7 The effect of grazing management on stored soil water

"How much a profile will store depends on rainfall, soil permeability, evaporation from the bare soil surface and transpiration by vegetation." Johns *et al.* (1984)

7.1 Introduction

Productive use of stored soil water is an integral component of a sustainable and productive grazing system (Thurow 1991; Mason and Andrew 1998). However, little information is available for the North-West Slopes describing the change in stored soil water below natural pastures that are subjected to different grazing strategies.

Previous studies of pasture systems have indicated that grazing intensity may affect surface runoff, infiltration, soil evaporation, and canopy interception (Gifford and Hawkins 1978; Lang 1979; Warren *et al.* 1986; Weltz *et al.* 1989). In the current study, the impact of grazing intensity on herbage mass, litter mass and ground cover was documented in Chapter 4, showing that continuous grazing led to lower amounts compared with rotational grazing. Surface runoff from these pastures was influenced by a change in ground cover, which was associated with grazing management (Chapter 5). Bare soil areas may have high rates of evaporation when wet, leading to faster surface drying (Chapter 6). Grazing management may also influence canopy interception of rainfall (Dunkerley and Booth 1999) due to the effect on herbage and litter mass, resulting in less water entering the soil profile. In the current study, apart from the addition of subterranean clover to one treatment, species composition was not affected by grazing management. However, the percentage of green leaf varied seasonally, which may influence the transpiration capacity of the pastures and so drying of the soil profile.

Rooting depth of pastures in the current study was documented by Lodge and Murphy (2002*b*) and they reported that mean maximum depth was around 115 cm. Studies elsewhere have indicated that grazing management may influence root depth and distribution (Milchunas and Lauenroth 1993; Chaieb *et al.* 1996), and so the grazing management strategies used in the current study may alter the root depth and distribution. Plants with deeper and more extensive root systems may have the opportunity to access greater amounts of stored soil water (Lolicato 2000) and so increase drying of the soil profile.

Recent studies of stored soil water have used the neutron scattering technique (Greacen *et al.* 1981) to estimate volumetric water content. The technique was developed in the mid twentieth century and early work focussed on determining its accuracy and reliability (e.g. van Bavel 1962). Many studies have reported issues concerning the methodology of the neutron scattering technique and the intention of this investigation is to use the technique mindful of its limitations. The neutron scattering technique presents a number of sources of variation (calibration, equipment and location error) in the estimation of soil water content and a range of studies have reported on these (e.g. Sinclair and Williams 1979). However, the technique remains ideal for repeated non-destructive estimates of stored soil water in grazed pasture situations.

The grazing management strategies used in the current study, through their impact on pasture characteristics, surface runoff, rainfall interception, and evapotranspiration may also have an impact on the amount of stored soil water within the profile. The current chapter reports on the regular monitoring of stored soil water in each grazing treatment, in an attempt to relate these other losses of water to changes in stored soil water. The objective if this study was to quantify the seasonal change in stored soil water and the magnitude of wetting and drying events as induced by grazing treatments. Specific aims were:

a) to quantify changes in stored soil water in response to climate and grazing treatment;
b) to test the hypothesis that grazing management may be used to increase extraction of stored soil water by pasture; and
c) to test the hypothesis that natural pastures over-sown with subterranean clover will increase soil drying.

To address these aims, the soil profile was divided into sections that related to the distribution of pasture roots (Lodge and Murphy 2002*b*).

7.2 Methods

The soil water content was estimated for the total profile (0-210 cm) using two separate techniques according to depth within the profile. Sub-soil soil water content (10 to 210 cm depth) was estimated using the neutron scattering technique of Greacen *et al.* (1981) while surface soil water content (2.5 and 7.5 cm depth) was estimated using the electrical resistance sensor method (Chapter 3). Collectively, profile soil water content was determined as the sum of the volumetric water content of individual layers. Profile soil water content was estimated at approximately monthly intervals between October 1997 and September 2001, and provided data to compare grazing treatment differences through time. All stored soil water data was expressed as a depth equivalent (millimetres) to be comparable to rainfall depth.

Data used in the calibration of the neutron moisture meter such as the soil physical description, field texture, clay content, bulk density, and colours were reported in Chapter 3.

7.2.1 Neutron moisture meter

A CPN503-DR Hydroprobe (Boart Longyear Co., Martinez, CA.) neutron moisture meter (NMM) was used to estimate profile soil water content. The NMM had an Am-241/Be source with an activity rating of 50 mCi. This instrument was commercially available and was commonly used for the estimation of SWC within research and commercial operations at the time of this study.

The NMM access tubes were made of aluminium tubing (4.9 cm o.d., 0.25 cm wall thickness, and 220 cm in length) and were sealed at the bottom with an aluminium bung. The bungs were sealed with silicon rubber and blind riveted in place to prevent water from entering the tube. NMM access tubes were installed (3 per plot plus 1 per surface runoff plot) in September 1997. The tubes were aligned along the central axis of each plot to form an approximate grid pattern over the entire site (Figure 7-1). Four extra access tubes for destructive calibration purposes, were installed adjacent to the weather station.

Each access tube was installed using a tractor mounted, hydraulic push-coring machine. Firstly, soil cores were taken to a depth of 210 cm using hollow coring tubes (5.1 cm o.d., 4.6 cm i.d., 200 cm length). A jackhammer was used to push the coring tubes to maximum depth when hard soil conditions were encountered. Coring tubes were tipped with a cutting head made of hardened steel, which had an opening of 3.8 cm diameter. The narrow opening of the head helped to retain the soil core inside the tube when it was pulled from the ground. The soil cores were retained for use in calibration and physical analyses (Chapter 3).

Using this approach, all access tubes were installed to 210 cm except plot 7: tube 3, which had a maximum depth of 190 cm. Approximately one litre of kaolinite clay slurry (2.5 kg of clay to 2 L of water) was poured down each hole to fill any voids and ensure good contact between the access tube and soil. Each access tube was then pushed into its hole using the hydraulic ram. As the tube reached the bottom, clay slurry exuded from around the tube, ensuring that air spaces were filled. The tube tops were left approximately 10 cm above the soil surface. A cap (50 mm PVC plumbing end cap on a section of 50 mm PVC pipe) was placed on each tube top to prevent rain or runoff water from entering.

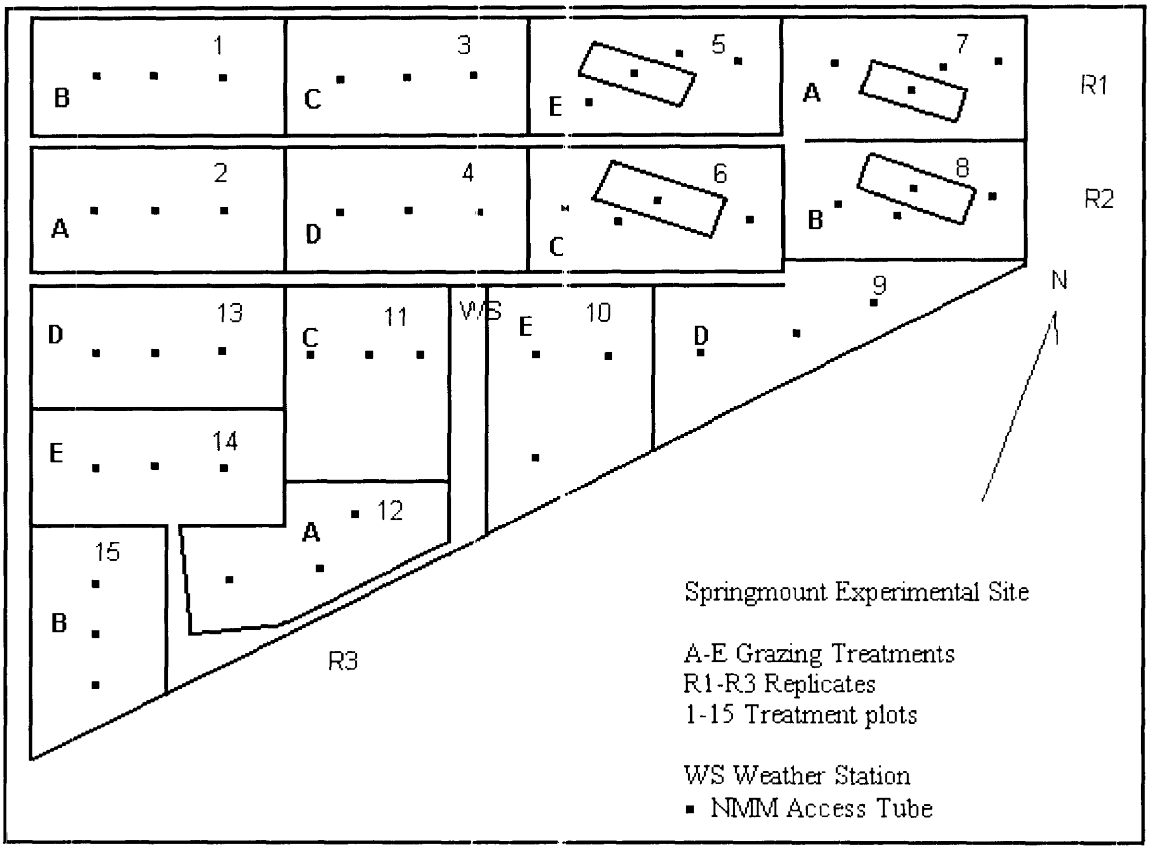

Figure 7-1. Approximate locations of neutron moisture meter access tubes at Springmount.

7.2.2 Calibration of the neutron moisture meter

The NMM was calibrated by determining the relationship between neutron count readings and soil water content for a range of soil samples (Greacen *et al.* 1981). Soil samples were collected in two stages: firstly, samples were collected during access tube installation, and secondly, when seasonal conditions were favourable (wet or dry). At the time of access tube installation, soil samples were retained from one core per plot to determine gravimetric and volumetric water content. This was done at five cm intervals down the profile and later averaged for 20 cm layers centred on the depth of neutron count readings. For these tubes, NMM counts were taken over a 16 s period at each depth the day after they were installed and it was assumed that soil water content did not change in the intervening period. Water held in the clay slurry was unlikely to influence the neutron count readings due its relatively low volume compared with the sphere of influence of the neutron source (15 cm diameter).

Four calibration tubes were used to collect specific calibration points at the extreme limits of water content. Dry calibration points (approximately 4 000 counts) were obtained during a period of below average rainfall (autumn 1998) when soils were dry. Wet calibration points (approximately 14 000 counts) were obtained during record rainfall conditions (spring 1998) when soil water content was at its peak. In addition, localised irrigation was used around one access tube to ensure neutron counts and soil water content values were maximal. Soil samples were obtained from the appropriate depths using a hand auger and were taken as close to the access tube as possible (< 20 cm) to ensure soil was taken within the sphere of influence of the neutron probe. Again, volumetric soil water content was determined using gravimetric water content and bulk density data.

Linear regression analysis ($\theta\% = aX + b$, where X = neutron count over 16 s) was used to determine the relationship between NMM count and gravimetric and volumetric water content (Figure 7-2, Table 7-1). Within the calibration data, neutron probe count ranged from 5 659 to 12 942 for dry and wet conditions, respectively. The wettest and driest values were recorded within 40 cm of the soil surface. Most calibration points were obtained during access tube installation (n=143) and a further 50 points were obtained from the dedicated calibration tubes. The effect of soil depth on the NMM calibration was investigated and it was found that no significant improvement could be made to the calibration by using multiple equations for multiple depths. Comparison of the linear regression equations for data collected from different depths showed that intercept and slope values were not significantly different, justifying a single calibration equation.

Table 7-1. Linear regression equations (Y = aX + b) relating neutron count (X) to gravimetric ($\theta_g\%$) or volumetric ($\theta_{vol}\%$) soil water content (Y) (values in parentheses are one se).

Soil Water Content	a	b	n	R^2
$\theta_g\%$	0.00164 (0.000079)	-1.995 (0.7852)	194	0.691
$\theta_{vol}\%$	0.00287 (0.000127)	-5.565 (1.2573)	194	0.729

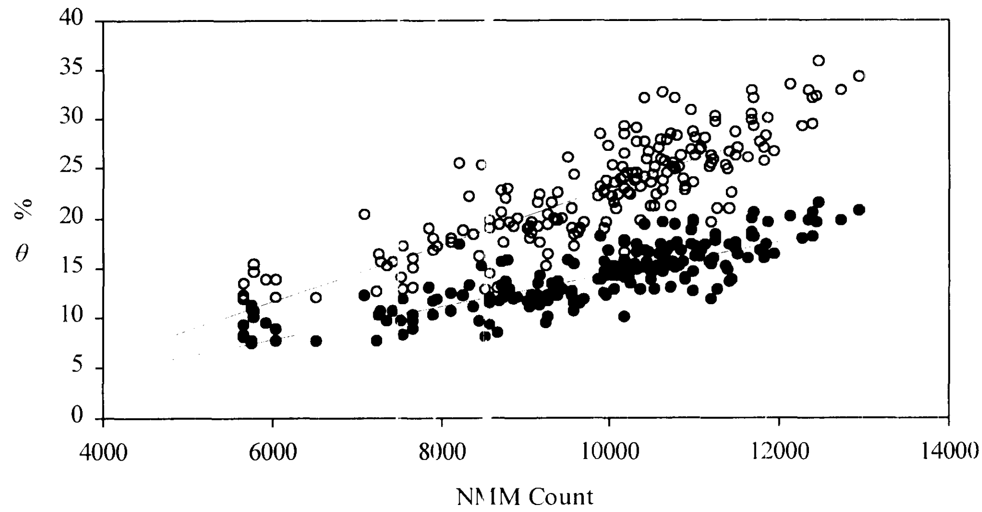

Figure 7-2. Calibration relationship between neutron moisture meter counts and soil water content (θ%) for θ_g% (•) and θ_{vol}% (○).

7.2.3 Measurement of soil water content using the neutron moisture meter

Boart Longyear Co. provided a range of typical count values recorded by the NMM in various media (Table 7-2). These data were used as reference points for data collected during both calibration and the experiment as a check on meter function. On each sample date, a standard count (mean of 16 s counts, n=30) was taken in a 200 L drum of water to monitor the activity of the neutron source (Figure 7-3). Linear regression analysis showed that the activity of the neutron source remained stable, with no significant change in count through time (Figure 7-3).

A 40 cm stand, made from steel exhaust pipe tubing with a galvanised plate base, was used to support the neutron moisture meter when taking counts. The stand provided a stable platform at a standard height above the soil surface, and minimised soil compaction and pasture disturbance. The soil profile was sampled in 20 cm layers (10-30, 30-50, 50-70, ...190-210 cm) with neutron counts taken in the centre of each layer, starting at the bottom of the access tube (200 cm depth) and raising the neutron source progressively to 20 cm depth. The soil profile was sampled at these intervals, as the sphere of influence of the neutron moisture meter in wet soil was approximately 15 cm in diameter. Neutron counts were converted directly to volumetric water content using the derived calibration equation. Equivalent stored soil water (mm) was calculated by multiplying the volumetric percentage by soil layer depth (e.g. 200 mm). Profile stored soil water was calculated as the sum of stored water for all layers.

Table 7-2. Range of typical count value for 16 s with standard deviation (SD) in various media for the neutron moisture meter as supplied by the manufacturer, Boart Longyear Co.

Medium	Count value	SD
Dry sand	189	18
Wet sand	13 706	100
Concrete*	6 445	1 934
Wax*	20 753	6 226
Water	19 513	144

* Values were recorded for a count of 256 s

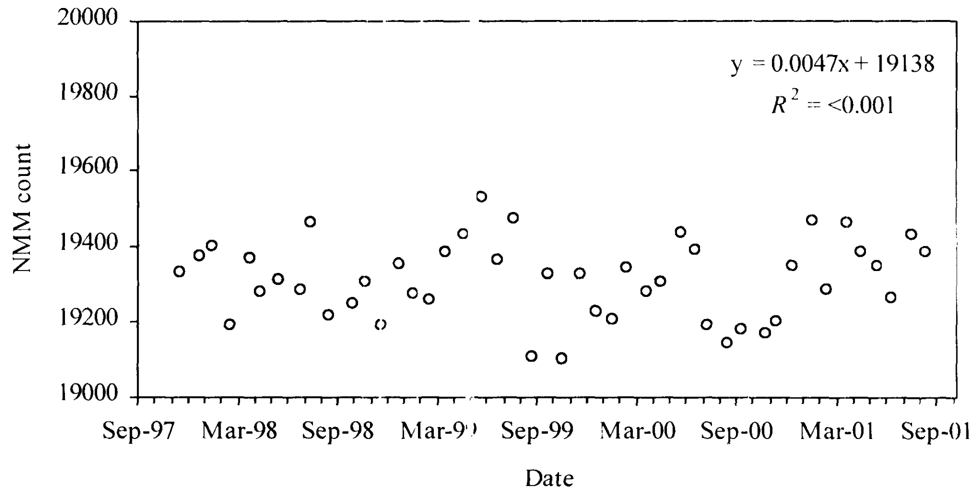

Figure 7-3. Neutron moisture meter standard counts (mean of 16 s counts, n=30) taken at each sample date in a drum filled with 200 L of water.

7.2.4 Surface stored soil water (0-10 cm)

The neutron scattering technique was not suitable for estimating stored soil water between the soil surface and 10 cm depth due to concerns for operator safety and neutron escape (Greacen *et al.* 1981; Johnston 2000). For four of the treatments (T1C4, T2C6, T3FERT8 and T5GR12) surface stored soil water (0 to 10 cm) was obtained directly from estimates by Watermark sensors installed (2.5, 5.0, 7.5 and 10 cm depths) in the surface runoff plot of those treatments (Chapter 3). The stored soil water estimated at 09:00 h on the day of NMM sampling was taken as representative for that treatment. For T4GR4, the mean of values taken from T1C4 and T5GR12 was used, as the herbage mass and ground cover conditions within T4GR4 were similar to these other treatments.

7.2.5 Profile stored soil water (0-210 cm)

Profile stored soil water was calculated as the sum of estimates of equivalent water depth (mm) for each 20 cm layer sampled using the NMM and the surface layer sampled using the Watermark sensor technique. Profile stored soil water data were used to explore the dynamics of soil water through time in response to rainfall, surface runoff and grazing treatment. Stored soil water was examined in four zones of the profile according to the root distribution estimated by Lodge and Murphy (2002*b*). The upper root zone (0-70 cm) contained 75% of pasture roots and was the zone where large changes in stored soil water were expected. The root zone (0-130 cm) included the maximum extent of pasture roots (c. 115 cm Lodge and Murphy 2002*b*) and represented the expected maximum depth of plant water extraction. The middle profile (70-130 cm) was within the lower limit of the root zone, and contained only about 25% of plant roots. The lower profile (130-210 cm) was beyond the pasture root zone and only small changes in stored soil water were expected in that layer.

Plant available water (PAW) was defined as stored soil water held at a potential high enough to be available to plants. It was estimated for each soil layer using two techniques:

a) laboratory, PAW = $\theta_{\mathrm{vol}}\% - \theta_{wp}\%$, where $\theta_{wp}\%$ is the estimated wilting point (ψ_s -1500 kPa); and
b) field, PAW = $\theta_{\mathrm{vol}}\% - \theta_{\mathrm{min}}\%$, where $\theta_{\mathrm{min}}\%$ represented the minimum water content recorded during the experiment.

The distribution of PAW within the profile was explored and its dynamics through time were recorded.

7.2.6 Data analysis

Analysis of variance (ANOVA) was used to determine treatment differences for stored soil water in each layer and profile zone at each sampling time using GENSTAT (Payne *et al.* 1988). Wetting and drying events were defined as consecutive monthly periods of increase or decrease in stored soil water, respectively, and graphing stored soil water data through time identified these. The duration of each phase ranged from one to six months. ANOVA was used to determine differences between treatments for the magnitude of each event. The magnitude of stored soil water change was used as in indicator of treatment differences in water extraction for each profile zone.

7.3 Results

7.3.1 Change in stored soil water through time with grazing treatment

Soil water content was sampled on 46 occasions between December 1997 and September 2001 at approximately monthly intervals (Figure 7-4). Profile stored soil water for all treatments showed a similar pattern of change in response to rainfall, but they showed no cyclical seasonal pattern (Figure 7-4). The maximum stored soil water was 598 mm (rotational grazing, T5GR12) recorded on 14 September 1998, while the minimum was 389 mm (subterranean clover, T3FERT8) recorded on 21 April 1998 (Figure 7-4 and Figure 7-5). Rainfall for the winter-spring period of 1998 was the highest on record for B irraba (Chapter 4, Clewett *et al.* 1999). Further peaks in stored soil water were observed in November 1999 (539 mm, T5GR12) and 2000 (539.4 mm, T5GR12) in response to high spring rainfall in those years. The subterranean clover treatment (T3FERT8) generally had a lower stored soil water compared with other treatments. Profile maxima and minima specific to each treatment are shown in Table 7-3 with their corresponding plant available water contents determined using the field technique, and the distribution of water within the profile at those times is shown in Figure 7-5.

Table 7-3. Mean profile (0-210 cm) minimum and maximum stored soil water (mm) for each grazing treatment at Springmount, together with the maximum plant extractable water and site mean.

Sample Date	T1C4	T2C6	T3FERT8	T4GR4	T5GR12	Mean Site
21 April 1998	419	411	389	398	402	404
14 September 1998	585	592	574	571	598	584
PAW[#]	166[a]	181[a b]	186[a b]	173[a]	196[b]	180

[#] PAW with same superscript are not significantly different based on least significant difference between means ($P<0.05$, least significant difference between means was 22 mm)

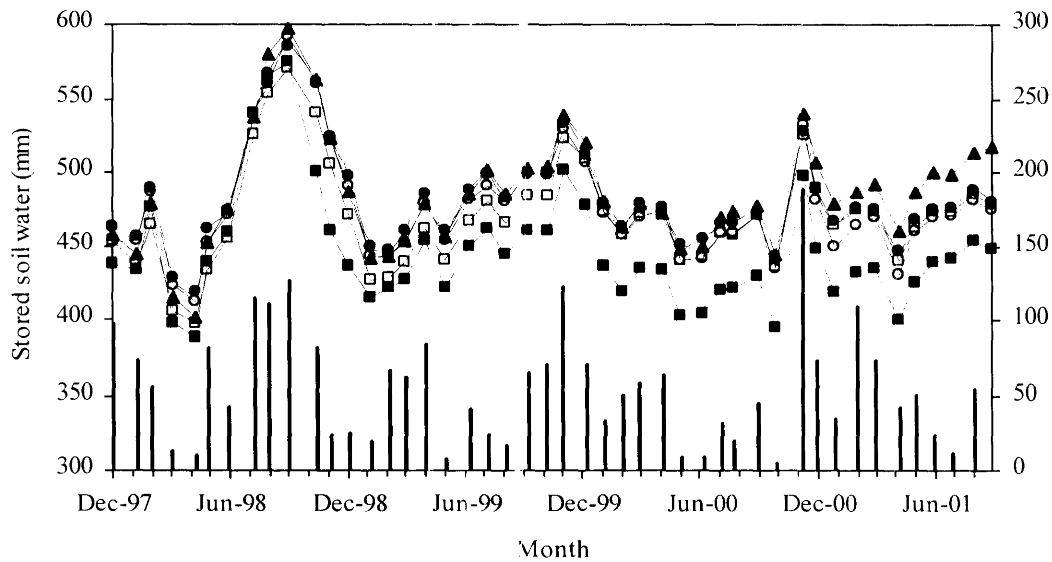

Figure 7-4. Monthly profile (0-210 cm) stored soil water (mm) for grazing treatments at Springmount, T1C4 (●), T2C6 (○), T3FERT8 (■), T4GR4 (□), and T5GR12 (▲) with cumulative rainfall (mm, vertical bars) between sample dates.

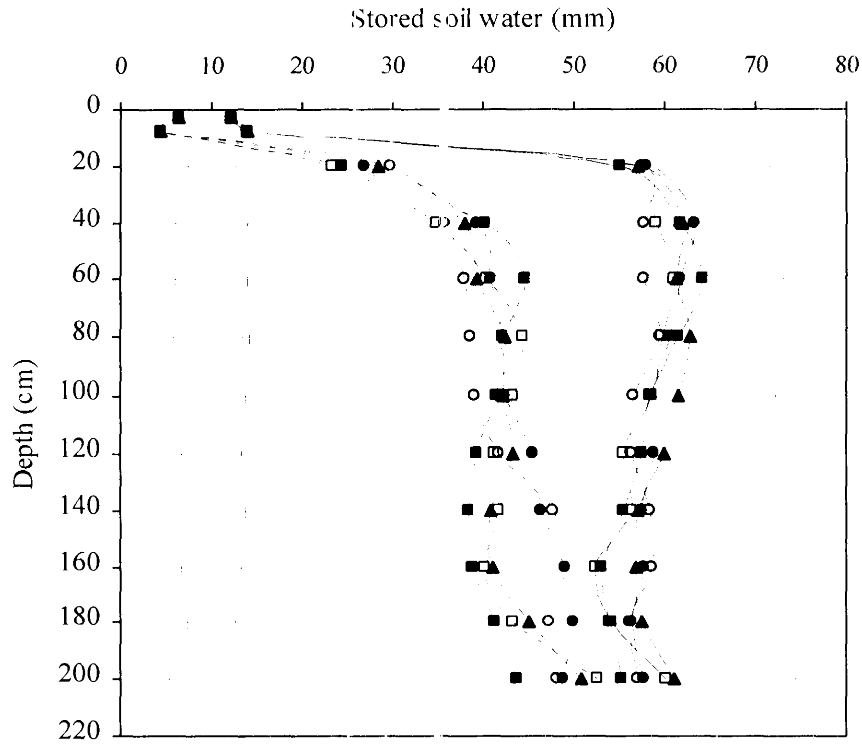

Figure 7-5. Profile (0-210 cm) distribution of soil water for maximum (solid line) and minimum (dashed line) stored soil water conditions for each grazing treatment at Springmount, T1C4 (●), T2C6 (○), T3FERT8 (■), T4GR4 (□), and T5GR12 (▲) (horizontal bars indicate one standard error of the difference of means).

7.3.2 Total profile stored soil water (0-210 cm)

Total profile stored soil water ranged from 389 mm (T3FERT8, 21 April 1998) after a period of below average rainfall to 598 mm (T5GR12, 14 September 1998) following record rain (Figure 7-6). Treatment means at each of these times were not significantly different (P>0.05).

There were few differences among grazing treatments for stored soil water through out the experimental period. In spring and early summer 1998 (October to December), the subterranean clover treatment (T3FERT8) had lower (P<0.01) values compared with all other treatments (Figure 7-6). In addition, subterranean clover had lower stored soil water (P<0.05) compared with other treatments for the periods, January to August 2000, October and December 2000, and January, February and April 2001. For December 1998, the stored soil water for T4GR4 was lower than T1C4 (Figure 7-6). There were no other significant differences between treatments at any time.

Fifteen wetting and drying events of different duration and magnitude were examined. Wetting events ranged from 21 to 196 mm for May to September 2000 (T1C4) and April to September 1998 (T5GR12), respectively. Drying events ranged from -12 to -160 mm for February to May 2000 (T1C4) and September 1998 to January 1999 (T3FERT8), respectively. The only significant difference ($P<0.05$) for drying events among treatments was for November 2000 to January 2001 with T2C6 and T3FERT8 (-83 and -79 mm, respectively) drying the profile more than other treatments (-61 to -62 mm, Table 7-4). These treatments also had larger wetting events in the preceding cycle (98 and 103mm, respectively), but were not significant ($P>0.05$, Table 7-4).

Table 7-4. Change in profile (0-210 cm) stored soil water (mm) for wetting (W) and drying (D) events for grazing treatments at Springmount.

Period	Wetting / Drying	T1C4	T2C6	T3FERT8	T4GR4	T5GR12	lsd (mm)
October to November 2000	W	85	98	103	90	95	20
November 2000 to January 2001	D	-61^{b}	-83^{a}	-79^{a}	-62^{b}	-61^{b}	15

NB. Same superscripts for each event denote similar values ($P<0.05$), where there are no superscripts, there were no significant differences.

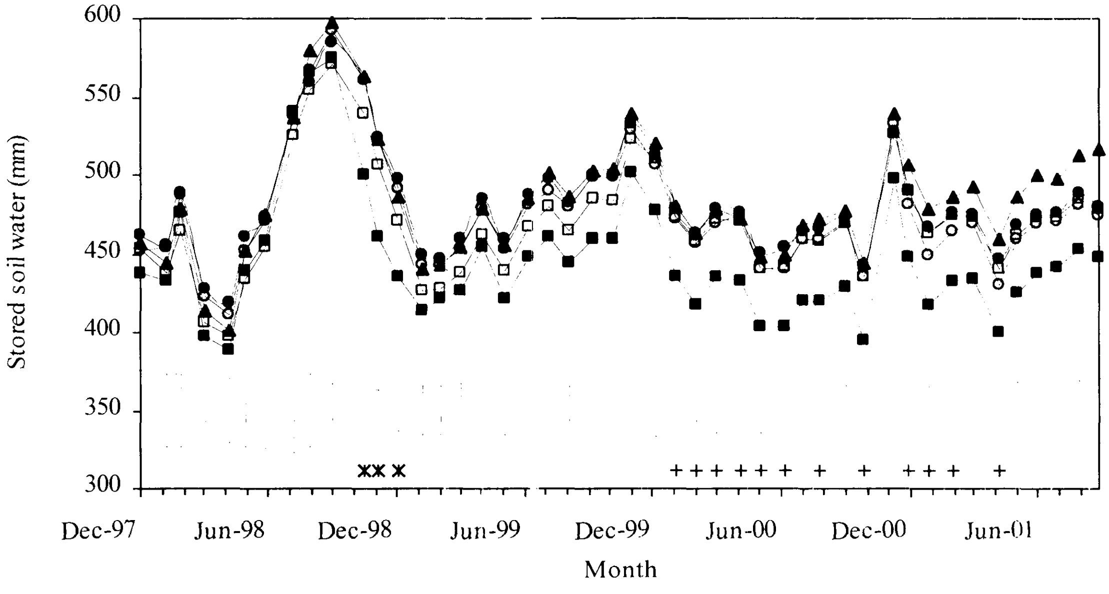

Figure 7-6. Monthly profile (0-210 cm) stored soil water (mm) for each grazing treatment at Springmount, T1C4 (●), T2C6 (○), T3FERT8 (■), T4GR4 (□), and T5GR12 (▲). Vertical bars indicate least significant difference between treatments for stored soil water. Significant differences are indicated by + ($P<0.05$) and * ($P<0.01$).

7.3.3 Upper root zone stored soil water (0-70 cm)

Upper root zone stored soil water was highly variable as it responded to rainfall and drying events (Figure 7-7). Stored soil water ranged from 105 to 211 mm for March 1998 (T4GR4) and July 1998 (T3FERT8), respectively. The only significant difference between treatments was recorded on the last sampling date (September 2001) with T5GR12 having higher stored soil water ($P<0.05$) than other treatments (Figure 7-7).

Wetting and drying events in the upper root zone were examined on 15 occasions, but differed among treatments for only six of these events (Table 7-5). Wetting events ranged from 1 to 97 mm for January to April 2001 (T3FERT8) and April to July 1998 (T3FERT8), respectively. Drying events ranged from -3 to -85 mm for December 1997 to April 1998 (T3FERT8) and July to November 1998 (T3FERT8), respectively. The treatment with subterranean clover (T3FERT8) showed the largest drying event (-85 mm) compared with other treatments for the period July to November 1998 (Table 7-5). In the subsequent period from November 1998 to January 1999, T3FERT8 dried significantly less than other treatments (-12 mm), as the soil had already dried.

Also, for the wetting event October to November 2000, rotationally grazed treatments (63 and 69 mm, T5GR12 and T4GR4, respectively) wet less ($P<0.05$) compared with continuously grazed treatments (75 and 80 mm, T2C6 and T3FERT8, respectively). In the following drying period (November 2000 to January 2001) the continuously grazed treatments dried significantly ($P<0.01$) (-74 and -68 mm, T2C6 and T3FERT8, respectively) compared with the rotationally grazed treatments (-58 and -55 mm, T4GR4 and T5GR12, respectively). The final wetting event of April to September 2001 showed that stored soil water for the rotationally grazed treatment (T5GR12) increased (41 mm) significantly compared with all other treatments. For this same period, subterranean clover (T3FERT8, 33 mm) also increased significantly compared with continuous grazing (T1C4, 23 mm).

Table 7-5. Change in upper root zone (0-70 cm) stored soil water (mm) for wetting (W) and drying (D) events for each grazing treatment at Springmount.

Period	Wetting / Drying	T1C4	T2C6	T3FERT8	T4GR4	T5GR12	lsd (mm)
July to November 1998	D	-55^{a}	-57^{a}	-85^{b}	-55^{a}	-59^{a}	14
November 1998 to January 1999	D	-33^{a}	-32^{a}	-12^{b}	-34^{a}	-33^{a}	6
October to November 2000	W	71^{ac}	75^{ac}	80^{a}	69^{bc}	63^{b}	10
November 2000 to January 2001	D	-60^{c}	-74^{a}	-68^{ac}	-58^{b}	-55^{b}	8
January to April 2001	W	-2^{b}	5^{c}	1^{b}	-2^{b}	6^{ac}	5
April to September 2001	D	23^{b}	28^{bc}	33^{c}	29^{bc}	41^{a}	7

NB. Same superscripts for each event denote similar values ($P<0.05$), where there are no superscripts, there were no significant differences.

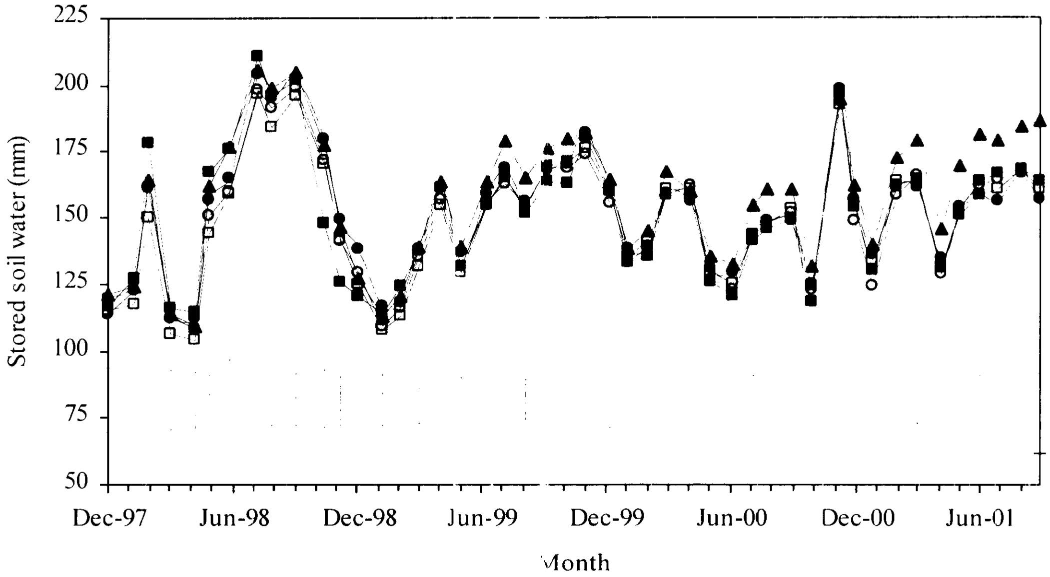

Figure 7-7. Monthly upper root zone (0-70 cm) stored soil water (mm) for grazing treatments at Springmount, T1C4 (●), T2C6 (○), T3FERT8 (■), T4GR4 (□), and T5GR12 (▲). Vertical bars indicate the least significant difference between treatments for stored soil water. Significant differences are indicated by + (P<0.05).

7.3.4 Root zone stored soil water (0-130 cm)

Root zone stored soil water was also highly variable, following the same pattern through time as for the upper root zone (Figure 7-8). Maximum and minimum stored soil water values were recorded at the same time as for the total profile, with 370 and 226 mm for September 1998 (T5GR12,) and April 1998 (T2C6), respectively. The subterranean clover treatment (T3FERT8) had significantly (P<0.05) less stored soil water (270 mm) compared with other treatments for November 1998. Rotational grazing (T5GR12) had a higher value (337 mm) in September 2001. At all other times, there were no significant differences between treatments (Figure 7-8).

Within the root zone, there were four occasions where treatments differed in their wetting or drying response (Table 7-6). For the period July to November 1998, the drying response of T3FERT8 (-104 mm) was significantly greater than all other treatments, and subsequently it dried less in the next period from November 1998 to January 1999 (-28 mm). The drying responses of T2C6 and T3FERT8 between November 2000 and January 2001 (-87 and -79 mm, respectively) were greater (P<0.05) compared with the other treatments (-64, -66, and -65 mm for T1C4, T4GR4 and T5GR12, respectively). The final wetting event between April and September 2001 was greater (P<0.05) for T5GR12 (55 mm) compared with T1C4 and T4GR4 (30 and 37 mm, respectively).

Table 7-6. Change in root zone (0-130 cm) stored soil water (mm) for wetting (W) and drying (D) events for each grazing treatment at Springmount.

Period	Wetting / Drying	T1C4	T2C6	T3FERT8	T4GR4	T5GR12	lsd (mm)
July to November 1998	D	-45 [b]	-45 [b]	-104 [a]	-50 [b]	-54 [b]	32
November 1998 to January 1999	D	-62 [b]	-67 [b]	-28 [a]	-62 [b]	-64 [b]	15
November 2000 to January 2001	D	-64 [b]	-87 [a]	-79 [a]	-66 [b]	-65 [b]	15
April to September 2001	W	30 [bd]	42 [cd]	43 [cd]	37 [bd]	55 [ac]	16

NB. Same superscripts for each event denote similar values ($P<0.05$), where there are no superscripts, there were no significant differences.

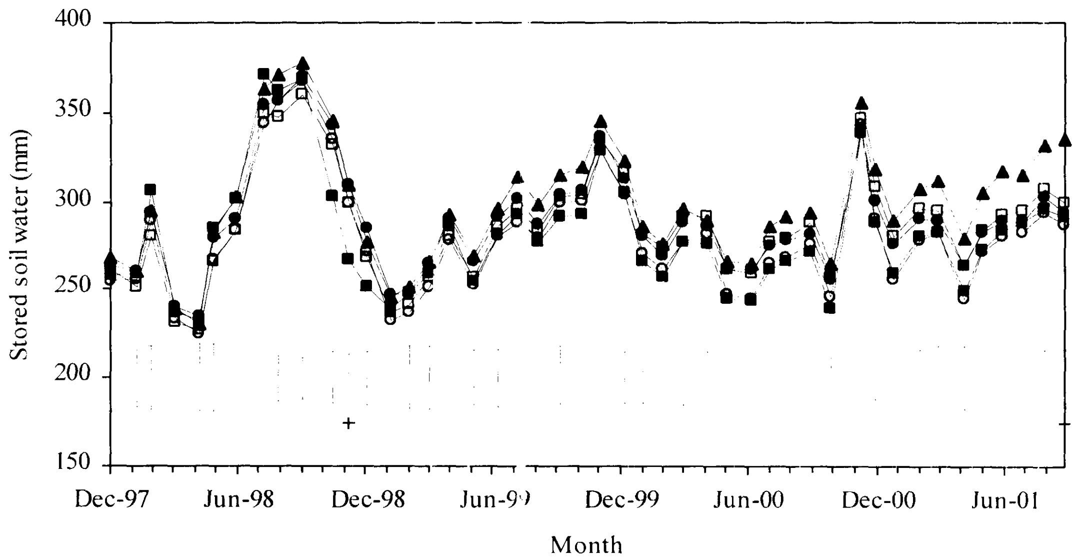

Figure 7-8. Monthly root zone (0-130 cm) stored soil water (mm) for grazing treatments at Springmount, T1C4 (●), T2C6 (○), T3FERT8 (■), T4GR4 (□), and T5GR12 (▲). Vertical bars indicate the least significant difference between treatments for stored soil water. Significant differences are indicated by + ($P<0.05$).

7.3.5 Middle profile stored soil water (70-130 cm)

Stored soil water within the middle profile was less variable than upper layers and showed three distinct wet periods of short duration (Figure 7-9). Stored soil water varied between 115 and 174 mm for April 1998 (T2C6) and September 1998 (T5GR12), respectively. The minimum values for this layer were recorded shortly after those at shallower depths within the profile. Peaks in stored soil water were short-lived, returning to lower values within three months of the peak. The only significant difference for stored soil water between treatments was recorded in

November 1998, with subterranean clover (T3FERT8) having a lower value compared with other treatments.

Within the middle profile, there were no significant differences among treatments for wetting and drying events. However, drying events ranged from -15 to -51 mm for November 2000 to March 2001 (T1C4) and November 1998 to March 1999 (T2C6). Wetting events were 2 to 3 mm for March to October 2000 (all treatments), and up to 52 mm for April to September 1998 (T2C6 and T5GR12).

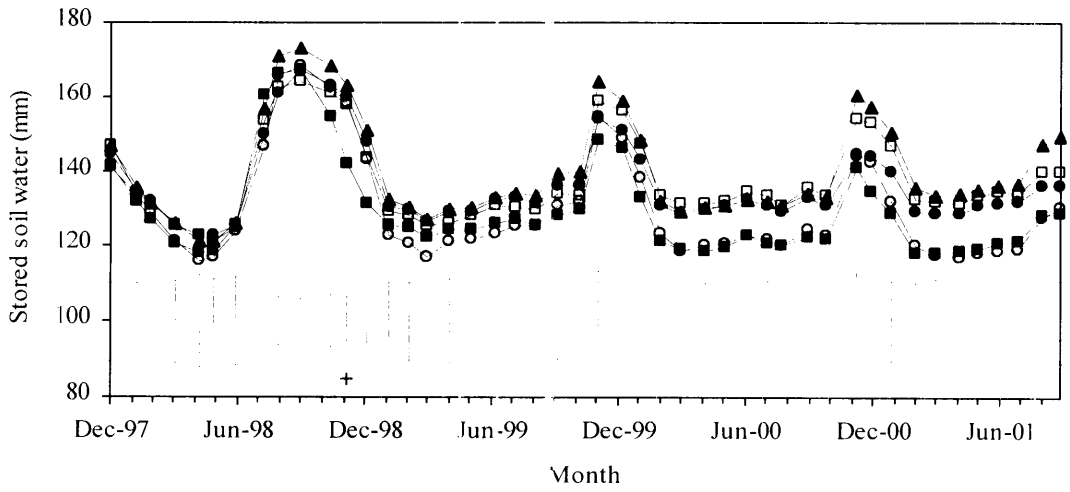

Figure 7-9. Monthly middle profile (70-130 cm) stored soil water (mm) for grazing treatments at Springmount, T1C4 (●), T2C6 (○), T3FERT8 (■), T4GR4 (□), and T5GR12 (▲). Vertical bars indicate the least significant difference between treatments for stored soil water. Significant differences are indicated by + (P<0.05).

7.3.6 Lower profile stored soil water (130-210 cm)

The stored soil water in the lower profile was more stable than upper layers, with slow changes occurring through time (Figure 7-10). One major wetting event was recorded at this depth following the above average rainfall in winter-spring 1998. Following that peak stored soil water declined gradually, with some minor variation through to September 2001. The peak and subsequent decline in stored soil water at this depth, which is below the root zone, may represent drainage of water to deeper in the profile. Stored soil water ranged from 153 to 220 mm for May 1998 (T3FERT8) and October 1998 (T2C6), respectively.

Differences between treatments occurred after the peaks of September 1998 with subterranean clover (T3FERT8) having lower (P<0.05) stored soil water compared with other treatments on many occasions. Stored soil water was lower (P<0.05) for T3FERT8 compared with T1C4, T2C6, and T5GR12 for the period November 1998 to October 1999. From February 2000 to September 2001, T3FERT8 had lower stored soil water than all other treatments. The periods of significant differences within this zone generally coincided with differences for the total soil profile, and thus total profile differences may be attributed to differences arising in the lower profile.

The only significant difference between treatments for change in stored soil water occurred in the wetting event between April and September 1998, with T1C4 (31 mm) having a smaller (P<0.05) change than both T3FERT8 and T5GR12 (49 mm each). Wetting events ranged from 1 to 49 mm for April to September 2001 (T5GR12) and April to September 1998 (T3FERT8 and T5GR12), respectively. Drying events ranged from -1 to -38 mm for April to October 2000 (T3FERT8) and September 1998 to March 1999 (T3FERT8), respectively.

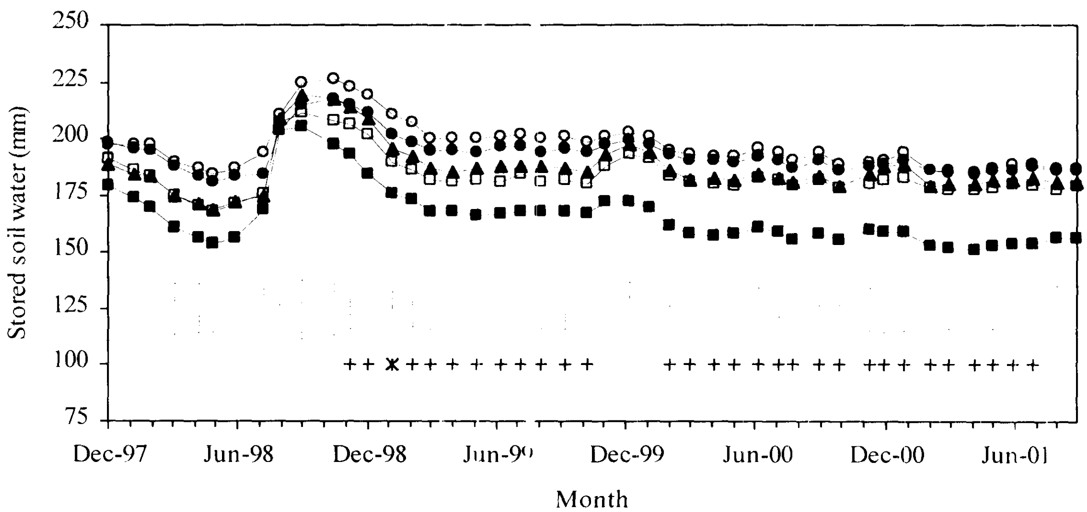

Figure 7-10. Monthly lower profile (130-210 cm) stored soil water (mm) for grazing treatments at Springmount, T1C4 (●), T2C6 (○), T3FERT8 (■), T4GR4 (□), and T5GR12 (▲). Vertical bars indicate the least significant difference between treatments for stored soil water. Significant differences are indicated by + (P<0.05) and * (P<0.01).

Stored soil water data for individual 20 cm layers corresponding with NMM sample depths were analysed separately, at each sampling time using ANOVA, and for the same wetting and drying events as for the amalgamated layers above. The complete results of these analyses are contained within Appendix 2. In summary, for the surface layer (0-30 cm) T3FERT8 had lower stored soil water than other treatments for spring 1998 and 2000, winter 2000 and July 2001. Otherwise, there were no differences between treatments for layers down to 90-110 cm. For layers between 110-150 cm and 170-210 cm, T3FERT8 had lower stored soil water on several occasions. However, the layer 150-170cm provided the greatest differences, with T3FERT8 having lower stored soil water on 32 of the 46 sample dates. Also, T4GR4 had lower stored soil water compared with T2C6 on 20 sample dates between October 1998 and July 2001.

For wetting and drying events, there were no differences among treatments for layers below 90 cm depth. However, for all layers between the surface and 90 cm, T3FERT8 showed greater drying between July and November 1998.

Investigation of lower stored soil water values for T3FERT8.
Much of the treatment differences in profile (0-210 cm) stored soil water appeared to be driven by differences within the lower profile (130-210 cm), which was below the root zone. Extraction of soil water by roots was considered unlikely to generate these differences at these depths (mean root depth 115 cm, Lodge and Murphy 2002*b*), so individual access tubes were investigated in an attempt to explain the difference. Lower profile (130-210 cm) stored soil water was graphed for each access tube through time to identify tubes that consistently gave lower values. Soil water content values recorded from three tubes, one in each replicate for T3FERT8 (plot 3 tube 1, plot 6 tube 1, plot 11 tube 2) were lower through out the experiment. These tubes were investigated for physical soil differences that might explain apparent variation in stored soil water.

Soil samples obtained from NMM access tube installation were archived after initial sampling and these were retrieved for further investigation. Soil texture was determined using the hand texture technique on each core segment (Chapter 3) to identify any differences in clay content within the lower profile. It was found that the access tubes that recorded low stored soil water also had lower clay content with texture classes ranging from loamy sand (5-10% clay) to sandy clay loam (20-30% clay). Mean clay content for those depths across the site was around 40%. Soils with lower clay content generally have lower water retention capacity, leading to lower values of stored soil water. Hence, soil physical characteristics appeared to cause lower stored soil water for this treatment, rather than plant water extraction. By excluding these three tubes from analyses, differences between treatments were not significant.

7.3.7 Plant available water

Profile wilting point (ψ_s -1500 kPa) and field capacity (ψ_s -10 kPa matric potential) estimated in the laboratory and in the field (driest and wettest soil water content) are shown in Figure 7-11. The driest soil water content showed good agreement with the wilting point estimate down to 60 cm depth, below which the laboratory estimates were slightly higher. Also, the wettest soil water content was in reasonable agreement with the field capacity values to 60 cm depth, but was well below laboratory estimates deeper in the profile. I believe the disparity was caused by a combination of poor accuracy of estimates obtained on the ceramic plate at lower pressures (e.g. -10 kPa) and a lack of wetting in the profile at depth. When soil samples from lower in the profile (> 60 cm depth) were saturated with water, they showed varying degrees of expansion, leading to a higher volume of water at each pressure and particularly -10 kPa. Comparing laboratory values with values from the field illustrated the effect. In the field, soils have considerable overburden pressure that prevents the sub-soil from expanding and so storing more water. Also in the field, other factors including total porosity, bulk density, soil pH and soil salinity may influence both the ability of soils to store water and plant roots to extract that water and so influence the field values of wettest and driest stored soil water.

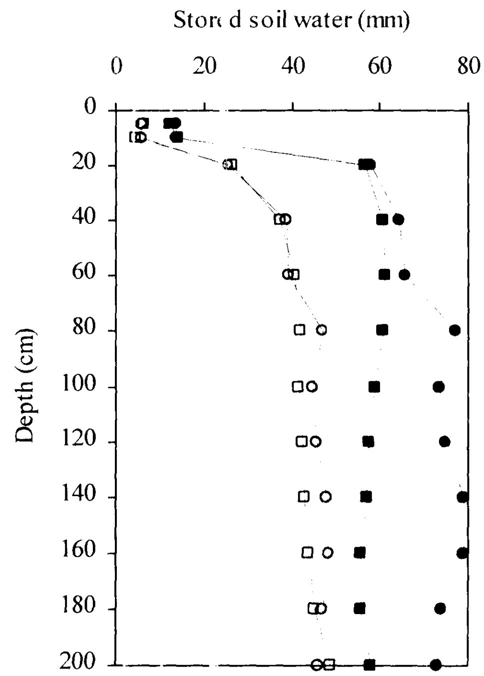

Figure 7-11. Profile distribution of stored soil water at field capacity (•, -10 kPa) and wilting point (○, -1500 kPa) using laboratory techniques, compared with mean wettest (■) and driest (□) stored soil water using the neutron moisture meter.

To explore the dynamics of plant available water (PAW), mean site values were investigated for each profile zone. PAW calculated using the laboratory technique showed that peak values were recorded in spring of each year. Maximum PAW for the profile was 132 mm in September 1998, but by December 1998 had declined to just 20 mm and negative values were regularly calculated (Figure 7-12). For the experiment, mean profile PAW was 29 mm, with 35 mm available within the root zone and -6 mm in the lower profile zone. The lower profile contributed little to PAW with values negative for most of the time (Figure 7-12). Importantly, PAW for the root zone during each summer (December to February) was low with mean values between -14 and 22 mm (Figure 7-12).

Values obtained using the field definition of plant available water followed the same patterns as for those defined in the laboratory, but for the total profile, they were around 50 mm greater. Using field estimation, the mean PAW for the total profile was 68 mm, which included 56 and 14 mm within and below the root zone, respectively. Maximum PAW for the profile was 180 mm in September 1998, but by January 1999, it reduced to approximately 30 mm, with less than 10 mm of this water available within the root zone. The lower profile contributed little to PAW, with a peak of 44 mm in September 1998, but declining steadily from that time. Regardless of the definition of plant available water, it could be seen that most plant available water was contained within the root zone, with little contributed from deeper in the soil profile.

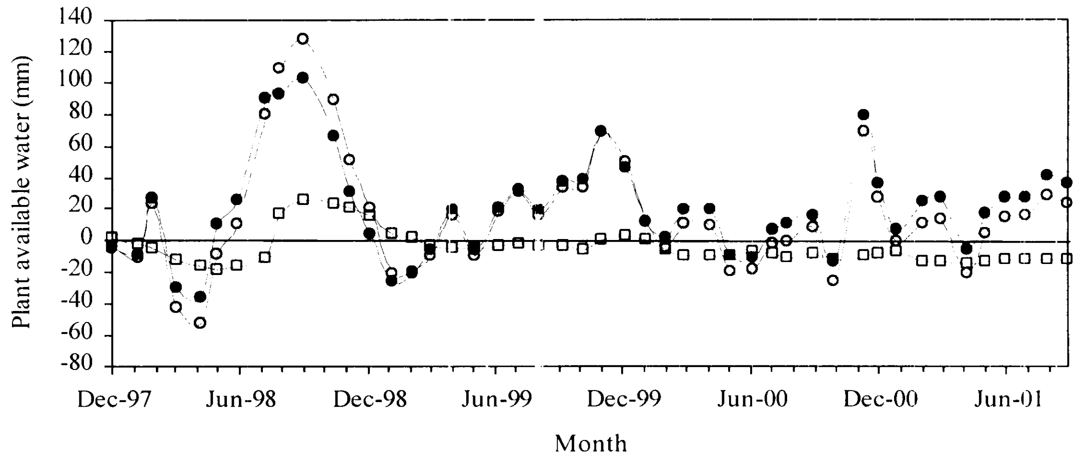

Figure 7-12. Monthly plant available water (mm) at Springmount for total profile (0-210 cm, ○), root zone (0-130 cm, •), and lower profile (130-210 cm, □).

7.3.8 Summary of results

Stored soil water ranged from 389 to 598 mm for autumn and spring 1998. Major peaks in stored soil water were recorded around spring of each year and they followed at least 150 mm of rainfall in the two months prior to sampling. Grazing treatment had some significant effects on total profile (0-210 cm) stored soil water, with the subterranean clover treatment (T3FERT8) being significantly lower on 16 of 46 sample dates compared with at least one other treatment. However, for each of the separate profile zones, there were few significant differences, with a difference on only one sampling date for the upper root zone (0-70 cm) and middle profile (70-130 cm), and two dates for the root zone (0-130 cm). Most treatment differences were recorded in the lower profile (130-210 cm) with T3FERT8 having lower stored soil water than other treatments and these were attributed to soil physical characteristics, as the mean rooting depth was 0-115 cm (Lodge and Murphy 2002*b*). The upper root zone was the most volatile with rapid changes in stored soil water, while the lower profile had only one major wetting event in spring 1998 followed by a gradual decline for the remainder of the experiment.

For the total profile, only one drying event (November 2000 to January 2001) provided a significant difference between treatments with T2C6 and T3FERT8 drying the profile more than other treatments. The upper root zone (0-70 cm) recorded significant differences among treatments for wetting (4) and drying (2) cycles, but treatment differences were not consistent. Within the root zone (0-130 cm), treatments differed for four events, but for the lower profile (130-210 cm), they only differed once.

The analyses of stored soil water for individual sampling layers showed that the greatest numbers of differences were recorded for the 150-170 cm layer with T3FERT8 having lower stored soil water compared with other treatments on 32 of 46 sampling dates. The lower stored soil water at this depth appeared to cause treatment differences both for the lower profile and the total profile.

Mean plant available water within the root zone ranged from 35 to 56 mm for field and laboratory based estimates, with very little water (< 14 mm) available below the root zone. Little water was available for plant growth during summer when the native grasses were active.

7.4 Discussion

The stored soil water dynamics recorded in this study show that wetting of the total profile and changes of water content at depth were rare events. Record rainfall in winter and spring 1998 (when evapotranspiration rate was low) resulted in maximum stored soil water and changes in the lower profile, but it rapidly dried through the following summer (1998-99). Most wetting and drying events affected the upper part of the profile (0-130 cm) with only short periods recorded with high stored soil water. This result is supported by the observation that grass pastures in this region are frequently subjected to drought with little available soil water and growth response is restricted to short periods when soil water is available following rain (Simpson *et al.* 1998). Mean plant available water content of just 35-56 mm, suggests that at most times pasture growth is likely to be limited. During summer when active grass species can grow, plant available water within the root zone was low (-14 to 22 mm). Without plant available water at these important times, accumulation of herbage mass over the summer will be low.

7.4.1 Effect of grazing management on stored soil water

The subterranean clover treatment (T3FERT8) showed some differences in stored soil water compared with other treatments, but usually for short periods. Two significant periods were spring 1998 and most of 2000, and at these times, differences were attributed to pasture and physical soil effects. In spring 1998, following the wet winter, subterranean clover (> 1700 kg DM/ha, Chapter 3) was well established and actively growing. At that time, significant differences between treatment stored soil water and change of stored soil water occurred in the upper root zone, the area likely to have the highest concentration of active subterranean clover roots. During this time it was likely that subterranean clover extracted significantly more water than other treatments. Similar levels of subterranean clover were never achieved at any other time during the experiment.

At other times, T3FERT8 had significantly lower profile stored soil water, with less stored water particularly in the 150-170 cm layer. It was unlikely that pasture root distribution would have a significant effect in this layer only, without influencing layers immediately higher or lower in the profile. After investigation of the soil physical characteristics at these depths, it was concluded that lower clay content (%) together with its effect on bulk density and water retention capacity, resulted in less water being stored at this depth. Also, it is likely that hydraulic conductivity would be higher in soil with lower clay content, leading to a faster rate of drainage that was initiated at lower soil water content.

The drying event within the upper root zone of November 2000 to January 2001 showed that T3FERT8 and T2C6 dried the profile more than other treatments. In November, all treatments had similar stored soil water, with values at near maximum levels and by January 2001, they had dried to low levels. It is proposed here that the two treatments dried for different reasons, ultimately reaching the same result. At the end of spring, subterranean clover in T3FERT8 was still actively growing and the perennial grasses were becoming active. leading to a rapid extraction of soil water. In the other treatment, low ground cover conditions may have allowed increased soil evaporation, depleting stored soil water. In addition, T2C6 recorded the highest total of surface runoff for the experiment (142 mm, Chapter 5), which represented water that was not stored in the profile for this treatment. This example highlights the contrasting processes that may produce a similar change in stored soil water.

7.4.2 Pasture water use and soil drying

Under non-irrigated conditions, it is difficult to identify treatment differences in pasture water use, as evaporative demand and rainfall patterns can not be manipulated (Johns and Lazenby 1973*a*). Australian perennial grass pastures grow in response to available soil water, actively growing when water is available and becoming dormant as the profile dries, which is well recognised as a drought survival mechanism.

In the present study, contrasting herbage mass (1000 to 6000 kg DM/ha, Chapter 3) and percentage of green leaf, could be analogous to different levels of leaf area (leaf area was not measured). However, differences in green herbage among treatments did not translate into stored soil water differences. In further studies, Johns and Lazenby (1973*b*) demonstrated that subterranean clover grown under dryland conditions used a similar amount of soil water to temperate grass species, but it produced considerably less herbage mass.

The lack of significant differences between grazing treatments in this study indicates that in order to manipulate the soil water store, plants would be required that use soil water more aggressively. In studies comparing the soil moisture stress beneath sown (phalaris and subterranean clover) and native pastures (redgrass, kangaroo grass and wallaby grass) near Armidale NSW, Begg (1959) reported that sown pastures used water more aggressively than the native types. From that study, he concluded that sown pastures would suffer longer periods of water stress than the native types, particularly during the warmer months. However, Snaydon (1971) reported that stored soil water beneath summer active (lucerne) and summer dormant pastures (phalaris, cocksfoot *Dactylus glomerata* L. and subterranean clover) were rarely different and were unlikely to have any major effect on the hydrological balance of the system.

The depth of extraction of soil water by plant roots has been shown to be the primary driver of differences in annual water use. Lolicato (2000) in recent studies reported significant differences between lucerne and other pasture plants (phalaris, cocksfoot, and birdsfoot trefoil *Lotus corniculatus* L.) in terms of their water use dynamics. Lucerne was found to extract water from greater depths in the profile compared with other species. While the use of lucerne was not considered in this study, it is recognised for its ability to extract soil water from greater depths through an extensive and aggressive root system. Dryland lucerne has been reported to extract water from depths ranging from 2 to 7 m (Murphy 1993; Lolicato 2000) across a range of soil types in southeast Australia and it may also be useful for extracting soil water held at soil water potential in excess of -1500 kPa. However, lucerne may achieve greater stored soil water change, but the effect on other components of the hydrological balance is unknown (i.e. runoff and evaporation).

For the pastures in the current study, the percentage of green leaf was low in winter due to frosting of the warm season perennial grasses. Mean daily potential evapotranspiration exceeds 1.5 mm/d in winter, which indicates a demand for water use. Increasing the productive use of water may be as simple as utilising species that remain green through out the year, such as wallaby grass (*Austrodanthonia spp.* H.P.Linder, Lodge and Whalley 1983). Two cultivars of wallaby grass have been domesticated (Lodge 1993) and they offer year round production of green leaf and so potentially greater use of water.

7.4.3 Sources of error for stored soil water data

The stored soil water data collected in this study showed few differences among treatments with respect to individual layers or profile zones. Least significant differences between mean stored soil water when the profile was wet were up to 54.5 mm (or ~10% profile stored soil water). This suggests that there was a high level of variation within the data set.

Calibration error. The neutron moisture meter was calibrated for volumetric soil water content using a field technique, as opposed to drum techniques reported in other studies (e.g. Sinclair and Williams 1979). Sources of variation in a field calibration include site heterogeneity, calibration tube representativeness and impact of bulk density. However, in studies of change in stored soil water, the impact of calibration may be relatively insignificant. Sinclair and Williams (1979) reported that the calibration determined the minimum level of variance within stored soil water data. However, when recording changes through time in heterogeneous soils, calibration effect can be relatively low compared with other sources of variance, such as placement error.

In this study, the bulked calibration relationship was based on data collected across the site and resulted in lower sensitivity at the extremes of soil clay content and bulk density. The stored soil water of access tubes with lower clay content was probably underestimated, while those with higher clay content were overestimated. O'Leary and Incerti (1993) showed that bulked calibration equations affected estimates deeper in the profile. At depth, the range of soil water content of samples collected for calibration is usually restricted, resulting in poor sensitivity (i.e. typical values at depth 25-30% compared with 5-35% near the surface). The bulk of data (~80%) used in calibrating the neutron moisture meter was obtained from soil cores taken from each plot, which introduced an underlying variability, but represented the site. A small number of tubes were used for destructive sampling and collecting calibration samples at the wet and dry extremes.

Bulk density has been reported to have a significant effect on variance of estimates of stored soil water particularly with respect to the estimation of volumetric water content. In the current study, bulk density was estimated from one soil pit and values were assumed representative of the site. The effect of bulk density is most evident in soils with a cracking nature (e.g. vertosols) imparted by expansive clay types (Greacen and Hignett 1979). Representative sampling is quite difficult as soil water content decreases and soil cracks become evident and bulk density changes in response to moisture content (Jayawardane *et al.* 1983). In a study of the impact of bulk density on NMM calibration, Greacen and Schrale (1976) reported its impact in a number of ways. Firstly, soils with a higher bulk density usually have a higher proportion of constitutional hydrogen (H^+) bound up in soil minerals resulting in higher observed soil water content values compared with soils of low bulk density. Secondly, the tighter packing of soil particles can reduce neutron penetration in the surrounding soil, producing increased detection rates for thermal neutrons close to the access tube and so higher soil water content. Thirdly, where the soil contains a high proportion of thermal neutron absorbers (e.g. Bo, Fe, Cl, and Mn ions), a higher proportion will be absorbed before reaching the detector within the probe, resulting in lower estimates of soil water content. Hence, in the current study, variation in bulk density across the study site may have led to variation in neutron count readings.

Equipment error. Modern neutron moisture meter units are relatively reliable compared with older instruments. Deficiencies in detector electronics, temperature effect on detector efficiency and activity of the radiation source can all cause systematics errors. The instrument used in the present study was monitored each sampling time for any decline in source activity or detector deficiency by taking standard counts. The instrument had a mean standard count of 19310 ± 110, which equated to a variation in stored soil water of approximately 6.5 mm per metre depth of soil. Sinclair and Williams (1979) reported a similar level of variance attributable to instrument error (i.e. 2 mm of water per metre depth of soil). In a study comparing a number of different neutron moisture meters, O'Leary and Incerti (1993) reported that the maximum variation in standard count would cause an error in water content of < 2% (equivalent to 12 mm at maximum water content in the current study). In the current study, equipment error was assumed to have a consistent effect at each sampling date and was unlikely to affect specific tubes, plots or treatments.

Location error. Location error has the largest influence on standard error of stored soil water values and results from a number of effects including site heterogeneity with respect to access tube location and random error relating to sensor location at each sampling time. In field studies, individual access tubes tend to have slightly different clay content, bulk density, and wetting and drying response, increasing variance of stored soil water (e.g. T3FERT8). Increased number of access tubes usually counters such variance. Sinclair and Williams (1979) reported that variance could be reduced by increasing the number of tubes up to approximately 10, after which error attributed to calibration will become the major source of variation. In the present study, treatment means were based on nine access tubes, accounting for site heterogeneity.

Random error attributed to positioning of the probe source at each depth may also contribute significantly to the error of the mean. The sphere of influence around a neutron moisture meter source (15 cm diameter) is relatively small and the zone of highest interaction is closest to the access tube. Small changes in absolute depth placement of the source could result in quite large variation of soil water content. In the current study, as pasture herbage mass around each access tube changed through time, the absolute placement of the probe also changed as the support stand settlwd at slightly different heights. However, when sampling each access tube an attempt was made to place the source consistently, but was other wise difficult to document.

7.5 Conclusion

The dynamics of stored soil water were quantified in relation to grazing treatments. Stored soil water (0-210 cm) ranged from 389 to 598 mm in a red chromosol, with the subterranean clover (T3FERT8) showing significant differences on 16 of the 46 sampling dates. This treatment had lower stored soil water due to soil physical characteristics in the lower profile, with lower clay contents (5 to 30%) compared with other treatments.

Change in stored soil water was most rapid in the upper root zone, with changes due to rainfall and evapotranspiration. Deeper in the profile, change was both slow and infrequent, with just one major wetting event (spring 1998) recorded in the lower profile. Treatment differences throughout the profile in wetting and drying cycles were rare, with only one drying cycle between November 2000 and January 2001 showing that T2C6 and T3FERT8 extracted more water compared with other treatments. For the upper root zone, six events were identified that showed treatment differences in either wetting or drying cycles, but the treatment differences were not consistent.

The amount of plant available water in the root zone (0-130 cm) was low in all treatments, with a mean of 35 or 56 mm using laboratory or field estimates, respectively. Maximum plant available water was 132 mm (laboratory) or 180 mm (field) during spring 1998, but declined within 4 months to negligible levels.

The data suggested that grazing management could not be used to increase stored soil water or its extraction by pasture. Treatment affects on herbage mass, ground cover and surface runoff and soil evaporation did not translate into significant differences between treatments for stored soil water. Similarly, over-sowing natural grass pasture with subterranean clover did not increase soil water use. Alternative species (lucerne) that have higher water use requirements or those that use water year round (wallaby grass) may influence stored soil water.

8 Simulation of long-term pasture growth and hydrological balance

"We model in order to define what we do not know about the problem."
Thornley and Johnson (2000)

8.1 Introduction

A problem that faces all short-term experiments is the application of results to a longer time frame. The current study at Springmount collected data over a 4 year period, which was reasonably long for a field experiment. However, the results collected are unlikely to be representative of long-term trends. For instance, annual rainfall was above average in 1997 and 1998, which may have led to higher surface runoff and deep drainage than might normally be expected. Similarly, rainfall was below average for three of the four summers during the experiment, which may have reduced growth of the perennial C4 grasses. Hence, to take the results from the current experiment at face value and extrapolate the implications to management of natural pastures on the North-West Slopes carries an inherent risk. A biophysical model might be used to simulate the grazing treatments over a much longer period in order to explore the possible effects over a range of seasons and ascertain the sustainability of those treatments.

The use of a biophysical simulation model offers the opportunity to improve understanding of the processes and interactions taking place between various components of the grazing system. For example, grazing may reduce the amount of pasture herbage mass and ground cover, which in turn may increase the amount of surface runoff. Water lost through runoff reduces the amount of water that enters the profile leading to drier soil conditions. Pasture growth is likely to be lower with drier soil conditions, and so on. Each component of the grazing system impacts upon other components and the interactions may be complex. A biophysical model may also allow the exploration of components that were not measured experimentally. For instance, deep drainage is very difficult to measure directly, and at low daily flux rates, the volume of water produced per unit area may be negligible. A biophysical model that adequately simulates these processes may be used to integrate small flux rates through time and estimate annual totals.

In an introduction to biophysical crop and plant modelling, Thornley and Johnson (2000) stated that for a biophysical model to be successful it needs to be developed as research is undertaken. The SGS Pasture Model (Johnson 2002; Johnson *et al.* 2002) was developed to meet the needs of the SGS National Experiment program (Mason and Andrew 1998). The Pasture Model is unique in that it incorporates climate, water, nutrient, plant, animal and management dynamics into one easy to use, Windows® based package (Johnson *et al.* 2002). The Pasture Model was developed to examine and analyse data from the SGS National Experiment and to improve understanding of the complex processes occurring between the various components of the grazing system (Johnson *et al.* 2002). Various studies have been reported that have used the Pasture Model including investigation of the seasonal variation in the hydrological balance (Lodge *et al.* 2002), timing and magnitude of surface runoff events (Murphy *et al.* 2003), and interpretation of pasture production under various grazing management regimes (Johnson *et al.* 2002). The Pasture Model also provided the opportunity to explore grazing management systems that at Springmount were not investigated experimentally. An example of such a system is one that is grazed so that herbage mass is maintained at 2000 kg DM/ha by adjusting stocking intensity at short intervals (7 d). As indicated by experimental results in Chapter 5, 6 and 7, herbage mass maintained at around this level may provide adequate ground cover to limit surface runoff, limit evaporation from bare soil, while having high transpiration and providing consistent herbage mass for livestock production.

The objective of this chapter was to use the Pasture Model to explore the impact of contrasting treatments on mean hydrological balance during the experimental period and for these same treatments over a longer period using historical data. Specific aims were:

a) to calibrate the Pasture Model for three contrasting treatments at Springmount and explore their impact on mean hydrological balance for the experimental period (1997-2001);
b) to simulate these same treatments over a long-term (1971-2001) to compare trends of herbage mass, surface runoff, evapotranspiration and stored soil water, with those indicated within the experimental period and explore their impact on mean hydrological balance; and
c) to simulate a hypothetical grazing strategy that may offer optimal hydrological performance and pasture production

8.2 Methods

8.2.1 Description of the Pasture Model

The SGS Pasture Model (Johnson 2002; Johnson *et al.* 2002; Lodge *et al.* 2002) was used to simulate grazing treatments at Springmount. The Pasture Model is a dynamic biophysical, mechanistic, process based simulation model with five principal components (water, pasture, nutrients, animals, and management) and complex and dynamic interactions between them (Johnson *et al.* 2002). The model is hierarchical in structure, firstly describing water dynamics, and attempts to simulate pasture processes and their interactions so that the impact of grazing management can be understood. While the Pasture Model is highly complex and process based, its greatest attribute is the framework that it provides to evaluate the experimental data and investigate long-term management impacts and interactions. A description of the principal components of the Pasture Model follows.

Climate and evapotranspiration data

The key driver of the Pasture Model is climate data that was entered as a spreadsheet data file. For simulations of the experimental period, climate data recorded at Springmount (30 minute data, Chapter 4) were used as inputs, while historic data sets were used (daily data) for long-term simulations. The Pasture Model calculated potential evapotranspiration for the experimental period using the Penman-Monteith formula (Smith *et al.* 1996), with modifications for amount of green and dead leaf, and bare soil and ground cover. Hence, daily potential evapotranspiration varied among treatments according to the amount and type of pasture. In the long-term simulations, climatic information (daily rainfall, minimum and maximum air temperature, global radiation, net radiation and potential evapotranspiration) was extracted for Springmount from the SILO data set (Jeffrey *et al.* 2001) and potential evapotranspiration was calculated using the Priestly-Taylor formula (Priestly and Taylor 1972). As SILO data contains both measured and modelled data, it was not expected to be identical to data collected at Springmount, so for the experimental period, data collected at Springmount were inserted into the data file.

Water dynamics module. This module incorporated the processes of water movement in soil and plants according to rainfall amount and potential evapotranspiration demand. The processes included soil water infiltration and through drainage, surface and sub-surface runoff, pasture transpiration, and evaporation (from pasture canopy, litter and bare soil). A capacitance model (e.g. WaterMod, Johnson 1996) described water movement through the profile in a similar way to the Richards equation (e.g. Ross 1990*b*). To reflect the effect of rainfall intensity on the generation of surface runoff (Chapter 5), 30 minute intensity data were used for the experimental period. Otherwise, daily rainfall values were disaggregated into hourly values according to a defined frequency distribution of rainfall intensity values for that time of the year (e.g. Connolly *et al.* 1998). The water dynamics module is represented diagrammatically in Figure 8-1.

Pasture growth module. Pasture growth was described by the flux of carbon through the pasture system, regulated by the rates of photosynthesis and respiration. Available radiation, temperature, and growth limiting factors relating to soil nutrient and water availability determined the dynamics within this module. Both annual and perennial species were described within the model. Growth was described using multiple leaf age classes, with the rate of transfer from one to the next being determined by climatic and grazing conditions (Johnson and Thornley 1983; Johnson and Parsons 1985).

Nutrient dynamics module. This module described the change in major plant related nutrients including nitrogen (N), phosphorus (P), potassium (K), and sulphur (S). The amount of each nutrient present in the system was determined according to plant uptake, organic matter turnover (including litter, animal dung and plant roots), leaching of mineral nutrients, and soil adsorption. For N, a diagrammatic representation is given to show the complex interactions captured within the Pasture Model for this nutrient, including dynamics of nitrate and ammonium, fixation and volatilisation (Figure 8-2).

Animal growth module. Sheep growth was determined according to metabolic energy demand and a simple energy balance process (Finlayson *et al.* 1995). Animals grew when their intake of energy was greater than their maintenance requirements. The energy content of pasture was determined according to its digestibility and nitrogen content, with green material being more digestible than dead. The age and type of animal determined maintenance requirements, while intake by the animals impacted upon pasture growth. Where intake was insufficient to satisfy maintenance, the model provided supplementary feed to prevent animals from losing excessive weight. A wether sheep (50 kg live-weight) was used as the base animal in all simulations.

Management module. Various grazing management strategies may be imposed, including set stocked, calendar based rotations, and variable stocking density. Also, through this module, fertiliser and irrigation may be applied to pastures as required.

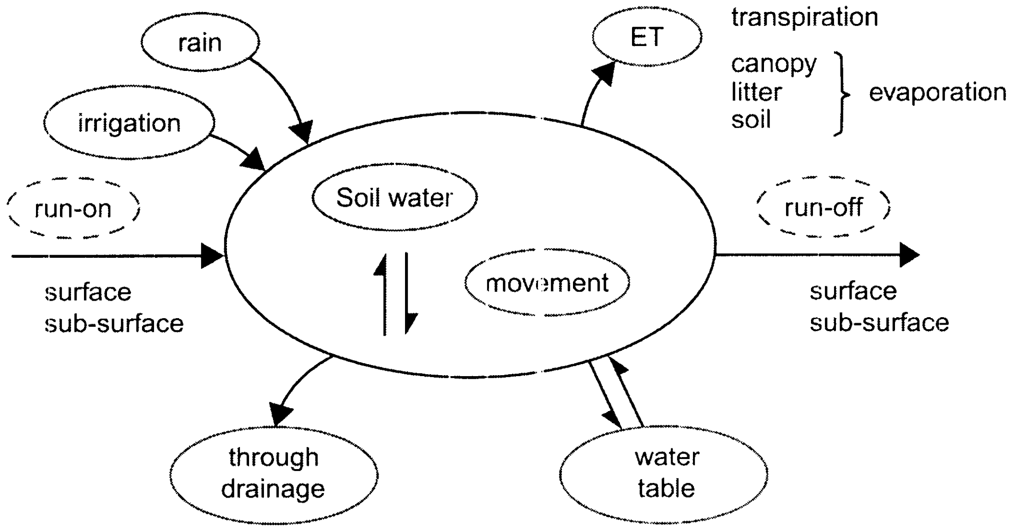

Figure 8-1. Diagrammatic representation of the hydrological processes captured within the water module of the Pasture Model (after Johnson 2001).

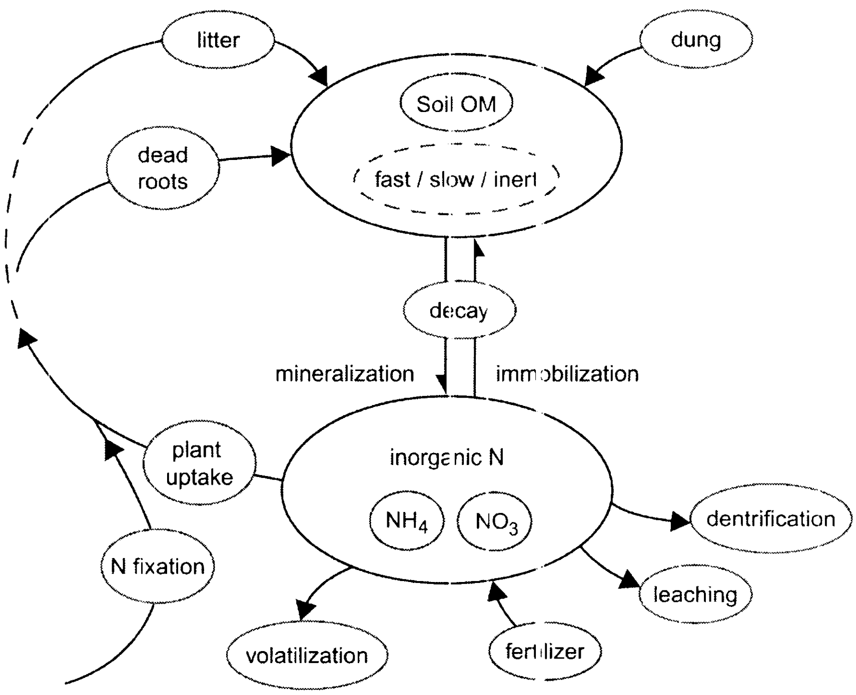

Figure 8-2. A diagrammatic representation of the nitrogen dynamic processes captured within the nutrient module of the Pasture Model (after Johnson 2001).

8.2.2 Calibration of the Pasture Model for three treatments

The Pasture Model was calibrated to simulate three contrasting treatment plots that had runoff data: Plot 5 (T5GR12, rotational grazing at 4 sheep/ha, representing a four paddock rotation), Plot 6 (T3FERT8, continuous grazing at 8 sheep/ha with fertiliser and subterranean clover applied), and Plot 8 (T2C6, continuous grazing at 6 sheep/ha without fertiliser). Grazing treatments were selected on the basis of their contrasting response during the experiment in terms of stored soil water, pasture herbage mass, surface runoff, and addition of subterranean clover. T2C6 had low herbage mass and high runoff; T3FERT8 subterranean clover had high herbage mass, low runoff and lower stored soil water; and T5GR12 rotational grazing had high herbage mass, low runoff, and higher stored soil water.

To calibrate simulations of each plot, key soil parameters were adjusted (Table 8-1) so that close agreement between simulated and observed stored soil water data was obtained as indicated by correlation coefficients (*r* values). The stored soil water data collected in Chapter 7, was the most reliable, consistent, and frequently recorded of the data sets collected during the experiment. Therefore, stored soil water provided an opportunity to critically evaluate parameters for each of the simulations. Each simulation was calibrated using stored soil water data as the prime focus. Soil water characteristics were refined by a process of differential evolution (Johnson *et al.* 2002), which involved modifying parameters until simulated stored soil water most closely matched observed values with minimal residual error. After attaining reasonable agreement for stored soil water, herbage variables were adjusted (Table 8-1) to attain highest correlation between simulated and observed data as indicated by *r* values. A complete list of parameter values used for each simulation is given in Appendix 3.

The soil profile was parameterised for 4 horizons (surface, A, B_1, and B_2) and each had values to describe saturated water content (θ_{vol}%), saturated hydraulic conductivity (cm/d), the drainage point (θ_{vol}%), wilting point (θ_{vol}%), and air dry water content (θ_{vol}%). For the T2C6 treatment simulation, saturated conductivity was increased in the B_1 and B_2 horizons compared with the other simulations (i.e. 19 vs. 10 and 7 cm/d, Table 8-1) so that simulated water movement more accurately reflected observed data using the neutron moisture meter. Daily simulated runoff was collated to compare timing and magnitude with observed events.

Three plant species were described including a perennial C4 grass (redgrass), perennial C3 grass (wallaby grass) and an annual C3 legume (subterranean clover). Optimum and maximum temperature (°C) for maximum photosynthetic rate of each plant was reduced for the T2C6 treatment to 28 and 32 °C, respectively, compared with 30 and 37 °C, for other treatments (Table 8-1). This was done to limit the growth of redgrass at higher temperature as observed soil surface temperatures exceeded 50 °C during summer months and was likely to have reduced pasture growth rate.

The leaf interval (d) for redgrass and wallaby grass was increased in the T2C6 treatment (40 and 30 d, respectively) compared with the other treatments (20 and 20 d, respectively, Table 8-1). Generally, BOTANAL data (Chapter 4) showed that the T2C6 treatment had a consistently high proportion of green leaf and the longer leaf interval was used so that the pasture remained green in the simulation.

A grazing pressure factor was used to describe the impact of grazing on the regeneration of each plant (Table 8-1). This factor described the time for pasture to recover to 90% of pre-grazing herbage mass (e.g. a factor of 0.850, indicated that pasture took 14.2 d to recover 90% of pre-grazing herbage mass). Observations on the experimental grazing plots indicated that growth of redgrass was slow following prolonged continuous grazing and that this parameter would be useful to describe growth in response to grazing intensity and duration.

For each simulation, fertiliser was applied if growth was limited by nutrient deficiency at autumn (1 March) or spring (1 October). If required, nutrients were applied at the following rates: N 25 kg/ha, P 15 kg/ha, and S 5 kg/ha. In spring, an extra 10 kg/ha of S was applied to satisfy legume requirements.

Table 8-1. Key parameters of the Pasture Model for each treatment simulation, showing soil water characteristics, pasture growth coefficients, and grazing pressure factors for each pasture species included in the simulations (P C4 – redgrass, P C3 – wallaby grass, A C3 – subterranean clover). Photosynthesis characteristics, transpiration parameters and root distribution are shown highlighting some small differences.

	T5GR12 (rotational grazing)				T3FERT8 (subterranean clover)				T2C6 (continuous grazing)			
Soil water characteristics	**Surface**	**A**	**B_1**	**B_2**	**Surface**	**A**	**B_1**	**B_2**	**Surface**	**A**	**B_1**	**B_2**
Saturated water content (θ_{vol}%)	43	43	38	35	43	43	38	35	43	43	38	35
K_{sat} (cm/d)	4	15	10	7	4	15	10	7	5	15	19	19
Drainage point (θ_{vol}%)	29	28	23	20	29	28	23	20	29	28	23	20
Wilting point (θ_{vol}%)	10	10	13	14	10	10	13	14	10	10	13	14
Air dry water content (θ_{vol}%)	4	4	4	4	4	4	4	4	4	4	4	4
Pasture Parameters												
Growth	P C4	P C3			P C4	P C3	A C3		P C4	P C3		
Leaf P_{max} (mg CO_2 / (m^2.s))	0.6	0.5			0.6	0.5	0.6		0.5	0.4		
Minimum temp for photosynthetic max. (°C)	15	5			15	5	2		15	5		
Optimum temp for photosynthetic max. (°C)	30	20			30	20	18		28	20		
Maximum temp for photosynthetic max. (°C)	37	30			37	30	28		32	30		
Curvature for P_{max} (T)	0.2	0.2			0.2	0.2	0.2		0.2	0.2		
Leaf interval (days)	20	20			20	20	40		40	30		
Root depth (cm)	50	40			50	40	40		50	40		
Depth for 50% root distribution (cm)	20	15			20	15	15		20	20		
Grazing pressure factor												
Time for pasture to recover 90% of herbage mass (days)	27.6	27.6			15.3	14.2	11.6		15.3	19.8		

8.2.3 Simulations

Animal live weight

Simulated animal live weight generally followed observed data (data not presented). The animals tended to maintain weight reasonably well through supplementation, but the main purpose of the animals was to provide grazing pressure and utilisation of the pasture. For the purpose of the current study, animal live weight was not a priority and will not be discussed further.

Experiment period (1 November 1997 to 31 October 2001)

The simulated stored soil water and pasture herbage mass were compared with observed experimental data for each of the treatments to demonstrate goodness of fit. Mean annual hydrological balance summaries were compared between the grazing treatments for this period and were also compared with observed data where available.

Long-term simulations (1 November 1971 to 31 October 2001)

Using the same parameters that were established for each treatment in the experimental period, the Pasture Model was used to simulate the grazing treatments for the period 1971 to 2001. A fourth simulation was developed based on a hypothetical grazing treatment with put and take stocking to maintain pasture herbage mass at a predetermined level. This treatment (variable stocking rate) maintained pasture herbage mass at 2000 kg DM/ha by adjusting stock density according to pasture growth rate at 7 d intervals. Stock density varied between 0 and 120 sheep/ha. The mean stocking rate of this treatment was compared with that of the other treatments. Such a grazing treatment may provide low surface runoff, low soil evaporation, high pasture growth rates, high water use and high sustainability.

Output data were collated on an annual basis to determine differences between the treatments in terms of net pasture growth, evapotranspiration, surface runoff, and deep drainage. The mean annual hydrological balance (1971-2001) for each treatment was summarised. Net pasture growth (kg DM/ha.y) was the balance of total growth and senescence and conversion to litter. The annual transpiration efficiencies (dry matter accumulation per mm of water transpired, kg DM/ha.mm) of these treatments were examined to explore pasture growth among the treatments. The quantity of supplement provided to the animals during the simulations was collated and used as an indicator of the sustainability of the treatment.

Statistical analysis

For each simulation of the experimental period, stored soil water (0-210 cm) and pasture herbage mass (kg DM/ha) was compared with observed data for the same sample dates and the 'goodness of fit' was determined using correlation coefficients (*r* value). For stored soil water data, the difference between observed and simulated data was calculated for each neutron moisture sample date and compared with least significant differences between treatment means as determined in Chapter 7. The mean (mean of daily values ± standard error) of simulated stored soil water and pasture herbage mass growth were calculated and compared with experimental data. Mean output data for each treatment for the long-term simulations were tested for differences by calculating the standard error of the difference between means.

8.3 Results

8.3.1 Calibration, stored soil water, herbage mass, and runoff

Stored soil water (0-210 cm)

For each treatment, observed and simulated stored soil water data were in reasonable agreement for the experimental period (1997-2001), with all treatments showing similar broad trends with correlation coefficients of 0.77, 0.78, and 0.86 for subterranean clover, continuous grazing and rotational grazing, respectively (Figure 8-3). Each simulation showed maximum stored soil water in winter-spring 1998, and peaks in November 1999 and 2000. However, the simulated data showed considerable short-term fluctuation with rapid wetting and drying compared with the observed data. Simulated stored soil water was often close to the observed data on any sample date, but had changed considerably between sample dates (Figure 8-3). These data show the dynamics of the soil water store that are not recorded when soil water is measured using the neutron moisture meter at monthly intervals.

The rotationally grazed simulation had the maximum mean daily stored soil water (438 ± 33 mm), while the continuously grazed subterranean clover treatment (T3FERT8) was 19 mm lower (419 ± 32 mm), which was consistent with the observed data (Chapter 7). The maximum differences between observed and simulated data were 47, 63 and 65 mm for T2C6, T5GR12 and T3FERT8, respectively. The mean differences between observed and simulated data were 18, 17, and 23 mm for T2C6, T5GR12 and T3FERT8, respectively. Mean differences as a percentage of observed stored soil water were 3.6, 4.1 and 5.3% for the rotational grazed, continuous grazed, and subterranean clover treatments, respectively.

For the rotationally grazed treatment, observed and simulated stored soil water were identical under very dry conditions (369 mm, 21 April 1998, Figure 8-3*a*). Values for each layer matched closely (< 2% difference per layer, Figure 8-5*a*). Under very wet conditions (e.g. 14 September 1998), simulated and observed values of total stored soil water also agreed closely (558 mm for model, 553 mm for observed, Figure 8-3*a*). However, the simulated values were greater in the upper profile (e.g. 10% higher at 20 cm depth, Figure 8-5*b*) and less in the middle (e.g. < 5% lower at 60 and 80 cm, Figure 8-5*b*), compared with observed data. Hence, overestimation in the surface layers was counteracted by underestimation in the middle profile. Where simulated and observed stored soil water values differed, the simulated data were usually lower, indicating that water was removed from the profile more rapidly (e.g. all treatments in spring 1998 and 1999, Figure 8-3).

Pasture herbage mass

Similar to the stored soil water data, the simulated herbage mass data for each treatment followed the same broad trends as the observed data, except for the continuously grazed treatment (T2C6, Figure 8-4*c*). The simulated data showed periods of both high and low herbage mass that had a similar order of magnitude to the observed data. Overall, the rotational grazing simulation (T5GR12) showed the highest mean herbage mass (3759 ± 815 kg DM/ha), while the continuously grazed simulation had the lowest (1925 ± 1129 kg DM/ha), which agreed with the observed data from Chapter 4. Herbage mass was least variable in the rotational grazing treatment (as indicated by the lower standard deviation) and the mean difference between observed and simulated data was 651 kg DM/ha. However, this was dependent upon accurately timing grazing periods within the simulation to those that occurred on the treatment plots. Varying the simulated grazing period by one month before or after the actual period produced a very different simulated herbage mass response (data not shown).

The simulated subterranean clover pasture showed its highest growth in spring 1998, coinciding with an observed peak in legume herbage mass of 2880 kg DM/ha (Chapter 4). However, in the simulation, herbage mass did not accumulate in spring 2000 compared with the observed data when herbage mass increased by ~4500 kg DM/ha (mainly perennial grasses, Chapter 4). Similarly, the simulation representing the T2C6 treatment showed greater herbage mass than was observed for summer 1997-98 and 1999-00 (Figure 8-4). Despite parameter settings to generate high grazing pressure, the simulated herbage mass showed accumulation of dry matter caused by the growth of redgrass (C4 perennial). Upon further investigation, this response was linked to parameters that enabled the C4 grass to transpire and grow without restriction even when soil water content was 50% of field capacity. Increasing the threshold to 90% of field capacity curtailed the growth response dramatically, making later simulations more realistic. Also, leaving animals on the simulations when herbage mass was low caused some substantial differences. Sheep within the simulation were fed supplement while remaining on the plot, which led to high grazing pressure and a low pasture growth response.

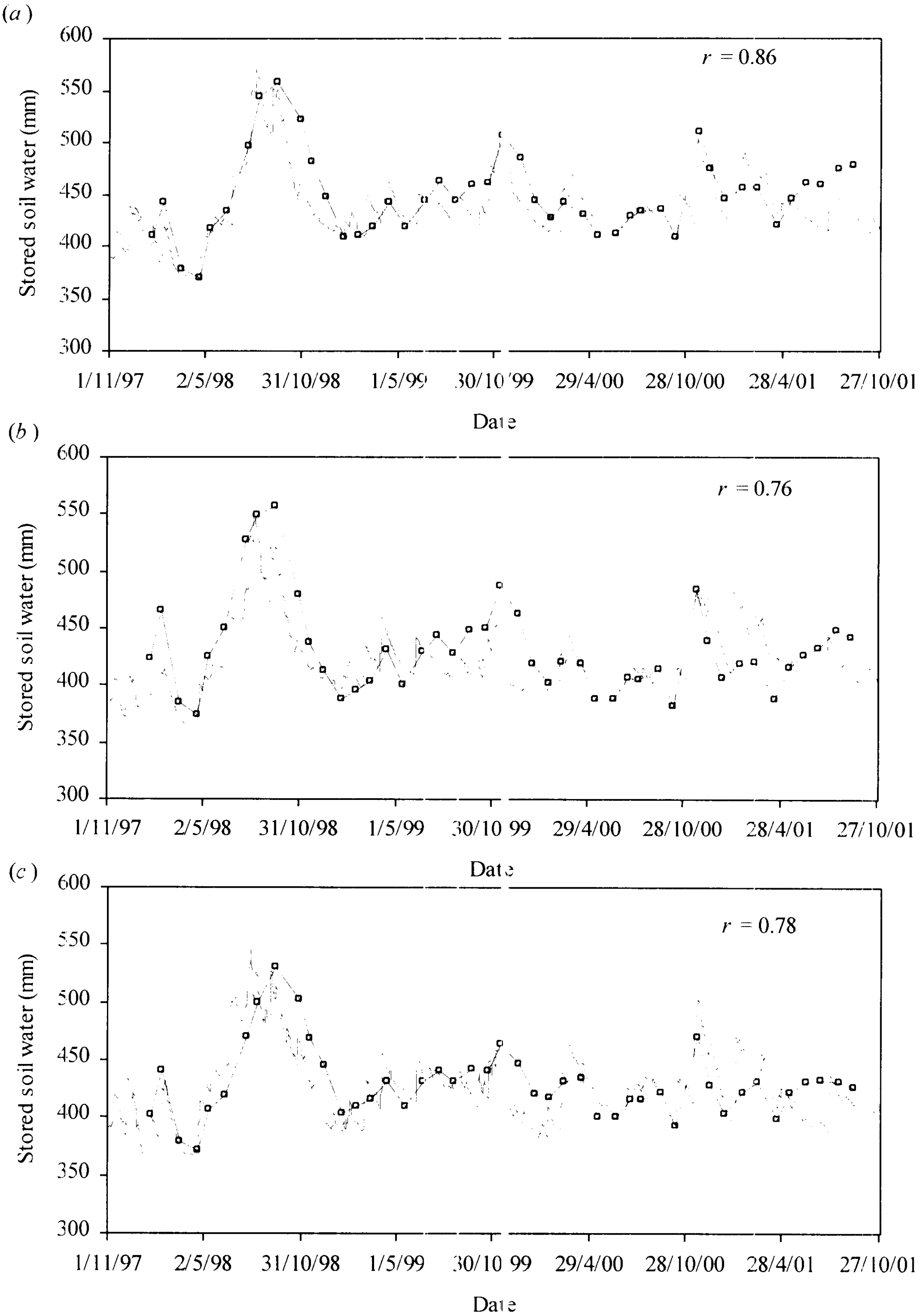

Figure 8-3. Simulated (smooth line) and observed (□) stored soil water (mm) for the experimental period 1 November 1997 to 31 October 2001 for (*a*) T5GR12, (*b*) T3FERT8, and (*c*) T2C6. The correlation coefficients (*r*) indicate goodness of fit between the simulated and observed data.

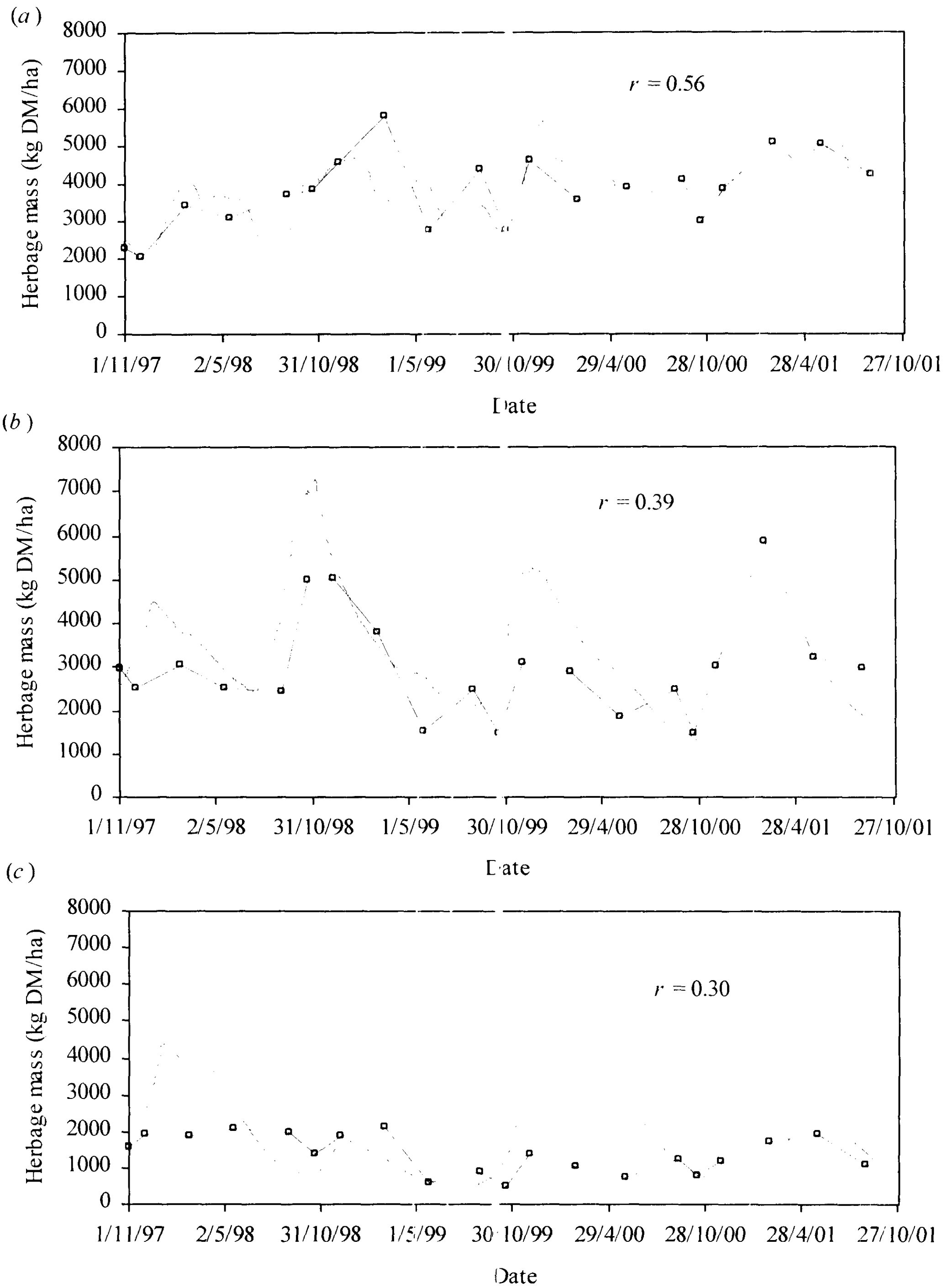

Figure 8-4. Simulated (smooth line) and observed (□) pasture herbage mass (kg DM/ha) for the experimental period 1 November 1997 to 31 October 2001 for (*a*) T5GR12, (*b*) T3FERT8, and (*c*) T2C6. The correlation coefficients (*r*) indicate the goodness of fit between the simulated and observed data.

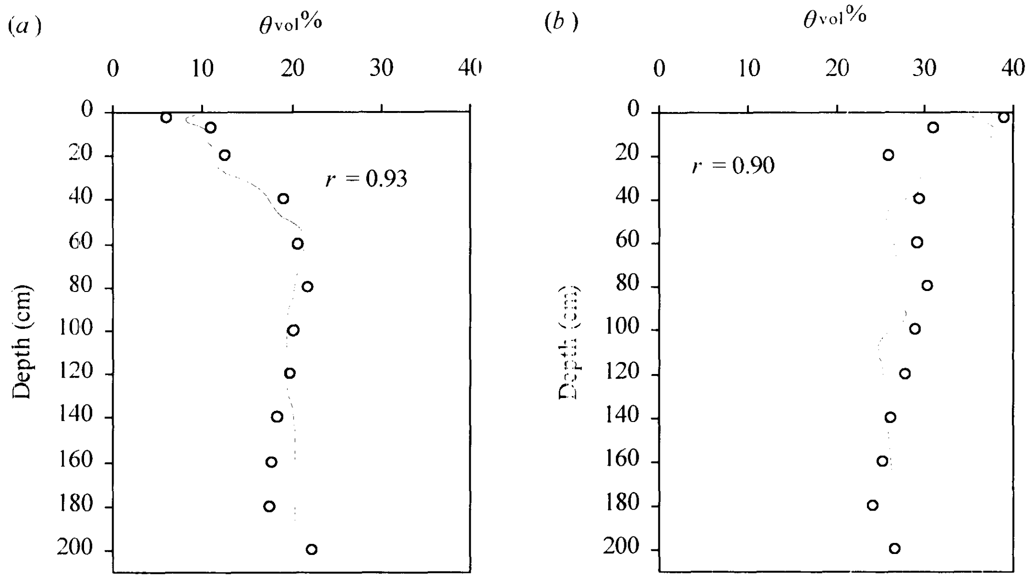

Figure 8-5. Simulated (line) and observed (O) profile distribution of volumetric soil water content (θ_{vol}%) in the T5GR12 treatment for (*a*) dry (21 April 1998), and (*b*) wet (14 September 1998) profile conditions, respectively.

Surface runoff

The simulated runoff more accurately reflected the observed events for the continuously grazed treatment compared with the rotational grazing or subterranean clover treatments (Figure 8-6). For the continuous grazing treatment (T2C6), the timing and number of events were equal, with 38 events for both the simulated and observed data. Also, total simulated and observed runoff was of the same order of magnitude with 225 and 142 mm, respectively. However, for the rotationally grazed and the subterranean clover treatments, simulated runoff events were more numerous and of greater magnitude compared with observed data (Figure 8-6). The rotational grazing simulation showed 16 events with a total of 82 mm of runoff compared with the observed 4 events with a total of 8 mm of runoff. Similarly, the subterranean clover simulation showed 27 events with a total of 160 mm of runoff compared with the observed 13 events with a total of 11 mm of runoff. However, the simulations accurately reflected the observed data in that rotational grazing had the least number of events and with smaller magnitude while for continuous grazing events there were more events of greater magnitude (Figure 8-6).

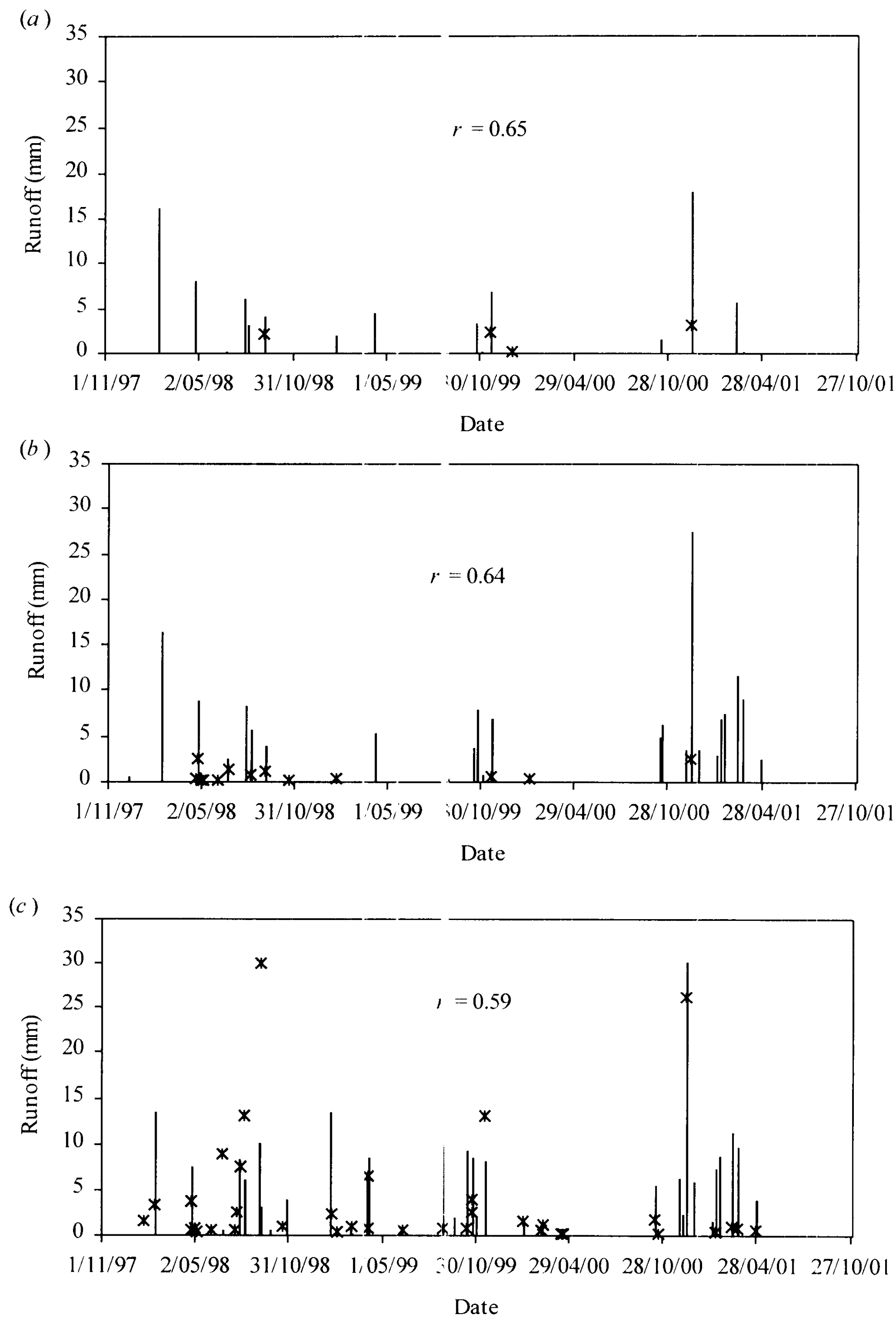

Figure 8-6. Simulated (vertical bars) and observed (*) surface runoff events (mm) for the experimental period 1 November 1997 to 31 October 2001 for (*a*) T5GR12, (*b*) T3FERT8, and (*c*) T2C6. The correlation coefficients (*r*) indicate the goodness of fit between the simulated and observed data.

8.3.2 Hydrological balance of the experimental period (1 November 1997 to 31 October 2001)

The simulated hydrological balance for each treatment was substantially different (Table 8-2). The maximum mean value of evapotranspiration was obtained for the subterranean clover simulation (T3FERT8, 586 ± 35 mm, Table 8-2), while the minimum was for the continuously grazed treatment (T2C6, 534 ± 9 mm, Table 8-2). However, the continuously grazed treatment had the maximum amount of transpiration (309 ± 16 mm) and the rotationally grazed treatment had the minimum (258 ± 29 mm).

Due to comparatively low levels of pasture and litter herbage mass in the continuously grazed simulation (T2C6) it showed very low levels of canopy and litter evaporation, with just 24 ± 6 and 10 ± 2 mm, respectively. However, there was a high level of bare soil evaporation (192 ± 16 mm, Table 8-2). Conversely, the simulations with higher pasture and litter herbage mass, intercepted greater amounts of rainfall, resulting in high evaporation (131 to 162 and 57 to 77 mm of canopy and litter evaporation, respectively) and lower bare soil evaporation (77 to 117 mm, Table 8-2). The continuously grazed treatment had the highest mean runoff and the rotationally grazed treatment the lowest, with 57 ± 14 and 21 ± 7 mm of runoff, respectively (Table 8-2).

Annual deep drainage was determined as the cumulative daily flux (mm/d) of soil water moving beyond the simulated profile depth (0-210 cm). Minimum deep drainage occurred in the subterranean clover treatment (T3FERT8) and the maximum in the continuously grazed treatment (T2C6), with 38 ± 25 and 73 ± 52 mm, respectively (Table 8-2). However, deep drainage was highly variable from year to year with the continuously grazed treatment having the maximum and minimum values of 226 and 4 mm in 1997-98 and 1999-00, respectively. Despite high transpiration and high runoff losses, more water moved through the profile as deep drainage in the continuously grazed treatment compared with the other treatments. The continuously grazed treatment had low rainfall interception losses, which led to higher deep drainage losses.

Table 8-2. Mean (± se) annual components of the hydrological balance generated by the Pasture Model for three treatments at Springmount between 1 November 1997 and 31 October 2001 (values in parentheses are % of annual rainfall).

Hydrological Balance Component	T5GR12	T3FERT8	T2C6
Initial soil water	451±22	426±14	436±16
Final soil water	459±15	429±12	439±13
Rainfall	668±83	668±83	668±83
Pasture transpiration	258±29 (38.6)	281±36 (42.1)	309±16 (46.3)
Canopy evaporation	162±10	131±24	24±6
Litter evaporation	77±2	57±5	10±2
Soil evaporation	77±8	117±17	192±16
Total evapotranspiration	574±28 (85.9)	586±35 (87.8)	534±9 (79.9)
Surface runoff	21±7 (3.1)	40±14 (6.0)	57±14 (8.5)
Sub-surface runoff	1	1	1
Deep drainage	65±34 (9.7)	38±25 (5.7)	73±52 (10.9)

8.3.3 Long-term simulations (1 November 1971 to 31 October 2001)

Mean annual rainfall for the long-term simulations was 654 mm (1 November to 31 October, Figure 8-7) compared with 668 mm during the experimental period. Although mean rainfall was not substantially different between the two simulation periods, the output response was quite different. The long-term rainfall record included several above average periods (e.g. 1976-78, 1983-84, and 1996-98) and below average periods (1980-82, and 1994-95, Figure 8-7).

Pasture growth

The pasture growth response for each simulation highlighted the inconsistent nature of pasture growth at Springmount. This was most clearly demonstrated by the subterranean clover treatment, where growth ranged between 810 and 7250 kg DM/ha.y for 1980 and 1983, respectively (Figure 8-8). The most consistent response was shown by the rotational grazed treatment with mean annual growth of 3020 ± 675 kg DM/ha.y, while the variable stocking rate simulation had higher growth but with more variability 3219 ± 976 kg DM/ha.y. The continuous grazed treatment without fertiliser had low, but consistent growth (2345 ± 739 kg DM/ha.y). These growth rates reflect the relative differences in pasture accumulation observed in Chapter 4.

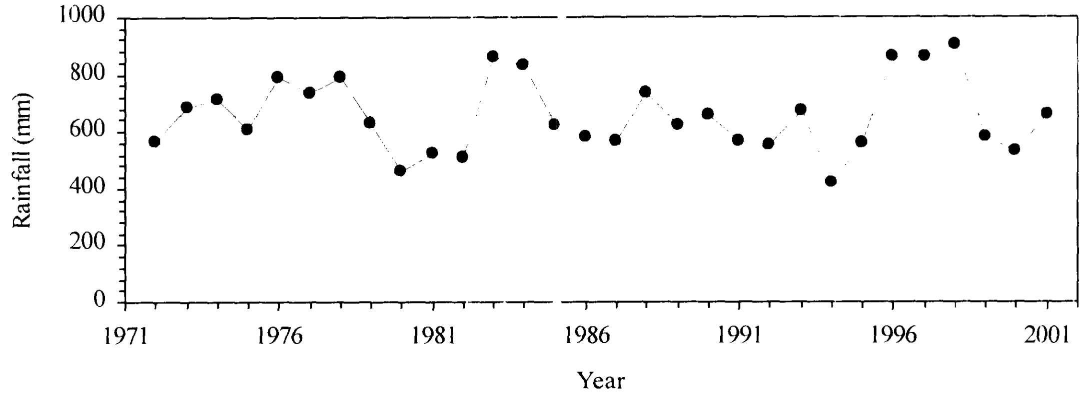

Figure 8-7. Annual rainfall (mm, 1 November to 31 October) used in the long-term simulations (1971-2001). Mean rainfall is indicated at 654 mm by a horizontal line. (Data from SILO database, Jeffrey *et al.* 2001)

Surface runoff

Output from the long-term simulations indicated that runoff occurred episodically and in years with above average rainfall (e.g. 1977, 1983, 1996, and 1997, Figure 8-9). As with the simulations of the experimental period, the rotationally grazed treatment had the minimum mean surface runoff (32 ± 5 mm, Table 8-3). The higher herbage mass in this treatment allowed higher rainfall interception, surface detention, increased infiltration and hence lower runoff. In contrast, the subterranean clover treatment showed the maximum mean surface runoff (83 ± 10 mm, Table 8-3). In this treatment, higher grazing intensity (8 sheep/ha) and associated grazing pressure prevented accumulation of pasture and litter herbage mass which allowed substantial surface runoff in most years, particularly when clover did not grow well (Figure 8-9). Interestingly, the continuously grazed treatment (T2C6) did not have the maximum simulated runoff in all years, as it did in the observed data (Chapter 5). However, of the 9 years that it did have the maximum runoff, 4 of those years were within the experimental period (i.e. 1997, 1998, 1999, and 2001), indicating that the experimental period may have been atypical compared with the previous 27 years (Figure 8-9). The variable stocking rate treatment showed moderate runoff control with a mean value of 65 ± 7 mm (Table 8-3).

Evapotranspiration

Annual evapotranspiration varied in response to rainfall, with low levels in dry years, and high levels in wet years, indicating relative soil water availability (Figure 8-10). Subsequently, there was a large range of values among the treatments and years ranging from 389 to 740 mm for 1981 and 1984, respectively, for the subterranean clover treatment (Figure 8-10). Evapotranspiration from the continuously grazed treatment without subterranean clover was lower due to less canopy and litter evaporation. The variable stocking rate simulation also had high levels of evapotranspiration in most years, being a combination of high transpiration and interception losses (Figure 8-10).

Transpiration

The amount of transpiration also varied in response to rainfall, ranging from 176 mm in 1995 to 482 mm in 1984 for T3FERT8 and T2C6, respectively (Figure 8-11). Mean transpiration was generally less than half of annual rainfall, and ranged from 38.9 to 45.7% for T5GR12 and T2C6, respectively (Table 8-3). Herbage mass accumulation was not directly related to transpiration, as T2C6 had the lowest mean value of herbage growth, yet it had the highest transpiration. However, the simulation with rotational grazing indicated that with high herbage mass conditions, transpiration would be lower as indicated by measurements of actual evapotranspiration (Chapter 6). When measured with the evaporation dome, plots with high herbage mass did not have the maximum evapotranspiration.

Mean annual transpiration efficiency ranged from 7.9 to 12.0 kg DM/ha.mm for the continuously grazed (T2C6) and rotationally grazed treatments (T5GR12), respectively. The subterranean clover (T3FERT8) and variable stocking rate (VAR) simulations had transpiration efficiencies of 10.9 and 11.1 kg DM/ha.mm. The simulations indicated that although the continuously grazed treatment transpired water readily, it was used at a lower efficiency and so resulted in lower herbage mass accumulation.

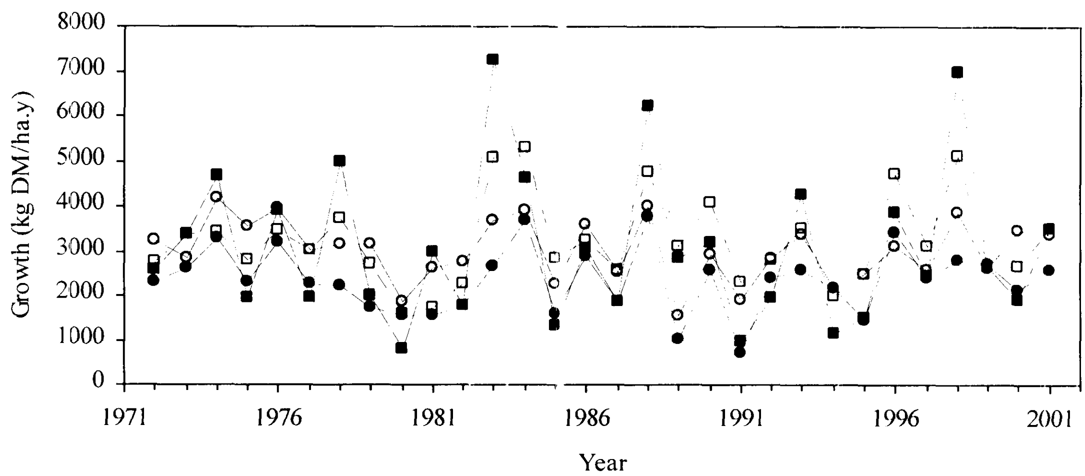

Figure 8-8. Annual pasture growth (kg DM/ha) for the long-term period 1 November 1971 to 31 October 2001 for three grazing treatments at Springmount (T5GR12 - O, T3FERT8 - ■, T2C6 - ●) and a hypothetical treatment with variable stocking density (VAR - □).

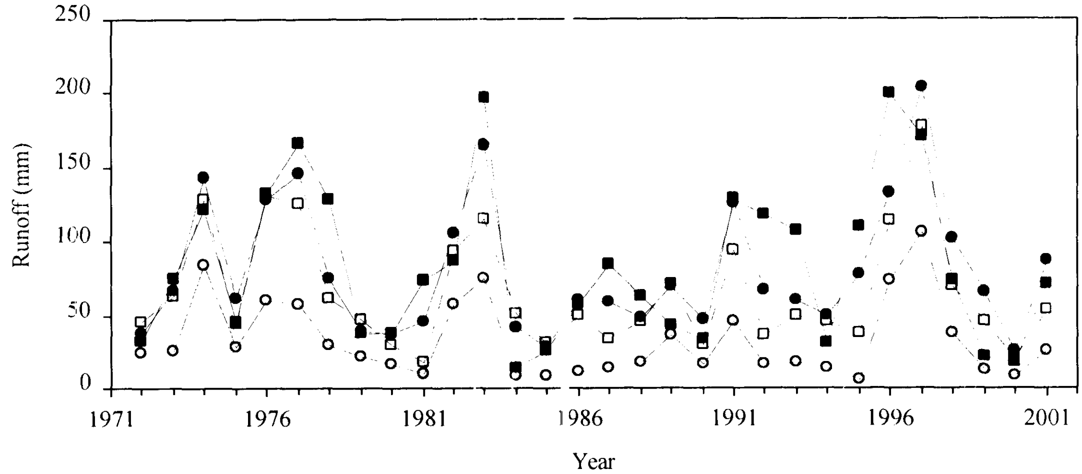

Figure 8-9. Annual surface runoff (mm) for the long-term period 1 November 1971 to 31 October 2001 for three grazing treatments at Springmount (T5GR12 - O, T3FERT8 - ■, T2C6 - ●) and a hypothetical treatment with variable stocking density (VAR - □).

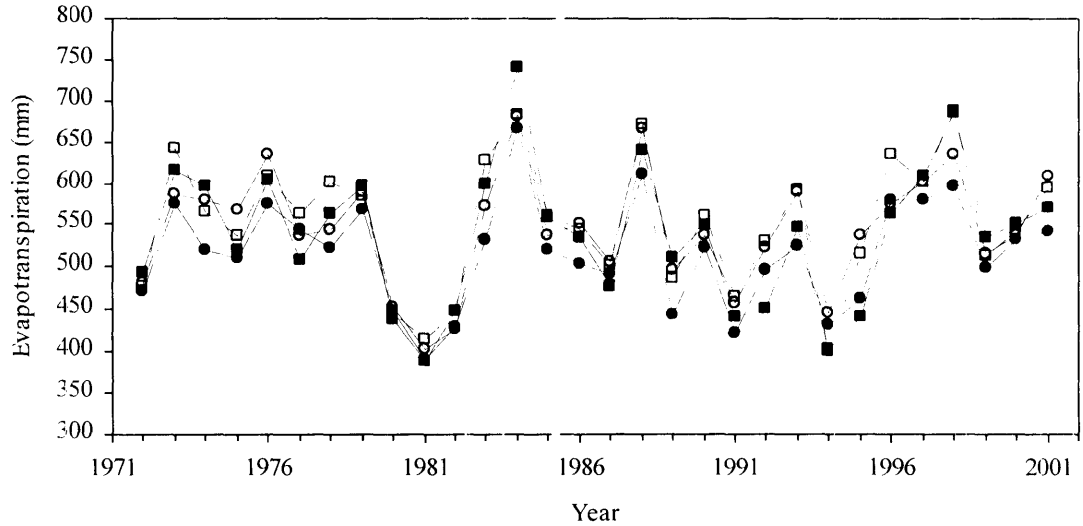

Figure 8-10. Annual evapotranspiration (mm) for the long-term period 1 November 1971 to 31 October 2001 for three grazing treatments at Springmount (T5GR12 - O, T3FERT8 - ■, T2C6 - ●) and a hypothetical treatment with variable stocking density (VAR - □).

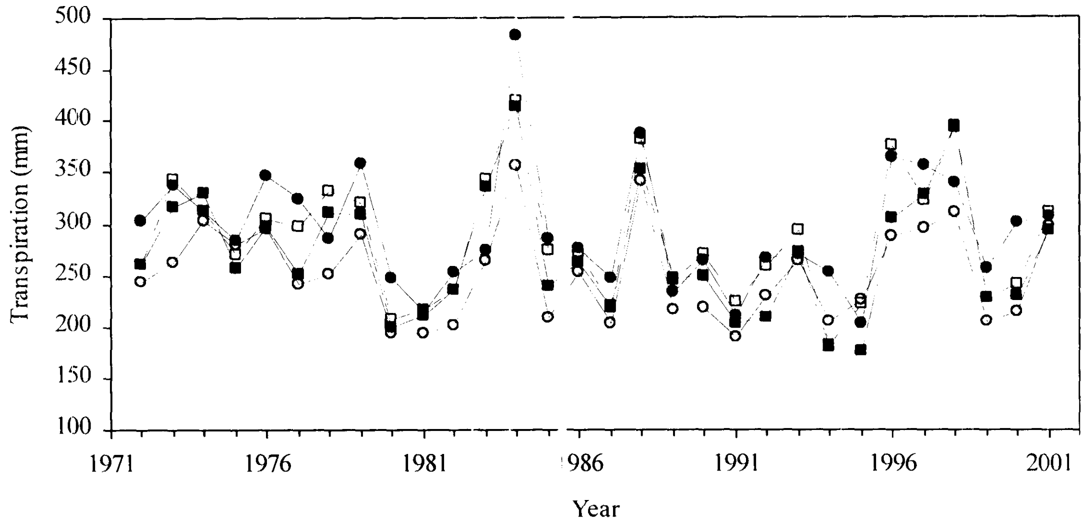

Figure 8-11. Annual transpiration (mm) for the long-term period 1 November 1971 to 31 October 2001 for three grazing treatments at Springmount (T5GR12 - O, T3FERT8 - ■, T2C6 - ●) and a hypothetical treatment with variable stocking density (VAR - □).

Deep drainage

The Pasture Model simulations indicated that deep drainage was broadly cyclical during the simulation period (Figure 8-12). Most deep drainage was confined to four periods (1976-78, 1982-84, 1988-90, and 1996-98) and it occurred in all treatments. These periods coincided with one or two years with above average rainfall (e.g. 1983-84). The rotationally grazed treatment (T5GR12) had the maximum amount of deep drainage with 220 mm for 1998 (Figure 8-12). The same treatment also had 226 mm of deep drainage for 1998 in the simulation of the experimental period, which illustrates the importance of comparing results from simulations of the same time period.

Interestingly, the simulation that had the maximum mean transpiration (295 mm, T2C6) did not have the minimum mean deep drainage (56 ± 10 mm, Table 8-3). High transpiration alone was not sufficient to reduce deep drainage. The rotational grazing treatment had high evapotranspiration (546 ± 12 mm), but also high drainage (74 ± 11 mm), which highlights the importance of a balance between canopy interception, transpiration, and surface runoff to achieve deep drainage control. Pasture structure and canopy interception may play an important role in reducing the amount of water entering the profile, and so problems of excess water.

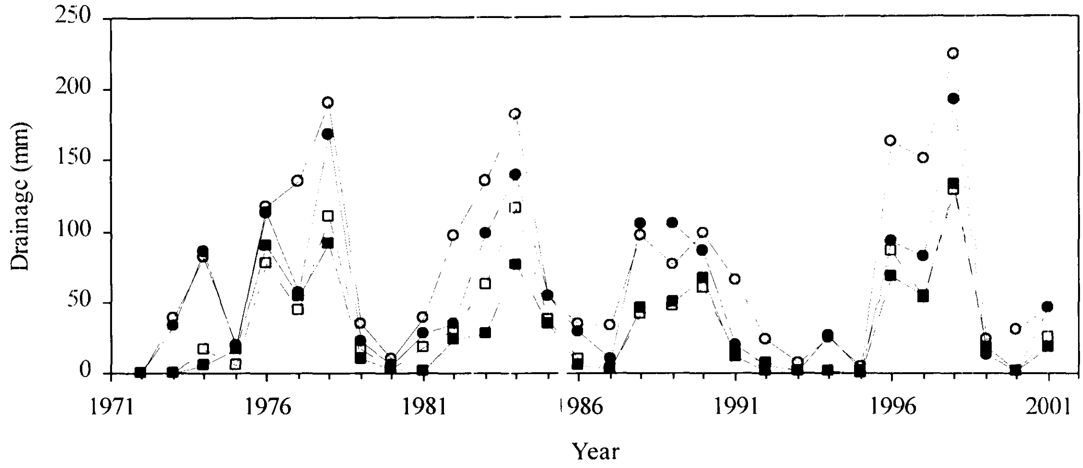

Figure 8-12. Annual deep drainage (mm) for the long-term period 1 November 1971 to 31 October 2001 for three grazing treatments at Springmount (T5GR12 - O, T3FERT8 - ■, T2C6 - ●) and a hypothetical treatment with variable stocking density (VAR - □).

Hydrological balance summary (1971-2001)

The rotational grazing treatment (T5GR12) had the maximum evapotranspiration and the continuously grazed treatment (T2C6) the minimum with 546 ± 12 and 517 ± 11 mm, respectively (Table 8-3). Transpiration was maximal in the continuously grazed treatment (295 ± 11 mm, Table 8-3), while it was lower in the subterranean clover and rotationally grazed treatments (252 ± 8 and 271 ± 11 mm, respectively). The subterranean clover treatment showed the greatest differences between the simulations for the experimental period compared with the long-term period for the evaporation components. In the long-term simulation, lower herbage mass, litter mass and ground cover led to high soil evaporation (155 ± 8 mm), while canopy (74 ± 9 mm) and litter (40 ± 3 mm) evaporation were substantially less (Table 8-3), compared with the experimental period (131 ± 24 and 57 ± 5 mm, respectively, Table 8-2). The variable pasture herbage mass and groundcover in the long-term simulation for the subterranean clover treatment also led to higher mean annual surface runoff (83 ± 10 mm). The deep drainage response of the treatments showed a similar pattern to the experimental period, with the rotationally grazed and continuously grazed treatments (74 and 56 mm, respectively) having higher amounts of drainage compared with the subterranean clover treatment (30 mm, Table 8-3).

Interestingly the simulation with variable stocking rate showed a similar response to the treatment with subterranean clover, which included high evapotranspiration (553 ± 14 mm), high transpiration (286 ± 11 mm), moderate runoff (65 ± 7 mm) and low drainage (35 ± 7 mm, Table 8-3). Canopy, litter and bare soil evaporation were all similar, reflecting the similar levels of herbage and litter mass in each of these two simulations.

Table 8-3. Mean (± se) annual components of the hydrological balance generated by the Pasture Model for three grazing treatments and one hypothetical treatment (Variable) at Springmount for the long-term period 1971-2001 (values in parentheses are % of annual rainfall).

Hydrological Balance Component	T5GR12	T3FERT8	T2C6	Variable
Initial soil water	443±5	412±4	422±5	414±4
Final soil water	445±5	412±4	423±5	415±4
Rainfall	654±24	654±24	654±24	654±24
Pasture transpiration	252±8 (38.5)	271±11 (41.4)	295±11 (45.1)	286±11 (43.7)
Canopy evaporation	131±8	74±9	14±2	71±2
Litter evaporation	65±2	40±3	6±0.5	44±2
Soil evaporation	98±5	155±8	202±6	152±3
Total evapotranspiration	546±12 (83.5)	539±15 (82.4)	517±11 (79.1)	553±14 (84.6)
Surface runoff	32±5 (4.9)	83±10 (12.7)	80±8 (12.2)	65±7 (9.9)
Sub-surface runoff	1	1	1	1
Deep drainage	74±11 (11.3)	30±6 (4.6)	56±10 (8.6)	35±7 (5.4)

Animal supplementary feeding requirements

Where pasture intake by animals was not sufficient to satisfy maintenance energy requirements, the animals were provided supplementary feed. The amount of supplement provided to the animals was used as a surrogate measure of productivity and sustainability of the grazing treatment, with higher amounts indicating that pasture quality and quantity were not adequate to meet the requirements of the animals. The maximum amount of supplement (29.3 ± 3.7 kg/sheep.y) was provided to animals in the continuous grazing treatment, and the minimum to those in the rotational grazing treatment (7.9 ± 0.7 kg/sheep.y). Interestingly, animals in the subterranean clover treatment also required high amounts of supplement (24.5 ± 3.2 kg/sheep.y) and the amount was not different to the continuous grazing treatment. The variable grazing treatment required a low amount of supplement (12.0 ± 1.3 kg/sheep.y) despite a high mean annual stocking rate of 8.7 sheep/ha.

8.4 Discussion

8.4.1 Simulation of the experimental period (1997-2001)

Using only a few parameter changes for each treatment, the simulation data from the Pasture Model showed general agreement with observed data for each of the key data sets (stored soil water, surface runoff and pasture herbage mass). The simulated treatments had a similar ranking to the observed data. For example, mean stored soil water was highest in the rotational grazing simulation (438 mm) and was lowest in the subterranean clover simulation (419 mm), with the continuously grazed simulation in between (424 mm) as was reported in Chapter 7. The rotational grazing simulation also had the highest mean herbage mass (3760 kg DM/ha), while the continuously grazed simulation had the lowest (1925 kg DM/ha) and the subterranean clover simulation was between the two (3080 kg DM/ha). The same trends were observed in the BOTANAL data presented in Chapter 4. Similarly, mean annual surface runoff was highest in the continuously grazed simulation (57 mm) and lowest in the rotational grazed simulation (21 mm) as was recorded during the experiment (Chapter 5). These broad trends provided confidence that the Pasture Model was adequately describing the processes so that the hydrological balance for the experimental period and for the long-term may be explored.

Stored soil water

Comparing simulated with observed stored soil water data showed that the maximum difference between them was ~64 mm with mean values of approximately ~18 mm. In Chapter 7, least significant differences between treatment means ranged from 25 to 50 mm. Based on these differences the simulated stored soil water values were considered acceptable and within the error of the neutron moisture meter technique. Further, there was excellent agreement under both dry and wet soil conditions as per the definition of soil water characteristics (e.g. April and September 1998, Figure 8-5).

The time series trend of stored soil water showed the same periods of wetting and drying compared with observed data, but showed considerable variation that the neutron moisture meter observations did not show. However, all simulations showed that more water was extracted from the profile during spring and early summer than was indicated by measurements using the neutron moisture meter (e.g. spring 1998 and 1999). This extra water use in the simulation was caused by redgrass transpiring when in the experimental paddock it probably was not as indicated by the amount of green leaf. However, it was possible to restrict pasture transpiration at this stage and hence growth by changing the 'growth limiting factor' for transpiration, so that transpiration slowed more rapidly with the onset of dry soil conditions. This effectively reduced the rate of photosynthesis under moisture stress conditions, which also reduced growth. In addition, with high potential evaporation demand (e.g. spring and early summer), transpiration may only meet half of that which is required, and so plants are stressed. When stressed, the growth response will be less. Under low potential evaporation demand (e.g. winter), transpiration is more likely to meet that which is required, and the plants are not stressed.

Pasture accumulation

The growth response of the pasture was more difficult to simulate as it was dependent upon a range of factors including stored soil water, temperature, solar radiation, soil nutrients and grazing pressure. For instance, herbage accumulation was very sensitive to the 'grazing pressure recovery factor'. For each simulation, above a certain threshold level of grazing pressure, the pasture grew without limitation, but below the threshold growth reduced dramatically (Johnson and Parsons 1985). Hence, this parameter required careful prescription for each simulation; lower values were used for the subterranean clover simulation (e.g. 15.3 d for redgrass) and higher values for rotational grazing (e.g. 27.6 d for redgrass). The continuous grazing treatment without subterranean clover was the most difficult treatment to simulate as the redgrass in the experimental plots showed poor growth (Chapter 4).

The pasture response within the rotational grazing simulation was sensitive to the timing of sheep grazing the pasture. Initial simulations were developed on a calendar year basis starting in January. However, this led to simulated grazing periods that differed to actual grazing periods and hence generated a vastly different herbage mass response. Thus, all simulations were developed around the actual dates that experimental plots were stocked (1 November to 31 October). Similarly, at various times during the experiment the T2C6 treatment was destocked and sheep were supplementary fed. For these periods, grazing pressure was maintained within the simulation, and pasture herbage growth was reduced.

While pasture production would be expected to increase with transpiration, the simulated data did not show that. The pasture growth data showed that the continuously grazed treatment had the minimum mean annual growth (2345 kg DM/ha.y) but the maximum mean annual transpiration (309 mm), which indicated that this treatment was less efficient at converting rainfall into pasture herbage mass (7.6 kg DM/ha.mm). Logically, a plant that is under considerable stress and that may have low carbohydrate reserves is unlikely to grow well. The redgrass in the continuously grazed experimental treatments responded this way, even following high rainfall.

Within the model, pasture growth rate and herbage mass accumulation was very sensitive to the rate of leaf appearance and the effect of grazing pressure. The rate of leaf appearance determined the rate at which leaves grew and progressed through their growth stages before dieing (Johnson and Thornley 1983). With a higher rate of turnover, dead leaves accumulate as standing dead material, or contribute to litter mass when detached through the impact of grazing animals and leaf fall. Both of these processes have implications for animal production (less green leaf) and the hydrological balance (interception of rainfall, reduced soil evaporation rates, and reduced surface runoff).

Surface runoff

The number and magnitude of runoff events simulated with the Pasture Model did not match those events observed during the experiment, which may suggest that the model was not adequately simulating runoff events. However, the response was consistent in that with higher ground cover and herbage mass, the frequency and magnitude of runoff events was lower, which supports observations from long term field studies reported by Lang (1979). Also, as the simulations are based on a single point in a paddock and not a runoff plot or treatment plot, they are not expected to be identical.

Hydrological Balance

The simulated hydrological balance for each treatment showed that evapotranspiration was the dominant component (79.9 to 87.8 % of rainfall) and was similar to that estimated by Simpson *et al.* (1998) for pasture near Tamworth on the North-West Slopes (93% of average rainfall). However, transpiration was around 45 to 57 % of evapotranspiration or 260 to 310 mm per year indicating that less than half of the annual rainfall was used for pasture growth. Evaporation from canopy, litter and soil contributed significant amounts of water loss in all treatments, and the proportion of soil evaporation increased as herbage and litter mass decreased. Although canopy interception in pasture is poorly understood it may well be a substantial component of the hydrological balance as indicated by these simulations using the Pasture Model.

Runoff (3.1 to 8.5% of rainfall) and deep drainage (5.7 to 10.9% of rainfall) were smaller components of the hydrological balance for all treatments. In comparison, Simpson *et al.* (1998) estimated that runoff, and drainage were likely to be around 3.5 and 3% of annual rainfall (708 mm), respectively, for the period 1971-1996. Simulations in the current study included two above average rainfall years with 858 and 905 mm in 1997-98 and 1998-99, respectively, which led to high amounts of deep drainage and runoff. Simulations reported by Simpson *et al.* (1998) did not include data from those years.

8.4.2 Long-term simulations (1971-2001)

Each component of the hydrological balance for the long-term simulations was similar to the experimental period for each treatment. For all treatments and as a proportion of annual rainfall, evapotranspiration ranged from 79.1 to 84.6%, transpiration 38.5 to 45.1%, evaporation 33 to 45%, runoff 4.9 to 12.7% and deep drainage 4.6 to 11.3 %. Higher evapotranspiration values were associated with higher mean herbage mass (e.g. T5GR12), while those with low herbage mass had higher runoff and deep drainage loss (e.g. T2C6). However, the mean values do not indicate the variability in these data as both runoff and deep drainage losses were episodic and associated with periods of above average rainfall.

Deep drainage, particularly, showed successive years with either high or low drainage, indicating the difficulty of managing such events. As with the experimental period, the treatment with the highest transpiration value (295 mm, T2C6) did not have the lowest drainage value. This suggests that management of pasture mass and litter mass may have significant implications for the hydrological balance. Interception of rainfall before it enters the soil could be an effective strategy to limit accumulation of water within the profile. Once water is in the profile, it has to be extracted via root uptake and soil evaporation, or move through the profile as deep drainage. The literature reports no consideration of this aspect of pasture management for deep drainage control.

Continuous grazing (T2C6)

In comparison with the other treatments, continuous grazing performed poorly. Particularly, it had the lowest mean annual evapotranspiration (517 mm), which indicated poor use of annual rainfall. With low mean pasture herbage mass, this treatment had low amounts of canopy interception and evaporation leading to a low evapotranspiration total. Although transpiration was the highest (295 mm), this did not equate to higher pasture production as found in other studies (Caldwell *et al.* 1993).

The continuous grazed treatment had a high amount of simulated runoff (80 mm) with peak annual values of up to 203 mm for 1996. Results from Chapter 5, showed that sediment and nutrient load increased with the size of runoff events, and hence these simulated runoff events may potentially transport substantial amounts of nutrient from the pasture system. Similarly, the continuous grazing treatment also showed high mean annual deep drainage and only the rotational grazing treatment had higher amounts. Pasture production was the lowest of all treatments, and as a result, the sheep required the highest amounts of supplementary feeding. The simulation results suggest that continuous grazing is not a favourable grazing management system, with high water losses (soil evaporation, runoff, and deep drainage), poor pasture production, and high amounts of supplementary feed required to maintain condition of the animals.

Subterranean clover (T3FERT8)

The most interesting result of this simulation was that it had the maximum mean annual runoff (83 mm). Experimental data (Chapter 5) indicated that runoff loss would be low with this type of management. However, in the long-term simulations, herbage mass and litter mass (and so ground cover) were not maintained throughout all seasons, leaving the pasture vulnerable to runoff losses. The high stocking rate (8 sheep/ha) provided enough grazing pressure to reduce herbage mass in many seasons, particularly when winter rainfall was low. In those years, the subterranean clover did not grow well, so herbage mass was low going into summer. In an investigation of the timing of runoff events at Springmount, Murphy *et al.* (2003) reported that runoff events were most common in summer and autumn. These simulation results indicate that the time and intensity of grazing is important each year, so that ground cover is maintained before high intensity rainfall occurs in summer.

While mean annual pasture production was high for this simulation, the between year variation was also high, which reflected the performance of the subterranean clover. This simulation had both the maximum and minimum annual growth rates of all the treatments. In good seasons, growth was excellent, but in poor seasons the continuous stocking led to low growth and in those seasons animals required high amounts of supplementary feed. Generally, high canopy interception together with high transpiration led to the lowest levels of deep drainage of all the simulations (30 mm or 4.6% of rainfall).

Rotational grazing (T5GR12)

The key feature of this treatment was the consistently high level of pasture growth (3020 ± 675 kg DM/ha.y), which reduced the amount of runoff and the amount of supplementary feeding that was required. However, despite high evapotranspiration (83.5% of rainfall), there was a substantial deep drainage loss (11.3% of rainfall). The reduction in runoff was effectively translated into increased deep drainage, but combined annual loss through these processes (106 mm) was less than either the subterranean clover (133 mm) or the continuously grazed treatments (136 mm).

Variable stocking (VAR)

As a hypothetical grazing treatment, the variable stocking density showed considerable promise in terms of producing high pasture growth, high transpiration, acceptable runoff losses and minimal deep drainage. This treatment had the highest mean pasture growth value of 3220 ± 976 kg DM/ha, and sustained the highest mean annual stocking density of 8.7 ± 3.7 sheep/ha. Despite the high stocking density, sheep in this simulation required less supplementary feed compared with the subterranean clover or continuously grazed treatments, suggesting that this level of animal production was sustainable. An herbage mass of around 2000 kg DM/ha was sufficient to limit mean annual runoff losses to 65 mm and drainage losses to 35 mm, but was not sufficient to reduce bare soil evaporation (152 mm).

Transpiration efficiency

Transpiration efficiency values for the simulations ranged from 7.9 to 12.0 kg DM/ha.mm for the continuous grazing (T2C6) and the rotational grazing (T5GR12) treatments, respectively. The remaining simulations were around 11 kg DM/ha.mm. Values like these may be used to illustrate that grazed dryland pastures are poor at converting rainfall into herbage mass. Studies of the summer active Rhodes grass (*Chloris gayana*) grown in dryland conditions showed that it had a mean water use efficiency of 7.2 kg DM/ha.mm (Snyman 1994). In addition, studies of dryland cocksfoot (*Dactylis glomerata*) and panic (*Panicum vergatum*) showed water use efficiency of 4.4 to 12.6 and 25 kg DM/ha.mm, respectively (Stout 1992). From the range of values reported in the literature, the values predicted from the Pasture Model are not atypical. Further, in studies of the effect of rangeland condition on water use efficiency, Snyman and Fouche (1991) reported that water use efficiency was lower for rangeland in poor condition compared with rangeland in good condition, with values of 0.6 and 2.0 kg DM/ha.mm, respectively. A possible explanation of lower values in heavily grazed pasture might be that stomatal conductance increases when grasses are defoliated (Doescher *et al.* 1997), which results in lower water use efficiency. Doescher *et al.* (1997) argued further that this response may be a competitive adaptation that allows individual plants to maximise water use rather than allow other members of the sward to utilise the resource.

Improvements to the simulations

Simulated herbage mass data for continuous grazing (summer 1997-98, 1999-00, Figure 8-4*c*) indicated that the Pasture Model produced pasture growth when none was observed (Chapter 4). For these simulations, the higher pasture growth was caused by the 'soil water growth limiting factor' for the redgrass being set too conservatively (i.e. 50% of field capacity). The growth limiting factor defined the point at which growth became limited by water stress (as a percentage of field capacity). Subsequently, the conservative value allowed the redgrass to grow successfully despite stored soil water being low. In further exploration, the value was increased so that growth became limited when stored soil water was < 90% of field capacity. The pasture growth response was reduced and it more closely resembled the observed data (r=0.71, Figure 8-13).

Similarly, the timing of grazing periods had a marked effect on the herbage mass response, and the continuous grazing simulation was modified to reflect periods that stock were removed from experimental plots due to low herbage mass. These periods allowed pasture to recover from grazing and increase herbage mass as indicated by the period between July 2000 and January 2001 (Figure 8-13). This also explains the flush of pasture growth in the early part of the simulation (November 1997 to March 1998) where animals were not included in the simulation. This approach improved the correlation between observed and simulated data, with r values increasing from 0.30 to 0.71 (Figure 8-13). Although this improved the herbage mass response substantially, the correlation between the simulated and observed stored soil water data did not change substantially between the two simulations (i.e. 0.78 vs. 0.75, data not presented).

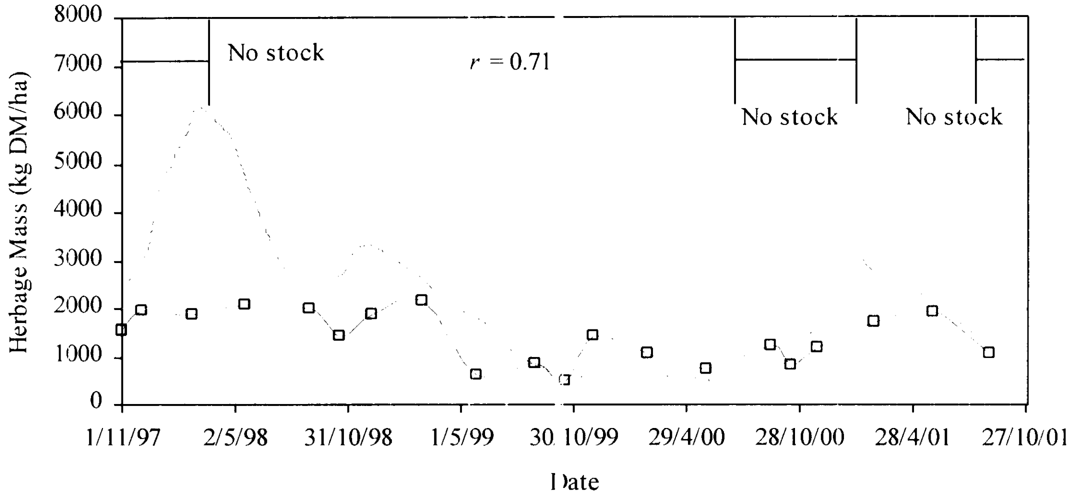

Figure 8-13. Improved correlation between simulated (smooth line) and observed (□) herbage mass data (kg DM/ha) after including periods that experimental plots were destocked, and growth limiting factors for transpiration were changed.

8.5 Conclusion

The Pasture Model was parameterised and calibrated to simulate three contrasting grazing treatments at Springmount for the experimental period. The parameterisation process identified small, but important differences between treatments for some key parameters including soil water characteristics, photosynthetic rates, and recovery from grazing. These treatment differences reflected response of stored soil water and herbage mass to different grazing management strategies and climatic conditions. For example, the rate of recovery following grazing was slower for continuous grazing without fertiliser, and the interval of leaf appearance was shorter (10 d) in the rotationally grazed treatment and longer (40 d) in the continuously grazed treatment.

For the experimental period, simulated and observed stored soil water data were highly correlated (r, 0.76-0.86) and mean differences between them were small (< 18 mm). These differences were less than the least significant differences between means calculated in Chapter 7 (i.e. 25-50 mm). Similarly, for each treatment, simulated pasture herbage mass followed the same broad trends as the observed data. The simulated data indicated that the rotational grazed treatment had the highest, and the continuously grazed treatment the lowest mean herbage mass as was indicated in the observed data. Surface runoff values generated by the Pasture Model were also similar to the observed values with the continuously grazed treatment generating the highest amount of runoff, and the rotational grazed treatment the least.

Long-term simulations were generated for the same three grazing treatments and an extra treatment that utilised variable stock density to maintain pasture herbage mass at around 2000 kg DM/ha. Mean annual evapotranspiration was lower for the continuously grazed treatment (517 mm, or 79.1% of rainfall) compared with the other treatments (539 to 553 mm, or 82 to 84.5%). Conversely, the variable stock density treatment and the continuously grazed treatment had higher transpiration (286 and 295 mm, or 43.7 to 45.1% of rainfall, respectively) compared with other treatments. Surface runoff was lowest in the rotational grazed treatment (32 mm, or 4.9% of rainfall), but was highest in the subterranean clover treatment (83 mm, or 12.7% of rainfall). Canopy interception and evaporation of water from the litter layer was found to be substantial for some treatments (e.g. 131 and 65 mm, or 20 and 9.9% of rainfall for T5GR12) and was crucial to avoid an overestimation of water in the soil profile. The rotational grazed treatment, despite having high evapotranspiration, had high deep drainage (74 mm, or 11.3% of rainfall) which was not different from the continuously grazed treatment (56 mm, or 8.6% of rainfall). The treatments with variable stock density or subterranean clover had low amounts of deep drainage with 35 and 30 mm respectively.

Pasture growth was highest in the variable stock density treatment (3220 kg DM/ha.y) and lowest in the continuously grazed treatment (2345 kg DM/ha.y). While the subterranean clover treatment had high mean growth (3088 kg DM/ha.y) it was highly variable and the sheep required a high level of supplementary feed (24.5 kg/sheep.y), as did the continuously grazed treatment (29.3 kg/sheep.y). The variable stock density treatment had high pasture growth, low deep drainage loss, acceptable surface runoff (65 mm), and sheep required little supplementary feed (12 kg/sheep.y), yet it supported the highest mean stock intensity (8.7 sheep/ha).

The long-term simulations suggested that rotational grazing might be a more favourable grazing strategy than continuous grazing (without the addition of subterranean clover). Continuous grazing had low pasture growth, high losses of water through soil evaporation, runoff and drainage, and livestock required high amounts of supplementary feeding. The rotationally grazed treatment had high pasture growth, low animal feeding, low losses of water through soil evaporation and runoff, but also had high drainage losses. Interestingly, the addition of subterranean clover increased mean pasture growth, but unless favourable rainfall was received in winter and spring, clover growth was low, leading to high losses of surface runoff and high supplementary feeding. The variable stocking density treatment may also be a favourable grazing strategy, as it maintained the highest stocking intensity, had low supplementary feeding requirements, had high pasture growth rates, moderate levels of runoff, and low deep drainage.

9 General discussion and conclusion

9.1 Introduction

Traditional grazing strategies have led to a decline in the productivity and sustainability of natural pastures (Lodge *et al.* 1991; Kemp *et al.* 2000). Particularly, low amounts of herbage mass, litter mass and ground cover have led to excessive surface runoff, high amounts of evaporation from bare soil surfaces, poor surface structure and poor soil health (Lang 1979; King 1997; Simpson *et al.* 1998; Gonzalez-Sosa *et al.* 1999; Murphy and Lodge 2001*a*). Litter mass is an integral component of a sustainable grazing system and may be an indicator of pasture health (McCormick and Lodge 2001) and potential production (Willms *et al.* 1993). The surface soil of pastures that have low ground cover and litter mass also have low porosity and infiltration capacity (Greenwood 1996; Lawson 1998), and these characteristics are exacerbated by increased grazing intensity (Johnston *et al.* 1971; Molinar *et al.* 2001).

Natural pastures may have a high proportion of standing dead material with low protein content and digestibility (Lodge and Whalley 1983) and pasture accumulation is often limited by short periods of growth when soil water is available (Simpson *et al.* 1998). However, pastures that maintain a strong base of perennial species were expected to have higher water use and more sustainable production (Kemp *et al.* 2000). Further, the development of sustainable grazing management strategies requires a thorough understanding of how grazing impacts upon the hydrological balance of pastures (Thurow 1991).

In an attempt to increase the productivity and sustainability of natural pastures on the North-West Slopes, the current study examined a range of simple strategies to improve grazing management and ascertain their impact on the physical characteristics of these pastures and so components of the hydrological balance. Higher sustainability of grazed pastures may be achieved through an improved hydrological balance that has less surface runoff, increased water use and lower soil evaporation.

9.2 Climate and grazing management affects on pasture characteristics

The seasonal conditions during the study included below average summer rainfall for three of the four years. Summer rainfall is essential to maintain herbage mass in these pastures (Garden *et al.* 2000). However, above average spring rainfall in three of the years provided adequate water for pasture growth leading into summer. Rainfall for winter and spring of 1998 particularly, was highest on record and this rain resulted in high runoff, likely deep drainage and high pasture growth. Another consequence of low summer rainfall was a reduced incidence of thunderstorm activity, which may bring high intensity rainfall and generate high amounts of runoff (Lang 1990).

The simple grazing management strategies examined in this study brought about significant changes to the physical characteristics of the pasture, including herbage mass, litter mass and ground cover. Continuous grazing led to lower herbage mass compared with either rotational grazing or over-sowing with subterranean clover. Continuous grazing (4 or 6 sheep/ha) resulted in mean herbage mass of 1500-1800 kg DM/ha and this was exacerbated by the dry summer conditions. Grazing the pasture with either a two or four paddock rotation (4 sheep/ha) resulted in higher mean herbage mass (3000-3500 kg DM/ha) and it was dominated by standing dead material as reported by Lodge and Whalley (1983). Sowing subterranean clover and application of fertiliser led to a mean herbage mass of 3100 kg DM/ha, despite having the highest stocking rate of 8 sheep/ha.

The rotational grazing treatments led to an excessive accumulation of standing dead material through under utilisation of pasture growth. Based upon these levels of accumulation, these pastures may tolerate a higher annual stocking rate of 5 or 6 sheep/ha as long as periods of rest were sufficient to allow herbage mass to recover following periods of grazing (e.g. Weltz *et al.* 1989). However, such a strategy would require careful management to avoid a decline in ground cover and litter mass.

The changes brought about by grazing management to both litter mass and ground cover conditions generally followed that of herbage mass conditions. Continuous grazing without fertiliser led to a mean litter mass that was half that with rotational grazing or with subterranean clover and fertiliser added (100-110 and 210-260 kg DM/ha, respectively). However, the amount of litter was quite low compared with that reported in other pasture studies (e.g. 600-900 kg DM/ha, Naeth *et al.* 1991*a*). These pastures tend to retain standing dead material (Lodge and Whalley 1983), making litter accumulation a slow process. Alternative management such as trampling by livestock (e.g. Schuman *et al.* 1996) may further increase litter mass for these pastures and maximum herbage mass production might then be expected with maximum litter mass (Willms *et al.* 1993). Similarly, mean ground cover conditions paralleled herbage mass, with lower levels in the continuously grazed treatments (70-73%) and higher levels with rotational grazing (83-85%) or added subterranean clover and fertiliser (90%). However, high ground cover may also exist with low herbage mass as reported for these pastures by Lodge and Murphy (2002*a*).

Both species composition and percentage of green leaf were unaffected by grazing management strategies in this study. The treatments were not actively managed to manipulate species composition (e.g. Lodge and Whalley 1985), and so no loss of perennial species was anticipated

(Garden *et al.* 2000). The species composition of all treatments remained dominated by redgrass (81-85%), wiregrass (8-13%) and wallaby grass (5-8%). Green leaf content responded to seasonal conditions with high amounts in spring of each year (up to 98%) but was very low in winter (3-4%) when the summer active perennial grasses were frosted as reported by Lodge and Whalley (1983). The lack of green leaf in winter may be a limitation to year round water use and so production by these pastures.

9.3 Surface runoff studies

Monitoring soil water content, rainfall and surface runoff in real time highlighted the importance of such information in understanding the dynamics of surface runoff generation. This dynamic process changed in response to initial soil water content, and the amount, intensity and duration of rainfall in each event (Srinivasan *et al.* 2002). Such information may only be quantified by recording these data at short time intervals (e.g. Murphy and Lodge 2001*b*).

The physical changes to the pasture characteristics that were caused by grazing management at Springmount, translated into substantial differences for runoff generated in each of the four runoff plots. Mean ground cover of runoff plots was lower for those grazed continuously (54%, T2C6) compared with those grazed rotationally or with fertiliser and subterranean clover added (94 and 96%, T3FERT8 and T5GR12, respectively). Total runoff losses amounted to 142 mm (or 6% of total rainfall) where ground cover was lowest, compared with less than 8 mm (or < 0.3% of rainfall) for the rotationally grazed plot. Linear regression models generated from the event data indicated that the magnitude of surface runoff events increased with greater rainfall intensity and rainfall amount, and these losses were magnified as ground cover decreased. This finding supports the conclusions reported by Lang (1990), that runoff increased exponentially as ground cover decreased. At Springmount, maintaining ground cover was very important to maintain surface infiltration and so water movement into the soil profile. Measurements at the site indicated that areas with low ground cover had low porosity, which led to a low infiltration capacity (Lawson 1998). Simple changes to grazing management that led to increased ground cover were sufficient to reduce the magnitude and frequency of surface runoff events and by doing so retained up to 142 mm more rainfall for pasture growth.

At other sites, runoff plots had higher ground cover (> 70% cover at all times) compared with Springmount and so other factors such as rainfall amount, rainfall duration, and soil depth were important to describe variation in runoff depth. At Eloura, the largest runoff events were generated from plots with a brown vertosol when large amounts of rainfall occurred with a high mean intensity. At Winchfield, the amount and duration of rainfall, soil depth and change in soil water content explained significant variation in runoff depth. These factors are beyond the influence of grazing management, but highlight the fact that runoff is generated through a complex interaction between soil, pasture and rainfall characteristics.

A pasture that is managed for high levels of ground cover (> 70%) is likely to maintain microbial health, soil physical structure and soil infiltration capacity (King and Hutchinson 1983; Greenwood 1996; Lawson 1998), reducing the incidence and magnitude of runoff events and so add more rainfall to the soil water store. Erosion and sediment loss are also likely to be less when adequate ground cover is maintained (Lang and McCaffrey 1984; McIvor *et al.* 1995). While high ground cover may not prevent runoff, it will reduce losses to those events generated through long duration rainfall that saturate the soil profile, which are comparatively rare events (Anon. 1980).

9.4 Evapotranspiration studies

Evapotranspiration (590-650 mm) was estimated to be the largest component (85-98%) of the hydrological balance for pastures on the North-West Slopes (Simpson *et al.* 1998; Lodge *et al.* 2002) and offers the greatest opportunity for change through grazing management. Particularly, those previous studies reported that > 50% of annual rainfall was lost through bare soil evaporation, with no productive benefit. A grazing management strategy that can slow the rate of bare soil evaporation may provide pasture plants the opportunity to access that water for transpiration and so pasture growth.

While previous studies have expended considerable effort to predict evapotranspiration (e.g. Smith *et al.* 1996), daily values of actual evapotranspiration are rare in the literature (e.g. McLeod *et al.* 1998). The studies performed here quantified actual rates of evapotranspiration for both small scale plots and natural pastures under both wet and dry soil surface conditions for each season of the year. These data provide valuable calibration values for biophysical simulation models (Lodge *et al.* 2001; Murphy and Lodge 2001*a*).

Hourly evapotranspiration ranged from 0.02 to 0.82 mm/h, with minimum values recorded around sunrise and maximum values around midday. Daily values ranged from 0.2 to 7.6 mm/d for winter and summer, respectively, with higher values for plots with wet soil surfaces. However, the maximum rate of evaporation from bare soil was 3.9 mm/d, and this highlighted the importance of controlling it in order to conserve soil water for pasture growth. While evapotranspiration was not measured beyond sunset, hourly rates indicated that evaporation might continue into the evening on some occasions, as reported by both Malek (1992) and Rosset *et al.* (1997), and this warrants further investigation.

Linear regression models indicated that net radiation and vapour pressure deficit were the dominant variables in accounting for variation in evapotranspiration values through out the year, but other pasture factors such as herbage mass and litter mass also explained significant proportions of that variation. High herbage mass with low green leaf content may inhibit transpiration, resulting in less water use. Although net radiant energy was important to describe that variation through out the year, there was little evidence relating a change in the physical structure of pasture to a change in radiation balance on a daily basis. However, there was some evidence that net radiation was higher for plots with wet soil surfaces and with higher herbage mass compared with dry surfaces and low herbage mass.

Albedo values were unknown for natural pastures and these studies quantified a range of values that varied with herbage mass, litter mass and ground cover conditions. The values of albedo documented in this study were all ≤ 0.23 (range 0.13 to 0.23) and showed that local values would be essential for the accurate calculation of reference evapotranspiration (E_o, Meyer *et al.* 1999).

Linear regression models indicated that when pastures were wet, high litter mass may reduce evaporation by up to 1.04 mm/d, which may represent substantial potential savings on an annual basis. In similar studies of volunteer pastures, Gonzalez-Sosa *et al.* (1999, 2001) reported that litter may reduce bare soil evaporation by up to 400%, resulting in water being available for higher amounts of transpiration (increase of 50%). This effect has great importance on the North-West Slopes where periods of high evaporative demand may follow summer thunderstorm activity (e.g. E_o 9.5 mm/d, Clewett *et al.* 1999). Barraba experiences a mean 22 d in summer with rainfall (Clewett *et al.* 1999) and pastures with high litter mass may retain a further 23 mm of soil water for the summer. Similarly, on an annual basis, these savings may amount to 80 mm of reduced soil evaporation. Reducing bare soil evaporation at that time might allow pasture plants an opportunity to access the stored soil water for transpiration, leading to extended growth periods and possibly higher pasture production. Pasture growth may be more consistent, rather than intermittent as reported by Simpson *et al.* (1998).

9.5 Grazing management and stored soil water

Rainfall events that resulted in full profile wetting were rare and occurred in response to above average rainfall in spring 1998, 1999 and 2000. Maximum stored soil water was 598 mm, but only 180 mm was available to plants. Few significant differences occurred among treatments for profile stored soil water, but differences did occur for the surface layer (0-30 cm) and deeper in the profile (150-170 cm). Mean plant available water for the profile ranged between 35 and 56 mm, with only short periods where water was available for growth, confirming the conclusions drawn from the simulation studies reported by Simpson *et al.* (1998). The low amount of plant available water indicated that plants were frequently subjected to semi-drought conditions and herbage accumulation was limited by short periods of growth, particularly during summer in the current study. Changes in stored soil water were very rapid, moving from abundant (e.g. 180 mm, September 1998) to low (30 mm, January 1999) plant available water within a short period.

There were few significant differences among treatments in regard to the magnitude of wetting or drying events. The drying event between November 2000 and January 2001 was the only major event where treatment had an effect on soil profile drying. For that event, the soil profile of both the subterranean clover treatment and the continuously grazed treatment dried more compared with other treatments. The subterranean clover treatment had higher green content with actively growing subterranean clover, while the continuously grazed treatment had low ground cover resulting in higher soil evaporation and surface runoff. These contrasting processes may have resulted in similar outcomes in terms of drying the soil profile.

The grazing management strategies used in the current study were not expected to manipulate species composition (Garden *et al.* 2000) and so there was little scope to alter the seasonal pattern of soil water extraction. To change the pattern, alternative species may be required that are either more aggressive in their rooting depth and water use, or use water at different times of the year. For south-eastern Australia, lucerne has been touted as the only alternative deep rooting perennial species suitable to extract greater amounts of stored soil water and so lessen the impacts of excessive deep drainage (e.g. Lolicato 2000). However, for the North-West Slopes of NSW, increasing the productive use of water may be as simple as utilising species that remain green through out the year, such as wallaby grass (*Austrodanthonia spp.* (Lindner), Lodge and Whalley 1983). Two cultivars of wallaby grass were domesticated by Lodge (1993) and they offer year round production of green leaf, and so potentially, productive use of water year round. Alternatively, grazing management might be used to increase the proportion of wallaby grass in these pastures (currently 5-8%) by using the techniques described by Lodge and Whalley (1985), resulting in higher proportions of green leaf year round.

9.6 Simulation studies and long-term hydrological balance

Simulation studies with the Pasture Model allowed the effects of contrasting grazing treatments on pasture and hydrological balance to be explored over a 31 year period. The simulations gave an indication as to how the different grazing treatments might influence pasture herbage mass accumulation, soil water use and surface runoff when simulated across a wide range of annual climatic conditions. Particular components of the hydrological balance were not measured empirically, and so modelling offered the opportunity to investigate the effect of grazing management on canopy interception, partitioning of evaporation and transpiration, and deep drainage.

Mean annual pasture growth was estimated to be higher in the subterranean clover treatment (> 3000 kg DM/ha.y) and the rotationally grazed treatment (3020 kg DM/ha.y) compared with the continuously grazed treatment (2345 kg DM/ha.y). Maximum growth was estimated for the hypothetical variable stocking rate treatment (3220 kg DM/ha.y). The continuously grazed treatment was predicted to have the minimum transpiration efficiency and the rotationally grazed treatment the maximum with values of 7.9 and 12 kg DM/ha.mm, respectively, which reflects the impact of grazing on water use efficiency. However, while the treatment with subterranean clover had a high mean growth rate, it was highly variable, and livestock required regular supplementary feeding (24.5 kg/head.y). The variability was due to poor growth response of clover in years with low winter rainfall (e.g. 1981-82, 1994-95) resulting in low herbage accumulation for those years.

Surface runoff was higher for the continuously grazed treatment (12.2% of rainfall) compared with the rotationally grazed treatment (< 5% of rainfall), as was found in the experiment (Chapter 5). However, contrary to the experimental data, the subterranean clover simulation had the maximum mean runoff (12.7% of rainfall). High runoff occurred in the years that subterranean clover did not grow. The high stocking intensity (8 sheep/ha) rapidly depleted pasture herbage mass and ground cover and created the opportunity for runoff to occur. During the experiment (1997-2001), this treatment always had high pasture herbage mass and ground cover and so runoff losses were small. Therefore, to minimise long-term runoff losses from these pastures, careful grazing management may be required in years that subterranean clover shows poor growth.

The simulations indicated that canopy interception of rainfall was an important and substantial component of the hydrological balance for those pastures that had higher herbage mass. The rotational grazing treatment had mean annual canopy interception of 131 mm (or 20% of rainfall), while the continuously grazed treatment had one-tenth of that amount (14 mm, or 2.1% of rainfall). In Australia, canopy interception of rainfall is poorly understood and few studies have attempted to quantify it for grass pastures (e.g. Dunkerley and Booth 1999). Canopy interception may reduce the amount of water entering the soil profile and so the amount of stored soil water for pasture growth. However, by reducing the amount of water entering the profile, it may also reduce the potential for excess water to accumulate in the profile and so deep drainage to occur. The effect of pasture physical characteristics on canopy interception and so water movement in grazed pastures warrants further investigation, particularly its variation through out the year and with varying rainfall characteristics and evaporative demand.

Deep drainage losses for all treatments were estimated to be highly episodic, with high amounts occurring in years that had above average rainfall (e.g. 1976-78, 1996-98). The rotationally grazed treatment had the maximum predicted amount of mean annual deep drainage (74 mm, or 11% of rainfall) and the subterranean clover treatment the minimum (30 mm, or 4.6% of rainfall), but annual values ranged from 4 to 220 mm. This indicates that in wet years, grazing management has little opportunity to prevent drainage (Simpson *et al.* 1998), but high canopy interception, transpiration and runoff may combine to reduce its magnitude. In the intervening years, the treatments with the highest productive use of water had the lowest drainage. To prevent deep drainage on the North-West Slopes, alternative plant species with deeper root systems or those that use water more aggressively would be required (e.g. lucerne or wallaby grass). However, the fate of water lost from the profile through deep drainage requires further investigation as that water may lead to recharge of freshwater aquifers for later extraction elsewhere (e.g. Weltz and Blackburn 1995) or mobilise stored salt and so initiate salinisation processes.

9.7 Conclusion

The objective of this study was to determine the effect of grazing management on pasture physical characteristics and so components of the hydrological balance for natural pastures on the North-West Slopes of NSW. Grazing management may be used to manipulate the herbage mass, litter mass and ground cover of natural pastures and by doing so manipulate components of the hydrological balance.

Herbage mass, litter mass and ground cover of natural pastures increased through rotational grazing or the addition of subterranean clover on the North-West Slopes (Chapter 4), which reduced surface runoff (including sediment and nutrient losses) and increased the retention of rainfall (Chapter 5). Evaporation from soil surfaces was reduced by high litter mass (Chapter 6). High herbage mass, litter mass and ground cover may limit the amount of bare soil evaporation, particularly after summer storms when soils are wet, providing pasture plants the greatest opportunity to access water for transpiration and so growth (Chapter 6). However, both stored soil water, and wetting and drying events rarely differed among treatments (Chapter 7), which indicated that alternative pasture species may be required to significantly increase water use. Simulation studies indicated that with high herbage mass, substantial rainfall was intercepted by canopy and litter and evaporated, coinciding with lower runoff losses (Chapter 8). Where excessive dead material accumulates, alternative management may be required to convert that material into litter on the soil surface, thereby maintaining optimal conditions for soil biological activity. The proportion of the hydrological balance partitioned to transpiration was less than 50% of annual rainfall for all treatments, which together with low transpiration efficiency and short growth periods accounted for the low productivity of these natural pastures. Simulation studies indicated that a grazing management strategy that changes stocking intensity in response to pasture growth may increase transpiration and transpiration efficiency while maintaining high cover and litter mass levels and so achieve the most productive and sustainable use of rainfall (Chapter 8).

Rotational grazing or sowing of legumes into the pasture are simple management strategies that, compared with continuous grazing, can be used to attain a pasture with more desirable characteristics and so offer the most productive and sustainable use of rainfall. Natural pastures that are managed to maintain an herbage mass of between 2000 and 3000 kg DM/ha with litter mass > 1000 kg DM/ha and ground cover > 70%, may offer the greatest productive and sustainable use of rainfall. While these strategies had significant effects on natural pastures for the North-West Slopes, these same principles may also apply to other temperate pastures. In wet years, grazing management is not likely to have a great impact on the amount of deep drainage from these pastures, but management that encourages an actively growing, healthy pasture sward is likely to minimise losses. To further minimise deep drainage losses, alternative species that remain green year-round (e.g. wallaby grass) or those with deeper root systems (e.g. lucerne) may be required.

Future research should aim to determine the effect of canopy and litter interception on evaporation losses and rainfall efficiency within grazed pastures, so that stored soil water and pasture growth may be maximised on the North-West Slopes. For these pastures evaporation at night, may be a substantial proportion of daily and annual totals and experiments should aim to quantify the magnitude of these. Similarly, the seasonal water use and herbage mass production capabilities of alternative species such as wallaby grass should be evaluated, so that pasture production and water use might be maximised.