was also a comparison of owner assessed grazing capacities which may not necessarily reflect actual livestock numbers. This result supports further development and a cautious broader application of the methodology. This is currently (July 1996) occurring in two activities being conducted under a regional reconstruction initiative in south-west Queensland (Williams 1995).

6.4.3.2 Ratio of owner assessed grazing capacity to Department of Lands rated carrying capacities

Results presented in this Chapter support the general consensus that Department of Lands pre-1989 rated carrying capacities for the Mulga lands were less conservative than those assessed by the grazing community (participants properties). This contrasts with the results presented in Chapter 5, where an analysis of 46 randomly chosen properties (Passmore 1990) indicated the Department of Lands rated carrying capacities were more conservative than the graziers actual stock numbers. This apparent contrast may be due to:

1. Differences in the method of choosing properties. Passmore (1990) made a random choice of properties to survey across the Mulga lands of south-west Queensland. The consultants based their choice of properties on the basis of local knowledge and geographical location. In selecting "participants" properties (Cooney 1995), the consultants may have selected a more conservatively stocked group of properties. No guidelines for property selection apart from covering a geographical range were provided to the grazier consultants.

2. Differences between average and actual livestock numbers. The Passmore (1990) survey was conducted during a period of high wool prices (1986 to 1988) and surveyed actual livestock numbers on the 46 properties during that period. These data represent a stocking rate for that unique period based on conditions at that time and did not reflect a long-term capacity for those properties (based on the benchmarks analysed in Figure 5.8). The consultants data were based on the owners assessed long-term average grazing capacity for the properties (not actual numbers in 1995) and were perhaps more closely aligned to the concept of a long-term or "safe" grazing capacity for the properties (i.e. 15%-20% utilisation of average long-term forage growth by domestic livestock.)

These results highlight the difficulties in examining grazing capacities of properties in south-west Queensland. Careful consideration needs to be given to the presentation of the data and how it is interpreted as recommended by Heady and Child (1994). Criticism of the Department of Lands rated carrying capacities may or may not be warranted depending on how and when grazing capacities are compared. This is highlighted by the fact that property and flock size were not related to the variation between the average owner records and the Department of Lands rated capacities.

6.4.3.3 Ratio of Department of Lands rated carrying capacity to the calculated "safe" grazing capacity

The greatest difference in grazing capacities occurred between those calculated by the model and the pre-1989 Department of Lands values. This may be due to the Department of Lands values not reflecting either changes in the land's condition and therefore declining productive capacity or changes in grazing practices. Pre-1989 values were determined in the 1940's and 1950's. In 1989, an attempt was made in south-west Queensland to review these capacities. This review was based on a response to perceived long-term changes in land condition and a recognition that actual grazing practice was not aligned to the values on record for many properties.

The Department of Lands is at the front-line in government land administration. Society is expecting the agency to be more proactive in influencing sustainable land use decisions (e.g. a change in the name to the Department of Natural Resources in April 1996). If the Department of Lands adopts the model evaluated here by the grazier consultants, "safe" grazing capacity estimates will become more dynamic and better reflect changes in land condition. There will also be a greater chance that "safe" grazing capacities will more closely reflect grazing practice. For land administrators, the end result will be greater confidence in the information base, and this will lead to more informed decisions regarding sustainable land management and administration. For land managers, there will be greater respect for the information used by land administrators in decision making affecting their properties and livelihoods.

6.4.4 Grazing capacities at a practical scale

The estimate of a "safe" long-term grazing capacity provides a valuable target around which seasonal livestock numbers on a property would be expected to fluctuate following responsive management. At this scale, grazing capacity information is of value to land administrators and to those purchasing and selling properties. However, for land managers, decisions regarding livestock generally occur at the paddock level. For the "safe" grazing capacity concept to be most useful to land managers, grazing capacities for individual paddocks must be estimated. The principles and procedures to conduct paddock scale estimates are the same for the whole property. The only difference lies in mapping land systems at the paddock level. When applied at the paddock scale, the estimate would provide a target around which livestock numbers would be adjusted depending upon season and management decisions (stocking rate). The paddock scale decisions on stocking rate therefore require application of the same objective of "safe" long-term grazing capacity as for a property, but are more aligned to practical livestock management. This is the scale where sustainable resource management decisions are made.

However, application of the approach at a more detailed scale requires recognition of the limitations of the broad-brush (property scale) approach when applied to paddocks (Table 6.4). Errors in estimating forage growth, FPC of trees or utilisation levels on relatively small land systems may not be significant to the overall result when the model is applied at the whole property scale. At the paddock scale these errors may become significant. Other factors would also become important when applying the approach to grazing capacity decisions at the paddock scale. The size and shape of paddocks, relative proportions of different land systems, location of waters and wind direction all influence the grazing behaviour of livestock and other herbivores. Application of the method at the paddock scale may need to include some or all of these factors.

Table 6.4 Strengths and weaknesses of the grazing capacity model as developed in Chapter 5 and applied to properties in south-west Queensland.

Strengths

Provides an objective quantitative approach to estimating long-term strategic (20-30 years) grazing capacities.
Can be applied to individual properties.
Recognises the unique mix of land systems on each property.
Could be adapted to the paddock scale with recognition of the potential for errors.
The method can be repeated to monitor grazing capacity over time.
Has been evaluated on actual properties.

Weaknesses

Does not link perennial grass basal area to forage growth.
Does not accommodate for grazing preferences and distribution of herbivores across the landscape.
Does not separate the effect of different tree and shrub species / land type combinations on forage growth.
Does not include the re-distribution of water in the landscape.
Does not include available browse from standing mulga trees.
Does not separate palatable and unpalatable forage.
Does not include a level of complementarity between sheep and cattle.
Assumes a average background level of grazing by feral and native herbivores.

6.5 Conclusions

This Chapter has summarised a successful approach to technology transfer in the area of grazing land management in south-west Queensland. In applying and evaluating a model to calculate a "safe" long-term grazing capacity for individual properties the grazier consultants developed a sound understanding of the ecological principles (rainfall-average forage growth-"safe" forage use-"safe" grazing capacity) and terminology behind the model. They contributed to refinement of the model and enhanced its introduction to the region through the development of partnerships among researchers, extensionists, graziers, financiers and administrators. In addressing sensitive issues such as grazing capacities of individual properties this approach may serve as a model for dealing with other issues and other regions.

7.0 CLOSING DISCUSSION AND CONCLUSIONS

In this thesis the role of modelling at a level useful for managing native pastures was described. An approach based on ecological principles was used to estimate sustainable "safe" long-term grazing capacities for individual properties in south-west Queensland. The methodology using systems analysis and modelling entailed:

1. Collection of net primary production data from the dominant land systems in south-west Queensland (Chapter 3);
2. Calibration of the plant production model GRASP for each of these land systems using these data (Chapter 4);
3. Validation of the plant production model GRASP using independent data from south-west Queensland (Chapter 4);
4. Combination of model outputs and resource inventories for individual land systems to estimate average pasture growth. Analysis of grazing practices on individual benchmark properties in conjunction with grazing trials to estimate "safe" levels of forage utilisation (15%-20%) for any location in south-west Queensland (Chapter 5);
5. Examination of real-time forage utilisation on 46 properties over the period 1986 to 1988 (Chapter 5); and,
6. Application and evaluation of a method for use by land managers and administrators for the estimation of "safe" grazing capacities for individual properties and the identification of the strengths and weaknesses of the approach (Chapter 5 and 6).

The hypothesis to be tested was that through the measurement of key plant production relationships, and extrapolation of these over time and space, that grazing capacities for individual properties could be estimated, and related to sustainable levels of forage utilisation.

Results from Chapters 3 to 5 support this hypothesis.

Chapter 3 indicated that primary production from a range of land systems could be measured and related to water use (evapo-transpiration) over short periods of time. The impact of the vapour pressure deficit (VPD) on water use efficiency and subsequent estimates of pasture growth was highlighted. The effects of tree basal area, total soil nitrogen and phosphorus, a moisture index and species composition (C3 vs C4) on pasture productivity and nitrogen utilisation were also indicated. Regression analysis using simple multiplicative indices of these factors explained up to 97% of the variation in the data for the time period under observation. However, the successful extrapolation of these results required the use of simulation modelling to handle the temporal and spatial variability in forage production relationships. Lauenroth *et al.* (1986) and Redman (1992) suggested this approach was the most promising procedure to estimate above-ground net primary production.

In Chapter 4, calibration, validation and extrapolation results indicated the suitability of using the GRASP model in a modelling approach to predict long-term patterns of forage production in south-west Queensland. From the results of simulations extrapolating the point based data, equations based on the water use efficiencies (rainfall) for selected pasture types were developed to estimate forage growth at a regional scale.

Some limitations of the version of the GRASP model used (version GVT74) were identified and described in Chapter 4 and are summarised in Table 7.1. The question arose as to the level of accuracy required. Methods for sampling and calculating above-ground net primary production were chosen at a similar level of resolution as the objectives of the study (Singh *et al.* 1975). In order to estimate long-term "safe" grazing capacities of properties in south-west Queensland, predictions of annual patterns of forage production were required. Short term fluctuations in forage production, although important for grazing management on seasonal basis, were less relevant to the long-term requirements of this study and the limitations of the GRASP model (version GVT74) (Table 7.1) while real, were considered less relevant to the examination of long-term forage production. The use of water use efficiencies (kg/ha/mm rainfall) to simplify model output adequately estimated long-term fluctuations in forage production (Table 4.8).

Table 7.1 Limitations identified in the GRASP model (version GVT74) during calibration to nine sites and validation with 6 data sets from south-west Queensland and the impact of these limitations on the estimation of "safe" grazing capacities.

Limitation	Impact on "safe" grazing capacity estimations.
1. Over-estimation of soil moisture in dry profiles.	Over-estimation of calculated rainfall use efficiency, forage growth and grazing capacity.
2. Under-estimation of soil moisture in wet profiles.	Under-estimation of calculated rainfall use efficiency, forage growth and grazing capacity. Over a number of years it is likely this limitation and the one above would cancel each other.
3. Rapid wetting and drying of the profile not predicted for cracking clay soils.	Short term changes in green cover and forage growth may not be predicted. This would have an impact on the prediction of shorter term stocking rates. However, as the impact on predicting the end of season yield was small the impact on longer-term grazing capacities would also be small.
4. Rates and timing of detachment of plant material not well predicted.	May lead to an under or over-prediction of forage yield, rainfall use efficiency and grazing capacity. This would have a greater impact on the prediction of shorter term stocking rates and over time a smaller impact on grazing capacities.
5. Under-estimation of peak yield.	Conservative estimation of calculated rainfall use efficiencies, forage growth and grazing capacity.
6. Inability to accommodate multiple species (e.g. annual/ephemeral species, mixes of C3 and C4 species and change over time in species composition).	Inability to include pasture quality and species change in the estimation of grazing capacities. Potential over-estimation of grazing capacity on land systems dominated by unpalatable species and where pasture degradation is not reflected by tree and shrub foliage projected canopy cover (%).
7. Inability to predict significant short term fluctuations in yield.	Similar consequences to the fourth limitation above.

In Chapter 5, the rainfall use efficiency concept was used to simplify the results of the simulation studies in Chapter 4 to enable the estimation of potential annual average forage growth for any land system in south-west Queensland. The effects of geographical location, trees and shrubs on forage growth were accounted for to produce an ecologically based estimate of the long-term grazing capacity for any land system in south west Queensland.

The methodology was repeatable enabling it to be applied equally to individual properties to provide an individual "safe" grazing capacity for that property. This alleviated problems of inaccurate estimates of property grazing capacities when determined using district average capacities. The repeatability of the method enables a review of "safe" grazing capacities if changes in pasture condition or pasture production occur for a particular property or land system on the property (e.g. an increase in shrub density or the clearing of timber and introduction of improved pasture.)

The methodology also enabled the examination of the risks associated with stocking rate decisions and resultant levels of pasture utilisation. For 46 properties in south-west Queensland, utilisation of annual average growth was 30.7% during the years 1986 to 1988. However, the range of pasture utilisation varied from 5% to 100% with 81% of properties exceeding 15% utilisation considered "safe" for mulga pastures based on benchmark properties, grazing trial results and consensus data.

Chapter 6 described the role two experienced graziers from south-west Queensland played in the application and evaluation of the methodology for estimating grazing capacities developed in Chapter 5. A number of strengths and weaknesses in the approach were identified and summarised in Table 6.4.

Despite these limitations the methodology offered a means to quantitatively review carrying capacities to remove the subjectivity and perceived inaccuracies surrounding the Department of Lands rated carrying capacities. The Department of Lands is at the front-line in government land administration. There is an expectation that it will be more proactive in influencing sustainable land use. If the Department of Lands adopts the model evaluated by the grazier consultants, the values the agency uses will become more dynamic and better reflect land condition. There will also be a greater chance that grazing capacities will more closely reflect grazing practice on soundly managed benchmark properties. For land administrators, this will lead to greater confidence in the information base allowing more informed decisions regarding sustainable land management and administration. For land managers, there will be greater ownership for the information used by land administrators.

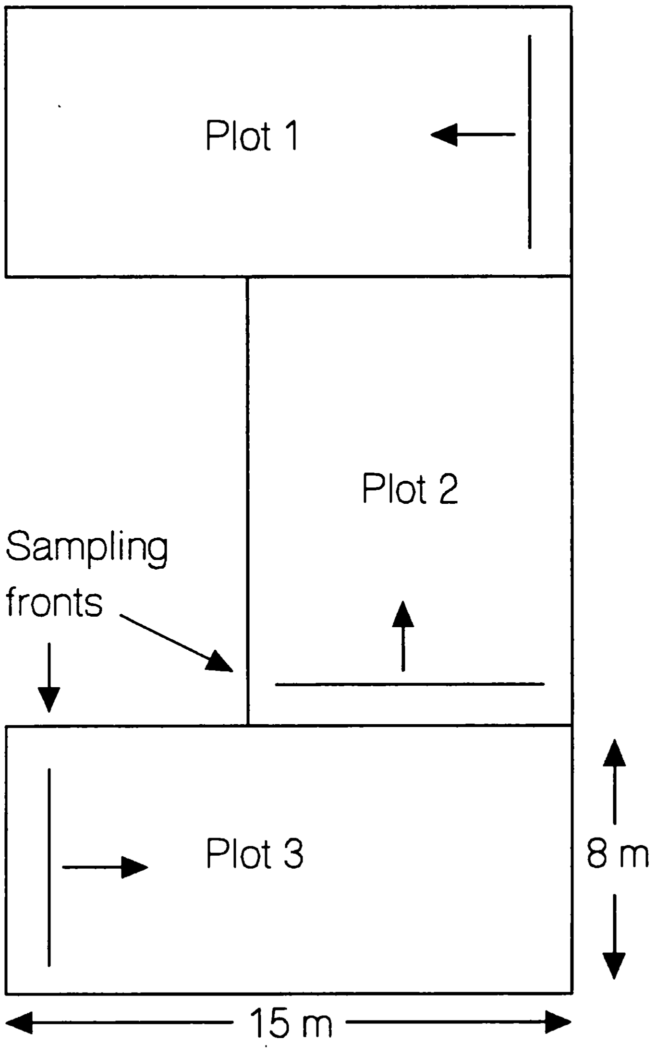
Coupled with financial and economic analyses for property aggregations, improved estimates of appropriate property size could be examined using the methodology. The determination of "living areas" would then have a quantifiable basis. Definition and implementation of drought assistance policies could also be improved with use of the methodology. Instances where disregard for resource capability and seasonal conditions inducing early "droughts" could be better identified. The method would also enable the assessment of the financial impacts and risk flowing from changes in commodity prices and cost structures associated with rural industry.

Beyond the existing rural industries of the region, alternative uses of rangelands offer different perspective's on acceptable levels of resource use. For example a “safe” grazing capacity for livestock production may have adverse effects on nature conservation. As society broadens its views of rangeland values, and as groups with conflicting values compete for rangeland resources, it is increasingly important to define degradation in relation to a particular use (Abel pers. comm.).

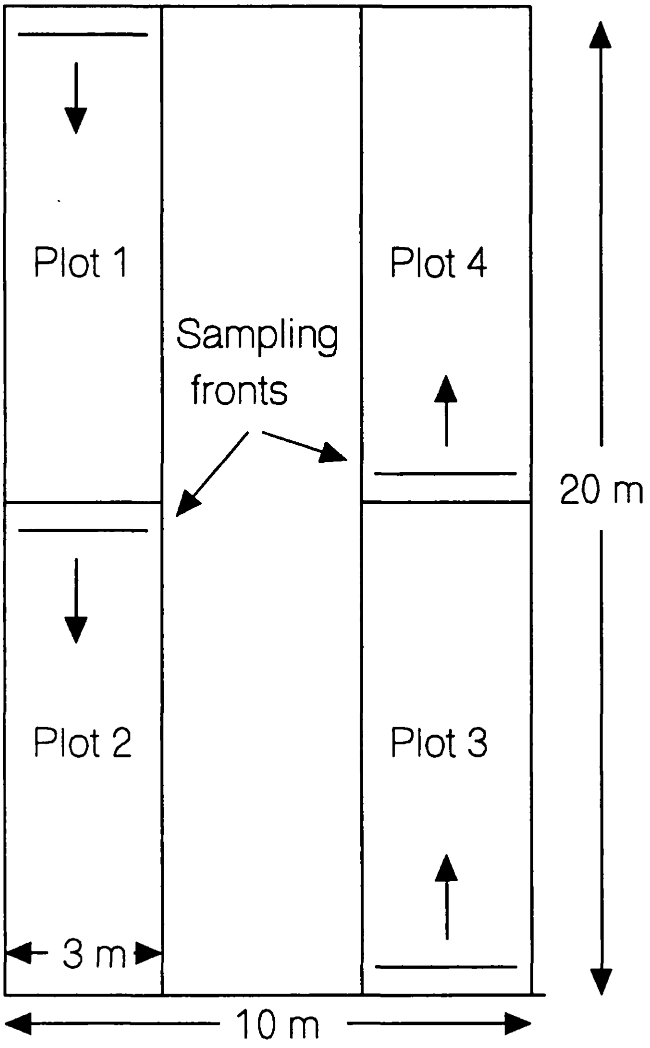
There is room for further refinement of the methodology (Tables 6.4 and 7.1) requiring a commitment from researchers and funding bodies. Any improvements must adhere to the ecological principles developed and focus on utilisation as the measure of "safe" grazing capacities for native pastures. Further application and evaluation must also build on the attempt at using a participatory approach to technology transfer described in Chapter 6. Through this, our understanding of the risks associated with grazing in south-west Queensland, and our ability to "safely" utilise the resource will be improved.

8.0 APPENDICES

Appendix 1. Plot layout and direction of sampling fronts for yield and soil moisture at sites 1 and 2 from October 1986 to November 1987.



Appendix 2. Plot layout and direction of sampling fronts for yield and soil moisture at sites 3 to 9 from October 1988 to November 1990.



Appendix 3. Detailed results of native pasture primary productivity experiments in south-west Queensland.

Table 8.1 Dry matter yield, green cover, nitrogen concentration of plant tops (where measured) and cumulative rainfall for nine native pasture primary production sites in south-west Queensland from October 1986 to November 1990. (Legend at end of Table 8.2)

Site and Date	Dry Matter Yield (kg/ha)		SD	Green Cover (%)		SD	Nitrogen Conc. (%)	Rain Cum. (mm)
Biddenham								
21.11.86								0.0
17.12.86	86	a	18	13.1	fg	2.5	2.57	62.0
07.01.87	187	b	7	16.5	g	4.2	2.12	103.5
26.02.87	1144	c-f	123	44.9	h	9.0	1.23	228.5
18.03.87	1633	ef	522	16.8	g	8.4	0.82	228.5
08.04.87	950	c	47	6.8	d-f	2.3	0.66	245.5
29.04.87	1238	c-f	98	4.1	b-e	1.0	M	269.5
21.05.87	1129	c-e	182	2.9	a-d	2.0	0.59	273.2
12.06.87	1040	c	225	0.6	a	0.8	0.64	273.2
24.06.87	1289	c-f	200	2	a-c	1.9	0.74	336.2
16.07.87	1463	d-f	81	1.2	ab	1.1	0.64	336.2
11.08.87	1678	f	147	3.9	b-c	2.6	0.64	343.2
26.08.87	1177	c-e	500	7.9	ef	5.3	0.63	370.2
18.09.87	1127	c-e	487	5.5	c-e	2.6	0.65	370.2
08.10.87	1093	cd	180	5.3	b-e	2.3	0.63	420.0
29.10.87	1405	c-f	284	7	d-f	3.7	0.65	426.2
25.11.87								476.2
10.12.87								479.7
Charleville								
24.10.86								0.0
05.12.86	206	a	65	16.7	de	2.9	2.46	120.4
31.12.86	243	a	105	9.1	bc	2.8	1.79	125.4
21.01.87	195	a	49	8.9	bc	5.6	1.77	145.4
11.02.87	275	a	165	19.6	e	9.5	2.08	276.4
04.03.87	703	b	485	29.3	f	15.7	2.42	338.4
26.03.87	645	b	387	17.1	de	8.6	1.20	395.4
16.04.87	799	bc	408	18.4	de	6.8	1.26	395.9
20.05.87	720	bc	190	6.6	b	1.9	1.04	416.9
11.06.87	847	bc	329	0	a	0.0	1.02	416.9
01.07.87	612	bc	104	10.4	b-d	2.1	1.45	495.9
29.07.87	834	bc	324	11.3	b-e	4.0	1.38	503.3
19.08.87	905	bc	429	12.5	c-e	3.6	1.67	536.9
02.09.87	943	bc	558	16.3	de	2.8	1.72	536.9
23.09.87	1190	e	139	16.6	de	3.4	1.24	545.4
15.10.87	985	bc	65	8.9	bc	1.9	0.83	595.9
05.11.87								605.4
26.11.87								640.4

Table 8.1 Continued

Site and Date	Dry Matter Yield (kg/ha)		SD	Green Cover (%)		SD	Rain Cum. (mm)
Airlie							
10.11.88							0.0
16.01.89	53	a	31	2.3	a	2.0	53.3
27.02.89	80	a	20	2.6	a	0.0	122.3
10.04.89	45	a	42	6.8	b	2.0	183.5
03.07.89	388	b	125	12.2	c	2.1	543.3
14.08.89	411	b	106	14.5	cd	2.6	560.1
25.09.89	560	b	135	21.3	d	1.6	560.1
28.11.89	1216	c	216	33.6	e	2.3	694.1
12.02.90							698.1
Lisnalee							
13.01.89							
02.03.89	648	a	77	24.2	c	2.9	31.5
14.04.89	1137	b-e	284	59.1	e	6.3	174.5
23.05.89	1052	b-d	170	43.0	d	6.5	228.5
06.07.89	1092	b-d	239	0.0	a	0.0	308.5
17.08.89	976	b-c	174	2.1	a	0.7	331.5
28.09.89	1385	e	91	7.5	b	1.5	331.5
01.12.89	1163	c-e	214	10.2	b	2.1	375.5
20.02.90	782	a	52	0.2	a	0.2	483.0
11.05.90	2009	f	236	81.6	f	7.1	816.0
22.11.90	1267	de	133				966.8
Maxvale							
14.09.88							0.0
09.12.88	20	a	3	0.3	ab	0.7	35.4
19.01.89	72	b	47	2.6	cd	1.4	84.2
01.03.89	54	ab	25	0.2	a	0.3	90.4
13.04.89	85	b	46	7.0	d	3.1	140.5
22.05.89	278	c	149	M		NC	333.9
05.07.89	444	de	241	26.7	f	6.0	410.3
17.08.89	495	c-e	269	19.6	ef	7.4	426.0
28.09.89	742	e	279	16.7	e	7.5	429.0
01.12.89	399	cd	168	3.1	bc	3.2	483.7
20.02.90							593.9
Turn Turn							
20.09.88							0.0
07.12.88	11	a	6	0.2	a	0.3	45.0
17.01.89	11	a	13	0.5	a	1.0	46.0
28.02.89	11	a	6	1.1	a	2.3	46.0
11.04.89	17	a	14	1.6	ab	1.3	139.0
04.07.89	302	b	180	21.4	d	6.5	334.0
15.08.89	370	b	104	18.2	d	6.7	338.0
26.09.89	371	b	125	7.0	c	5.9	338.0
29.11.89	259	b	80	5.0	bc	4.3	343.0
13.02.90							358.0

Table 8.1 Continued

Site and Date	Dry Matter Yield (kg/ha)		SD	Green Cover (%)		SD	Rain Cum. (mm)
Wittenburra Open							
21.09.88							0.0
07.12.88	9	a	8	0.3	a	0.7	6.0
17.01.89	61	b	19	3.4	b	1.9	28.0
28.02.89	16	a	6	0.3	a	0.7	28.0
11.04.89	7	a	4	0.5	a	0.3	105.0
04.07.89	64	b	22	6.7	bc	1.8	281.0
15.08.89	178	c	110	10.7	c	8.8	281.0
26.09.89	260	c		5.9	bc		281.0
Wittenburra Enclosed							
21.09.88							0.0
07.12.88	4	a	3	0.0	a	0.0	6.0
17.01.89	19	a	20	1.1	a	1.3	28.0
28.02.89	7	a	6	0.3	a	0.7	28.0
11.04.89	0	a	0	0.7	a	0.9	105.0
04.07.89	157	b	161	16.4	b	17.4	281.0
15.08.89	228	b		10.4	b		281.0
26.09.89	193	b	134	0.5	a	0.6	281.0
29.11.89							303.0
Wongalee							
22.09.88							0.0
07.12.88	83	a	21	4.5	a	1.4	31.5
16.01.89	225	ab	151	6.0	a	6.3	33.5
27.02.89	395	bc	304	8.5	a	6.6	33.5
10.04.89	443	bc	219	4.9	a	4.3	112.5
22.05.89	648	c	405	M		NC	309.5
03.07.89	426	bc	506	8.9	a	1.7	388.5
14.08.89	288	bc	129	9.4	a	5.1	406.5
25.09.89	295	bc	217	13.6	ab	8.8	413.0
28.11.89	621	c		27.3	b		493.0
12.02.90							536.5

Table 8.2 Soil moisture for three layers (0-50cm, 50-100cm, 0-100cm), cumulative rainfall and calculated cumulative evapo-transpiration for nine native pasture primary production sites in south-west Queensland from October 1986 to November 1990.

Site and Date	Soil Water (mm)	SD	Soil Water (mm)	SD	Rain Cum. (mm)	Total Soil Water (mm)	SD	ET Cum. (mm)
Biddenham	0-50cm		50-85cm			0-85cm		
21.11.86	101.8 b-d	15.6	73.6 +		0.0	175.4 +		0.0
17.12.86	120.0 e	6.9	95.8 d	9.9	62.0	215.8 cd	7.3	21.7
07.01.87	108.5 de	9.8	86.4 c	8.7	103.5	194.9 b	16.9	84.1
26.02.87	118.5 e	4.3	78.1 ab	5.1	228.5	196.6 b	1.3	207.4
18.03.87	97.8 b-d	5.6	81.7 a-c	1.9	228.5	179.5 a	5.1	224.5
08.04.87	86.1 ab	8.0	D		245.5	D		NC
29.04.87	104.2 cd	7.0	80.1 a-c	3.9	269.5	184.3 ab	8.9	260.7
21.05.87	99.5 b-d	2.5	84.1 bc	1.6	273.2	183.6 ab	4.1	265.1
12.06.87	94.1 bc	4.4	83.9 bc	3.6	273.2	178.0 a	4.0	270.6
24.06.87	149.8 h	3.9	79.8 a-c	4.6	336.2	229.6 d	8.5	282.0
16.07.87	108.5 de	0.9	73.1 a	5.0	336.2	181.6 ab	15.3	330.1
11.08.87	120.2 ef	11.1	81.3 a-c	3.8	343.2	201.5 bc	14.9	317.1
26.08.87	126.2 +		D		370.2	D		NC
18.09.87	103.1 cd	3.5	D		370.2	D		NC
08.10.87	131.3 fg	11.1	84.6 bc	3.7	420.0	215.9 cd	9.2	379.5
29.10.87	105.8 d	3.5	82.7 a-c	1.6	426.2	188.5 ab	3.9	413.2
25.11.87	143.0 gh	12.0	83.3 a-c	4.4	476.2	226.3 d	16.4	425.4
10.12.87	79.9 a	3.3	D		479.7	D		NC
Charleville	0-50cm		50-100cm			0-100cm		
24.10.86	24.6 c	1.7	25.5 ab	1.4	0.0	50.1 bc	3.1	0.0
05.12.86	32.6 d-f	4.0	35.5 +		120.4	68.1 +		102.3
31.12.86	15.6 a	0.5	22.8 a	1.3	125.4	38.4 a	1.8	137.1
21.01.97	18.0 ab	0.7	23.2 a	1.3	145.4	41.2 ab	1.9	154.3
11.02.87	22.2 bc	2.2	30.9 bc	3.3	276.4	53.1 c	5.1	273.1
04.03.87	34.0 ef	8.6	30.5 bc	7.6	338.4	64.5 d	15.9	323.8
26.03.87	53.5 i	5.5	30.6 bc	3.9	395.4	84.1 f	9.3	361.4
16.04.87	20.0 a-c	1.5	24.9 ab	2.3	395.9	44.9 a-c	3.5	400.5
20.05.87	23.9 c	1.2	26.0 ab	2.1	416.9	49.9 bc	3.3	417.1
11.06.87	19.7 a-c	0.5	23.8 a	0.4	416.9	43.5 a-c	0.2	423.5
01.07.87	41.6 gh	2.6	34.9 c	2.7	495.9	76.5 ef	5.2	469.5
29.07.87	37.3 fg	1.3	34.6 c	3.3	503.3	71.9 de	4.6	481.4
19.08.87	46.2 h	5.0	33.5 c	5.8	536.9	79.7 ef	10.5	507.2
02.09.87	32.0 de	2.3	33.5 c	3.4	536.9	65.5 d	4.9	521.5
23.09.87	21.3 bc	1.5	24.4 a	1.3	545.4	45.7 a-c	2.3	549.7
15.10.87	20.9 bc	1.1	24.9 ab	0.7	595.9	45.8 a-c	1.2	600.5
05.11.87	20.8 a-c	1.5	23.9 a	1.5	605.4	44.7 a-c	3.0	610.7
26.11.87	20.9 bc	1.4	24.1 a	0.7	640.4	45.0 a-c	2.1	645.4

Table 8.2 Continued

Site and Date	Soil Water (mm)	SD	Soil Water (mm)	SD	Rain Cum. (mm)	Total Soil Water (mm)	SD	ET Cum. (mm)
Airlie	0-50cm		50-100cm			0-100cm		
10.11.88	43.2 b	9.1	D		0.0	86.5 +		0.0
16.01.89	44.3 b	6.4	D		53.3	88.6 +		51.2
27.02.89	43.8 b	7.1	D		122.3	87.6 +		121.2
10.04.89	66.4 c	6.3	D		183.5	132.9 +		137.1
03.07.89	133.8 d	3.0	140.8 +		543.3	274.7 +		355.1
14.08.89	M		M		560.1	M		NC
25.09.89	20.4 a	6.8	D		560.1	40.8 +		605.8
28.11.89	73.5 c	5.5	D		694.1	146.9 +		633.7
12.02.90	34.6 b	7.2	D		698.1	69.3 +		715.3
Lisnalee	0-50cm		50-100cm			0-100cm		
13.01.89	38.1 cd	2.4	D			95.5 +		0.0
02.03.89	17.4 a	3.1	D		31.5	43.6 +		83.4
14.04.89	40.4 c-e	3.4	D		174.5	101.3 +		168.7
23.05.89	37.2 bc	3.9	D		228.5	93.2 +		230.8
06.07.89	47.9 f	3.5	64.8 b	3.0	308.5	112.8 b	6.2	291.2
17.08.89	43.2 d-f	1.1	54.5 a	4.4	331.5	97.7 a	4.5	329.3
28.09.89	41.2 c-e	4.1	70.4 b	6.6	331.5	111.6 ab	11.3	315.4
01.12.89	19.1 a	2.1	D		375.5	47.9 +		423.1
20.02.90	44.2 ef	8.4	D		483.0	110.8 +		467.7
11.05.90	48.4 f	3.5	86.2 c	6.0	816.0	134.6 c	8.9	777.7
22.11.90	31.8 b	4.3	D		966.8	79.7 +		982.6
Maxvale	0-50cm		50-100cm			0-100cm		
14.09.88	39.3 c	9.0	56.3 a	1.8	0.0	95.7 a	7.3	0.0
09.12.88	M		M		35.4	M		NC
19.01.89	10.9 a	0.7	D		84.2	28.7 +		151.2
01.03.89	9.6 a	0.5	D		90.4	25.3 +		160.8
13.04.89	26.5 b	6.4	D		140.5	69.8 +		166.4
22.05.89	85.5 e	1.9	95.5 c	6.5	333.9	181.0 d	8.3	248.5
05.07.89	56.6 d	7.0	93.2 c	3.7	410.3	149.8 c	6.9	356.2
17.08.89	29.5 b	5.2	83.6 b	7.4	426.0	113.1 b	11.0	408.6
28.09.89	30.9 b	2.2	D		429.0	81.3 +		443.4
01.12.89	14.7 a	0.5	D		483.7	38.6 +		540.8
20.02.90	16.3 a	0.6	D		593.9	42.7 +		646.9
TurnTurn	0-50cm		50-100cm			0-100cm		
20.09.88	21.8 c	1.3	D		0.0	43.6 +		0.0
07.12.88	12.0 ab	2.1	D		45.0	24.0 +		64.6
17.01.89	12.0 ab	2.5	D		46.0	24.0 +		65.6
28.02.89	10.8 ab	2.0	D		46.0	21.6 +		68.0
11.04.89	30.9 d	8.1	D		139.0	61.5 +		120.8
04.07.89	33.7 d	6.9	D		334.0	67.5 +		310.2
15.08.89	M		M		338.0	M M		NC
26.09.89	14.5 b	3.4	D		338.0	29.1 +		352.6
29.11.89	16.2 bc	4.1	17.6		343.0	33.8 +		352.8
13.02.90	6.3 a	0.9	D		358.0	12.6 +		389.0

Table 8.2 Continued

Site and Date	Soil Water (mm)	SD	Soil Water (mm)	SD	Rain Cum. (mm)	Total Soil Water (mm)	SD	ET Cum. (mm)
Wittenburra Open	0-50cm		50-100cm			0-50cm		
21.09.88	33.0 c	2.4	D		0.0	33.0 +		0.0
07.12.88	19.7 a	0.7	D		6.0	19.7 +		19.3
17.01.89	27.1 b	3.1	D		28.0	27.1 +		33.9
28.02.89	22.8 ab	3.6	D		28.0	22.8 +		38.1
11.04.89	34.4 c	3.9	D		105.0	34.4 +		103.6
04.07.89	59.4 d	2.6	D		281.0	59.4 +		254.5
15.08.89	M		M		281.0	M		NC
26.09.89	25.2 b		D		281.0	25.2 +		288.7
Wittenburra Enclosed	0-50cm		50-100cm			0-50cm		
21.09.88	36.4 c	4.4	D		0.0	36.4 +		0.0
07.12.88	20.5 a	3.2	D		6.0	20.5 +		21.8
17.01.89	21.8 a	1.3	D		28.0	21.8 +		42.6
28.02.89	18.7 a	2.3	D		28.0	18.7 +		45.7
11.04.89	34.7 c	1.9	D		105.0	34.7 +		106.7
04.07.89	59.0 d	5.4	D		281.0	59.0 +		258.5
15.08.89	M		M		281.0	M		NC
26.09.89	28.5 b	2.2	D		281.0	28.5 +		288.9
29.11.89	29.6 b	2.8	D		303.0	29.6 +		309.8
Wongalee	0-50cm		50-100cm			0-100cm		
22.09.88	34.4 b	3.4	47.7 a	4.2	0.0	82.1 a	2.5	0.0
07.12.88	M		M		31.5	M		NC
16.01.89	11.3 a	1.6	D		33.5	25.4 +		90.2
27.02.89	9.3 a	1.3	D		33.5	20.8 +		94.8
10.04.89	48.2 c	4.5	58.5 a	11.1	112.5	106.8 b	15.1	87.9
22.05.89	102.7 e	11.7	W		309.5	231.0 +		160.6
03.07.89	97.4 e	8.1	88.2 b	5.3	388.5	185.7 d	11.7	284.9
14.08.89	M		M		406.5	M		NC
25.09.89	66.4 d	5.7	85.1 b	18.0	413.0	151.5 c	15.9	343.5
28.11.89	31.3 b	4.0	48.9 a	11.8	493.0	80.2 a	15.6	494.8
12.02.90	8.2 a	0.7	D		536.5	18.4 +		600.2

Legend for Tables 8.1 and 8.2

M	Missing value
NC	Not Calculated due to missing value
D	Profile too dry to auger
W	Profile too wet to auger
SD	Based on 8 quadrats of 0.5*1.0m
*	Peak yield used to calculate water use efficiency (WUE)
WUE	Peak yield / Cumulative evapo-transpiration to peak yield
+	Insufficient samples to calculate LSD

Values followed by the same letter are not significantly different at P<0.05

Table 8.3 Percent composition of dry matter yield by weight at the Biddenham (mitchell grass) and Charleville (mulga pastures) native pasture primary productivity sites from October 1986 to November 1987.

Site and Date	Green Leaf %	Dead Leaf %	Green Stem %	Dead Stem %	Seed Head %	Forbs %
Biddenham						
21.11.86						
17.12.86	82.5	0.8	13.5	2.6	0.0	0.7
07.01.87	55	4.1	23.2	0.0	0.8	16.9
26.02.87	M					
18.03.87	16.0	24.7	39.5	6.3	11.4	2.1
08.04.87	10.8	20.9	30.1	24.2	5.1	9.1
29.04.87	4.6	38.9	31.6	19.6	4.9	0.4
21.05.87	6.4	39.4	32.1	13.2	4.4	4.5
12.06.87	1.7	39.7	30.5	19.8	6.8	1.5
24.06.87	1.6	41.3	42.3	11.5	2.6	0.8
16.07.87	2.9	43.2	38.9	10.2	0.3	4.6
11.08.87	3.9	40.7	48.6	3.9	2.2	0.8
26.08.87	1.5	32.6	52.2	8.4	2.3	3.0
18.09.87	2.5	34.7	45.9	8.8	2.2	5.9
08.10.87	5.4	37.8	40.8	14.1	1.0	0.9
29.10.87	11.9	38.5	33.2	12.9	1.9	1.6
25.11.87						
10.12.87						
Charleville						
24.10.86						
05.12.86	63.8	9.7	15.6	10.5	0.5	0.0
31.12.86	48.5	27.8	13.0	6.7	2.0	2.0
21.01.97	30.9	35.6	22.0	7.3	4.1	0.0
11.02.87	37.3	9.8	31.1	14.8	7.1	0.0
04.03.87	9.0	14.0	40.1	3.0	4.6	28.4
26.03.87	17.5	32.6	28.2	14.0	6.2	1.6
16.04.87	32.1	30.4	21.5	6.8	6.0	3.2
20.05.87	15.3	40.6	16.7	17.1	5.6	4.5
11.06.87	13.2	37.9	28.1	14.6	3.2	3.1
01.07.87	17.9	33.8	21.6	13.8	4.7	8.2
29.07.87	17.3	36.5	20.0	18.7	2.3	5.4
19.08.87	23.0	33.0	20.2	22.1	1.6	0.0
02.09.87	31.4	34.5	8.5	20.6	5.0	0.0
23.09.87	23.2	25.5	13.1	27.5	8.5	2.3
15.10.87	17.6	36.1	12.8	20.8	12.2	0.4
05.11.87						
26.11.87						

M = Missing data

Table 8.4 Ground cover at the Biddenham (mitchell grass) and Charleville (mulga pastures) native pasture primary productivity sites from October 1986 to November 1987.

Site and Date	Green Cover %	Dead Cover %	Litter Cover %	Bare Ground %
Biddenham				
21.11.86				
17.12.86	13.1	0.4	18.1	66.9
07.01.87	16.5	0.7	19.3	63.4
26.02.87	44.9	3.4	9.5	42.9
18.03.87	16.8	21.5	16.0	45.2
08.04.87	6.8	30.3	20.4	42.4
29.04.87	4.1	34.5	19.6	41.8
21.05.87	2.9	34.3	26.2	36.7
12.06.87	0.6	31.0	30.3	37.9
24.06.87	2.0	37.3	20.6	39.9
16.07.87	1.2	44.3	19.8	34.6
11.08.87	3.9	47.2	20.7	28.3
26.08.87	7.9	36.7	26.8	28.7
18.09.87	5.5	38.2	27.5	28.8
08.10.87	5.3	34.2	25.3	36
29.10.87	7.0	32.2	29.6	31.1
25.11.87				
10.12.87				
Charleville				
24.10.86				
05.12.86	16.7	1.3	20.9	60.3
31.12.86	9.1	4.3	15.6	71.2
21.01.97	8.9	6.2	15.8	69.1
11.02.87	19.6	0.7	6.8	72.8
04.03.87	29.3	0.9	8.9	60.8
26.03.87	17.1	7.5	12.0	63.2
16.04.87	18.4	11.6	13.1	57.9
20.05.87	6.6	21.3	16.8	55.0
11.06.87	0.0	29.3	18.2	52.5
01.07.87	10.4	20.1	14.5	54.7
29.07.87	11.3	27.3	14.8	46.5
19.08.87	12.5	20.0	12.6	54.7
02.09.87	16.3	19.3	19.3	44.7
23.09.87	16.6	14.5	24.8	41.9
15.10.87	8.9	17.8	18.9	54.1
05.11.87				
26.11.87				

Appendix 4. Average proportion of soil moisture in top half of the profile (where complete profiles were available) for nine native pasture primary productivity sites in south-west Queensland.

Site	Proportion in Top Half of Profile (%)	SD
Biddenham	49	4.69
Charleville	49	5.73
Airlie	47	2.63
Lisnalee	40	4.07
Maxvale	38	8.90
Turn Turn	48	NC*
Wittenburra Open	NC	
Wittenburra Enclosed	NC	
Wongalee	44	4.63
Average	45	

NC*=Not Calculated

The equation to estimate the total soil moisture in the profile to allow the calculation of evapo-transpiration for all sampling times was as follows.

Total Moisture in Profile (mm) = (100*Amount in Top (mm)) / (Proportion in Top (%))

Appendix 5. Structure and operation of the GRASP model.

Main program

- Organise input/output and control the logical flow.
- Call for daily climate data and soil, plant and animal parameters to calculate daily soil water balance and plant growth.
- Call for simulation of annual crop growth if required.
- Call for management information at the appropriate time.
- Repeat operations daily for desired period and printout results at time intervals specified by the user.
- Call for probability analysis if sufficient data.

Subroutines (in the order in which they occur in the main program listing)

- AINPUT - Used for entering text while in the interactive mode of operation.
- DEFAUL - Writes values from the parameter file to a file and to the screen.
- IINPUT - Used for entering integer values, checking that they fall within a specified (sensible) range. Default values are supplied.
- INTERA - Used for changing parameter values in the interactive mode of operation.
- ERRCHK - A check on selected parameter values as with IINPUT.
- METONE - Locates appropriate climatic data within the computer system.
- METSTA - Interactive location of specific climatic data.
- TREERT - Calculates tree root distribution for subsequent tree water use.
- METIN - Reads climatic data into the model.
- SOIL - Calculates soil moisture variables, for example, soil evaporation, plant transpiration, tree water use, water supply index, runoff, drainage, adjusted soil water and totals using climatic data and calculated biomass.
- TEMPER - Calculates a temperature index for the selected pasture community.
- GROWPL - Calculates all pasture components, for example, growth limited by moisture, temperature and cover, regrowth, death and detachment rates, litter disappearance rates, consumption by animals, trampling losses and totals.
- BASALA - Calculates a dynamic basal area using summer rainfall.
- BURN7 - Resets various pasture components following fire.
- CROPEM - Simulates management of an annual crop through fallow, planting and harvest, with feedbacks to GROWPL.
- MANAGE - Causes management changes within the model on specified days, covering stocking rate, starting liveweight, pasture harvest, burning, irrigation, runoff, resetting soil moisture and nitrogen

uptake. Observed values from experiments (Chapter 3) are entered here and compared with predictions made by the model.

- RESETSM- Resets soil moisture each year.
- PDISTX - Calculates probability distribution of climatic, soil water balance and growth components in annual totals if more than ten years are modeled, and calls subroutine PDIST to obtain deciles.
- RUNOF2 - Calculates runoff as a function of pasture cover and soil moisture.
- NUPTAK - Calculates nitrogen uptake.
- ANIMAL - Calculates daily liveweight gain of beef cattle taking into account the size of the animal, restriction on intake when pasture yield is low and season. Sheep are converted to beef equivalents.
- NTSDM - Calculates nitrogen content of dry matter accounting for uptake and losses via detachment and nutrient dilution as pastures age.
- GDLW - Calculates liveweight gain from number of green days (McCown 1980).
- NLWG - Calculates liveweight gain from dietary N (Siebert and Hunter 1977).
- PDIST - Calculates deciles of the cumulative probability distribution for each observation and returns them to PDISTX.

Operating the GRASP model

There are two modes of operating the GRASP model, interactive and batch. Interactive operation enables one treatment of one experiment to be analysed many times while varying parameters between runs. This mode is used while calibrating the model to a particular data set. Batch operation enables a number of runs to be performed in the one operation. This mode is used for simulation studies once calibration is completed.

Both modes use three main file groups (input files, main program and subroutines and output files).

A number of files are used as input to GRASP. The most important are the parameter and management record files. Values in these files are used to calibrate the model to individual data sets. Parameters define physical and biological processes (derived from Chapter 3) and others are used as switches to select alternatives. Together they cover soil water storage characteristics, soil evaporation, runoff, plant cover, plant temperature index, plant growth, plant senescence and litter breakdown, nitrogen uptake, grazing, simulation control, climate stations and experimental observations.

The main program and subroutines, described above, manage the flow of data and equations describing the biological processes within the model. Parameter values from the input files are used as coefficients in these equations. In this way the main program and subroutines are independent of the parameters describing individual sites, and do not require modification for each new data set.

A number of output files are produced by the model. These are used for examining results during either calibration or simulation studies.

Appendix 6. Default parameter file used as input to the GRASP forage production model

		PARAMETER values for Gunsynd from ron gun	
		First number = parameter code number	1
		Second number = parameter value	2
		SOIL PARAMETERS	4
20	100.000	Thickness (mm) of soil layer 1 (surface 100mm approx)	6
		which can be air dried. Nemonic = SW(8,1).	7
21	400.000	Thickness (mm) of soil layer 2. This layer cannot dry	8
		below permanent wilting point, and is the main	9
		zone of root activity. Nemonic = SW(8,2).	10
22	500.000	Thickness (mm) of soil layer 3. The lower limit of this	11
		layer is the limit of root penetration (=SW(8,3)).	12
26	36.000	SW(2,1) Layer 1 maximum soil moisture (mm).	15
27	174.000	SW(2,2) Layer 2 maximum soil moisture (mm).	16
28	105.000	SW(2,3) Layer 3 maximum soil moisture (mm).	17
19	10.000	AIRDRY Layer 1 air dry soil moisture content (mm).	19
29	15.000	SW(3,1) Layer 1 wilting point soil moisture (mm).	20
30	70.000	SW(3,2) Layer 2 minimum soil moisture (mm).	21
31	65.000	SW(3,3) Layer 3 minimum soil moisture (mm).	22
		SOIL EVAPORATION	24
33	4.000	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		STARTING SOIL MOISTURE also used when p289 is a date	28
23	15.000	SW(9,1) Starting value for soil moisture layer 1 (mm).	29
24	108.000	SW(9,2) Starting value for soil moisture layer 2 (mm).	30
25	71.000	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
		RUNOFF	33
270	0.000	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.000	tsdm yield at 50% cover for run-off calculation	36
272	0.950	k value in cover=y**k / (y**k + p271**k)	37
273	1.000	maximum runoff of rainfall at zero cover, wet soil	38
		I15 Brian P= 1.016+0.465*cos,	39
		I15 Charters = 0.9+0.7*cos	40
		I15 Capella = 0.867+0.582*cos	41
104	1.016	constant in I15 equation I15=p104+p105*cos(dayno+15)	42
105	0.465	slope in I15 equation I15=p104+p105*cos(dayno+15)	43
		OBSERVED SOIL MOISTURE	44
282	0.000	if=1.0 reset to observed soil moisture in management file	45
		ROOT DISTRIBUTION	
106	0.500	relative supply of layer 3 cf layers 1,2. Usually 0.5	
		PLANT COVER	47
210	2.000	Selector for cover function; 1=f(time) P(38...43) ,2=f(yields).	49
38	0.625	SCOV mean) SCOV = P38 +P39*cos(0.01720*(idayno+P40))	50
39	0.325	SCOV amplitude) = total surface cover calculated as a	51
40	-30.000	SCOV lag) function of time.(-30 : max cover=Jan30	52
41	0.425	GCOV mean) GCOV = P41 +P42*cos(0.01720*(idayno+P43))	54
42	0.325	GCOV amplitude) = green surface cover calculated as a	55
43	-30.000	GCOV lag) function of time.(-30 : max cover=Jan30	56
45	1600.000	green yield (kg/ha) when green cover for transpiration is 50%	58
107	1.000	A value to transform green cover to POT TRANS/PAN	
		PLANT TEMPERATURE INDEX selection parameters.	60
209	4.000	TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0	62
		6=maize, 7=combined NP, 8=NP f(max,min)	63
61	14.000	If temp is less than P61, temperature index (TIX) is zero.	64
62	24.000	As temp increases from P61 to P62, TIX increases from 0 to 1.	65
63	45.000	As temp increases from P62 to P63, TIX remains at 1.	66

64	50.000	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	67
		PLANT SOLAR RADIATION INDEX & INTERCEPTION	69
46	1600.000	green yield (kg/ha) when radiation interception is 50%	70
8	12.000	Radiation use efficiency kg/ha per MJ/sqm of solar radiation	71
		PLANT GROWTH	73
5	6.800	Initial plant density e.g. % basal area	74
6	0.000	Potential daily regrowth rate (kg/ha/day/unit of density)	75
		This is with water, temperature and light non-limiting,	76
		(growth index = 1), and represents the potential rate at	77
		which a pasture will regrow in the first few weeks after	78
		burning or cutting. Density unit is same as P5	79
7	15.000	Transpiration efficiency (kg/ha/mm of transpired at vpd 20hPa	81
		Daily growth =p(7)*vpdix*daily transpiration	82
		vpd is vapour pressure deficit input from met data with .v51	83
		vpdix=10/(vpd*f(height))	85
		te=p(7)*vpdix	87
94	1.500	Multiplier of VPD for zero height	88
95	20.000	Height at which VPD multiplier = 1.0	89
96	10.000	Height (cm) of 1000 kg/ha	90
		height=p(96)*(tsdm/1000.0)	91
		vpdhgt=amax1(1.0,amin1(p(94),	92
		$ 1.0+(height-p(95))*(p(94)-1.0)/(0.0-p(95))))	93
		if(vpd.gt.10.0)vpdix=amax1(0.0,amin1(1.0,10.0/(vpd*vpdhgt)))	94
		SOIL MOISTURE SUPPLY EFFECT ON PLANT GROWTH	96
274	0.000	if=1 use denmead and shaw for limiting soil moisture index	97
275	13.000	layer 1 p275*awr1**2 mm/day	98
276	13.000	layer 2 p276*awr2**2 mm/day	99
277	3.600	layer 3 p277*awr3**2 mm/day	100
149	0.400	Soil water index at which above-ground growth stops.	102
		PLANT SENESCENCE AND LITTER BREAKDOWN	104
9	0.100	Soil water index. Maximum green cover = amin1(0.99,swix/p(9))	106
11	2.000	Minimum screen temperature (c) at which green cover = 0%	107
10	0.002	death constant) DEATH = (P51*(1-swix) + P10) * green pool	108
51	0.013	death slope) where swix = soil water index	109
13	0.002	Prop of standing dry matter detached per day. DETAC = P13* SDM2	111
258	401.000	Detachment of old pool begins month,day	112
15	0.500	Proportion of pasture which can be eaten by stock. The rest is	113
		lost by trampling. DEIN2 = TINT/P15 - TINT	114
		P16 and P18 are constants for litter breakdown	116
		BREAK = (SW(6,1) * temp/25 * P16 + P18 * stockrate)*litter pool	117
		Thus, breakdown is rapid when soil water in layer 1 is high,	118
		when temperature is high, and the pasture is grazed.	119
16	0.040	rate of litter breakdown when hot and wet	121
18	0.000	Coefficient of stocking rate on litter breakdown	122
		GRAZING	124
		P142, P143 & P144 define an intake restriction index from the	126
		proportion of pasture eaten (PCON) and total standing DM.	127
		RESTR = max(0.0, min(P142 + P143 * PCON, TSDM/P144, 1.0)	128
		When RESTR = 0, intake is fully restricted, and	129
		when RESTR = 1, intake is not restricted	130
		McCaskill's model	
117	0.000	Output for animal model to lw21.ogp 0=no output	
118	18.000	Default animal age (months) when LW's are reset	
119	1.000	No. of experimental treatment for liveweight gain	
120	1.000	Animal model; 0 or 1 for utilization model, 2 for GRASP green	
		days, 3 for WATBAL green days, 4 for old diet N method,	
		5 for new diet N method	
121	0.493	Animal growth rate for green days (native 0.493, imp 0.613)	

122	-0.163	Animal growth rate for non-green days (native -0.163, imp -0.043	
142	1.050	Intercept in equation of reln between intake and utilisation	132
143	-0.500	Slope in equation of reln between intake and utilisation	133
144	230.000	Yield (kg/ha) at which intake restriction no longer operates	134
145	70.000	Expected live weight gain (kg/hd) in summer at low stocking rate	136
146	35.000	Expected live weight gain (kg/hd) in autumn at low stocking rate	137
147	10.000	Expected live weight gain (kg/hd) in winter at low stocking rate	138
148	35.000	Expected live weight gain (kg/hd) in spring at low stocking rate	139
		These values are used only to adjust intake.	140
150	0.000	Initial stocking rate (weaners/ha, live weight = 200 kg)	142
		SIMULATION CONTROL	145
261	1.000	batch operation=0 ;interactive=1	147
203	1900.000	Starting year of simulation; 1800 to begin at start of metfile.	148
204	7.000	Starting month of simulation	149
206	0.000	Number of days in simuln run,last date : 1st Mar 1986=198603	150
		if=0 150 years	151
		CLIMATE STATIONS	153
263	39039.000	Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)	155
264	42.000	No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures	156
250	6.000	if=1 full daily met data, if=3 weekly austclm	157
		4=daily rain in dr2 format, with either AUSTCLIM or station p269	158
		6=daily rain + daily climate, no in p269 type 1	159
269	8.000	monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM	160
		OUTPUT CONTROL	162
		mndy=monthday eg 0315 is 15th March	164
		P247 - Output of totals : 365=yearly,91=seasonally,30=monthly,	165
		7=weekly,1=daily,999=each observation. If P247=mndy and	166
		182 Nov-Apr, 183 Dec-May, 988 for each management date	100
		P249 = 0 then probabilities will be printed.	167
		p247=9901 for totals between srate change	
		for totals between obs,code 15 must be first rec on date	
		P248 - Output of model : 365=yearly,91=seasonally,30=monthly,	168
		7=weekly,1=daily,999=each observation, 988=soil moisture	169
		P249 - if = 1,totals are summed; if = 0 and P247 = mndy then	170
		probabilities will be printed	171
		P262 - Output to screen : 365=yearly,91=seasonally,30=monthly,	172
		7=weekly,1=daily,999=each observation,988=soil moisture	173
		11=growth model, 12= total days for each growth limit	174
		988=soilmoisture, 977=runoff, 976=water balance on p247	175
246	132.000	Output type: 80=80 column output, 132= 132 output 0=132 col	177
247	999.000	Output of totals:365 - 999=yr - obs.If=mndy & P249=0,print prob	178
		999 for pasture observations, 988 for soil moisture	179
		For probabilities p247=date e.g 930 is 30th September	180
248	0.000	Output of model:365=yr,91=seas,30=mthly,7=wkly,1=daily,999=obs	181
		999 for pasture observations, 988 for soil moisture	182
249	1.000	if=1,totals are summed;if=0 and P247=mndy then probs are printed	183
262	999.000	Output to screen:365=yr,91=seas,30=mthly,7=wkly,1=daily,999=obs	184
		999 for soil moisture & pasture observations,	185
		998 for detailed pasture observations, green, dead, litter	186
		988 for soil moisture	187
		978 for nitrogen change in TSDM	
		977 for runoff output to screen	188
		976 for water balance in long term simulations & tree water use	189
		975 for tree water use	190
		974 for nitrogen uptake	191
		973 for output of both water balance & nitrogen uptake on p247	192
		972 for surface conditions and litter breakdown	

		971 for simulation output for GRASSMAN	
		284 for TE & RUE growth analysis	193
		286 for rainfall use efficiency on screen	194
		11 for growth model debugging	195
		12 for growth model debugging	196
259	1.000	Output to screen: 1= stop screen scrolling	197
283	1.000	if=1 ET output to file soilwa18.ogp, p246 must be 132	199
284	2.000	if=1 TE output to file pasture9.ogp, p246 must be 132	200
		if=2 RFUE,ETUE,TUE	
		if=3 Comparison of N models	
		if=970 for daily output used in estab4	
211	0.000	if=1-365 gives output of observed & predicted , and	
		simulated : 365=yearly,91=seasonally,30=monthly,	
		7=weekly,1=daily,999=each observation,mndy=monthday	
		output in mongro15.ogp or m1	
285	0.000	if=1 monthly growth output to file mongro15.ogp, p211 must be 0	201
		if=2 monthly growth in rainman output	
286	0.000	if=1 rainfall use efficiency to rainue17.ogp, p246 must be 132	202
287	0.000	if=1 runoff output to pastur19.ogp, only days with rain GE p287	203
		p270 must be 1 for output, p246 must be 132	204
		soil water deficit, cover, I15, rain, run-off are output	205
		ANNUAL CROP MANAGEMENT	207
		To be used only in simulation studies of annual forage	209
		P151, P152 & P153 control 3 decision rules for planting a crop.	210
		Crop can be planted if the avail water ratio in the whole	211
		profile > P151, in layer 1 > P152	212
251	0.000	if=1 call crop emergence subroutine and use options P252to 260.	214
151	0.500	Min available water ratio in total profile required for planting	215
152	0.900	Min available water ratio in layer one required for planting	216
153	0.300	Max awr in layer one so it's dry enough to plant	217
252	901.000	First date for planting; month day 0901 = 1st Sept.	218
253	1231.000	Last date for planting; month day 1231 = 31st Dec.	219
254	25.000	Yield at emergence (kg/ha)	220
255	10.000	Number of days from planting to emergence	221
256	90.000	Number of days from emergence to end of crop growth	222
260	70.000	Number of days from emergence to end of green growth	223
257	401.000	End of crop on month, day due to temperature	224
		PASTURE BURNING MANAGEMENT	226
265	0.000	if=1 call pasture burning subroutine and use options 266-7	228
266	1001.000	First date of burning; month day 1001 = 1st Oct	229
267	0.000	Threshold yield required for burn; total standing DM kg/ha	230
268	0.000	if=1 call dynamic basal area subroutine	231
288	5.000	Water (ET) use efficiency for basal area change	232
		barea=(growly+ETsu*p(288))/1000.0	233
290	0.000	Date for resetting soil moisture to p23..25, 930 is 30th Sept	235
		TREE WATER USE	237
291	0.000	MATURE TREE BASAL AREA	
292	0.000	Layer 1 minimum soil moisture (mm) with trees	239
293	0.000	Layer 2 minimum soil moisture (mm) with trees.	240
294	0.000	Layer 3 minimum soil moisture (mm) with trees.	241
295	100.000	Layer 4 available water (trees only)	242
296	300.000	Maximum rooting depth of trees in cm	243
297	1.440	Tree Root length at surface, rl= p297*exp(-p298*z)	
298	0.610	Tree Root length exponent, rl= p297*exp(-p298*z)	
299	100.000	asw4 Starting value for soil moisture layer 4 (mm), trees only	
		NITROGEN UPTAKE	245
97	5.000	N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100	246
98	5.800	N uptake per 100 mm of transpiration	247

99	23.000	Maximum N uptake (kg/ha)	248
100	2.500	Maximum % N in growth	249
101	0.400	% N at zero growth Nitrogen index = (%N-p101)/(p102-p101)	250
102	0.500	% N at maximum growth Nitrogen index = (%N-p101)/(p102-p101)	251
103	1.000	N uptake per 100 mm of soil water	247
108	0.000	Proportional decline per day in % N for green material	
109	0.015	Proportional decline per day in % N for dead material	
110	1.000	Minimum % N in green & maximum in dead	249
111	0.400	Minimum % N in dead	
112	915.000	Date for resetting Nitrogen uptake	
300	0.000	Indicates end of parameter file	253

Appendix 7. Diaries describing steps taken to calibrate the GRASP model to individual sites.

Biddenham

1. Soil moisture, soil depth, dry matter yield, green cover and nitrogen concentration, perennial grass basal area and tree basal area data were entered in a parameter file specific for Biddenham (bidd2.mrx). Where data was missing or unavailable the entry was left blank. In most cases this was confined to soil moisture data for the third layer in the profile, due to difficulty in auguring dry soil.

2. Daily rainfall for the site was entered in a file suitable as input to GRASP (bidd.dr2). Temperature, evaporation, solar radiation and vapor pressure deficit data for Charleville was used (chlv8690.v51). The site was 80km north of Charleville.

3. The temperature response appropriate for the C4 Mitchell grass community was selected in this parameter file.

4. The best estimates of the wettest and driest soil moisture profiles (from Chapter 3) were entered in the parameter file for each layer (0-10cm, 10-50cm and 50-85cm).

5. Estimates of potential growth rate, transpiration efficiency, soil moisture effect on green cover and rate of nitrogen uptake per mm of transpiration (from data presented in Chapter 3) were entered in the parameter file.

6. The model was run, and calibrated using the above two parameters to check that modelled dry matter yields approximated observed dry matter yields.

7. Steps 4-6 were repeated to manually calibrate growth and soil moisture parameters. The model was again run to check the differences between observed and modeled wettest and driest soil moisture profiles. A regression analysis comparing modeled and observed soil moisture for the total profile calculated a RMS of 13. Using output from the model the parameters describing the wettest and driest profiles were modified, given the dates of measurement were not necessarily wilting point and field capacity. The new values for each layer were estimated as follows;

Wilting point = modeled lowest - 1.0

Field capacity = modeled highest + 1.0

8. The simulation results allowed an interpretation of the observed soil moisture. Model results indicated there was little variation in the moisture content in the third layer between the 26.02.87 and 29.10.87. Statistical analysis of the fluctuations in moisture in this layer, indicated no significant changes between observations over this period (Appendix 3, Table 9.2). The average modeled moisture content for the third layer over this period was 81.1 mm. This value was entered in the parameter file where data were unavailable for the third layer due to the difficulty in auguring dry soil to allow calculation of accumulative evapo-transpiration.

9. The model was run again using 81.1 mm as the start up value for layer three.

10. Despite an RMS of 13, on several dates modeled soil moistures varied from those observed.

On 07.01.87 a dry profile was observed in contrast to a wet profile being predicted by the model. A check on the rainfall data indicates rain fell the day before the observation. The Biddenham site is located some 3km from the house and it is likely that the rain measured on 06.01.87 fell some days earlier, therefore allowing the profile to dry down. Thus, the difference between simulated and observed is likely to be due to possible error in the recording date for rain.

On 10.12.87 the observed soil moisture for the second layer was drier (by 23mm) than that predicted by the model. However, the moisture observed on this date for the 0-50cm layer was not significantly different to that observed on 08.04.87, and hence is considered a realistic value. As these are both the significantly driest profiles at this depth, large cracks forming in these soils, and the resulting circulation of air could dry these soils to these levels. The model does not simulate drying of the 10-50cm zone below wilting point and hence in the absence of green cover at this date, simulated ET (mainly soil evaporation) is too low.

Cracks may also explain the significant increase in soil moisture for the third layer on 17.12.86. The previous observation (21.11.86) indicated a dry profile. Rainfall of 60mm between these periods may have fallen as several storms and water flow down cracks may explain the significant increase in soil moisture.

Thus, application of the model to cracking clays will require modification of soil evaporation functions and also allow infiltration to lower soil layers (for example Clewett 1986).

11. With the model calibrated with soil moisture data, attention was directed towards plant growth. Chapter 3 describes the significant changes in yield and green cover. Model results are compared to observed data. In general, predicted yields reflected observed values. However, the model did not reflect significant decline in yields occurring after the fourth and eleventh observations.

<u>Parameter file for Biddenham</u> (BIDD2.MRX)

```
PARAMETER values for Biddenham Mitchell grass Charleville 1986/7
                layer 3 missing values 81.0 replaced with 81.0
  26     42.0   SW(2,1) Layer 1 maximum soil moisture (mm).                        15
  27    113.0   SW(2,2) Layer 2 maximum soil moisture (mm).                        16
  28    107.0   SW(2,3) Layer 3 maximum soil moisture (mm).                        17
  19     12.0   AIRDRY  Layer 1 air dry soil moisture content (mm).                19
  29     14.0   SW(3,1) Layer 1 wilting point soil moisture (mm).                  20
  30     64.0   SW(3,2) Layer 2 minimum soil moisture (mm).                        21
  31     81.1   SW(3,3) Layer 3 minimum soil moisture (mm).                        22
                STARTING SOIL MOISTURE also used when p289 is a date               28
  23     15.0   SW(9,1) Starting value for soil moisture layer 1 (mm).             29
  24     80.0   SW(9,2) Starting value for soil moisture layer 2 (mm).             30
  25    118.0   SW(9,3) Starting value for soil moisture layer 3 (mm).             31
  33      2.0   EPLIM  Upper limit to daily soil evaporation (mm/day)              26
                RUNOFF                                                             33
 270      1.0   0 for free draining soils, 1for runoff as a f(yield)               35
 271   1150.0   yield at 50% cover for run-off calculation                         36
 272      1.0   k value in cover=y**k / (y**k + p271**k)                           37
 273      1.0   maximum  runoff of rainfall  at zero cover, wet soil               38
                I15 Brian P=  1.016+0.465*cos,
                I15 Charters =  0.9+0.7*cos
                I15 Capella = 0.867+0.582*cos
 104      1.0   constant in I15 equation I15=p104+p105*cos(dayno+15)               43
 105      0.5   slope    in I15 equation I15=p104+p105*cos(dayno+15)               43
                ROOT DISTRIBUTION
 106      0.5   relative supply of layer 3 cf layers 1,2. Usually 0.5
  45   1200.0   green yield (kg/ha) when green cover for transpiration is 50%      58
  46   1400.0   green yield (kg/ha) when  radiation interception is 50%            70
```

```
209      4.0  TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0          62
              6=maize, 7=combined NP, 8=NP f(max,min)                          63
 61     14.0  If temp is less than P61, temperature index (TIX) is zero.       64
 62     24.0  As temp increases from P61 to P62, TIX increases from 0 to 1.    65
 63     35.0  As temp increases from P62 to P63, TIX remains at 1.             66
 64     45.0  As temp increases from P63 to P64, TIX decreases from 1 to 0.0   67
  5      4.0  Initial plant density e.g. % basal area                          74
  6      2.0  Potential daily regrowth rate (kg/ha/day/unit of density)        75
  7     21.0  Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb    81
  9      1.0  Soil water index. Maximum green cover = amin1(0.99,swix/p(9))   106
 11     -4.0  Minimum screen temperature (c) at which green cover = 0%        107
 13      0.0  Prop of standing dry matter detached per day. DETAC = P13* SDM2 111
258    801.0  Detachment of old pool begins month,day                         112
 96     20.0  Height (cm) of 1000 kg/ha                                        90
 97      2.0  N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100 246
 99     21.0  Maximum N uptake (kg/ha)                                        248
101      0.5  % N at zero growth  Nitrogen index = (%N-p101)/(p102-p101)      250
102      0.6  % N at maximum growth  Nitrogen index = (%N-p101)/(p102-p101)   251
100      2.5  Maximum % N in growth                                           249
108      0.0  Proportional decline per day in % N for green material
109      0.0  Proportional decline per day in % N for dead material
110      1.0  Minimum % N in green & maximum in dead NOT USED in gvt72
111      0.6  Minimum % N in  dead
263  44021.0  Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)  155
264     13.0  No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures  156
250      6.0  if=1 full daily met data, if=3  weekly austclm                   157
              4=daily rain in dr2 format, with either AUSTCLIM or station p269 158
              6=daily rain + daily climate, no in p269 type 1                  159
269     10.0  monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM        160
206    730.0  Number of days in simuln run,last date : 1st Mar 1986=198603     150
211      7.0  if=1-365 gives output of observed & predicted , and
              simulated : 365=yearly,91=seasonally,30=monthly,
              7=weekly,1=daily,999=each observation,mndy=monthday
              output in mongro15.ogp or m1
262    999.0  Output to screen:365=yr,91=seas,30=mthly,7=wkly,1=daily,999=obs  184
 98     12.0  N uptake per 100 mm of transpiration                             247
284      0.0  if=1 TE output to file pasture9.ogp, p246 must be 132            200
300      0.0  Indicates end of parameter file                                  253
```

```
Biddgun  19861121 2 reset yld      0.0    50.0     0.0   0.60  0.00
Biddgun  1986112114reset soil     19.9    81.7    81.1   0.00  0.00  extrapolated
Biddgun  1986112116observatio     19.9    81.7    73.6   0.10  0.00
Biddgun  1986121719reset soil     19.5   100.5    95.8  13.10  0.00
Biddgun  1986121715observatio     19.5   215.7    85.6  13.10  2.57
Biddgun  19861217 2 reset yld     86.0     0.0     0.0   2.57  0.00
Biddgun  1986121715observatio     19.5   215.7    85.6  13.10  2.57
Biddgun  1986121716observatio     19.5   100.5    95.8  13.10  0.00
Biddgun  1987010715observatio     19.4   194.9   187.0  16.50  2.12
Biddgun  1987010719 reset yld    187.0     0.0     0.0   2.12  0.00
Biddgun  1987010716observatio     19.4    89.1    86.4  16.50  0.00
Biddgun  1987022615observatio     28.4   196.6  1144.0  44.90  1.23
Biddgun  1987022616observatio     28.4    90.1    78.0  44.90  0.00
Biddgun  1987031815observatio     15.1   179.5  1633.0  16.80  0.82
Biddgun  1987031816observatio     15.1    82.8    81.7  16.80  0.00
Biddgun  1987040815observatio     13.4   167.3   949.8   6.80  0.66
Biddgun  1987040816observatio     13.4    72.8    81.1   6.80  0.00
Biddgun  1987042915observatio     21.5   184.2  1237.6   4.10  0.00
```

Biddgun	1987042916observatio	21.5	82.7	80.0	4.10	0.00	
Biddgun	1987052115observatio	17.3	183.6	1129.4	2.90	0.59	
Biddgun	1987052116observatio	17.3	82.2	84.0	2.90	0.00	
Biddgun	1987061215observatio	14.4	178.0	1040.5	0.60	0.64	
Biddgun	1987061216observatio	14.4	79.7	83.9	0.60	0.00	
Biddgun	1987062415observatio	40.9	229.7	1288.6	2.00	0.74	
Biddgun	1987062416observatio	40.9	108.9	79.8	2.00	0.00	
Biddgun	1987071615observatio	23.7	181.5	1463.2	1.20	0.64	
Biddgun	1987071616observatio	23.7	84.8	73.1	1.20	0.00	
Biddgun	1987081115observatio	28.8	201.6	1678.2	3.90	0.64	
Biddgun	1987081116observatio	28.8	91.5	81.3	3.90	0.00	
Biddgun	1987082615observatio	28.4	209.1	1177.3	7.90	0.63	
Biddgun	1987082616observatio	28.4	99.6	81.1	7.90	0.00	
Biddgun	1987091815observatio	17.4	184.8	1126.7	5.50	0.65	
Biddgun	1987091816observatio	17.4	86.3	81.1	5.50	0.00	
Biddgun	1987100815observatio	35.9	215.9	1092.6	5.30	0.63	
Biddgun	1987100816observatio	35.9	95.4	84.6	5.30	0.00	
Biddgun	1987102915observatio	19.3	188.5	1405.4	7.00	0.65	
Biddgun	1987102916observatio	19.3	86.5	82.7	7.00	0.00	
Biddgun	1987112516observatio	30.2	112.8	83.0	0.00	0.00	
Biddgun	1987121016observatio	16.0	64.0	81.1	0.00	0.00	layer 3=118
ppm30	1988080215obs	0.0	0.0	0.0	0.00	0.00	ppm=30
file end	99990000 for GRASP						

Charleville site

1. Soil moisture, soil depth, dry matter yield, green cover and nitrogen concentration, perennial grass basal area and tree basal area data were entered in a parameter file specific for the Charleville site (mulga.mrx). Where data was missing or unavailable the entry was left blank.

2. Daily climate from the Charleville Bureau of Meteorology (1km away) was entered in a file suitable as input to GRASP (chlv8690.v51). This data included daily rainfall, maximum and minimum temperature, 9am wet and dry bulb temperature, pan evaporation, and vapor pressure deficits. Daily solar radiation was estimated using the TAMSIM program.

3. The temperature response appropriate for the predominantly C3 mulga grass community was selected in this parameter file.

4. The best estimates of the wettest and driest soil moisture profiles (from Chapter 3) were entered in the parameter file for each layer (0-10cm, 10-50cm and 50-100cm). Due to the proximity of *Acacia aneura* trees, a mature tree basal area was estimated at 0.5 m^2/ha. The default distribution of roots in the profile was chosen

5. Estimates of potential growth rate, transpiration efficiency, soil moisture effect on green cover and rate of nitrogen uptake per mm of transpiration (from Chapter 3) were entered in the parameter file.

6. The model was run, and calibrated using the potential regrowth rate and transpiration efficiency to check that modelled dry matter yields approximated observed dry matter yields.

7. Steps 4-6 were repeated to manually calibrate growth and soil moisture parameters. The model was again run to check the differences between observed and modeled wettest and driest soil moisture profiles. Calculating runoff as a function of yield improved the simulation of soil moistures. A regression analysis indicated a good comparison between modeled and observed soil moisture for the total profile (RMS 5).

8. Simulation results allowed an interpretation of the observed soil moisture. While cover levels were low (first three months following initial mowing) the model underestimated water use from the 10-50cm layer of the profile. As layer 1 and layer 3 varied little from the observed it was postulated that neighbouring trees may be using water from layer 2. The effect of a different root distribution based on the shallow rooting nature of *Acacia aneura* was investigated (0-10cm 19.1%, 10-50cm 47.4%, 50-100cm 24.5% and 100-150cm 9%). A simulation study using a high tree basal area (5 m^2/ha) and low grass basal area (1%) indicated little impact of tree root distribution on dry matter production. (Simulated dry matter yields were 250 kg/ha under the modified root distribution and 265 kg/ha under the default root distribution).

High soil evaporation rates during periods of low cover offer an alternative explanation for the low moisture contents of the 10-50cm zone.

9. With the model calibrated with soil moisture data, attention was directed towards plant growth. Chapter 3 describes the significant changes in yield and green cover. Model results are compared to observed data. In general, predicted yields reflected observed values.

Parameter file for Charleville site (MULGA.MRX)

PARAMETER values for DPI mulga site Charleville site 1986/7

26	13.0	SW(2,1) Layer 1 maximum soil moisture (mm).	15
27	40.8	SW(2,2) Layer 2 maximum soil moisture (mm).	16
28	37.8	SW(2,3) Layer 3 maximum soil moisture (mm).	17
19	1.0	AIRDRY Layer 1 air dry soil moisture content (mm).	19
29	1.1	SW(3,1) Layer 1 wilting point soil moisture (mm).	20
30	13.0	SW(3,2) Layer 2 minimum soil moisture (mm).	21
31	22.8	SW(3,3) Layer 3 minimum soil moisture (mm).	22
		STARTING SOIL MOISTURE also used when p289 is a date	28
23	1.0	SW(9,1) Starting value for soil moisture layer 1 (mm).	29
24	13.0	SW(9,2) Starting value for soil moisture layer 2 (mm).	30
25	22.8	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
33	8.0	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		TREE WATER USE	237
291	0.5	MATURE TREE BASAL AREA	
292	1.0	Layer 1 minimum soil moisture (mm) with trees	239
293	13.0	Layer 2 minimum soil moisture (mm) with trees.	240
294	20.0	Layer 3 minimum soil moisture (mm) with trees.	241
295	15.0	Layer 4 available water (trees only)	242
296	150.0	Maximum rooting depth of trees in cm	243
297	1.4	Tree Root length at surface, rl= p297*exp(-p298*z)	
298	0.6	Tree Root length exponent, rl= p297*exp(-p298*z)	
299	0.0	asw4 Starting value for soil moisture layer 4 (mm), trees only	
		RUNOFF	33
270	1.0	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.0	yield at 50% cover for run-off calculation	36
272	1.0	k value in cover=y**k / (y**k + p271**k)	37
273	1.0	maximum runoff of rainfall at zero cover, wet soil	38
45	1200.0	green yield (kg/ha) when green cover for transpiration is 50%	58
46	1400.0	green yield (kg/ha) when radiation interception is 50%	70
209	4.0	TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0	62
		6=maize, 7=combined NP, 8=NP f(max,min)	63
61	9.0	If temp is less than P61, temperature index (TIX) is zero.	64
62	18.0	As temp increases from P61 to P62, TIX increases from 0 to 1.	65
63	30.0	As temp increases from P62 to P63, TIX remains at 1.	66

64	45.0	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	67
5	4.4	Initial plant density e.g. % basal area	74
6	1.5	Potential daily regrowth rate (kg/ha/day/unit of density)	75
7	10.0	Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb	81
96	33.0	Height (cm) of 1000 kg/ha	90
9	1.0	Soil water index. Maximum green cover = amin1(0.99,swix/p(9))	106
11	-4.0	Minimum sreen temperature (c) at which green cover = 0%	107
13	0.0	Prop of standing dry matter detached per day. DETAC = P13* SDM2	111
258	0.0	Detachment of old pool begins month,day	112
97	2.0	N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100	246
98	10.0	N uptake per 100 mm of transpiration	247
99	22.0	Maximum N uptake (kg/ha)	248
101	1.2	% N at zero growth Nitrogen index = (%N-p101)/(p102-p101)	250
102	1.3	% N at maximum growth Nitrogen index = (%N-p101)/(p102-p101)	251
108	0.0	Proportional decline per day in % N for green material	
109	0.0	Proportional decline per day in % N for dead material	
100	2.5	Maximum % N in growth	249
110	1.0	Minimum % N in green & maximum in dead Not used in gvt72	
111	0.8	Minimum % N in dead	
263	44021.0	Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)	155
264	10.0	No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures	156
250	1.0	if=1 full daily met data, if=3 weekly austclm	157
		4=daily rain in dr2 format, with either AUSTCLIM or station p269	158
		6=daily rain + daily climate, no in p269 type 1	159
269	0.0	monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM	160
203	1986.0	Starting year of simulation; 1800 to begin at start of metfile.	148
204	7.0	Starting month of simulation	149
206	730.0	Number of days in simuln run,last date : 1st Mar 1986=198603	150
211	7.0	if=1-365 gives output of observed & predicted , and simulated : 365=yearly,91=seasonally,30=monthly, 7=weekly,1=daily,999=each observation,mndy=monthday output in mongro15.ogp or m1	
284	0.0	if=1 TE output to file pasture9.ogp, p246 must be 132	200
300	0.0	Indicates end of parameter file	253

mulgagun	19861024 2 reset yld	0.0	50.0	0.0	0.00	0.00	
mulgagun	1986102414reset soil	6.1	18.5	25.5	0.00	0.00	
mulgagun	1986102416observatio	6.1	18.5	25.5	0.00	0.00	
mulgagun	1986120515observatio	7.4	68.1	205.6	16.70	2.46	
mulgagun	19861205 2 reset yld	205.6	0.0	0.0	2.46	0.00	
mulgagun	1986120515observatio	7.4	68.1	205.6	16.70	2.46	
mulgagun	1986120516observatio	7.4	25.2	35.5	16.70		
mulgagun	1986123115observatio	1.1	38.4	242.6	9.10	1.79	
mulgagun	1986123116observatio	1.1	14.5	22.8	9.10		
mulgagun	1987012115observatio	2.8	41.2	194.8	8.90	1.77	
mulgagun	1987012116observatio	2.8	15.2	23.2	8.90		
mulgagun	1987021115observatio	3.1	52.9	275.4	19.60	2.08	
mulgagun	1987021116observatio	3.1	19.1	30.7	19.60		
mulgagun	1987030415observatio	7.8	64.7	703.4	29.30	2.42	
mulgagun	1987030416observatio	7.8	26.3	30.7	29.30		
mulgagun	1987032615observatio	13.0	84.1	645.2	17.10	1.20	
mulgagun	1987032616observatio	13.0	40.5	30.6	17.10		
mulgagun	1987041615observatio	3.6	45.0	798.9	18.40	1.26	
mulgagun	1987041616observatio	3.6	16.4	24.9	18.40		
mulgagun	1987052015observatio	4.7	49.9	720.1	6.60	1.04	
mulgagun	1987052016observatio	4.7	19.1	26.0	6.60		
mulgagun	1987061115observatio	2.5	43.5	846.7	8.50	1.02	gcov estimated

```
mulgagun   1987061116observatio     2.5    17.2     23.8    8.50          gcov estimated
mulgagun   1987070119 reset yld   240.0   372.0      0.0    1.45   0.00
mulgagun   1987070115observatio     8.0    76.5    611.9   10.40   1.45
mulgagun   1987070116observatio     8.0    33.6     34.9   10.40
mulgagun   1987072915observatio     8.0    71.9    834.0   11.30   1.38   replace 1157.6
mulgagun   1987072916observatio     8.0    29.3     34.7   11.30
mulgagun   1987081915observatio     9.7    79.7    905.3   12.50   1.67
mulgagun   1987081916observatio     9.7    36.5     33.6   12.50
mulgagun   1987090215observatio     5.0    65.5    943.1   16.30   1.72
mulgagun   1987090216observatio     5.0    27.0     33.5   16.30
mulgagun   1987092315observatio     3.1    45.7   1189.9   16.60   1.24
mulgagun   1987092316observatio     3.1    18.2     24.4   16.60
mulgagun   1987101515observatio     3.1    45.8    984.6    8.90   0.83
mulgagun   1987101516observatio     3.1    17.8     25.0    8.90
mulgagun   1987110516observatio     3.4    17.4     24.0    0.00
mulgagun   1987112616observatio     3.6    17.4     24.0    0.00
file end   99990000  for GRASP
```

<u>Parameter file for Airlie</u> (AIRL2.MRX)

```
PARAMETER values for Airlie (Biddenham) Mitchell grass Charleville 1986/87
  26     25.0  SW(2,1) Layer 1 maximum soil moisture (mm).                          15
  27    100.0  SW(2,2) Layer 2 maximum soil moisture (mm).                          16
  28    125.0  SW(2,3) Layer 3 maximum soil moisture (mm).                          17
  19      3.0  AIRDRY  Layer 1 air dry soil moisture content (mm).                  19
  29      5.0  SW(3,1) Layer 1 wilting point soil moisture (mm).                    20
  30     40.0  SW(3,2) Layer 2 minimum soil moisture (mm).                          21
  31     50.0  SW(3,3) Layer 3 minimum soil moisture (mm).                          22
               STARTING SOIL MOISTURE also used when p289 is a date                 28
  23      7.0  SW(9,1) Starting value for soil moisture layer 1 (mm).               29
  24     37.0  SW(9,2) Starting value for soil moisture layer 2 (mm).               30
  25     43.0  SW(9,3) Starting value for soil moisture layer 3 (mm).               31
  33      2.0  EPLIM  Upper limit to daily soil evaporation (mm/day)                26
               RUNOFF                                                               33
 270      0.0  0 for free draining soils, 1for runoff as a f(yield)                 35
 271   1150.0  yield at 50% cover for run-off calculation                           36
 272      1.0  k value in cover=y**k / (y**k + p271**k)                             37
 273      1.0  maximum  runoff of rainfall  at zero cover, wet soil                 38
  45   1000.0  green yield (kg/ha) when green cover for transpiration is 50%        58
  46   1300.0  green yield (kg/ha) when  radiation interception is 50%              70
 209      4.0  TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0              62
               6=maize, 7=combined NP, 8=NP f(max,min)                              63
  61     14.0  If temp is less than P61, temperature index (TIX) is zero.           64
  62     24.0  As temp increases from P61 to P62, TIX increases from 0 to 1.        65
  63     40.0  As temp increases from P62 to P63, TIX remains at 1.                 66
  64     50.0  As temp increases from P63 to P64, TIX decreases from 1 to 0.0       67
   5      4.0  Initial plant density e.g. % basal area                              74
   6      0.5  Potential daily regrowth rate (kg/ha/day/unit of density)            75
   7     10.0  Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb        81
   9      0.1  Soil water index.  Maximum green cover = amin1(0.99,swix/p(9))      106
  11     -2.0  Minimum sreen temperature (c) at which green cover = 0%             107
  13      0.0  Prop of standing dry matter detached per day. DETAC = P13* SDM2     111
 258    401.0  Detachment of old pool begins month,day                             112
  96     30.0  Height (cm) of 1000 kg/ha                                            90
  97      2.0  N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100    246
  98      5.0  N uptake per 100 mm of transpiration                                247
  99     13.5  Maximum N uptake (kg/ha)                                            248
```

```
101       0.5  % N at zero growth   Nitrogen index = (%N-p101)/(p102-p101)          250
102       0.6  % N at maximum growth   Nitrogen index = (%N-p101)/(p102-p101)       251
108       0.0  Proportional decline per day in % N for green material
109       0.0  Proportional decline per day in % N for dead material
100       2.5  Maximum % N in growth                                                249
110       1.0  Minimum % N in green & maximum in dead NOT USED in gvt72
111       0.6  Minimum % N in  dead
263   44021.0  Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)      155
264      68.0  No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures     156
250       6.0  if=1 full daily met data, if=3  weekly austclm                       157
               4=daily rain in dr2 format, with either AUSTCLIM or station p269     158
               6=daily rain + daily climate, no in p269 type 1                      159
269      10.0  monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM            160
211       7.0  if=1-365 gives output of observed & predicted , and
               simulated : 365=yearly,91=seasonally,30=monthly,
               7=weekly,1=daily,999=each observation,mndy=monthday
               output in mongro15.ogp or m1
262     999.0  Output to screen:365=yr,91=seas,30=mthly,7=wkly,1=daily,999=obs      184
206     730.0  Number of days in simuln run,last date : 1st Mar 1986=198603         150
284       0.0  if=1 TE output to file pasture9.ogp, p246 must be 132                200
300       0.0  Indicates end of parameter file                                      253
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Airlie     19881110 2 reset yld   0.0    50.0     0.0    0.00   0.00
Airlie     1988111014reset soil   6.6    36.7    43.3    0.00   0.00
Airlie     1988111016observatio   6.6    36.7    43.3    0.00   0.00  est layer 3
Airlie     1989011615observatio  10.4    88.6    53.0    2.30   0.00
Airlie     1989011616observatio  10.4    33.9    44.3    2.30   0.00  est layer 3
Airlie     1989022715observatio   9.4    87.6    80.0    2.60   0.00
Airlie     1989022716observatio   9.4    34.5    43.8    2.60   0.00  est layer 3
Airlie     1989041015observatio  16.6   132.9    45.0    7.80   0.00
Airlie     1989041016observatio  16.6    49.9    66.5    7.80   0.00  est layer 3
Airlie     1989070315observatio  21.8   274.7   388.0   12.20   0.00
Airlie     1989070316observatio  21.8   112.0   140.9   12.20   0.00
Airlie     1989081415observatio   0.0     0.0   411.0   14.50   0.00
Airlie     1989081419observatio   0.0     0.0     0.0   14.50   0.00
Airlie     1989092515observatio   4.8     0.0   560.0   21.30   0.00
Airlie     1989092516observatio   4.8    15.6    43.3   21.30   0.00  est layer 3
Airlie     1989112815observatio  10.9   146.9  1216.0   33.60   0.00
Airlie     1989112816observatio  10.9    62.6    73.4   33.60   0.00  est layer 3
Airlie     1990021215observatio   6.3    69.3  1000.0    0.50   0.00  yield est.
Airlie     1990021216observatio   6.3    28.4    34.6    0.00   0.00  est layer 3
Airlie     1990112815observatio   0.0     0.0  1300.0   10.50   0.00  yld est.
file end   99990000  for GRASP
```

Parameter file for Lisnalee (LISN4.MRX)

```
PARAMETER values for Lisnalee Buffel (Biddenham Mitchell grass 1986/87)
  26      12.0  SW(2,1) Layer 1 maximum soil moisture (mm).                          15
  27      45.0  SW(2,2) Layer 2 maximum soil moisture (mm).                          16
  28      85.0  SW(2,3) Layer 3 maximum soil moisture (mm).                          17
  19       4.0  AIRDRY  Layer 1 air dry soil moisture content (mm).                  19
  29       4.0  SW(3,1) Layer 1 wilting point soil moisture (mm).                    20
  30      12.0  SW(3,2) Layer 2 minimum soil moisture (mm).                          21
  31      25.0  SW(3,3) Layer 3 minimum soil moisture (mm).                          22
                STARTING SOIL MOISTURE also used when p289 is a date                 28
  23       8.0  SW(9,1) Starting value for soil moisture layer 1 (mm).               29
  24      30.0  SW(9,2) Starting value for soil moisture layer 2 (mm).               30
```

25	57.0	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
33	4.0	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		RUNOFF	33
270	0.0	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.0	yield at 50% cover for run-off calculation	36
272	1.0	k value in cover=y**k / (y**k + p271**k)	37
273	1.0	maximum runoff of rainfall at zero cover, wet soil	38
		ROOT DISTRIBUTION	
106	0.5	relative supply of layer 3 cf layers 1,2. Usually 0.5	
45	800.0	green yield (kg/ha) when green cover for transpiration is 50%	58
46	1000.0	green yield (kg/ha) when radiation interception is 50%	70
209	3.0	TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0	62
		6=maize, 7=combined NP, 8=NP f(max,min)	63
61	14.0	If temp is less than P61, temperature index (TIX) is zero.	64
62	24.0	As temp increases from P61 to P62, TIX increases from 0 to 1.	65
63	40.0	As temp increases from P62 to P63, TIX remains at 1.	66
64	50.0	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	67
5	6.2	Initial plant density e.g. % basal area	74
6	5.0	Potential daily regrowth rate (kg/ha/day/unit of density)	75
7	12.0	Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb	81
9	0.1	Soil water index. Maximum green cover = amin1(0.99,swix/p(9))	106
11	2.0	Minimum green temperature (c) at which green cover = 0%	107
13	0.0	Prop of standing dry matter detached per day. DETAC = P13* SDM2	111
258	515.0	Detachment of old pool begins month,day	112
96	30.0	Height (cm) of 1000 kg/ha	90
97	5.0	N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100	246
98	5.0	N uptake per 100 mm of transpiration	247
99	24.0	Maximum N uptake (kg/ha)	248
101	0.5	% N at zero growth Nitrogen index = (%N-p101)/(p102-p101)	250
102	0.6	% N at maximum growth Nitrogen index = (%N-p101)/(p102-p101)	251
108	0.0	Proportional decline per day in % N for green material	
109	0.0	Proportional decline per day in % N for dead material	
100	2.5	Maximum % N in growth	249
110	1.0	Minimum % N in green & maximum in dead NOT USED in gvt72	
111	0.6	Minimum % N in dead	
263	44021.0	Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)	155
264	69.0	No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures	156
250	6.0	if=1 full daily met data, if=3 weekly austclm	157
		4=daily rain in dr2 format, with either AUSTCLIM or station p269	158
		6=daily rain + daily climate, no in p269 type 1	159
269	10.0	monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM	160
211	7.0	if=1-365 gives output of observed & predicted , and simulated : 365=yearly,91=seasonally,30=monthly, 7=weekly,1=daily,999=each observation,mndy=monthday output in mongro15.ogp or m1	
206	730.0	Number of days in simuln run,last date : 1st Mar 1986=198603	150
284	0.0	if=1 TE output to file pasture9.ogp, p246 must be 132	200
300	0.0	Indicates end of parameter file	253

Lisnalee	19890113 2 reset yld	0.0	50.0	0.0	0.00	0.00	
Lisnalee	1989011314reset soil	8.4	29.7	57.4	0.00	0.00	layer 3 est
Lisnalee	1989011316observatio	8.4	29.7	57.4	0.00	0.00	layer 3 est
Lisnalee	1989030215observatio	2.7	57.4	648.0	24.20	0.00	layer 3 est
Lisnalee	19890302 2 reset yld	500.0	148.0	0.0	0.00	0.00	
Lisnalee	1989030216observatio	2.7	14.7	40.0	24.20	0.00	layer 3 est
Lisnalee	1989041415observatio	7.3	101.3	1137.0	59.10	0.00	layer 3 est
Lisnalee	1989041416observatio	7.3	33.1	60.9	59.10	0.00	layer 3 est

Lisnalee	1989052315observatio	8.6	93.2	1052.0	43.00	0.00	layer 3 est
Lisnalee	1989052316observatio	8.6	28.6	56.0	43.00	0.00	layer 3 est
Lisnalee	1989070615observatio	6.9	112.8	1092.0	0.10	0.00	gcov zero
Lisnalee	1989070616observatio	6.9	41.1	64.8	0.10	0.00	gcov zero
Lisnalee	1989081715observatio	6.5	97.7	976.0	2.10	0.00	
Lisnalee	1989081716observatio	6.5	36.6	54.5	2.10	0.00	
Lisnalee	1989092815observatio	5.7	111.6	1385.0	7.50	0.00	
Lisnalee	1989092816observatio	5.7	35.5	70.4	7.50	0.00	
Lisnalee	1989120115observatio	2.8	59.1	1163.0	10.20	0.00	layer 3 est
Lisnalee	1989120116observatio	2.8	16.3	40.0	10.20	0.00	layer 3 est
Lisnalee	19900210 2 reset yld	500.0	282.0	0.0	0.00	0.00	
Lisnalee	1990022015observatio	11.5	110.8	782.0	0.20	0.00	layer 3 est
Lisnalee	1990022016observatio	11.5	32.7	66.6	0.20	0.00	layer 3 est
Lisnalee	1990051115observatio	6.3	134.6	2009.0	81.60	0.00	
Lisnalee	1990051116observatio	6.3	42.1	86.2	81.60	0.00	
Lisnalee	1990112215observatio	4.1	79.7	1267.0	0.00	0.00	layer 3 est
Lisnalee	1990112216observatio	4.1	27.7	47.9	0.00	0.00	layer 3 est
file end	99990000 for GRASP						

<u>Parameter file for Maxvale</u> (MAX2.MRX)

Maxvale (M3) Mulga/box flat loamy red earth PWJ, PARAMETERS from mulga 1986/87

26	15.0	SW(2,1) Layer 1 maximum soil moisture (mm).	15
27	71.0	SW(2,2) Layer 2 maximum soil moisture (mm).	16
28	96.0	SW(2,3) Layer 3 maximum soil moisture (mm).	17
19	1.0	AIRDRY Layer 1 air dry soil moisture content (mm).	19
29	1.1	SW(3,1) Layer 1 wilting point soil moisture (mm).	20
30	8.0	SW(3,2) Layer 2 minimum soil moisture (mm).	21
31	18.0	SW(3,3) Layer 3 minimum soil moisture (mm).	22
		STARTING SOIL MOISTURE also used when p289 is a date	28
23	8.0	SW(9,1) Starting value for soil moisture layer 1 (mm).	29
24	32.0	SW(9,2) Starting value for soil moisture layer 2 (mm).	30
25	56.0	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
33	8.0	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		TREE WATER USE	237
291	0.8	MATURE TREE BASAL AREA	
292	1.0	Layer 1 minimum soil moisture (mm) with trees	239
293	5.0	Layer 2 minimum soil moisture (mm) with trees.	240
294	15.0	Layer 3 minimum soil moisture (mm) with trees.	241
295	0.0	Layer 4 available water (trees only)	242
296	100.0	Maximum rooting depth of trees in cm	243
297	1.4	Tree Root length at surface, rl= p297*exp(-p298*z)	
298	0.6	Tree Root length exponent, rl= p297*exp(-p298*z)	
299	0.0	asw4 Starting value for soil moisture layer 4 (mm), trees only	
		ROOT DISTRIBUTION	
106	0.5	relative supply of layer 3 cf layers 1,2. Usually 0.5	
		RUNOFF	33
270	0.0	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.0	yield at 50% cover for run-off calculation	36
272	1.0	k value in cover=y**k / (y**k + p271**k)	37
273	1.0	maximum runoff of rainfall at zero cover, wet soil	38
		PLANT GROWTH	
45	800.0	green yield (kg/ha) when green cover for transpiration is 50%	58
46	1000.0	green yield (kg/ha) when radiation interception is 50%	70
209	4.0	TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0	62
		6=maize, 7=combined NP, 8=NP f(max,min)	63
61	9.0	If temp is less than P61, temperature index (TIX) is zero.	64

62	18.0	As temp increases from P61 to P62, TIX increases from 0 to 1.	65
63	34.0	As temp increases from P62 to P63, TIX remains at 1.	66
64	50.0	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	67
5	2.7	Initial plant density e.g. % basal area	74
6	1.5	Potential daily regrowth rate (kg/ha/day/unit of density)	75
7	9.0	Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb	81
96	40.0	Height (cm) of 1000 kg/ha	90
9	0.1	Soil water index. Maximum green cover = amin1(0.99,swix/p(9))	106
11	-7.0	Minimum sreen temperature (c) at which green cover = 0%	107
13	0.0	Prop of standing dry matter detached per day. DETAC = P13* SDM2	111
258	0.0	Detachment of old pool begins month,day	112
97	5.0	N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100	246
98	9.0	N uptake per 100 mm of transpiration	247
99	12.0	Maximum N uptake (kg/ha)	248
101	1.2	% N at zero growth Nitrogen index = (%N-p101)/(p102-p101)	250
102	1.3	% N at maximum growth Nitrogen index = (%N-p101)/(p102-p101)	251
108	0.0	Proportional decline per day in % N for green material	
109	0.0	Proportional decline per day in % N for dead material	
100	2.5	Maximum % N in growth	249
110	1.0	Minimum % N in green & maximum in dead Not used in gvt72	
111	0.8	Minimum % N in dead	
203	1988.0	Starting year of simulation; 1800 to begin at start of metfile.	148
204	7.0	Starting month of simulation	149
263	44021.0	Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)	155
264	10.0	No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures	156
250	1.0	if=1 full daily met data, if=3 weekly austclm	157
		4=daily rain in dr2 format, with either AUSTCLIM or station p269	158
		6=daily rain + daily climate, no in p269 type 1	159
269	0.0	monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM	160
211	7.0	if=1-365 gives output of observed & predicted , and	
		simulated : 365=yearly,91=seasonally,30=monthly,	
		7=weekly,1=daily,999=each observation,mndy=monthday	
		output in mongro15.ogp or m1	
206	730.0	Number of days in simuln run,last date : 1st Mar 1986=198603	150
284	0.0	if=1 TE output to file pasture9.ogp, p246 must be 132	200
300	0.0	Indicates end of parameter file	253

Maxvale	19880914 2 reset yld	0.0	50.0	0.0	0.00	0.00	
Maxvale	1988091414reset soil	7.8	31.6	56.2	0.00	0.00	
Maxvale	1988091416observatio	7.8	31.6	56.2	0.10	0.00	
Maxvale	1988120915observatio	0.0	0.0	20.0	0.30	0.00	
Maxvale	1989011915observatio	1.6	28.7	72.0	2.60	0.00	
Maxvale	1989011916observatio	1.6	9.3	17.8	2.60	0.00	est 1 3
Maxvale	1989030115observatio	1.5	25.3	54.0	0.20	0.00	
Maxvale	1989030116observatio	1.5	8.1	15.7	0.20	0.00	est 1 3
Maxvale	1989041215observatio	5.6	69.8	85.0	7.00	0.00	
Maxvale	19890412 2 reset yld	0.0	85.0	0.0	0.00	0.00	
Maxvale	1989041216observatio	5.6	21.0	43.2	7.00	0.00	est 1 3
Maxvale	1989052215observatio	14.4	181.1	278.0	0.00	0.00	
Maxvale	1989052216observatio	14.4	71.2	95.5	16.70	0.00	est gcov
Maxvale	1989070515observatio	10.0	149.8	444.0	26.70	0.00	
Maxvale	1989070516observatio	10.0	46.6	93.2	26.70	0.00	
Maxvale	1989081715observatio	3.9	113.0	495.0	19.60	0.00	
Maxvale	1989081716observatio	3.9	25.5	83.6	19.60	0.00	
Maxvale	1989092815observatio	5.5	81.3	742.0	16.70	0.00	est 1 3
Maxvale	1989092816observatio	5.5	25.5	50.4	16.70	0.00	
Maxvale	1989120115observatio	2.2	38.6	399.0	3.10	0.00	est 1 3

Maxvale	1989120116observatio	2.2	12.5	23.9	3.10	0.00	
Maxvale	1990022015observatio	6.4	42.7	550.0	3.10	0.00	est yld,gcov
Maxvale	1990022016observatio	6.4	9.9	26.4	3.00	0.00	est yld, 13
file end	99990000 for GRASP						

<u>Parameter file for Turn Turn</u> (TURN2.MRX)

Turn Turn (S2) Eulo Sandplain sandy red earth PWJ, PARAMETERS from mulga 1986/87

26	13.0	SW(2,1) Layer 1 maximum soil moisture (mm).	15
27	30.0	SW(2,2) Layer 2 maximum soil moisture (mm).	16
28	33.0	SW(2,3) Layer 3 maximum soil moisture (mm).	17
19	1.0	AIRDRY Layer 1 air dry soil moisture content (mm).	19
29	1.1	SW(3,1) Layer 1 wilting point soil moisture (mm).	20
30	6.0	SW(3,2) Layer 2 minimum soil moisture (mm).	21
31	10.0	SW(3,3) Layer 3 minimum soil moisture (mm).	22
		TREE WATER USE	237
291	2.0	MATURE TREE BASAL AREA	
292	1.0	Layer 1 minimum soil moisture (mm) with trees	239
293	6.0	Layer 2 minimum soil moisture (mm) with trees.	240
294	10.0	Layer 3 minimum soil moisture (mm) with trees.	241
295	50.0	Layer 4 available water (trees only)	242
296	300.0	Maximum rooting depth of trees in cm	243
297	1.4	Tree Root length at surface, rl= p297*exp(-p298*z)	
298	0.6	Tree Root length exponent, rl= p297*exp(-p298*z)	
299	0.0	asw4 Starting value for soil moisture layer 4 (mm), trees onl	
		STARTING SOIL MOISTURE also used when p289 is a date	28
23	4.0	SW(9,1) Starting value for soil moisture layer 1 (mm).	29
24	18.0	SW(9,2) Starting value for soil moisture layer 2 (mm).	30
25	21.0	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
33	8.0	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		RUNOFF	33
270	0.0	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.0	yield at 50% cover for run-off calculation	36
272	1.0	k value in cover=y**k / (y**k + p271**k)	37
273	1.0	maximum runoff of rainfall at zero cover, wet soil	38
		PLANT GROWTH	
45	750.0	green yield (kg/ha) when green cover for transpiration is 50%	58
46	900.0	green yield (kg/ha) when radiation interception is 50%	70
209	4.0	TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0	62
		6=maize, 7=combined NP, 8=NP f(max,min)	63
61	9.0	If temp is less than P61, temperature index (TIX) is zero.	64
62	18.0	As temp increases from P61 to P62, TIX increases from 0 to 1.	65
63	30.0	As temp increases from P62 to P63, TIX remains at 1.	66
64	50.0	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	67
5	1.6	Initial plant density e.g. % basal area	74
6	1.5	Potential daily regrowth rate (kg/ha/day/unit of density)	75
7	8.0	Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb	81
9	0.1	Soil water index. Maximum green cover = amin1(0.99,swix/p(9))	106
11	-7.0	Minimum sreen temperature (c) at which green cover = 0%	107
13	0.0	Prop of standing dry matter detached per day. DETAC = P13* SDM2	111
258	0.0	Detachment of old pool begins month,day	112
96	40.0	Height (cm) of 1000 kg/ha	90
97	5.0	N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100	246
98	13.0	N uptake per 100 mm of transpiration	247
99	12.0	Maximum N uptake (kg/ha)	248
101	1.2	% N at zero growth Nitrogen index = (%N-p101)/(p102-p101)	250
102	1.3	% N at maximum growth Nitrogen index = (%N-p101)/(p102-p101)	251

```
108        0.0  Proportional decline per day in % N for green material
109        0.0  Proportional decline per day in % N for dead material
100        2.5  Maximum % N in growth                                            249
110        1.0  Minimum % N in green & maximum in dead Not used in gvt72
111        0.8  Minimum % N in  dead
263    44021.0  Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)  155
264       67.0  No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures 156
250        6.0  if=1 full daily met data, if=3  weekly austclm                   157
                4=daily rain in dr2 format, with either AUSTCLIM or station p269 158
                6=daily rain + daily climate, no in p269 type 1                  159
269       10.0  monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM        160
211        7.0  if=1-365 gives output of observed & predicted , and
                simulated : 365=yearly,91=seasonally,30=monthly,
                7=weekly,1=daily,999=each observation,mndy=monthday
                output in mongro15.ogp or m1
206      730.0  Number of days in simuln run,last date : 1st Mar 1986=198603     150
284        0.0  if=1 TE output to file pasture9.ogp, p246 must be 132            200
300        0.0  Indicates end of parameter file                                  253
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Turn Turn   19880920 2 reset yld     0.0   10.0     0.0    0.00   0.00
Turn Turn   1988092014reset soil     3.5   18.3    21.6    0.00   0.00
Turn Turn   1988092016observatio     3.5   18.3    21.6    0.00   0.00
Turn Turn   1988120715observatio     2.4   24.0    11.0    0.20   0.00
Turn Turn   19881207 2 reset yld     0.0   10.0     0.0    0.00   0.00
Turn Turn   1988120716observatio     2.4    9.6    12.0    0.20   0.00   est l3
Turn Turn   1989011715observatio     1.9   24.0    11.3    0.50   0.00
Turn Turn   1989011716observatio     1.9   10.1    12.0    0.50   0.00   est l3
Turn Turn   1989022815observatio     1.8   21.6    10.8    1.10   0.00
Turn Turn   1989022816observatio     1.8    9.0    10.8    1.10   0.00   est l3
Turn Turn   1989041115observatio     6.0   61.8    16.8    1.60   0.00
Turn Turn   19890411 2 reset yld     0.0   17.0     0.0    0.00   0.00
Turn Turn   1989041116observatio     6.0   24.9    30.9    1.60   0.00   est l3
Turn Turn   1989070415observatio     5.6   67.5   302.0   21.40   0.00
Turn Turn   1989070416observatio     5.6   28.1    33.8   21.40   0.00
Turn Turn   1989081515observatio     0.0    0.0   370.0   18.20   0.00
Turn Turn   1989081516observatio     0.0    0.0     0.0   18.20   0.00
Turn Turn   1989092615observatio     2.3   29.1   371.0    7.00   0.00
Turn Turn   1989092616observatio     2.3   12.2    14.6    7.00   0.00   est l3
Turn Turn   1989112915observatio     2.7   33.8   258.8    5.00   0.00
Turn Turn   1989112916observatio     2.7   13.5    17.6    5.00   0.00
Turn Turn   1990021315observatio     0.7   12.6     0.0    5.00   0.00   est yld cover
Turn Turn   1990021316observatio     0.7    5.6     6.3    0.00   0.00   est l3
file end    99990000  for GRASP
```

Parameter file for Wittenburra Open (WITOP2.MRX)

```
Wittenburra open (H2) Eulo hard mulga red earth PWJ, Parameters from mulga 1986/87
  20     100.0  Thickness (mm) of soil layer 1 (surface 100mm approx)          6
                which can be air dried. Nemonic = SW(8,1).                      7
  21     400.0  Thickness (mm) of soil layer 2. This layer cannot dry           8
                below permanent wilting point, and is the main                  9
                zone of root activity. Nemonic = SW(8,2).                      10
  22     300.0  Thickness (mm) of soil layer 3. The lower limit of this        11
                layer is the limit of root penetration ( =SW(8,3)).            12
  26      13.0  SW(2,1) Layer 1 maximum soil moisture (mm).                    15
  27      55.0  SW(2,2) Layer 2 maximum soil moisture (mm).                    16
  28      45.0  SW(2,3) Layer 3 maximum soil moisture (mm).                    17
```

19	2.0	AIRDRY Layer 1 air dry soil moisture content (mm).	19
29	2.0	SW(3,1) Layer 1 wilting point soil moisture (mm).	20
30	14.0	SW(3,2) Layer 2 minimum soil moisture (mm).	21
31	16.0	SW(3,3) Layer 3 minimum soil moisture (mm).	22
		TREE WATER USE	237
291	0.0	MATURE TREE BASAL AREA	
292	1.0	Layer 1 minimum soil moisture (mm) with trees	239
293	12.0	Layer 2 minimum soil moisture (mm) with trees.	240
294	15.0	Layer 3 minimum soil moisture (mm) with trees.	241
295	0.0	Layer 4 available water (trees only)	242
296	80.0	Maximum rooting depth of trees in cm	243
297	1.4	Tree Root length at surface, rl= p297*exp(-p298*z)	
298	0.6	Tree Root length exponent, rl= p297*exp(-p298*z)	
299	0.0	asw4 Starting value for soil moisture layer 4 (mm), trees only	
		STARTING SOIL MOISTURE also used when p289 is a date	28
23	7.0	SW(9,1) Starting value for soil moisture layer 1 (mm).	29
24	27.0	SW(9,2) Starting value for soil moisture layer 2 (mm).	30
25	18.0	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
33	1.0	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		RUNOFF	33
270	0.0	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.0	yield at 50% cover for run-off calculation	36
272	1.0	k value in cover=y**k / (y**k + p271**k)	37
273	1.0	maximum runoff of rainfall at zero cover, wet soil	38
45	500.0	green yield (kg/ha) when green cover for transpiration is 50%	58
46	600.0	green yield (kg/ha) when radiation interception is 50%	70
		PLANT GROWTH	
61	9.0	If temp is less than P61, temperature index (TIX) is zero.	64
62	18.0	As temp increases from P61 to P62, TIX increases from 0 to 1.	65
63	30.0	As temp increases from P62 to P63, TIX remains at 1.	66
64	50.0	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	67
5	0.5	Initial plant density e.g. % basal area	74
6	1.5	Potential daily regrowth rate (kg/ha/day/unit of density)	75
7	5.0	Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb	81
9	0.1	Soil water index. Maximum green cover = amin1(0.99,swix/p(9))	106
11	-7.0	Minimum sreen temperature (c) at which green cover = 0%	107
13	0.0	Prop of standing dry matter detached per day. DETAC = P13* SDM2	111
258	0.0	Detachment of old pool begins month,day	112
96	40.0	Height (cm) of 1000 kg/ha	90
97	5.0	N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100	246
98	9.0	N uptake per 100 mm of transpiration	247
99	18.0	Maximum N uptake (kg/ha)	248
101	1.2	% N at zero growth Nitrogen index = (%N-p101)/(p102-p101)	250
102	1.3	% N at maximum growth Nitrogen index = (%N-p101)/(p102-p101)	251
263	44021.0	Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)	155
264	66.0	No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures	156
250	6.0	if=1 full daily met data, if=3 weekly austclm	157
		4=daily rain in dr2 format, with either AUSTCLIM or station p269	158
		6=daily rain + daily climate, no in p269 type 1	159
269	10.0	monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM	160
211	7.0	if=1-365 gives output of observed & predicted , and	
		simulated : 365=yearly,91=seasonally,30=monthly,	
		7=weekly,1=daily,999=each observation,mndy=monthday	
		output in mongro15.ogp or m1	
206	730.0	Number of days in simuln run,last date : 1st Mar 1986=198603	150
284	0.0	if=1 TE output to file pasture9.ogp, p246 must be 132	200
300	0.0	Indicates end of parameter file	253

Wittenopen	19880921 2 reset yld	0.0	5.0	0.0	0.00	0.00	
Wittenopen	1988092114reset soil	6.5	26.5	18.0	0.00	0.00	
Wittenopen	1988092116observatio	6.5	26.5	18.0	0.00	0.00	
Wittenopen	1988120715observatio	2.9	34.7	8.5	0.30	0.00	
Wittenopen	1988120716observatio	2.9	16.8	15.0	0.30	0.00	
Wittenopen	1989011715observatio	3.6	48.1	61.0	3.90	0.00	
Wittenopen	1989011716observatio	3.6	23.5	21.0	3.90	0.00	
Wittenopen	1989022815observatio	3.7	46.7	16.0	0.30	0.00	
Wittenopen	1989022816observatio	3.7	19.2	24.0	0.30	0.00	
Wittenopen	1989041115observatio	8.4	52.4	7.3	0.50	0.00	
Wittenopen	1989041116observatio	8.4	26.0	18.0	0.50	0.00	
Wittenopen	1989070415observatio	9.5	79.4	64.0	6.70	0.00	
Wittenopen	1989070416observatio	9.5	49.9	20.0	6.70	0.00	13 est dry
Wittenopen	1989081515observatio	0.0	0.0	178.0	10.70	0.00	
Wittenopen	1989092615observatio	5.2	43.3	260.0	5.90	0.00	
Wittenopen	1989092616observatio	5.2	20.1	18.0	5.90	0.00	
Wittenopen	1989112915observatio	0.0	0.0	0.0	0.00	0.00	no obs.
Wittenopen	1989112916observatio	0.0	0.0	0.0	0.00	0.00	no obs.
file end	99990000 for GRASP						

Parameter file for Wittenburra Enclosed (WITEX2.MRX)

Wittenburra enclosed (H2) Eulo hard mulga red earth PWJ, Parameters mulga 1986/87

20	100.0	Thickness (mm) of soil layer 1 (surface 100mm approx)	6
		which can be air dried. Nemonic = SW(8,1).	7
21	400.0	Thickness (mm) of soil layer 2. This layer cannot dry	8
		below permanent wilting point, and is the main	9
		zone of root activity. Nemonic = SW(8,2).	10
22	300.0	Thickness (mm) of soil layer 3. The lower limit of this	11
		layer is the limit of root penetration (=SW(8,3)).	12
26	13.0	SW(2,1) Layer 1 maximum soil moisture (mm).	15
27	55.0	SW(2,2) Layer 2 maximum soil moisture (mm).	16
28	45.0	SW(2,3) Layer 3 maximum soil moisture (mm).	17
19	2.0	AIRDRY Layer 1 air dry soil moisture content (mm).	19
29	2.0	SW(3,1) Layer 1 wilting point soil moisture (mm).	20
30	14.0	SW(3,2) Layer 2 minimum soil moisture (mm).	21
31	16.0	SW(3,3) Layer 3 minimum soil moisture (mm).	22
		TREE WATER USE	237
291	1.5	MATURE TREE BASAL AREA	
292	1.0	Layer 1 minimum soil moisture (mm) with trees	239
293	12.0	Layer 2 minimum soil moisture (mm) with trees.	240
294	15.0	Layer 3 minimum soil moisture (mm) with trees.	241
295	0.0	Layer 4 available water (trees only)	242
296	80.0	Maximum rooting depth of trees in cm	243
297	1.4	Tree Root length at surface, rl= p297*exp(-p298*z)	
298	0.6	Tree Root length exponent, rl= p297*exp(-p298*z)	
299	0.0	asw4 Starting value for soil moisture layer 4 (mm), trees only	
		STARTING SOIL MOISTURE also used when p289 is a date	28
23	6.0	SW(9,1) Starting value for soil moisture layer 1 (mm).	29
24	30.0	SW(9,2) Starting value for soil moisture layer 2 (mm).	30
25	25.0	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
33	1.0	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		RUNOFF	33
270	0.0	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.0	yield at 50% cover for run-off calculation	36
272	1.0	k value in cover=y**k / (y**k + p271**k)	37
273	1.0	maximum runoff of rainfall at zero cover, wet soil	38

```
 45     500.0  green yield (kg/ha) when green cover for transpiration is 50%          58
 46     600.0  green yield (kg/ha) when  radiation interception is 50%                70
               PLANT GROWTH
 61       9.0  If temp is less than P61, temperature index (TIX) is zero.             64
 62      18.0  As temp increases from P61 to P62, TIX increases from 0 to 1.          65
 63      30.0  As temp increases from P62 to P63, TIX remains at 1.                   66
 64      50.0  As temp increases from P63 to P64, TIX decreases from 1 to 0.0         67
  5       0.5  Initial plant density e.g. % basal area                                74
  6       1.5  Potential daily regrowth rate (kg/ha/day/unit of density)              75
  7       6.0  Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb          81
  9       0.1  Soil water index.  Maximum green cover = amin1(0.99,swix/p(9))        106
 11      -7.0  Minimum sreen temperature (c) at which green cover = 0%               107
 13       0.0  Prop of standing dry matter detached per day. DETAC = P13* SDM2       111
258       0.0  Detachment of old pool begins month,day                               112
 96      40.0  Height (cm) of 1000 kg/ha                                              90
 97       5.0  N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100      246
 98       9.0  N uptake per 100 mm of transpiration                                  247
 99      18.0  Maximum N uptake (kg/ha)                                              248
101       1.2  % N at zero growth   Nitrogen index = (%N-p101)/(p102-p101)           250
102       1.3  % N at maximum growth   Nitrogen index = (%N-p101)/(p102-p101)        251
263   44021.0  Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)       155
264      66.0  No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures      156
250       6.0  if=1 full daily met data, if=3  weekly austclm                        157
               4=daily rain in dr2 format, with either AUSTCLIM or station p269      158
               6=daily rain + daily climate, no in p269 type 1                       159
269      10.0  monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM             160
211       7.0  if=1-365 gives output of observed & predicted , and
               simulated : 365=yearly,91=seasonally,30=monthly,
               7=weekly,1=daily,999=each observation,mndy=monthday
               output in mongro15.ogp or m1
206     730.0  Number of days in simuln run,last date : 1st Mar 1986=198603          150
284       0.0  if=1 TE output to file pasture9.ogp, p246 must be 132                 200
300       0.0  Indicates end of parameter file                                       253
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Witten exc   19880921 2 reset yld     0.0     5.0     0.0    0.00   0.00
Witten exc   1988092114reset soil     6.3    30.1    25.1    0.00   0.00
Witten exc   1988092116observatio     6.3    30.1    25.1    0.00   0.00
Witten exc   1988120715observatio     3.5    35.9     4.0    0.00   0.00
Witten exc   1988120716observatio     3.5    17.1    15.3    0.00   0.00
Witten exc   1989011715observatio     3.2    39.0    19.0    1.10   0.00
Witten exc   1989011716observatio     3.2    18.6    17.2    1.10   0.00
Witten exc   1989022815observatio     2.8    31.9     7.0    0.30   0.00
Witten exc   1989022816observatio     2.8    15.9    13.2    0.30   0.00
Witten exc   1989041115observatio     8.1    55.9     0.0    0.70   0.00
Witten exc   1989041116observatio     8.1    26.6    21.2    0.70   0.00
Witten exc   1989070415observatio    10.0   102.3   157.0   16.40   0.00
Witten exc   1989070416observatio    10.0    49.0    43.3   16.40   0.00
Witten exc   1989081515observatio     0.0     0.0   228.0   29.10   0.00
Witten exc   1989092615observatio     4.9    49.3   193.0    0.50   0.00
Witten exc   1989092616observatio     4.9    23.6    20.8    0.50   0.00
Witten exc   1989112915observatio     5.0    45.5     0.0    0.00   0.00
Witten exc   1989112916observatio     5.0    24.6    15.9    0.00   0.00
file end     99990000  for GRASP
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Parameter file for Wongalee (WONG2.MRX)

Wongalee (N1) Spinifex heathland sandy yellowish earth PWJ

		PARAMETER values for mulga Charleville 1986/7	
26	22.0	SW(2,1) Layer 1 maximum soil moisture (mm).	15
27	85.0	SW(2,2) Layer 2 maximum soil moisture (mm).	16
28	95.0	SW(2,3) Layer 3 maximum soil moisture (mm).	17
19	1.1	AIRDRY Layer 1 air dry soil moisture content (mm).	19
29	2.1	SW(3,1) Layer 1 wilting point soil moisture (mm).	20
30	7.0	SW(3,2) Layer 2 minimum soil moisture (mm).	21
31	40.0	SW(3,3) Layer 3 minimum soil moisture (mm).	22
		TREE WATER USE	237
291	0.5	MATURE TREE BASAL AREA	
292	1.0	Layer 1 minimum soil moisture (mm) with trees	239
293	5.0	Layer 2 minimum soil moisture (mm) with trees.	240
294	35.0	Layer 3 minimum soil moisture (mm) with trees.	241
295	110.0	Layer 4 available water (trees only)	242
296	300.0	Maximum rooting depth of trees in cm	243
297	1.4	Tree Root length at surface, rl= p297*exp(-p298*z)	
298	0.6	Tree Root length exponent, rl= p297*exp(-p298*z)	
		STARTING SOIL MOISTURE also used when p289 is a date	28
23	5.0	SW(9,1) Starting value for soil moisture layer 1 (mm).	29
24	30.0	SW(9,2) Starting value for soil moisture layer 2 (mm).	30
25	48.0	SW(9,3) Starting value for soil moisture layer 3 (mm).	31
33	8.0	EPLIM Upper limit to daily soil evaporation (mm/day)	26
		RUNOFF	33
270	0.0	0 for free draining soils, 1for runoff as a f(yield)	35
271	1150.0	yield at 50% cover for run-off calculation	36
272	1.0	k value in cover=y**k / (y**k + p271**k)	37
273	1.0	maximum runoff of rainfall at zero cover, wet soil	38
104	0.9	constant in I15 equation I15=p104+p105*cos(dayno+15)	43
105	0.6	slope in I15 equation I15=p104+p105*cos(dayno+15)	43
45	1000.0	green yield (kg/ha) when green cover for transpiration is 50%	58
46	1300.0	green yield (kg/ha) when radiation interception is 50%	70
209	4.0	TIX 1=FSS, 2=GP , 3= NP ,4= use p61 and p62 ,5= tix=1.0	62
		6=maize, 7=combined NP, 8=NP f(max,min)	63
61	14.0	If temp is less than P61, temperature index (TIX) is zero.	64
62	24.0	As temp increases from P61 to P62, TIX increases from 0 to 1.	65
63	40.0	As temp increases from P62 to P63, TIX remains at 1.	66
64	50.0	As temp increases from P63 to P64, TIX decreases from 1 to 0.0	67
5	2.7	Initial plant density e.g. % basal area	74
6	4.5	Potential daily regrowth rate (kg/ha/day/unit of density)	75
7	10.0	Transpiration efficiency (kg/ha/mm of transpired at vpd 20 mb	81
149	0.1	Soil water index at which above-ground growth stops.	102
9	0.1	Soil water index. Maximum green cover = amin1(0.99,swix/p(9))	106
11	2.0	Minimum sreen temperature (c) at which green cover = 0%	107
13	0.0	Prop of standing dry matter detached per day. DETAC = P13* SDM2	84
258	601.0	Detachment of old pool begins month,day	112
96	20.0	Height (cm) of 1000 kg/ha	90
97	4.0	N uptake (kg/ha) at zero transpiration, N=p(97)+p(98)*(trans/100	246
98	7.0	N uptake per 100 mm of transpiration	247
99	5.0	Maximum N uptake (kg/ha)	248
101	0.4	% N at zero growth Nitrogen index = (%N-p101)/(p102-p101)	250
102	0.5	% N at maximum growth Nitrogen index = (%N-p101)/(p102-p101)	251
108	0.0	Proportional decline per day in % N for green material	
109	0.0	Proportional decline per day in % N for dead material	
100	2.5	Maximum % N in growth	249
110	1.0	Minimum % N in green & maximum in dead NOT USED in gvt72	

```
111        0.6  Minimum % N in  dead
263    44021.0  Station no. of AUSTCLIM station from menu option(39039=GAYNDAH)    155
264       70.0  No. of daily (rainfall) station in pmbstat2.pat, 1=BrianPastures   156
250        6.0  if=1 full daily met data, if=3  weekly austclm                     157
                4=daily rain in dr2 format, with either AUSTCLIM or station p269   158
                6=daily rain + daily climate, no in p269 type 1                    159
269       10.0  monthly climate station type 5 in pmbstat2, if=0 AUSTCLIM          160
211        7.0  if=1-365 gives output of observed & predicted , and
                simulated : 365=yearly,91=seasonally,30=monthly,
                7=weekly,1=daily,999=each observation,mndy=monthday
                output in mongro15.ogp or m1
206      550.0  Number of days in simuln run,last date : 1st Mar 1986=198603       150
284        0.0  if=1 TE output to file pasture9.ogp, p246 must be 132              200
300        0.0  Indicates end of parameter file                                    253
```

```
Wongalee   19880922 2 reset yld    0.0    50.0     0.0    0.00   0.00
Wongalee   1988092214reset soil    5.4    29.0    47.7    0.00   0.00
Wongalee   1988092216observatio    5.4    29.0    47.7    0.00   0.00
Wongalee   1988120715observatio    0.0     0.0    83.0    4.50   0.00
Wongalee   1988120719observatio    0.0     0.0     0.0    4.50   0.00
Wongalee   1989011615observatio    1.9    55.4   225.0   10.40   0.00  30 in 13
Wongalee   1989011616observatio    1.9     9.6    43.9   10.40   0.00  30 in 13
Wongalee   1989022715observatio    1.6    50.8   335.0    8.50   0.00  30.0
Wongalee   1989022716observatio    1.6     7.6    41.6    8.50   0.00  30.0
Wongalee   1989041015observatio    7.3   106.7   492.0    4.90   0.00
Wongalee   1989041016observatio    7.3    40.9    58.5    4.90   0.00
Wongalee   1989052215observatio   17.7   211.2   676.0    0.00   0.00
Wongalee   1989052216observatio   17.7    85.0   108.5    0.00   0.00
Wongalee   1989070315observatio   21.8   185.6   318.0    8.90   0.00
Wongalee   1989070316observatio   21.8    75.6    88.2    8.90   0.00
Wongalee   1989081415observatio    0.0     0.0   311.0    9.40   0.00
Wongalee   1989081419observatio    0.0     0.0     0.0    9.40   0.00
Wongalee   1989092515observatio    9.5   151.5   314.0   13.60   0.00
Wongalee   1989092516observatio    9.5    56.9    85.1   13.60   0.00
Wongalee   1989112815observatio    3.8    80.2   621.0   22.10   0.00
Wongalee   1989112816observatio    3.8    27.5    48.9   22.10   0.00
Wongalee   1990021215observatio    1.0    48.4     0.0    0.00   0.00  30.0
Wongalee   1990021216observatio    1.0     7.2    40.2    0.00   0.00  30.0
file end   99990000  for GRASP
```

Appendix 8. Observed and predicted green cover (%) of pasture from nine native pasture primary productivity sites in south-west Queensland.

Site and Date	Observed Green Cover (%)	SD	Predicted Green Cover (%)
Biddenham			
21.11.86			
17.12.86	13.1 g	7.6	6.3
07.01.87	16.5 g	7.8	10.3
26.02.87	44.9 h	14.0	40.1
18.03.87	16.8 g	9.6	15.7
08.04.87	6.8 ef	4.5	12.8
29.04.87	4.1 c-f	2.3	8.6
21.05.87	2.9 b-d	2.9	11.6
12.06.87	0.6 a	1.2	7.8
24.06.87	2.0 a-c	1.8	7.4
16.07.87	1.2 ab	1.4	7.1
11.08.87	3.9 b-e	3.3	7.0
26.08.87	7.9 f	7.3	8.1
18.09.87	5.5 d-f	3.9	10.0
08.10.87	5.3 d-f	3.1	13.6
29.10.87	7.0 ef	5.5	21.2
25.11.87			
10.12.87			
Charleville			
24.10.86			
05.12.86	16.7 de	7.8	5.9
31.12.86	9.1 bc	5.5	5.7
21.01.97	8.9 bc	6.3	7.1
11.02.87	19.6 e	13.2	11.7
04.03.87	29.3 f	16.5	18.1
26.03.87	17.1 de	8.9	14.2
16.04.87	18.4 e	8.9	18.6
20.05.87	6.6 b	4.9	14.8
11.06.87	0.0 a	0.0	6.1
01.07.87	10.4 b-d	4.1	7.3
29.07.87	11.3 b-d	6.0	10.1
19.08.87	12.5 c-e	5.8	15.0
02.09.87	16.3 de	8.0	21.1
23.09.87	16.6 de	8.0	22.8
15.10.87	8.9 bc	5.1	13.1
05.11.87			
26.11.87			

Appendix 8 Continued

Site and Date	Observed Green Cover (%)	SD	Predicted Green Cover (%)
Airlie			
10.11.88			
16.01.89	2.3 a	2.7	0.6
27.02.89	2.6 a	2.1	2.7
10.04.89	6.8 b	5.1	4.2
03.07.89	12.2 c	6.3	15.6
14.08.89	14.5 cd	5.5	15.3
25.09.89	21.3 d	5.8	17.4
28.11.89	33.6 e	6.3	40.1
12.02.90			
Lisnalee			
13.01.89			
02.03.89	24.2 d	5.9	29.9
14.04.89	59.1 f	14.4	59.8
23.05.89	43.0 e	14.1	58.4
06.07.89	0.0 a	0.0	0.3
17.08.89	2.1 b	1.4	0.0
28.09.89	7.5 c	3.7	2.4
01.12.89	10.2 c	4.5	23.8
20.02.90	0.2 a	0.1	36.7
11.05.90	81.6 g	14.4	71.0
22.11.90			
Maxvale			
14.09.88			
09.12.88	0.3 ab	0.6	1.9
19.01.89	2.6 cd	2.0	4.4
01.03.89	0.2 a	0.6	2.5
13.04.89	7.0 d	4.8	5.0
22.05.89	M	NC	8.4
05.07.89	26.7 f	7.9	19.8
17.08.89	19.6 ef	10.2	29.3
28.09.89	16.7 e	8.1	32.1
01.12.89	3.1 bc	4.8	23.1
20.02.90			

Appendix 8 Continued

Site and Date	Observed Green Cover (%)	SD	Predicted Green Cover (%)
Turn Turn			
20.09.88			
07.12.88	0.2 a	0.4	1.8
17.01.89	0.5 a	1.0	0.0
28.02.89	1.1 a	3.2	0.0
11.04.89	1.6 a	2.0	2.0
04.07.89	21.4 c	7.1	21.0
15.08.89	18.2 c	7.3	17.8
26.09.89	7.0 b	2.8	10.7
29.11.89	5.0 b	4.8	2.9
13.02.90			
Wittenburra Open			
21.09.88			
07.12.88	0.3 a	0.9	0.0
17.01.89	3.4 b	2.7	0.7
28.02.89	0.3 a	0.9	0.4
11.04.89	0.5 a	0.7	1.3
04.07.89	6.7 c	2.8	18.5
15.08.89	10.7 c	9.0	21.5
26.09.89	5.9 bc	1.0	13.5
Wittenburra Enclosed			
21.09.88			
07.12.88	0.0 a	0.0	0.1
17.01.89	1.1 a	1.6	0.5
28.02.89	0.3 a	0.3	0.0
11.04.89	0.7 a	1.0	0.8
04.07.89	16.4 b	16.3	20.4
15.08.89	10.4 b	9.1	19.4
26.09.89	0.5 a	0.7	11.5
29.11.89			
Wongalee			
22.09.88			
07.12.88	4.5 a	2.8	5.2
16.01.89	6.0 a	15.0	2.9
27.02.89	8.5 b	7.6	1.6
10.04.89	4.9 a	4.8	9.4
22.05.89	M	NC	23.7
03.07.89	8.9 b	6.2	0.4
14.08.89	9.4 b	6.2	0.0
25.09.89	13.6 bc	9.1	3.3
28.11.89	27.3 c	3.6	27.2
12.02.90			

Appendix 9. Detailed annual rainfall (mm), tree and shrub foliage projected canopy cover (FPC%) for 77 land systems (Dawson 1974 and Mills and Lee 1990) encountered in the assessment of 20 grazing properties in south-west Queensland.

Land System	Area (ha)	Rainfall (mm)	Tree (FPC %)	Shrub (FPC %)	Total (FPC %)
A1	6991	385	0.0	0.0	0.0
A2	740	330	0.0	5.0	5.0
A2	848	310	0.0	0.0	0.0
A2	170	312	0.0	0.0	0.0
A2/A3	1225	300	0.0	3.0	3.0
A2/A3/W3	1776	320	0.0	0.0	0.0
A2/M2/W3	1170	312	0.0	0.0	0.0
A2/W3	2270	312	0.0	0.0	0.0
A2/W4	4512	303	0.0	0.0	0.0
A3	210	351	0.0	8.0	8.0
A3	138	380	1.0	5.0	6.0
A5/W4	5718	310	8.4	1.3	9.5
A6	1654	300	12.0	0.0	12.0
A6	2394	380	2.0	3.0	4.9
A6	1969	340	18.0	5.0	22.1
A6	1239	310	6.5	3.0	9.3
A6	316	303	5.5	6.0	11.2
C3	718	303	5.0	0.0	5.0
D1	312	399	7.5	10.0	16.8
D1	100	320	5.0	5.0	9.8
D7	1270	351	18.0	19.0	33.6
D7	1485	303	0.0	2.0	2.0
D7/S2	1292	351	11.0	20.0	28.8
D7/S2	9155	303	3.5	17.0	19.9
E1	1694	415	5.0	1.3	6.2
E1	176	450	13.0	0.0	13.0
E2	1837	500	9.8	3.6	13.0
E2	2269	425	9.2	5.0	13.7
E2	1671	385	11.6	10.0	20.4
E3	2090	490	11.0	5.0	15.5
E4	1646	415	12.5	1.5	13.8
E4	717	450	23.2	5.8	27.7
E4	1262	399	11.7	1.7	13.2
E4	2419	444	16.5	11.5	26.1
E4	2747	399	6.3	0.5	6.7
F2	132	340	0.0	0.0	0.0
F2	115	310	0.0	0.0	0.0
G1	110	351	20.0	18.0	34.4
G1	4147	300	10.0	3.0	12.7
G2	279	330	0.0	0.0	0.0
G2	6690	340	2.0	12.0	13.8
G2	262	340	6.0	5.0	10.7
G2	346	303	3.0	17.0	19.5
G2	1034	399	25.0	12.5	34.4

Appendix 9 Continued

Land System	Area (ha)	Rainfall (mm)	Tree (FPC %)	Shrub (FPC %)	Total (FPC %)
G2/H2	4796	330	12.0	7.0	18.2
G2/H2	501	330	0.0	12.0	12.0
G2/H2	6985	310	7.5	1.5	8.9
G2/H2	3644	310	6.9	1.0	7.8
G2/H2/H4	785	303	5.0	0.0	5.0
G3	2432	385	4.0	1.2	5.2
G4	3849	310	5.0	0.0	5.0
G5	134	330	15.0	10.0	23.5
G5	122	330	16.0	15.0	28.6
G5	1800	312	25.0	0.0	25.0
G5/W6	1460	300	12.0	9.0	19.9
G5/W6	1170	320	19.0	5.0	23.1
H1	6640	500	15.5	0.0	15.5
H1	3848	450	20.3	3.0	22.7
H1	421	330	5.0	10.0	14.5
H1cleared	416	490	1.0	0.0	1.0
H1natural	4408	490	25.4	0.0	25.4
H2	235	330	0.0	0.0	0.0
H2	4559	351	4.0	6.0	9.8
H2	3462	380	5.0	13.0	17.4
H2	12457	425	11.4	6.0	16.7
H2	2362	310	7.0	0.0	7.0
H2	13669	385	3.7	14.1	17.3
H2	4060	312	0.0	0.0	0.0
H2/G2	4566	300	5.0	0.0	5.0
H2/G2	4330	312	7.0	0.0	7.0
H2/G2	9840	312	0.0	0.0	0.0
H2/H4	3181	330	13.0	4.0	16.5
H2/H4	7221	300	6.0	1.0	6.9
H2/H4	928	380	6.0	6.0	11.6
H2/H4	6032	330	5.0	2.0	6.9
H2/H4	1310	312	0.0	0.0	0.0
H2/H4	2060	303	9.0	0.0	9.0
H2/M2	4065	300	15.0	0.0	15.0
H2/M2	1540	312	0.0	0.0	0.0
H3	15954	415	6.4	5.9	11.9
H3	684	450	19.5	0.0	19.5
H3	2606	351	1.0	15.0	15.9
H3	536	303	12.0	9.0	19.9
H3	12029	444	12.0	1.7	13.5
H3/H4	4905	303	6.7	9.5	15.6
H3/R3	3395	310	9.0	1.5	10.4
H3/R5	4711	351	0.0	4.0	4.0
H4	178	330	10.0	4.0	13.6
H4	2175	300	15.0	5.0	19.3
H4	553	399	6.0	0.0	6.0
H4	2029	310	1.0	1.5	2.5
H4	285	340	5.0	4.0	8.8
H4	9613	399	4.2	19.5	22.9
H4/G2	980	340	16.0	3.0	18.5
H4/G2	1536	310	6.0	4.0	9.8
H4/G2	6379	310	8.8	3.8	12.2

Appendix 9 Continued

Land System	Area (ha)	Rainfall (mm)	Tree (FPC %)	Shrub (FPC %)	Total (FPC %)
H4/H2	565	330	4.0	2.5	6.4
H4/H2	17024	340	7.0	3.0	9.8
H4/R2	8745	380	20.0	8.0	26.4
H4/R5	134	303	5.0	0.0	5.0
L1	874	415	0.0	0.0	0.0
L1	58	330	0.0	0.0	0.0
L1	902	351	27.0	12.0	35.8
L1	2640	399	0.0	0.0	0.0
L1	613	303	0.0	0.0	0.0
L1	1581	444	8.5	0.0	8.5
L2	499	450	10.4	0.0	10.4
L2	908	351	0.0	0.0	0.0
L2	891	320	3.5	4.0	7.4
L2	2576	399	5.2	0.8	6.0
M1	9899	500	15.4	0.0	15.4
M1	72	330	18.0	0.0	18.0
M1	1399	300	15.0	19.0	31.2
M1	678	380	13.0	5.0	17.4
M1	386	340	6.0	0.0	6.0
M1	1416	303	21.0	0.0	21.0
M1/M2	775	340	24.0	6.0	28.6
M1	3889	490	3.2	0.0	3.2
M1	6972	490	16.9	4.0	20.2
M1	3055	490	30.6	0.0	30.6
M2	12324	415	10.9	5.1	15.4
M2	1936	330	7.0	0.0	7.0
M2	16648	450	19.9	0.3	20.1
M2	1848	351	19.0	0.0	19.0
M2	3920	380	12.0	2.0	13.8
M2	26078	399	10.7	5.4	15.6
M2	2684	330	14.0	2.0	15.7
M2	253	310	15.0	0.0	15.0
M2	4588	340	18.0	0.0	18.0
M2	5050	312	14.2	0.0	14.2
M2	13500	444	12.0	9.6	20.4
M2	18958	399	12.2	13.3	23.9
M2/H2	1105	330	10.0	27.0	34.3
M2/H2	5913	351	12.0	5.0	16.4
M2/H2	4698	300	10.0	0.0	10.0
M2/H2	1126	380	7.0	5.0	11.7
M2/H2	2481	320	9.0	14.0	21.7
M2/M1	8414	351	19.0	0.0	19.0
M2/M1	2500	340	13.0	4.0	16.5
M2/M3	5203	380	12.0	8.0	19.0
M2/S2	1893	351	10.0	8.0	17.2
M2/S2	1964	303	14.5	2.0	16.2
M2cleared	2969	450	13.6	1.0	14.5
M3	144	330	20.0	8.0	26.4
M3	672	380	7.0	18.0	23.7
M4	4822	425	11.8	2.8	14.2
M4/H2	15302	340	13.0	6.0	18.2
M5	1978	385	10.3	7.0	16.5

Appendix 9 Continued

Land System	Area (ha)	Rainfall (mm)	Tree (FPC %)	Shrub (FPC %)	Total (FPC %)
N1	4953	450	6.0	26.3	30.8
N1	9100	399	12.7	15.0	25.8
N1	2200	444	11.3	18.4	27.6
N1	1951	399	0.0	7.0	7.0
R1	1124	490	30.0	0.0	30.0
R2	1382	415	8.4	37.3	42.6
R2	2681	425	10.3	38.3	44.7
R2	64	340	0.0	0.0	0.0
R2/H4	8375	300	0.0	7.0	7.0
R2/H4	3161	340	6.0	13.0	18.2
R3	5511	385	11.0	22.0	30.6
R5	6671	310	10.0	5.0	14.5
R5	280	312	0.0	0.0	0.0
R5	556	303	9.0	0.0	9.0
R6/H4/G5	7504	340	19.0	6.0	23.9
S2	4820	330	6.0	27.0	31.4
S2	6760	351	7.0	24.0	29.3
S2	166	385	18.0	2.0	19.6
S2	12635	320	10.6	20.6	29.0
S2	9310	312	8.0	23.6	29.7
S2	2505	399	5.3	14.0	18.5
S3	3660	312	8.6	14.5	21.9
W1	1064	415	5.0	0.0	5.0
W1	1418	330	5.0	0.0	5.0
W1	1878	330	5.0	0.0	5.0
W1	1131	385	11.0	5.6	16.0
W1/A3	1414	330	0.0	0.0	0.0
W2	413	330	0.0	8.0	8.0
W3	1172	330	0.0	24.0	24.0
W3	404	351	0.0	0.0	0.0
W3	584	340	0.0	0.0	0.0
W3	2374	340	11.0	7.0	17.2
W3	7310	312	0.0	0.0	0.0
W3/A2	2610	312	0.0	0.0	0.0
W3/A5	3230	312	0.0	0.0	0.0
W3/A6	7507	330	14.0	7.0	20.0
W3/G5	1280	340	15.0	7.0	21.0
W4	1194	380	8.0	0.0	8.0
W4	368	330	10.0	11.0	19.9
W4	970	312	0.0	0.0	0.0
W6	197	330	8.0	13.0	20.0
W6	515	300	0.0	0.0	0.0
W6	154	330	12.0	19.0	28.7
W6	695	340	25.0	0.0	25.0
W6	1151	385	20.0	0.0	20.0
W7	2250	312	0.0	0.0	0.0
Sum	658325				
Average	3393	357	8.7	5.6	13.7
Maximum	26078	500	30.6	38.3	44.7
Minimum	58	300	0.0	0.0	0.0

Appendix 10. Recent validation of the GRASP model to independent data from south-west Queensland.

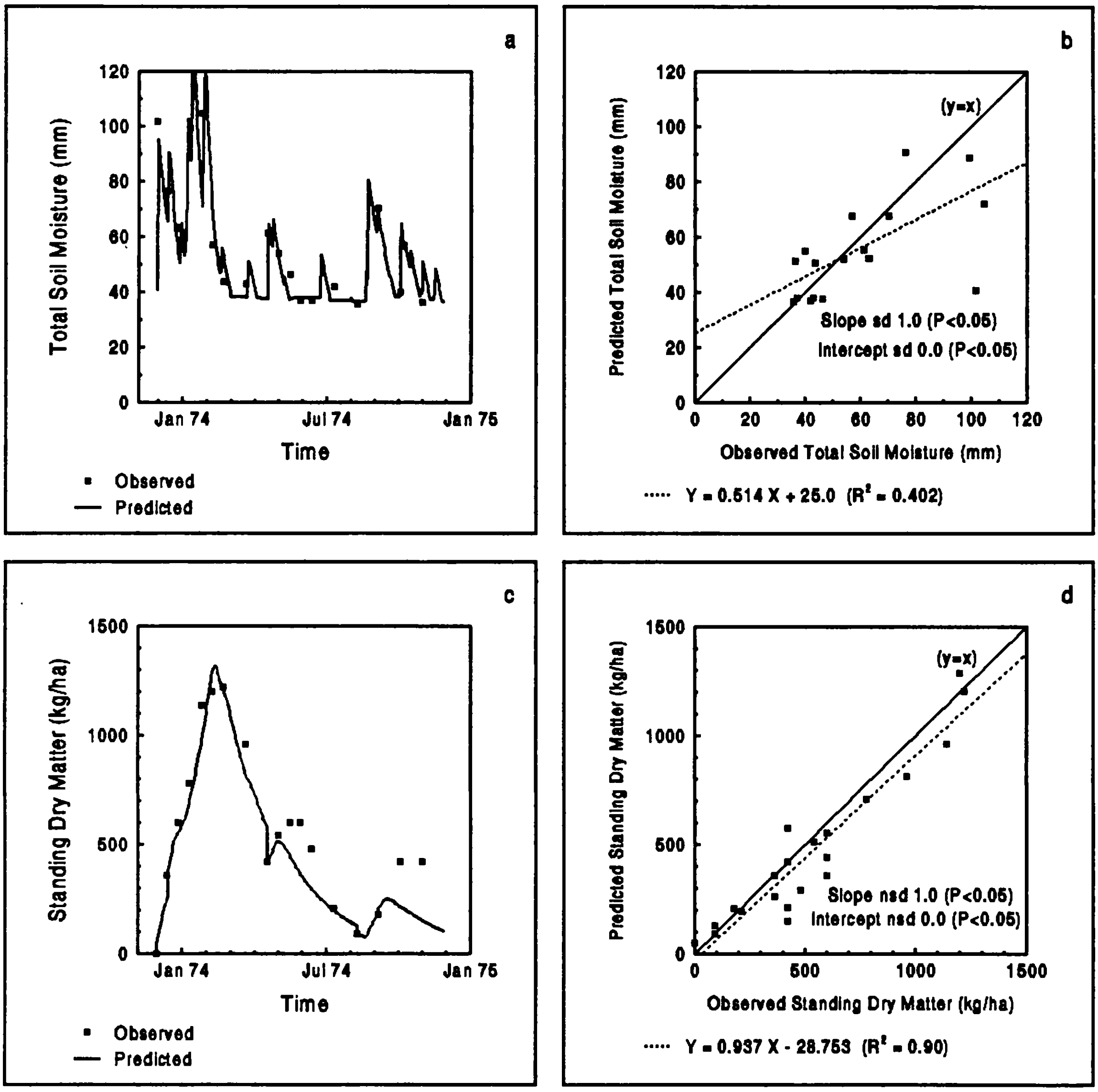

Figure 10.1 Predicted and observed standing dry matter and total soil moisture using the data of Christie (1978) to validate the GRASP model to mulga pastures near Charleville in south-west Queensland (Same data as Figure 4.14 on Page 68).

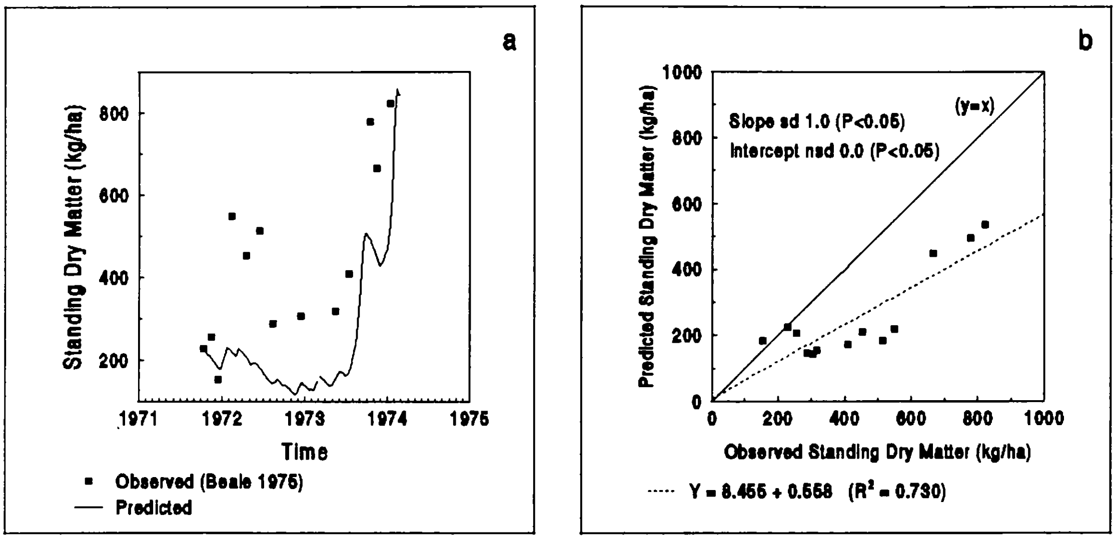

Figure 10.2 Predicted and observed standing dry matter using the data of Beale (1975) to validate the GRASP model to mulga pastures at 'Halton' near Charleville in south-west Queensland.

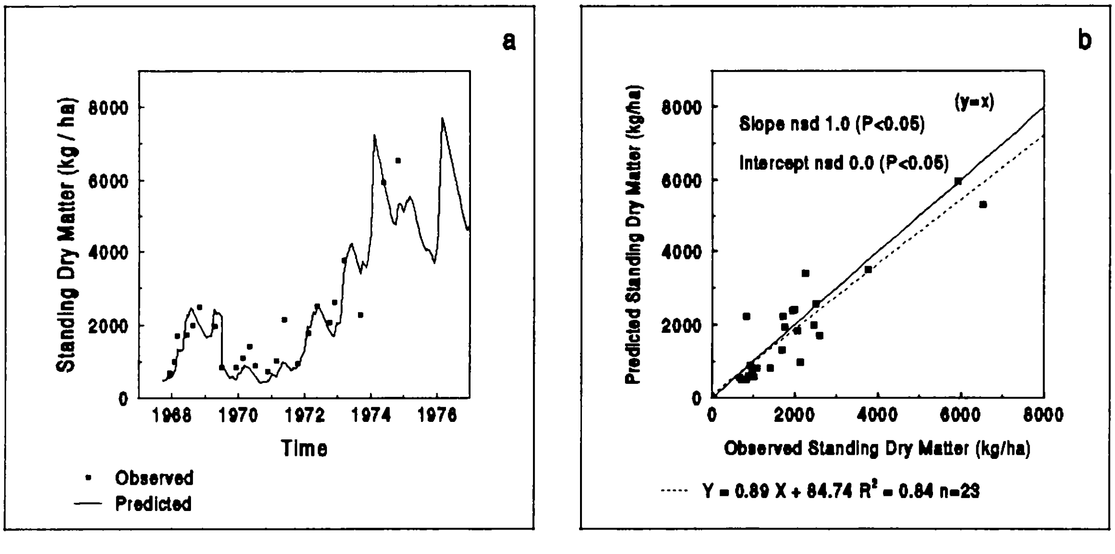

Figure 10.3 Predicted and observed standing dry matter using the data of Orr *et al.* (in prep.) to validate the GRASP model to buffel grass pastures on cleared gidyea country in the 'Eastwood' grazing trial (0.4 ha/DSE treatment) near Blackall in south-west Queensland.

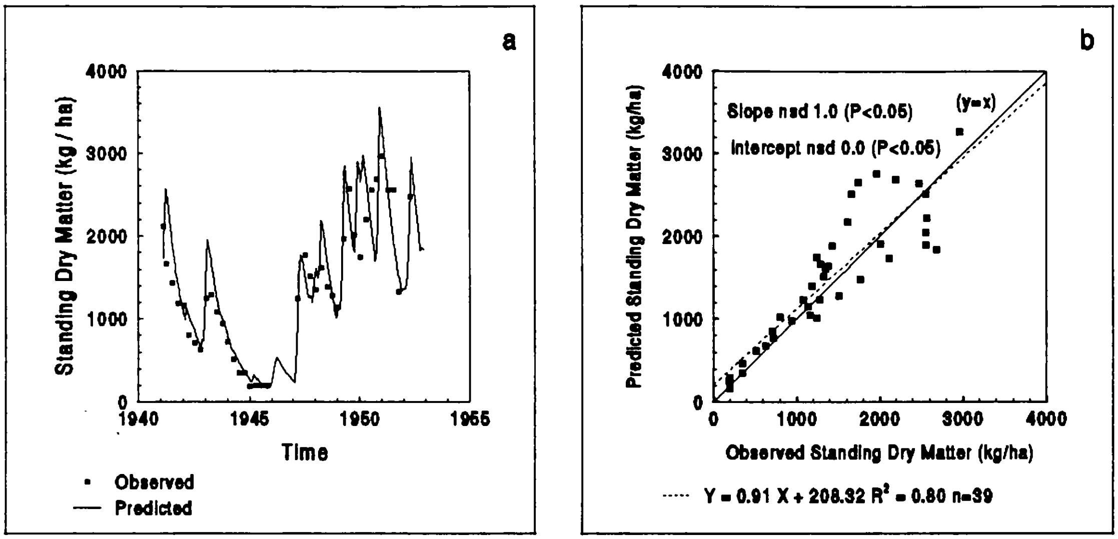

Figure 10.4 Predicted and observed standing dry matter using the data of Roe and Allen (1945,1993) to validate the GRASP model to mitchell grass pastures in the 'Gilruth Plains' grazing trial (1 DSE/2ha treatment) near Cunnamulla in south-west Queensland.

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