5 The effects of ground cover, rainfall characteristics and soil water content on surface runoff

"That portion of precipitation not immediately absorbed into or detained upon the soil and which thus becomes surface flow." (Houghton and Charman 1986)

5.1 Introduction

In a long-term modelling study of the soil hydrological balance for pastures near Tamworth NSW, Simpson *et al.* (1998) predicted that mean annual runoff was around 20 mm (or 3% of average annual rainfall). In studies at Gunnedah NSW, Lang (1979) showed that runoff could be as high as 160 mm (22.6% of average annual rainfall) when ground cover levels were low (around 20%). These data, together with reports that over 80% of the cropping and grazing lands on the North-West Slopes are eroded (Emery 1975), suggest that runoff continues to be an important component of the hydrological balance. A substantial amount of water may be lost from grazed pastures through runoff.

Ground cover can be a complex mosaic of vegetative (e.g. plants, litter, canopy) and non-vegetative (e.g. stones, gravel, animal dung) components that prevent both raindrop impact and soil detachment by overland surface flow. In a study of the effect of ground cover on runoff and erosion, Lang (1990) described in detail the various components of vegetative cover in a pasture situation and their effect on water movement through and across the soil surface. Canopy cover may correlate better with hydrologic variables such as soil infiltration capacity (Wilcox *et al.* 1988) and runoff (McIvor *et al.* 1995). For the current study, two aspects of cover were considered: (a) ground cover, the percent cover of all non-soil material on or near the soil surface, and (b) canopy cover, the percent cover provided by foliar plant canopies greater than 5 cm in height.

For the North-West Slopes, a lack of ground cover can be an indicator that soil infiltration capacity is low. In a study of runoff from plots with varying degrees of ground cover, Lang (1979) showed that infiltration capacity decreased sharply as ground cover declined, resulting in more runoff events and larger runoff volumes. Increased grazing intensity may cause surface infiltration capacity of soil to decline (Gifford and Hawkins 1978). Increased hoof action, compaction and removal of herbage mass are all components of the animal effect. Greenwood and McKenzie (2001) reported studies performed across a wide range of pastures, soil types and climate and concluded that grazing at any intensity is deleterious to infiltration. Generally, infiltration capacity declines as the impacts of compaction, loss of pore structure and connectivity, and surface sealing take effect. Other studies have reported that infiltration declines and sediment production increases with increased stock trampling (e.g. Warren *et al.* 1986).

Previous studies have suggested a broad range of ground cover thresholds (20 to 75%, Chapter 2) that are required to control surface runoff. These thresholds tend to be location specific, and vary in relation to other soil, rainfall, and pasture characteristics. For the North-West Slopes, Lang (1979) proposed a threshold of 70% ground cover, below which, the frequency and magnitude of runoff events increase exponentially.

Pasture herbage mass may provide crucial protection to the soil surface through the effect of canopy cover intercepting raindrops and reducing their kinetic energy. The pasture canopy then provides stem flow, delivering water at a slower rate to the soil surface near the base of the tussock where macropores are likely to be abundant (Freudenberger *et al.* 1997). Canopy cover is often the first to decline with over grazing, but provides a crucial role in maintaining infiltration rates. Pasture tussocks and litter combine to detain water on the soil surface, giving it more time to infiltrate. The tussock bases provide obstacles and restrictions to overland flow, causing it to pond, where a slight positive hydraulic head aids infiltration. Hence, pasture and litter cover might both be essential factors that combine to reduce runoff.

Both the soil water content and the available storage capacity of the soil influence the infiltration rate during a rainfall event. Studies of the interaction between infiltration and runoff using simulated rainfall have often collected soil water content data at the beginning or end of each session (e.g. van Rees and Boston 1986) to gain an appreciation of its effect on runoff. In a study of runoff in grazed woodland, Scanlan *et al.* (1996) showed the importance of soil dryness or soil water deficit in absorbing rainfall events and preventing runoff. In a study of farming and fallow management, Freebairn and Boughton (1981) reported that antecedent soil moisture conditions positively affected runoff volume but cover management moderated the relationship. Other studies have documented the importance of such information, but lacked suitable technology to collect it (e.g. Dunin 1969*a*). Continuous soil water content monitoring technology reported by Murphy and Lodge (2001*b*) might aid the interpretation of surface runoff generation processes. No other field-scale runoff studies have reported the use of continuous soil water content monitoring to explore the dynamic interaction between these factors during rainfall events.

Previous studies have shown that the magnitude and intensity of rainfall events may influence the generation of runoff. Generally, as storm size and intensity increase, surface runoff increases and higher thresholds of cover are required to reduce erosion and sediment load (McIvor *et al.* 1995). Larger storm sizes increase the likelihood of soil erosion and damage for a given level of ground cover (Logan 1965). In relation to the North-West Slopes, where high intensity storms are frequent in the warmer months (Lea 1977), ground cover management is critical to prevent runoff and erosion. Lang (1990) also reported that runoff generation and sediment production was likely to increase with larger storm size and intensity. However, such events may be rare as indicated by examination of daily rainfall for Tamworth recorded in the SILO database (Jeffrey *et al.* 2001), which showed that the probability of daily rainfall being > 50 mm was 0.01%.

Grazing management that influences the herbage mass, litter mass, ground cover and canopy cover of a pasture is likely to have an effect on both the generation and magnitude of surface runoff. Manipulation of the pasture should affect the soil water content and exposure of the soil surface to raindrop impact, and so influence the nature of runoff. The effect of animal trampling may reduce surface porosity and thus increase the generation of runoff in treatments with higher grazing intensity. The objective of this chapter was to explore the effect of these interactions on the generation of surface runoff and assess the role of grazing management on control of runoff generation for grazed natural pastures on the North-West Slopes. Specific aims were:

a) to determine if a ground cover level of > 70% prevents surface runoff;
b) to determine if a canopy cover level of > 40% prevents surface runoff;
c) to determine if surface runoff decreases with higher herbage mass and litter mass; and
d) to determine if surface runoff decreases with a larger soil water deficit.

5.2 Methods

Surface runoff was quantified for a range of ground cover and pasture conditions by measuring water collected from bounded runoff plots. Studies were carried out at Springmount and two satellite study sites, Winchfield and Eloura.

5.2.1 Surface runoff plots

Installation and construction

Runoff plots were assigned to treatment plots based on expected herbage mass and groundcover differences (Table 5-1). In addition, all runoff plots at Springmount were located in adjacent plots for practicality of installation (Figure 5-).

Each runoff plot was approximately 3.3 m wide and 30 m long, bounded by a mounded earth bank. The bank was formed using a one-way four disc mounding plough (a farm implement with offset discs used to create earthen contour and irrigation banks). Two passes of the plough were usually required to build a mound approximately 30 cm high. Soil was thrown towards the runoff plot so the plot surface remained intact. Damage to the soil surface of the runoff plots was minimised wherever possible by limiting the amount of tractor and foot traffic. After the runoff plots were established, they were surveyed using a surveyor's level to determine the actual dimension and surface slope (Table 5-1).

Table 5-1. Expected range of herbage mass (kg DM/ha) and ground cover (%) conditions for each surface runoff plot at Springmount, together with their actual slope (%) and surface area (m^2).

Grazing Treatment	Plot	Herbage mass (kg DM/ha)	Ground Cover (%)	Slope (%)	Area (m^2)
T5GR12	5	> 3000	100	3.4	117
T3FERT8	6	2000-3000	75	3.2	107
T1C4	7	1000-2000	60	3.1	104
T2C6	8	< 1000	< 40	2.4	108

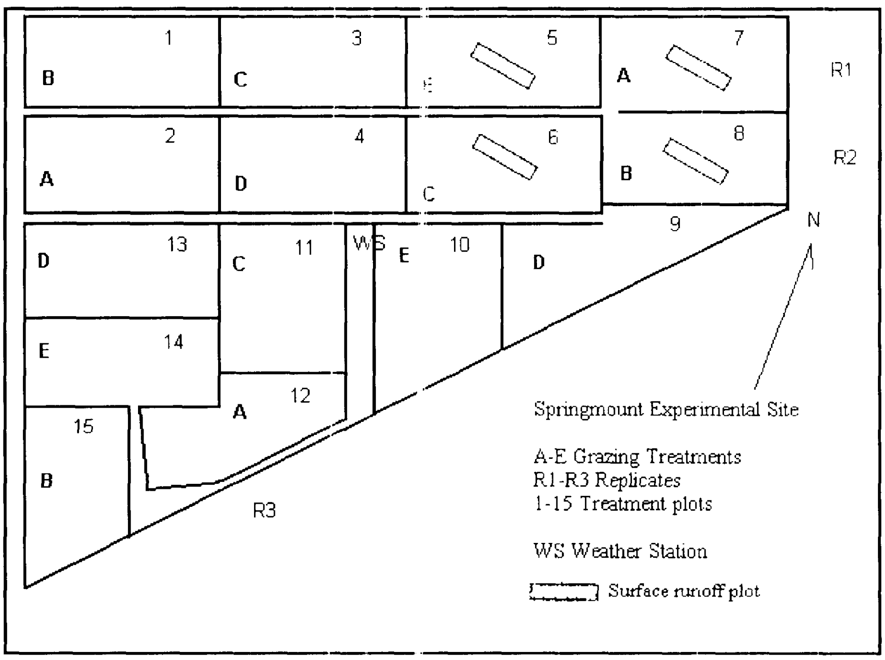

Figure 5-1. Approximate location and orientation of surface runoff plots at Springmount.

A Gerlach type trough was installed to collect runoff water at the toe of each plot (Gerlach 1967). Each trough was manufactured from folded galvanised steel plate (1 mm thick) with overall dimension of 4 m long by 0.4 m wide by 0.3 m deep (surface area of 1.6 m^2). There was a leading edge with a horizontal flap 6 cm wide which lay flat on the soil surface to direct runoff water into the trough and it also provided a stable edge. The trough was laid on a bed of crushed limestone gravel for stability and at a slope of 1% towards the tipping bucket gauge. A baffle separated pasture litter and dung, allowing water to pass through. A second baffle collected any fine material before water passed though to a tipping bucket gauge below.

A pit (approximately 1.8 by 1.2 by 0.75 m deep) was dug at the lower end of each runoff plot to house the tipping bucket gauge, water sampling equipment and plumbing. The pit was lined with steel sheeting to prevent erosion. The pit floor was packed with crushed limestone gravel and lined with concrete, with the gravel providing an excellent base material for levelling and compacting.

Runoff water was disposed of using 100 mm PVC storm water pipe and plumbing fittings were installed in the bottom of the pit to drain water under gravity. A drain hole was installed on each side of the tipping bucket to take water from each bucket tip. Runoff water was carried offsite by the storm water pipe.

Estimation of runoff water volume (L) and depth (mm)

Runoff volume (L) was measured with tipping bucket gauges (Ciesiolka and Rose 1998) with the tip count recorded by Tain data logger at 1 or 4 minute intervals. Each of the gauges measured a different volume of water ranging from 4-7 L per tip. As the tipping rate increased, the volume of water measured with each bucket tip also increased and this was described by individual calibration equations (Table 5-2). These volumes were appropriate to measure runoff volume from an area of ~100 m^2 at sampling intervals of 1 and 4 minutes within an acceptable error limit (Yu *et al.* 1997). Equivalent runoff depth (rainfall equivalent, mm) was calculated by dividing the volume of water (L) by the surface area of each runoff plot (m^2).

Surface soil water store (0-20cm)

Surface stored soil water (θ mm) of each runoff plot was monitored using the technique described in Chapter 3. Watermark sensors installed at depths between 2.5 and 20 cm (Chapter 3) provided an estimate of θ at four minute intervals as recorded by a Tain data logger.

Sediment and nutrient concentration

A water sample splitter was installed on one side of the tipping bucket to collect samples for analysis of nutrient and sediment concentration. The water sample was stored in a sealed container located below a concrete slab in darkness, where it was more likely to remain cool, until it was collected and taken to the laboratory for analysis (Tamworth City Council Environmental Laboratory). Water samples were collected within 24 h of a runoff event and transported to the laboratory in a cooled storage unit. Concentration (mg/L) of total phosphorus (P) and total nitrogen (N) was determined using persulphate digestion (Hosomi and Sudo 1986) and suspended sediment concentration (mg/L) was determined gravimetrically (APHA 1995). For each runoff event, the total sediment, P, and N load (kg/ha) was calculated using the volume of runoff water.

Table 5-2. Polynomial regression relationships between tip rate (tips/minute) and water volume (L) of each tipping bucket gauge installed at Springmount.

Grazing Treatment	Plot	Volume/tip relationship (L/*x*), x = tips per minute	R^2
T5GR12	5	$4.669 - 0.2095x - 0.00964x^2 + 0.0001635x^3$	0.949
T3FERT8	6	$5.3956 + 0.0856x - 0.00178x^2 + 0.0000194x^3$	0.979
T1C4	7	$4.622 + 0.2004x - 0.008x^2 + 0.0001204x^3$	0.94
T2C6	8	$5.2657 - 0.12698x - 0.00512x^2 + 0.0000898x^3$	0.979

Pasture characteristics

Percentage ground cover and canopy cover was estimated visually in 10 randomly located quadrats along a central transect of each runoff plot each calendar month (Chapter 3, Murphy and Lodge 2002). Linear interpolation between sampling dates estimated values on the day of each runoff event. Herbage mass (kg DM/ha) and litter mass (kg DM/ha) data were collected (Chapter 4) for each grazing treatment plot and linear interpolation was used to determine values on the day of each runoff event. Herbage and litter mass conditions within runoff plot areas were assumed similar to the entire grazing plot, as there was no evidence of preferential grazing within the runoff plot area.

5.2.2 Satellite runoff sites

The core runoff data were collected from Springmount, with supporting data collected at satellite sites at Winchfield and Eloura (Chapter 3). The same techniques were used to install runoff plots and record runoff, but soil and pasture types were different at these other sites (Table 5-3). The runoff events recorded at these sites increased the number and diversity of events included in the data analysis.

Table 5-3. Range of pasture type, soil type, slope (%) and herbage mass herbage (kg DM/ha) at Eloura and Winchfield surface runoff sites.

Site	Pasture Type	Soil Type	Slope (%)	Herbage mass (kg DM/ha)
Eloura	Natural – wallaby grass, blue grass, red grass and wire grass	Red chromosol – Brown vertosol	3.2	800 – 8000
Winchfield	Sown – phalaris, subterranean clover, annual ryegrass	Brown podosol – Yellow sodosol	6.4	1500 - 15000

5.2.3 Data analysis

Surface runoff results collected during this experiment were related to both physical soil and pasture characteristics and rainfall characteristics. Firstly, the ground cover and canopy cover conditions for each runoff plot at Springmount were investigated to ascertain differences between grazing treatments. Secondly, the characteristics of each rainfall event were summarised to illustrate the type of rainfall events received at the site in relation to the runoff events. Thirdly, total runoff and frequency distribution of events were quantified. A linear regression model identified key variables that explained significant proportions of the variation in runoff depth for events at each site, and for all sites combined (Table 5-4).

Rainfall intensity was estimated at one minute intervals by an automatic pluviometer and total rainfall depth was measured at 30 minute intervals. A rainfall event was defined as rainfall > 0.2 mm depth, temporally separated from another rainfall event by at least 30 minutes using the same rationale as Lang (1990), who used a 6 h period to separate events. A runoff event was defined when the water volume recorded with a tipping bucket gauge exceeded the equivalent rainfall volume that would have been received by the open runoff trough (1 mm rain = 1.6 L of water). Runoff volume was calculated for each four minute period by subtracting the volume of rainfall water received from the volume measured by the tipping bucket. The period of a runoff event was defined as the time (minutes) from the start of rainfall contributing to the runoff event, to the end of the water flow through the tipping bucket gauge. If a runoff event was recorded for one plot, the same event period was defined for the other plots, even if no runoff occurred on those plots. All data calculations were performed in a Microsoft Access® relational database (designed by Mr Colin Lord, University of New England).

Grouping of surface runoff events according to rainfall event depth and peak intensity allowed the effect of ground cover on runoff generation to be further explored (e.g. McIvor *et al.* 1995). Three groupings were used: small (rainfall < 25 mm and rainfall intensity < 25 mm/h), medium (rainfall 25-50 mm and rainfall intensity 25-45 mm/h), and large (rainfall > 50 mm and rainfall intensity ≥ 45 mm/h). Correlation coefficients indicated that exponential equations best described the relationship between ground cover and runoff depth for each group (Lang 1979; McIvor *et al.* 1995).

Linear regression model

A linear regression model (S-Plus, MathSoft 1999) examined runoff data to assess the importance of up to 12 variables collectively (Table 5-4) in explaining variation in runoff depth (mm). For each analysis, all variables were fitted and the proportion of variation that each explained was determined. Based on the *F*-values and the proportion of variance explained by each variable in the presence of the others (*F*-value inc.), the least important ones were removed from the model leaving a minimum set of explanatory variables in a simpler model that still adequately explained the variation in runoff data. The same process was applied to data from individual sites and for data combined across all sites. A total of 276 runoff events were quantified.

Key runoff events

The linear regression model was based on summary data about each runoff event, but provided no insight into processes as they occurred during each event. The continuous monitoring technology used in this study provided real time data of changes in stored soil water, rainfall and surface runoff. These data were analysed graphically for specific events to aid the interpretation of the processes at work during those events.

Four key runoff events were identified that showed the characteristics of infiltration and saturation excess generation of surface runoff. These events were selected as they had similar total rainfall (48.2-64.6 mm), but generated very different surface runoff depths (0-30 mm). Soil water deficits (mm) at the beginning of these rainfall events ranged from -58.5 to -31 mm, which represented a difference in storage capacity of nearly 30 mm. For these events, rainfall, runoff, and soil water deficit were displayed graphically to illustrate interactions through time at 30 minute intervals for periods up to 24 h. Cumulative rainfall and runoff were also shown for each period. Data from one event was presented at four minute intervals to further enhance analysis of interactions taking place within the event through time.

Table 5-4. The range of variables that were quantified in relation to each runoff event and tested in a linear regression model to identify which were the most important in describing runoff generation.

Variable
Duration of event (minutes); rainfall depth (mm); peak rainfall intensity (mm/h, 4 minute interval); mean rainfall intensity (mm/h, for the runoff event); stored soil water (mm) for the surface layer (0-22.5 cm); change in stored soil water (mm); surface soil water deficit at the start of the event (mm); herbage mass (kg DM/ha); litter mass (kg DM/ha); ground cover (%); and, canopy cover (%)

5.3 Results

5.3.1 Ground cover on runoff plots

Ground cover and canopy cover was estimated on 43 occasions for each runoff plot between April 1998 and September 2001 (Figure 5-2). The initial estimates of cover were taken approximately six months after grazing treatments were stocked, and so some influence from the grazing treatments was evident, but values generally reflected those obtained for the wider treatment plots (Chapter 4). Initial ground cover for all treatments was similar (60-80%), but diverged through the course of the experiment (Figure 5-2). Minimum mean ground cover was 54% for the continuously grazed treatment (T2C6, range 44 to 72%) and maximum was 96% for the rotationally grazed treatment (T5GR12, range 81.5 to 100%). The continuously grazed treatment (T2C6) tended to have low ground cover of around 40-60% compared with all other treatments having > 80% ground cover (Figure 5-2). The rotationally grazed and the subterranean clover treatments (T5GR12 and T3FERT8) generally had high ground cover of around 90-100% (Figure 5-2).

Canopy cover on each runoff plot was less than ground cover for all treatments (Figure 5-3). Minimum mean canopy cover was 1.8% for the T2C6 treatment (range 0 to 8.5%) and the maximum was 68% for the T5GR12 treatment (range 52 to 96.5%, Figure 5-3). Apart from the periods September to October 1998, and December 2000 to August 2001, the rotationally grazed plot had the maximum canopy cover (Figure 5-3). On the other occasions, canopy cover was similar in both the subterranean clover and rotationally grazed treatments (T3FERT8 and T5GR12). For approximately half of the experimental period (21 sample dates), T1C4 and T3FERT8 had similar levels of canopy cover (Figure 5-3). The level of canopy cover in the T3FERT8 treatment was the most variable and changed in response to each growing season and the performance of the subterranean clover. Canopy cover peaked (98%, Figure 5-3) in this treatment during October 1998, when the growth of subterranean clover was highest.

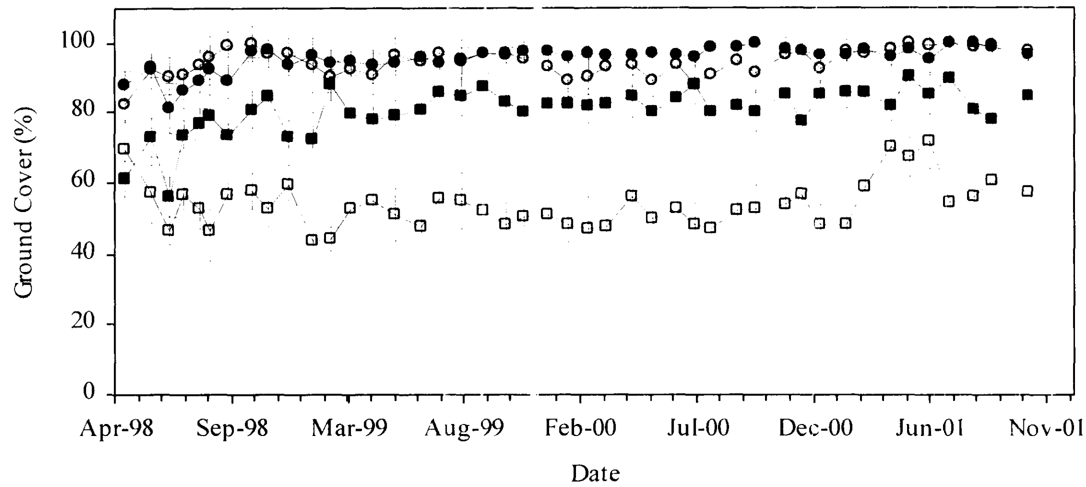

Figure 5-2. Ground cover (%) of surface runoff plots for the period April 1998 to September 2001 (T1C4 - ■, T2C6 - □, T3FERT8 - ○, T5GR12 - ●). Vertical bars for each treatment indicate one standard error of the mean.

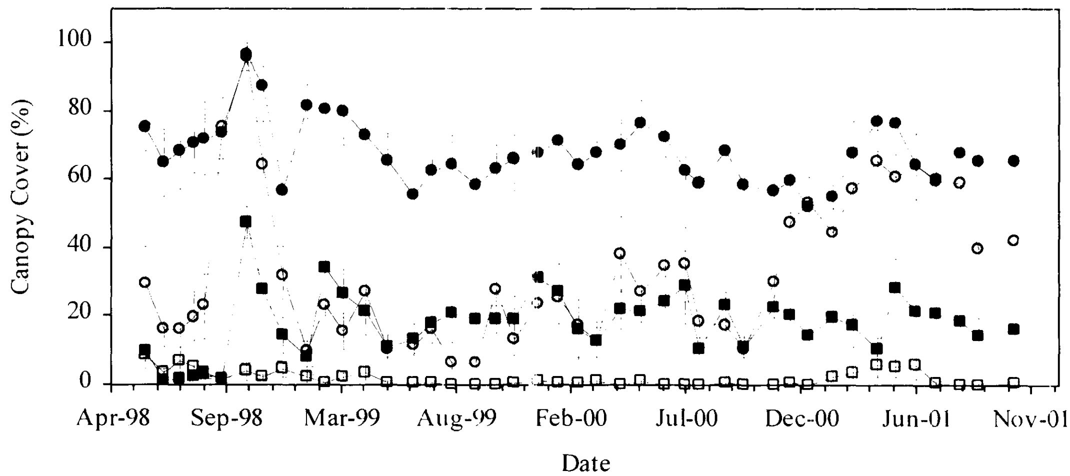

Figure 5-3. Canopy cover (%) of surface runoff plots for the period April 1998 to September 2001 (T1C4 - ■, T2C6 - □, T3FERT8 - ○, T5GR12 - ●). Vertical bars for each treatment indicate one standard error of the mean.

5.3.2 Rainfall events

The characteristics of 1337 rainfall events were quantified at Springmount, these ranged from 0.2 to 75.5 mm, with 63.9% of events < 1 mm and only 1.1% was > 20 mm (Figure 5-4). The frequency distribution of rainfall depth was highly skewed towards small events. Forty events were associated with runoff generation. Peak rainfall intensity (4 minute interval) ranged from 3 to 123 mm/h. Higher intensity events were associated with thunderstorm activity, but these were rarely experienced during the experiment (only 4 events had intensity > 100 mm/h).

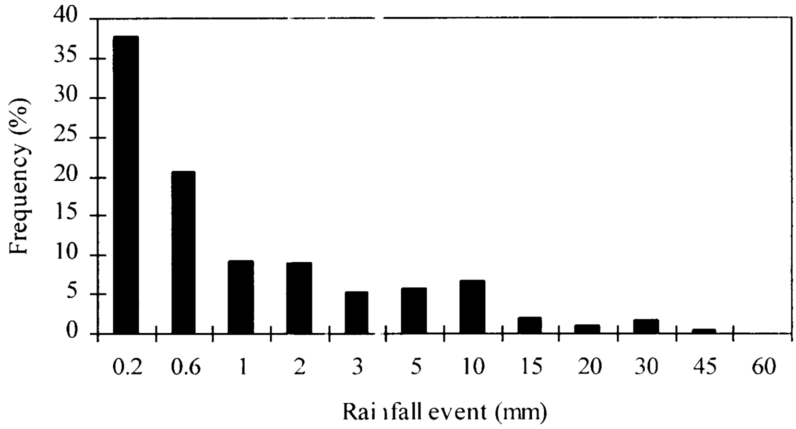

Figure 5-4. The frequency distribution of rainfall events (mm) recorded at Springmount.

5.3.3 Runoff events

At Springmount between February 1998 and September 2001, runoff occurred in 39 separate periods at any time of year. The largest runoff depth of 30 mm was recorded on 13 December 2000, for the T2C6 treatment. Maximum total runoff for the experiment was 142 mm (or 6.0% of total rainfall) for T2C6, while T5GR12 had the minimum of 7.9 mm (or 0.3% of total rainfall, Figure 5-5). Most runoff events (66%) were ≤ 0.5 mm, while a few large events made substantial contributions to the total (Figure 5-6). Small runoff events occurred more readily on the continuously grazed treatments, which had lower ground cover.

Runoff was associated with rainfall events ranging from 5 to 75.5 mm and large runoff events were associated with comparatively rare rainfall events. Frequency distribution of rainfall events that contributed to runoff events at Springmount showed that for 50.3% of events, rainfall > 30 mm was required to generate any runoff. However, rainfall events of that size were less than 2.5% of all the events recorded. Similarly, to generate large runoff events (> 7 mm) required a rainfall > 45 mm, but of rainfall events < 0.7% were of that magnitude.

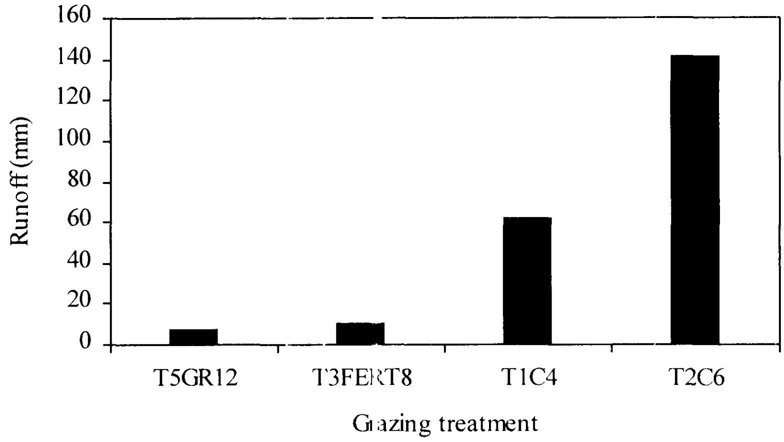

Figure 5-5. Total runoff depth (mm) recorded for runoff plots at Springmount between February 1998 and September 2001.

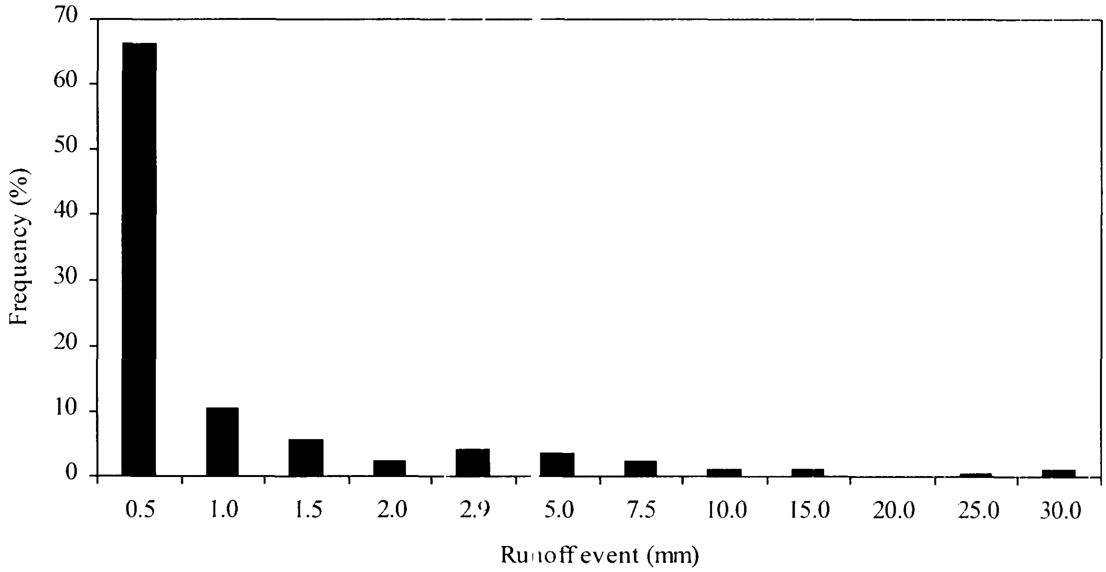

Figure 5-6. Frequency distribution of runoff events (mm) for all events recorded at Springmount.

5.3.4 Runoff and ground cover

Ground cover and runoff were correlated within each grouping for small (r=0.53, P<0.05, n=13), medium (r=0.68, P<0.01, n=11), and large (r=0.90, P<0.01, n=9) events, respectively (Figure 5-7). While the curve parameter changed for each group (i.e. -0.033 to -0.049), further analysis showed that using varying coefficients, a single curve parameter could be used for all groups (i.e. -0.056) without loss of significance. The coefficient increased significantly as the group size increased (2.8-160.8), indicating that ground cover was more important for runoff control in larger rainfall events. Higher rainfall amounts and intensities generated more runoff depth and so ground cover was more important to limit runoff. For cover levels below about 60%, runoff volume increased markedly, illustrating that cover did reduce runoff significantly for high magnitude events. A limitation of this analysis was the range of ground cover levels experienced during the experiment, the minimum being 44% for all plots. Had grazing treatments resulted in lower cover levels, larger runoff events may have been generated at those low levels.

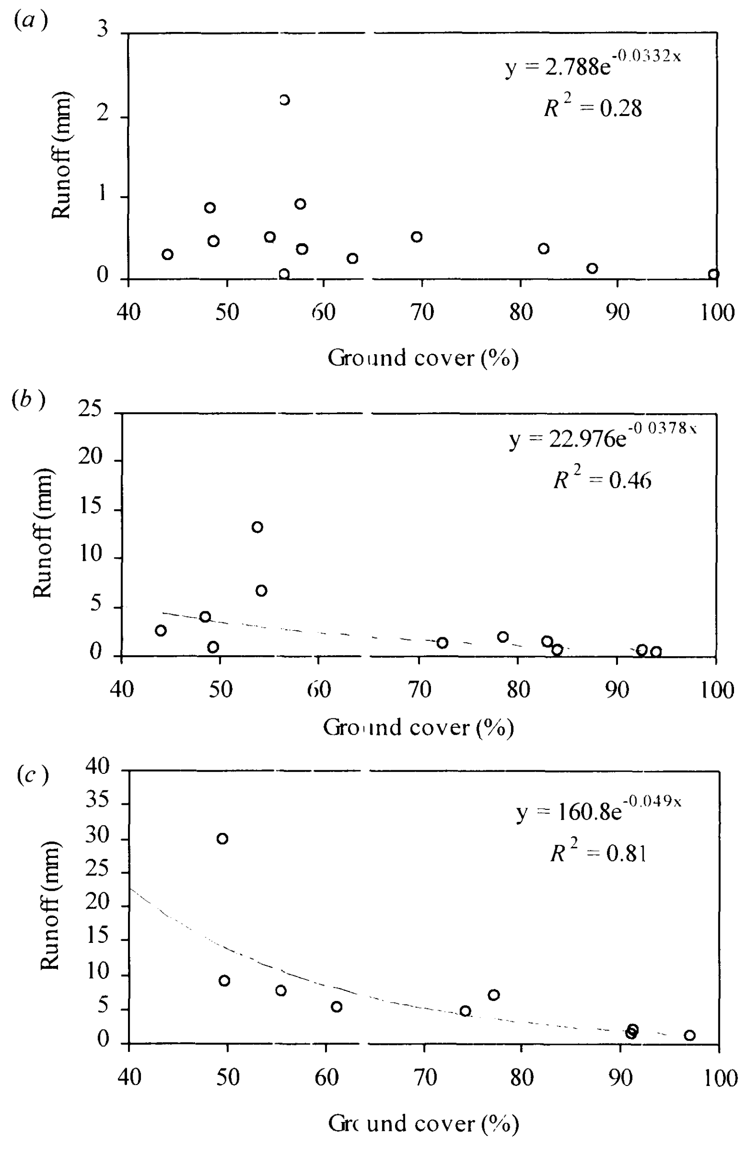

Figure 5-7. Relationships between ground cover (%) and runoff (mm) for (*a*) small rainfall events (rainfall < 25 mm and peak intensity < 25 mm/h), (*b*) medium rainfall events (rainfall 25-50 mm and peak intensity 25- 45 mm/h), and (*c*) large rainfall events (rainfall > 50 mm and peak intensity ≥ 45 mm/h).

5.3.5 Linear regression analysis of runoff data for Springmount

The linear regression model accounted for 38.3% of the variation in surface runoff depth with a residual mean square error of 3.3 mm (df=149, Table 5-5). The incremental *F*-values indicated that peak rainfall intensity (7.5% of variation), ground cover (4.9%), and rainfall depth (4.6%) were important variables in the generation of surface runoff. Conversely, herbage mass (1.4%), canopy cover (0.7%), soil water deficit (0.4%) and litter mass (0.3%) were minor variables and were not included in further models. A simple linear model incorporating rainfall, peak intensity, and ground cover explained 35.7% of the variation in surface runoff depth with a residual mean square error of 3.26 mm (df=156, Table 5-6). Ground cover was the only variable within the simple model that had a negative coefficient.

Table 5-5. The *F*-values and incremental *F*-values of each variable, including the percentage of variation accounted for in the linear model describing surface runoff (mm) generation at Springmount (R^2 = 38.3, RMS = 3.3 mm on df=149).

Variable	*F*-value	Percentage of variation (%)	*F*-value (inc.)	Percentage of variation (%)
Rainfall duration	0.3	0.1	0.2	0.1
Rainfall depth	34.8	14.4	11.1	4.6
Mean rainfall intensity	8.0	3.3	1.1	0.5
Peak rainfall intensity	17.5	7.3	18.2	7.5
Herbage mass	7.2	3.0	3.3	1.4
Litter mass	1.5	0.6	0.6	0.3
Ground cover	19.2	7.9	11.8	4.9
Canopy cover	1.4	0.6	1.6	0.7
Soil water deficit	0.4	0.2	0.9	0.4
Change in soil water deficit	2.4	1.0	2.4	1.0

Table 5-6. Group of variables that explained a significant proportion of surface runoff at Springmount. The regression coefficient (R^2), the residual mean square error (RMS, mm), and the degrees of freedom (df) together with the *F*-value and the percentage of variation that was explained by each variable are presented.

Variable	Coefficient	*F*-value	Percentage of variation (%)	R^2	RMS	df
Rainfall	0.064	32.3	13.3	35.7	3.26	156
Peak rainfall intensity	0.054	27.7	11.4			
Ground cover	-0.078	26.5	10.9			

5.3.6 Linear regression analysis of runoff data for combined sites

Eloura

Eleven runoff events were recorded with the largest event (24.2 mm) being on a rotationally grazed plot (4 weeks grazing; 12 weeks rest) on 4 September 1998. This treatment also had the maximum total runoff (43.8 mm or 1.7% of total rainfall). The continuously grazed treatment

(3.1 sheep/ha) on a red chromosol soil had the lowest amount of runoff (6.6 mm or 0.3% of total rainfall). Runoff was associated with rainfall events ranging from 17.9 to 106 mm, but large events were comparatively rare. The duration of events at this site was longer than at Springmount, ranging from 236 to 3522 minutes.

An initial linear regression model accounted for 55.8% of the variation in surface runoff depth with a residual mean square error of 3.2 mm (df=33). The incremental *F*-values indicated that mean rainfall intensity (6.4% of variation), soil type (6.1%), and rainfall depth (4.7%) were important variables in the generation of surface runoff. A simple linear model incorporating these same terms explained 49.7% of the variation in surface runoff depth with a residual mean square error of 3.13 mm (df=40, Table 5-7). The soil type variable indicated that the highest runoff totals were generated from the runoff plots on a brown vertosol type.

Winchfield

Eighteen runoff events were recorded with the largest (47.6 mm on 27 July 1998) generated on the runoff plot in the treatment that had reduced grazing pressure in spring and autumn. This same treatment also had the highest total runoff (185.1 mm or 5.7% of total rainfall) and the shallowest soil depth (< 80 cm). The continuously grazed treatment had the least amount of runoff (6.8 mm or 0.2 % of total rainfall), but the maximal soil depth (> 210 cm). Runoff was associated with rainfall events ranging from 9 to 81 mm with duration ranging from 273 to 6131 minutes.

An initial linear regression model accounted for 46.8% of the variation in surface runoff depth with a residual mean square error of 7.0 mm (df=58). The incremental *F*-values indicated that soil depth (8.6% of variation), rainfall duration (2.6%), rainfall depth (1.8%) and change in soil water deficit (0.5%) were important variables in the generation of surface runoff. A simple linear model incorporating these same terms explained 45.5% of the variation in surface runoff depth with a residual mean square error of 6.7 mm (df=65, Table 5-7). Soil depth was the key variable, with higher amounts of surface runoff generated on plots with shallow soil depth (< 80 cm). Large rainfall events with a long duration were also required to generated substantial surface runoff.

Combined sites

An initial linear model incorporating data from all sites explained 40.8% of the variation in surface runoff depth, with a residual mean square error of 4.5 mm (df=260). The incremental *F*-values indicated that 7 variables were important when explaining variation in surface runoff across all sites and were dominated by soil depth (11.2% of variation), rainfall depth (5.6%), and rainfall duration (1.9%). A simpler model that included those 7 variables explained 39.5% of the variation in runoff depth with a residual of 4.6 mm (df=265, Table 5-7). Coefficients for each variable indicated that surface runoff depth increased as soil depth decreased, and rainfall events became larger (duration, depth, and intensity). Conversely, surface runoff decreased as ground cover increased and the change in soil water deficit increased. For the combined site analysis, herbage mass, litter mass, and canopy cover were not important variables for describing runoff generation.

Table 5-7. Groups of variables that explained a significant proportion of surface runoff at Eloura and Winchfield, and for all sites combined. For each group, the regression coefficient (R^2), the residual mean square error (RMS, mm), and the degrees of freedom (df) together with the F-value and the percentage of variation that was explained by each variable are presented.

Variable	F-value	Percentage of Variation (%)	R^2	RMS	df
		Eloura			
Rainfall depth	26.7	33.6	49.7	3.1	40
Mean rainfall intensity	4.1	5.2			
Soil type	8.8	11.0			
		Winchfield			
Rainfall depth	2.7	2.2	45.5	6.7	65
Rainfall duration	23.5	19.7			
Change in soil water deficit	7.3	6.1			
Soil depth	20.9	17.5			
		All sites combined			
Rainfall depth	10.8	10.1	39.5	4.6	265
Rainfall duration	8.00	7.4			
Peak rainfall intensity	1.3	1.2			
Mean rainfall intensity	1.7	1.6			
Ground cover	0.9	0.8			
Change in soil water deficit	5.9	5.5			
Soil depth	13.8	12.8			

5.3.7 Characteristics of key runoff events

Automatically logged soil water content data from 'Watermark' resistance sensors located in each runoff plot allowed the interactions between stored soil water, rainfall and runoff to be examined for different events. These data are presented for 4 runoff events from the same plot (Springmount, T2C6, plot 8), where the rainfall amounts were similar, but with their differing intensities and duration gave varying runoff responses (Table 5-8). For these events, interaction between stored soil water and runoff indicated that runoff was mainly generated by saturation excess processes.

Event 1 - 31 January 2001 a long duration rainfall event on dry soil with no runoff.

The surface soil was very dry at the start of this rainfall event with a soil water deficit of -58.5 mm. Total rainfall recorded during the event was 48.2 mm with a peak intensity of 30 mm/h. Through a 16 h period (16:00-08:00 h) during the rainfall event, the soil water deficit progressively changed from -58.5 to -3.4 mm as the soil wet (Figure 5-8). Peak rainfall intensity was low and all rainfall was stored by the soil.

Event 2 - 13 October 2000 a long duration event on dry soil with little runoff.

Again, the surface soil was very dry at the start of the event with the same soil water deficit as for Event 1. Total rainfall was 54.8 mm with a peak intensity of 30 mm/h. The surface soil water store filled over a 4 h period (15:00-19:00 h) and a small amount of runoff (1.8 mm) was generated when peak rainfall intensity coincided with the soil being wet (00:00 h, Figure 5-9). Runoff was 3.3% of rainfall and was generated by saturation excess of the surface layer.

Event 3- 4 September 1998 a long duration event on wet soil with high runoff.

At the start of this event the soil surface was moderately dry with a soil water deficit of -30 mm. Total rainfall for the event was 64.6 mm, with a small amount (0.6 mm) falling 9 h prior (around 14:00 h) to the main part of the event when higher intensity rain (63 mm/h) occurred at around 23:00 h (Figure 5-10). Within 1 h of that time the soil water deficit was completely replenished and substantial runoff (30 mm or about half of the incoming rainfall) was generated (Figure 5-10). Since most of the runoff occurred after the surface soil was near maximum soil water content, it was generated by saturation excess of the surface layer.

Event 4- 13 December 2000 a short duration and high intensity event on dry soil with high runoff.

This event was an example of a high intensity summer thunderstorm that generated infiltration excess surface flow with total runoff being 26.2 mm or > 50% of rainfall. The soil surface at the start of the event was moderately dry (soil water deficit of -40 mm) and total rainfall was 51.8 mm. At about 14:00 h rainfall was moderately heavy and its intensity steadily increased to a maximum of 123 mm/h at around 14:30 h (Figure 5-11). Runoff depth peaked after most rainfall had occurred at about 15:00 h. In the early part of the event, soil water deficit remained unchanged, but after further rainfall and another 10 h duration (until about 00:00 h) it was replenished.

Further interpretation of the runoff generation process was enhanced by examining these data at a shorter time interval (4 minute) over a 2 h duration (Figure 5-12). This clearly showed that the peak in runoff (5.7 mm, at 14:32 h) coincided with a second peak in rainfall intensity, approximately 30 minutes after the rainfall event started (Figure 5-12). At that time (14:32 h), soil water deficit had started to reduce, as water infiltrated the soil. However, most surface runoff was generated before soil water deficit had changed substantially (-40.7 to -28.6 mm, 14:40 h, Figure 5-12). This describes a runoff event generated by infiltration excess, where rainfall intensity exceeded the infiltration capacity of the surface soil.

Table 5-8. Characteristics of four key runoff events, including rainfall (mm), initial soil water deficit (SWD mm), rainfall intensity (R_{fi} mm/h) and runoff (R_o mm).

Event	Rainfall (mm)	SWD (mm)	R_{fi} (mm/h)	R_o (mm)
1	48.2	-58.5	30	0
2	54.8	-58.5	30	1.8
3	64.6	-30.0	63	30
4	51.8	-40.0	111	26.2

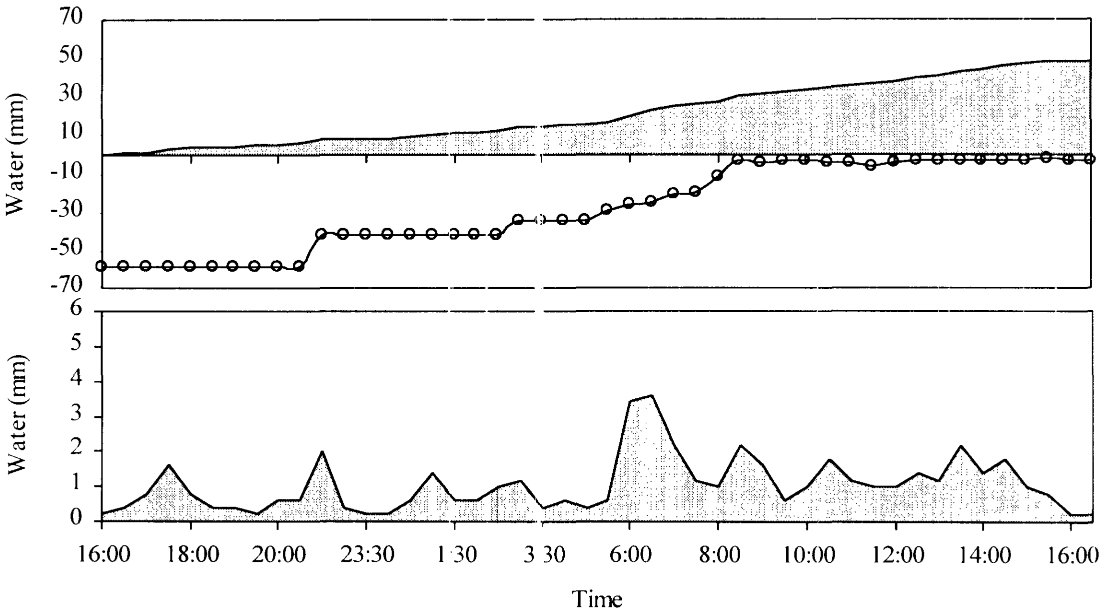

Figure 5-8. Runoff event of 31 January 2001, showing rainfall (grey shading) and soil water deficit (○) data recorded at 30 minute intervals and cumulative for a 24 h period. All rainfall was stored in the soil profile.

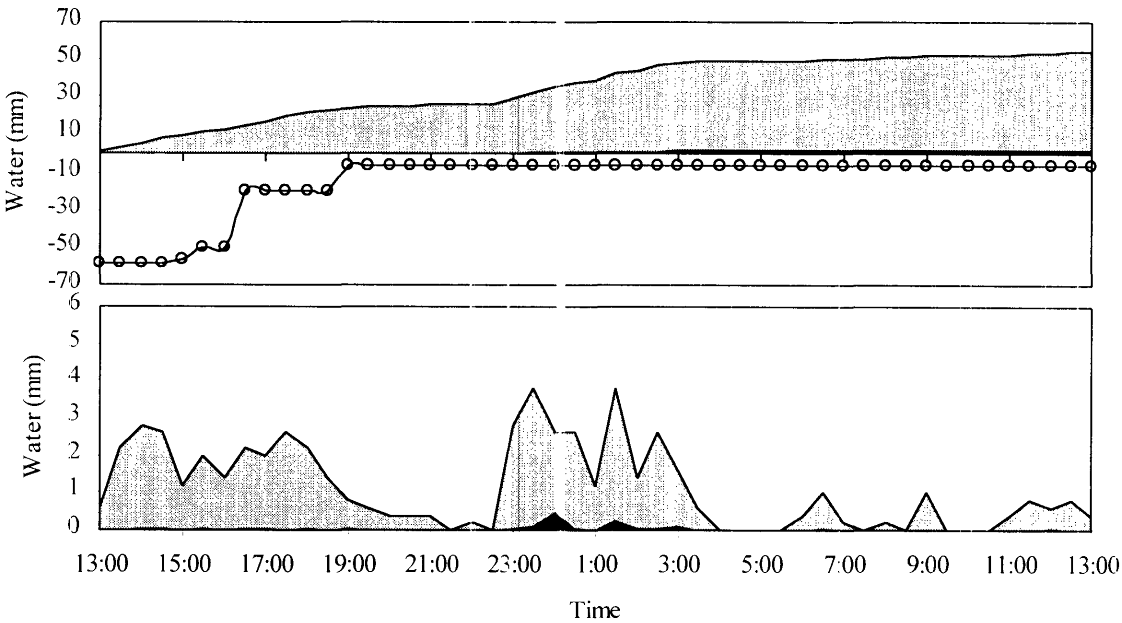

Figure 5-9. Runoff event of 13 October 2000, showing rainfall (grey shading), soil water deficit (○), and runoff data (black shading) recorded at 30 minute intervals and cumulative for a 24 h period. A small amount of runoff was generated after the surface soil water deficit was removed.

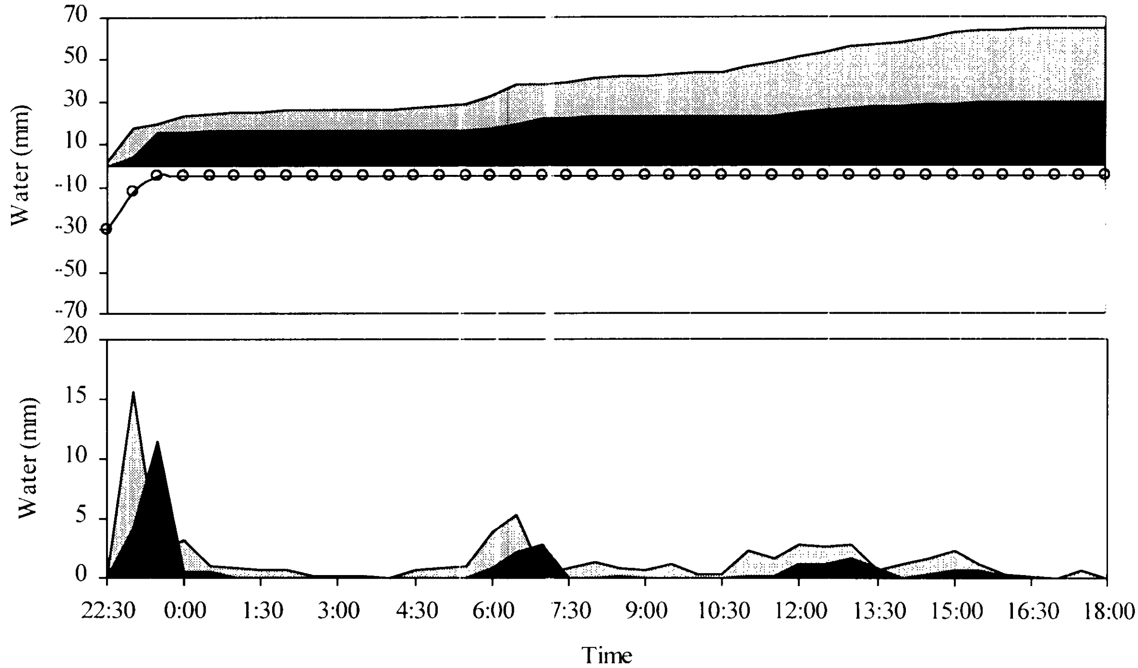

Figure 5-10. Runoff event of 4 September 1998, showing rainfall (grey shading), soil water deficit (○), and runoff data (black shading) recorded at 30 minute intervals and cumulative for a 18 h period. A high proportion of runoff was generated after the soil water deficit was removed.

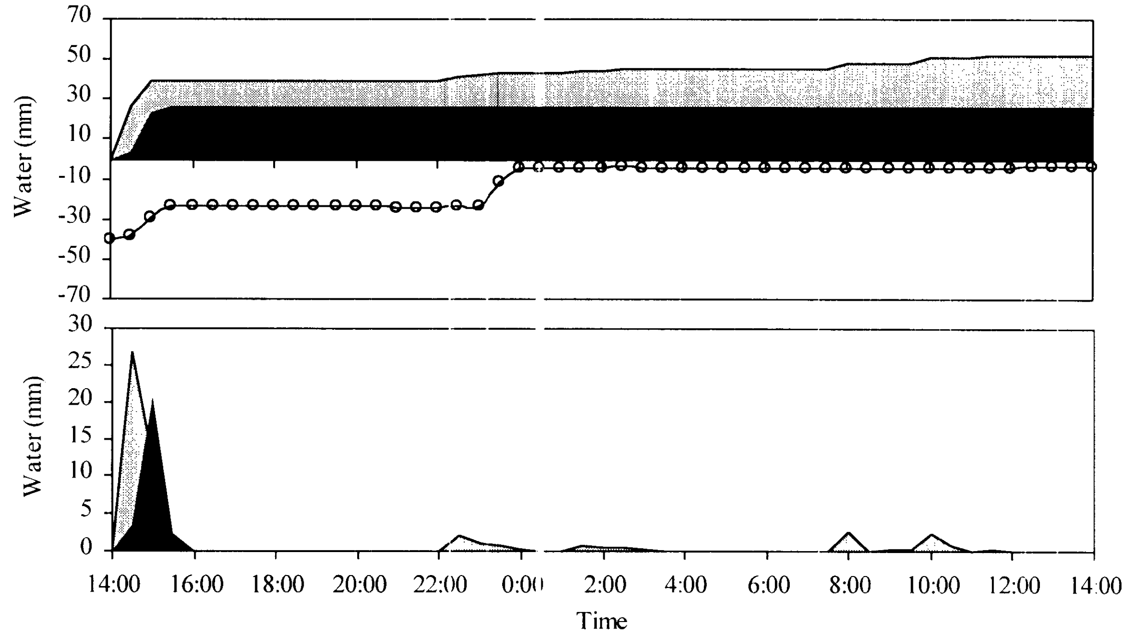

Figure 5-11. Runoff event of 13 December 2000, showing rainfall (grey shading), soil water deficit (○), and runoff data (black shading) recorded at 30 minute intervals and cumulative for a 24 h period. A large amount of runoff was generated, well before soil was wet.

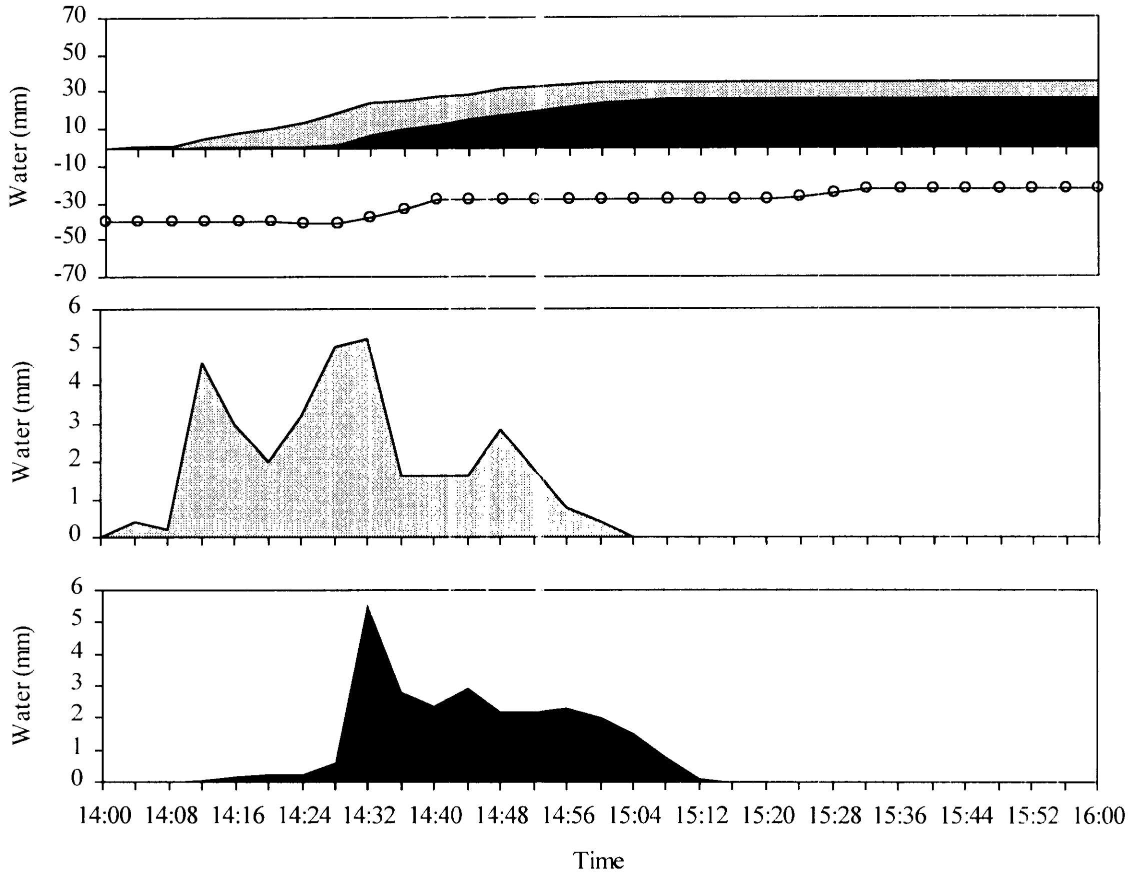

Figure 5-12. Runoff event of 13 December 2000, showing rainfall (grey shading), soil water deficit (○), and runoff data (black shading) recorded at 4 minute intervals and cumulative for a 2 h period. Runoff was generated around 30 minutes from the start of the rainfall event, while the soil was still relatively dry.

5.3.8 Nutrient and sediment load of runoff water

Samples of surface runoff water collected from each plot were analysed for total nitrogen (N), total phosphorus (P) and non-filterable residues. Most samples of runoff water were too small to analyse (< 0.5 L) and so only 19 events were analysed. Generally, nutrient and sediment concentration increased as runoff depth increased, with maximum concentrations of 1.99, 10.44, and 1390 mg/L for P, N and sediment, respectively. Maximum loads were 0.44, 0.69, and 277 kg/ha for P, N, and sediment, respectively, which were associated with larger runoff depths. Linear regression was used to describe the relationship between nutrient load and sediment load (kg/ha) and runoff volume for 19 samples collected during the experimental period.

The mass of sediment per hectare (kg/ha) removed in runoff events ranged from < 2 to > 250 kg/ha and was not correlated with ground cover, but was positively correlated with runoff volume (r=0.91, Figure 5-13*a*). A minimum of 6 mm of runoff was required to remove 50 kg /ha of sediment per event.

The mass of phosphorus removed in runoff events was relatively low, with a maximum of 0.44 kg/ha removed in a 22 mm runoff event. Phosphorus removal was correlated with runoff volume (r=0.83, Figure 5-13*b*) and sediment removed (r=0.93). The mass of phosphorus was not significantly correlated with ground cover (%) conditions. Mass of phosphorus removed is more likely to be correlated with sediment mass due to adsorption to soil particles.

The mass of nitrogen removed in runoff events was also relatively low, with a maximum of 0.69 kg/ha removed in a 30 mm runoff event. In addition, nitrogen removal was not correlated with ground cover (%) or grazing management. Nitrogen removal was correlated with volume of runoff (r=0.98, Figure 5-13*c*) and mass of sediment removed (r=0.92). The higher correlation between nitrogen removal and runoff volume suggests that most nitrogen was in the soluble fraction rather than being adsorbed to soil particles.

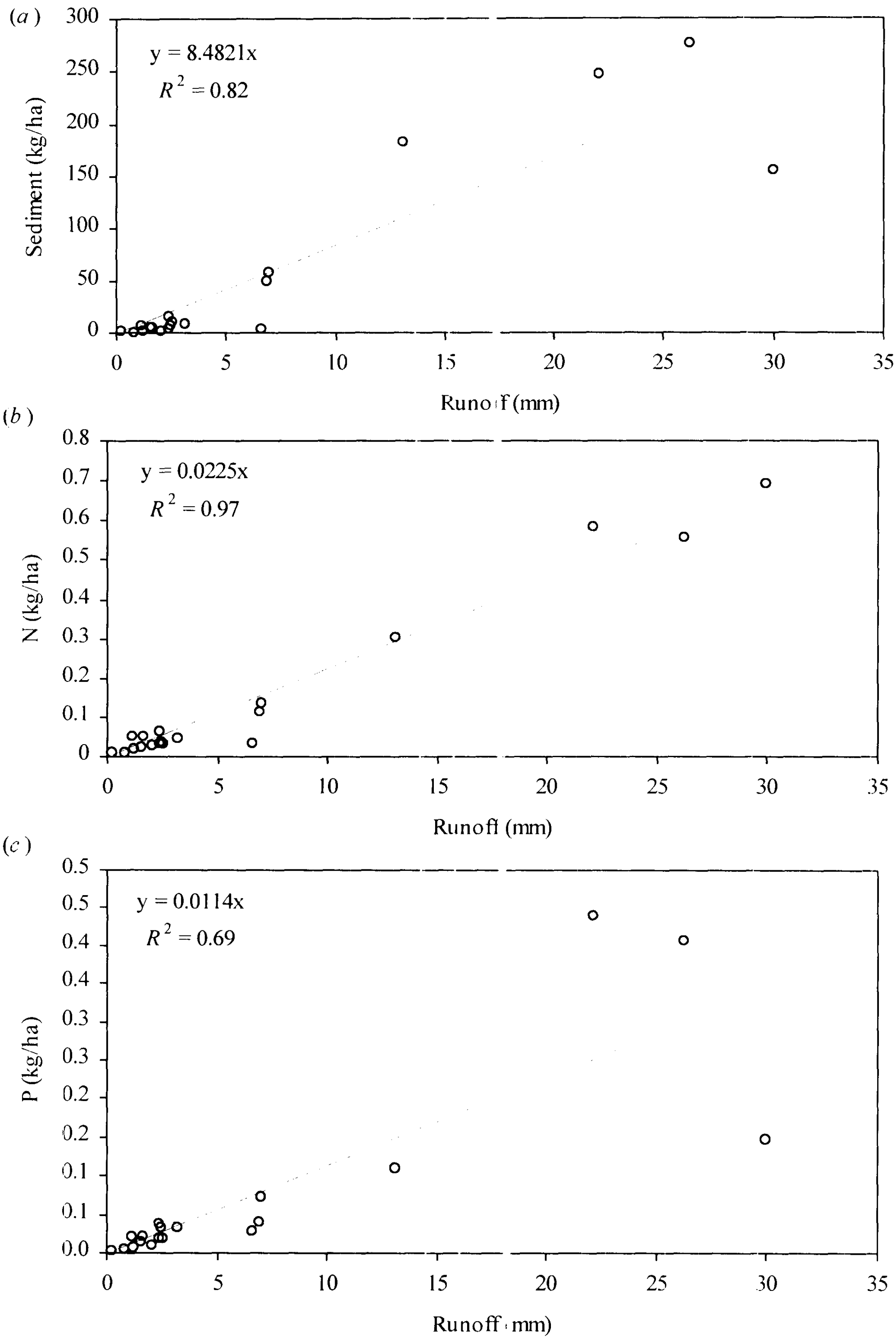

Figure 5-13. Relationships between runoff depth (mm) and loss of (*a*) sediment (kg/ha), (*b*) total nitrogen (kg/ha), and (c) total phosphorus (kg/ha), for runoff water samples collected at Springmount.

5.3.9 Summary of results

Grazing treatment had a significant effect on ground cover and canopy cover on runoff plots at Springmount, with higher levels in the rotationally grazed and subterranean clover plots (T5GR12 and T3FERT8). The lowest ground cover value was just 44% for the T2C6 treatment, but generally, the range in cover levels was quite narrow (55 to 100%). Canopy cover levels ranged from 0 to 91% and the T1C4 and T2C6 treatments had the lower levels.

The distribution of the 1337 rainfall events recorded at Springmount was dominated by events that were <1 mm in magnitude (> 63%). Large rainfall events that generated runoff were rare, with < 1.1% of events being greater than 20 mm. Also, high intensity rainfall events were uncommon, with just four events having a peak intensity of greater than 100 mm/h.

Total runoff depth at Springmount ranged between 0.3 and 6.0% of total rainfall received for the T5GR12 and T2C6 treatments, respectively. The runoff plots with lower ground cover (eg. T2C6) generated runoff more frequently and with greater magnitude. The linear regression model for data collected at Springmount showed that rainfall depth, peak intensity and ground cover were important variables that explained significant variation in the data. The effect of ground cover depended on the size and intensity of rainfall, with cover having very little effect on small rainfall events, but a significant effect for rainfall events with a depth > 50 mm and a peak intensity of > 45 mm/h. However, these analyses showed that ground cover was the only variable to significantly reduce runoff depth.

The cross-site linear regression model showed that soil depth, rainfall depth, rainfall duration and change in soil water deficit were the major variables that explained significant variation in runoff data. Other important variables included peak rainfall intensity, mean rainfall intensity and ground cover. Runoff generation was brought about by a complex interaction of a range of variables, with no dominant factor accounting for a majority of the variation in runoff depth.

Analyses of real time data for some key runoff events showed that runoff was produced through both saturation excess and infiltration excess flow conditions at the Springmount site. However, it appeared that most runoff events were generated through saturation excess flow conditions. Sediment and nutrient losses were relatively minor and both were highly correlated with runoff depth rather than ground cover.

5.4 Discussion

5.4.1 Ground cover on runoff plots

The minimum ground cover for any runoff plot at the time of an event was only 44%, with most runoff events recorded from plots with ground cover > 50%. Although values collected for the runoff plots were not directly comparable with those of the wider treatment plots due to unequal sample numbers and replicates, the two data sets showed similar trends. The continuously grazed runoff plots without subterranean clover had low levels of ground cover while with rotational grazing or subterranean clover and fertiliser added the values were high. Generally, Springmount had the lowest ground cover and the highest number of events. Eloura had slightly higher cover levels than Springmount, but fewer runoff events, while Winchfield rarely had cover levels of < 100%. Subsequently, ground cover data for runoff events was skewed toward high cover situations. Had the range of ground cover conditions been greater, the linear regression model may have placed more importance on this variable in accounting for variation in runoff data.

Previous studies have reported ground cover thresholds, below which runoff increased markedly (e.g. 75%, Lang 1979). While a similar trend was indicated at Springmount, it was not as evident at the other sites, but ground cover was an important variable in explaining the variation in runoff across all sites (Table 5-7). At Winchfield, which rarely had ground cover levels of < 100%, some of the highest runoff amounts were generated (up to 47.6 mm). Had ground cover at Winchfield been lower (e.g. < 50% as at Springmount), runoff losses may have been magnified even further due to the higher surface slope of 6 8%. The interaction between runoff and ground cover is complex and other authors (Lang 1990; McIvor *et al.* 1995) have attempted to explain it. However, in those studies, minimum cover levels were < 20% and high amounts of runoff were generated, making identification of a threshold value much easier. Threshold values may be identified where non-saturated soil conditions exist, but with saturated conditions, cover appears to have no effect on runoff generation.

The current study aimed to determine if a ground cover level of 70% was a threshold value above which runoff from grazed native red grass runoff plots was controlled. Rather than a single threshold value, the level of ground cover at which runoff was minimised varied according to the magnitude and intensity of the rainfall event in relation to stored soil water conditions. However, 70% ground cover at Springmount reduced runoff for larger rainfall events.

Small areas (e.g. < 5m^2 or 5% of plot area) of some runoff plots developed very low ground cover as herbage mass declined. These areas may well have contributed significant proportions of surface runoff, both earlier and more frequently during certain rainfall events. No attempt was made to apportion runoff spatially according to surface area of different cover conditions. Technology described by Srinivasan *et al.* (2002) would be ideal to identify spatial and temporal variation of runoff generation within plots. That technology was developed for studying runoff generation processes in a small pasture catchment and used miniature electronic V-notch weirs to detect where and when runoff was being generated within the catchment (Srinivasan *et al.* 2002). In the current study, such instruments could be strategically located within the surface runoff plots to estimate the relative spatial and temporal contributions of areas with differing ground cover.

5.4.2 Rainfall

Despite high intensity storms being relatively common for the study area (Lea 1977), most rainfall events recorded during the study had low peak intensity values. The maximum intensity recorded at any site was 188 mm/h for a 4 minute period, which would be expected to occur one year in every five as interpolated from Logan (1965). Summer rainfall at Springmount was below average (Chapter 3), which reduced the likelihood of receiving high intensity storm events. Had higher intensity storms occurred, runoff might well have been generated through surface sealing and infiltration excess processes as described by Horton (1933).

For small rainfall events (< 25 mm) with low intensity (< 25 mm/h), runoff volume was correlated with ground cover level (r=0.53, P<0.05), despite runoff amounts being < 2.5 mm. These events were probably generated via saturation excess processes, following periods of continuous rain, as it is unlikely that such a small amount of rainfall could generate runoff on a dry soil. The storage capacity (indicated by soil water deficit) would store all rainfall received at lower magnitude and intensity. Once the soil surface layer was wet, further rainfall may lead to a small amount of runoff.

For medium rainfall events (25-50 mm) with moderate intensity (25-45 mm/h), runoff volume was correlated with ground cover level (r=0.68, P<0.05). Runoff generation within rainfall events of this type was probably caused through a mixture of both infiltration and saturation excess processes. Rainfall events with moderate intensity and magnitude were likely to generate infiltration excess flows under low cover level conditions. Also, longer duration rainfall events on wet soil were likely to generate saturation excess flows, regardless of ground cover level through exceeding the soil water storage capacity.

For large rainfall events (> 50 mm with intensity ≥ 45 mm/h), runoff was highly correlated with ground cover level (r=0.90, P<0.001). Rainfall events of this size and intensity generated substantial runoff depths, increasing in magnitude as ground cover decreased. For rainfall events of this type, a ground cover level > 70% would reduce runoff to low levels (< 10% of rainfall).

Although this type of rainfall event was a relatively rare phenomenon, significant reductions of total runoff were achieved by maintaining high ground cover levels, as the larger events contributed substantially to the annual total. The frequency distribution of the size of runoff events showed that there were many small events and large events were uncommon. The exponential relationship between runoff and ground cover suggested that at cover levels below 50%, runoff volume would increase rapidly for this type of rainfall event. At a cover level of 20%, runoff was likely to be near 100% of the rainfall amount for events of this type. While high cover level did not prevent surface runoff, it did reduce the size of the event and the runoff coefficient. The data collected in this study suggested that a ground cover level of > 60% will reduce runoff to low levels for all storm types, but overall, ground cover level alone did not explain a very large proportion of the variation in runoff depth.

5.4.3 Linear regression analyses

The linear regression model of the Springmount data showed that three factors made significant contributions to the explanation of variation in runoff data; rainfall depth, peak rainfall intensity, and ground cover. The low regression coefficient (R^2=35.7%) suggested these factors had only a small influence on surface runoff, or perhaps other factors were important, but were not estimated. Gutierrez and Hernandez (1996) demonstrated that runoff in a semi-arid grassland was affected by many factors including grass canopy cover, soil water content, organic matter and cover of rock and gravel. However, no single factor explained a large proportion of the variation at any one time. Different factors were important for various reasons at different times, making the prediction of runoff depth a difficult and complex task. The cross site linear regression model of runoff data included seven variables that made significant contributions to accounting for variation in runoff data. This reinforces the concept that runoff control depends upon a range of factors under different conditions.

Herbage mass was expected to assist in controlling surface runoff at Springmount, but there was no significant relationship between them Where substantial differences in herbage mass occurred between sites, such as Springmount compared with Winchfield, herbage mass was expected to have a significant limiting effect on runoff. However, this was confounded by the fact that the largest runoff events (up to 48 mm) were recorded from Winchfield, which had higher herbage mass (up to 7800 kg DM/ha). Those runoff events were generated under saturated flow conditions. Also, in a separate study of ground cover in grazed native grass pastures on the North-West Slopes, Lodge and Murphy (2002*a*) reported that there was an exponential relationship between ground cover and herbage mass. They found that in these pastures regardless of herbage mass, ground cover could vary between 0 and 100%, and so was not likely to significantly influence runoff generation.

The current studies indicate that it is difficult to prescribe a 'rule of thumb' level of ground cover to control surface runoff in grazed pastures on the North-West Slopes. Runoff was generated at any time of the year and by different processes, regardless of the level of cover or herbage mass. Also, the minimum level of ground cover required to control runoff varied according to the characteristics of rainfall generating the event, as was found in other studies (e.g. McIvor *et al.* 1995). They reported that for increasing storm size (up to 100 mm and 45 mm/h), increasing cover levels were required to control runoff and erosion. For smaller storms, they reported that low levels of cover (~40%) were adequate to significantly reduce runoff and erosion.

5.4.4 Runoff and soil physical parameters

Eldridge and Rothon (1992) in a study of runoff in semi-arid grasslands in western NSW reported that runoff was not related to ground cover. However, in that study they concluded that ground cover was important for erosion and sediment control, which contrasted to the current study where there was no correlation between sediment loss and ground cover. Areas with low ground cover were likely to have degraded soil structure, reduced porosity, and higher bulk density and other soil physical properties which are detrimental to water infiltration and conductance (Lawson 1998; Greenwood and McKenzie 2001). Conversely, soil surfaces with high ground cover are less likely to exhibit physical impediments to water infiltration. Also, in a study of the effect of grazing management and fertiliser application on soil properties, Rafique (1994) reported that where ground cover was maintained, soil porosity was appreciably higher and infiltration rate increased. This leads to the conclusion that ground cover alone may not be the driving variable affecting surface runoff flow, but an indicator of soil structure decline which may determine the rate of infiltration and water movement into the soil profile.

Soils with a high level of ground cover and litter mass will most likely have a higher level of microbial organism activity. Tisdall (1994) concluded that soil microbial organism activity was essential for building soil structure and providing polysaccharide compounds or the organic 'cement' that holds soil aggregates together. Microbial carbon sampling conducted on the Springmount study site (G.M. Lodge and S.R. Murphy, unpublished data) indicated that levels were highly correlated with herbage mass, litter mass and ground cover. Also, earthworm numbers (up to 1,000 000 worms per ha) were greater in treatments with higher ground cover and litter mass, leading to higher organic matter incorporation and development of macropores.

In a study of surface infiltration rates at Springmount, Lawson (1998) reported that areas with high cover (85-100%) had high infiltration rates (135-215 mm/h) and areas with low ground cover (< 20%) had low infiltration rates (28-39 mm/h). Measurements were performed at a tension of

-10 mm, so that they approximated water movement through soil pores with a diameter of 3 mm. Lawson concluded that maintaining ground cover in pasture systems also maintained porosity, particularly in the range 1.5-3.0 mm diameter, enabling higher infiltration rates.

The surface soil at Springmount had high silt (2-20 μm in diameter) content in the surface soil (34-37% g/g, Lawson 1998) and it was predisposed to surface sealing and crusting during rainfall events. For this reason, raindrop interception and detention were important roles of herbage mass, litter and ground cover. When the soil surface was exposed to raindrop impact and particle detachment, surface capillaries were likely to be blocked by silt particles, which reduced the infiltration rate leading to greater runoff generation from comparatively smaller amounts of rainfall (Bradford *et al.* 1987*a*). This process was probably the driving process of runoff generation on any bare soil surfaces of each runoff plot. Surface crusts formed by raindrop impact and particle detachment also have a high soil shear strength, which may reduce the rate of overall soil loss (Bradford *et al.* 1987*b*).

Through the course of the experiment, the soil surface between perennial grass bases on one runoff plot (Plot 8, T2C6) gave the appearance of sealing over and stabilising, despite having low ground cover. It appeared to have less loose soil material on the surface, despite the continued effect of stock trampling. Anecdotal evidence suggested that this was the nature of the surface setting red chromosol soil type in the local area. Closer examination of the soil surface revealed that a biological crust (or cryptogam) had developed on the surface. Biological crusts, which are a complex arrangement of cyanobacteria, typically form on bare soil surfaces that have a physical surface crust (Eldridge and Robson 1997). Surface crusting on the red chromosol soil type was highly likely as discussed previously, predisposing it to biological crust development. In a study of the influence of woody weed control on soil physical properties in western NSW, Eldridge and Robson (1997) concluded that biological crusts could inhibit soil water infiltration through water repellence and hence actively increase the volume of surface runoff. It was highly likely that the same process occurred on the bare soil areas at Springmount. By the end of the grazing experiment, biological crusts had colonised up to 30% of the surface area of the T2C6 runoff plot (S.R. Murphy, personal observation) and may explain a proportion of the surface runoff losses.

Studies conducted elsewhere of the impact of grazing intensity and management on soil hydraulic properties (eg. Gifford and Hawkins 1978; Warren *et al.* 1986; Weltz *et al.* 1989; Greenwood 1996), have all reported that grazing via stock trampling and soil compaction, was detrimental to infiltration capacity. Also, even with exclusion of grazing, soil hydraulic properties may take considerable time (e.g. > 2.5 years, Greenwood *et al.* 1998) to return to a condition similar to pre-grazing. The recovery time might be dependent upon such factors as soil wetting and drying cycles, root extension, and soil organism activity. Hence, it was curious that in the current study, the grazing treatment with the highest stocking rate produced a low amount of runoff (10.2 mm, 8 sheep/ha, T3FERT8). A possible explanation might be that ground cover was high in this treatment (mean > 90%), and it had the highest litter mass among the treatments (up to 780 kg DM/ha, Chapter 3), which may have aided soil structural development and maintained the infiltration capacity of the soil surface despite the action of the livestock. From a study of the impact of fertiliser application and grazing management on infiltration rates for rangelands, Wood *et al.* (1986) reported that increased plant production mitigated the effects of increased stocking rate. This is an important issue where grazing management is used to achieve runoff control, as it appears that the level of grazing intensity becomes less important as long as ground cover and litter mass are maintained.

5.4.5 Erosion and nutrient removal

Sediment and nutrient removal were positively correlated with the magnitude of each runoff event, indicating that erosive forces and soil transportation were greater in larger events. The surface soils at Springmount had a high amount of total phosphorus (~600 mg/kg, Chapter 3), which indicated the importance of controlling erosion in order to limit nutrient removal. The concentration of total phosphorus for eroded material is often greater (up to 3.5 times) than that of the soils from which it is derived as the phosphorus is mainly adsorbed to clay particles that are transported more readily than larger particles (Sharpley 1980). Given the enrichment of phosphorus in eroded sediments, the maximum concentration for phosphorus of 1.99 mg/L is not surprising but when compared with other values reported for pastures it is relatively high (e.g. McCaskill *et al.* 2003). In addition, although concentration values may be high for individual events, over the long-term nutrient removal is likely to be low because these events are comparatively rare.

The data collected here did not indicate that higher ground cover reduced the amount of sediment and nutrient removed for individual events. Other studies (e.g. Lang and McCaffrey 1984) found that ground cover was not correlated with erosion rates for individual runoff events, but was correlated with the frequency and magnitude of soil loss overall. McIvor *et al.* (1995) reported that both runoff and soil loss were reduced by increasing ground cover, while for larger events ground cover reduced the rate of soil loss but may not reduce the volume of surface runoff. In a study of the hydrologic impacts of sheep grazing in semiarid rangelands, Wilcox and Wood (1988) reported that higher sediment loads were attributed to larger runoff volume rather than a significantly higher sediment concentration of the runoff water. In addition, the development of a biological crust may have stabilised the soil surface and so reduced sediment losses (Eldridge and Robson 1997). Clearly, the effect of ground cover on soil and nutrient removal would depend largely on the soil type and rainfall event characteristics being studied. The range of ground cover conditions and nutrient loss sampled in the current study may not have been adequate to fully assess the effect of ground cover on soil and nutrient loss.

5.4.6 Limitations of the methodology

The continuous recording methodology used in this study provided information about the process of runoff generation in grazed natural pasture on the North-West Slopes. Surface runoff data recorded simultaneously with stored soil water and rainfall data provided opportunity to observe interactions in real time. Previously, studies of surface runoff and its interaction with stored soil water have been performed under simulated rainfall conditions, where rainfall and soil water content were controlled. The technique detailed in the current study has shown that real time data may be collected and the approach has high value for use in further runoff studies. Other studies (Srinivasan *et al.* 2002) have used alternative real time technology for detecting saturation and surface runoff to identify spatial and temporal variation in runoff generation processes. The approach used in those studies however, could not determine rates of runoff at each location, rather its presence or absence. Generation of runoff is likely to change both temporally and spatially between infiltration excess and saturation excess processes.

Other studies of surface runoff have estimated soil surface microtopography in order to ascertain its affect on surface detention (e.g. Lang 1990; Eldridge and Rothon 1992; Eldridge and Robson 1997). A rough soil surface would provide areas where rainwater may collect and subsequently infiltrate, rather than create surface flow. No attempt was made in the current study to estimate soil microtopography, despite simple methods being available, such as a profilemeter (e.g. Semple and Leys 1987). Data that described soil surface microtopography, particularly in the down slope direction may have improved the explanation of variation within the surface runoff data from Springmount, as was reported for rangelands by Sanchez and Wood (1987).

5.5 Conclusion

Grazing treatments influenced ground cover and canopy cover levels of runoff plots with continuously grazed plots having low levels compared with plots that were rotationally grazed or those with subterranean clover added. Mean ground cover ranged from 54 to 96% (T2C6 and T5GR12, respectively) and mean canopy cover from 2 to 68% for the same treatments. Total surface runoff losses were greatest (142 mm or 6% of total rainfall) from the plot with low mean ground cover and losses were least (8 mm or 0.3% of total rainfall) for the plot with high mean ground cover.

Large rainfall events were rare (< 1% of events were > 20 mm) and high intensity storms were infrequent (four events had a peak intensity > 100 mm/h). However, runoff depth at Springmount was positively correlated with both rainfall depth and peak intensity. Ground cover was negatively correlated with runoff depth, while herbage mass, litter mass and canopy cover had no significant effect.

Ground cover levels greater than 70% did not prevent surface runoff, but they did reduce the frequency and magnitude of losses. The probability and frequency distribution of large rainfall events may influence the level of cover required to control surface runoff and erosion processes. Grazing management may need to vary in order to control runoff generation in different locations and season as inferred by Lang (1990). Canopy cover levels had no significant affect on surface runoff losses at any site, but may provide other benefits associated with raindrop interception and soil particle detachment. Higher herbage mass and litter mass did not significantly reduce losses as runoff often occurred through saturation flows. Generally, runoff decreased with drier surface soils at the beginning of the rainfall event, as drier soils had a larger capacity absorb rainfall and reduce surface runoff.

The combined site linear regression model showed that rainfall depth, rainfall intensity and event duration all led to higher runoff losses, but all of these factors are beyond the control of the grazing manager. Conversely, greater soil depth, changes in stored soil water, and ground cover all led to lower runoff losses. Grazing management may directly affect ground cover and the frequency and magnitude of runoff losses may be minimised by maintaining levels above 70%. Prediction of surface runoff losses proved to be a difficult task, owing to the complex interactions of many variables that changed both temporally and spatially within runoff events.

6 The effects of herbage mass, litter mass, and soil water content on actual evapotranspiration and net radiant energy balance

> "*... evaporation is the most desperate branch of the most desperate science of meteorology.*"
> (Symons 1967)

6.1 Introduction

The impetus for this experiment was provided by examining the long-term hydrologic balance for natural perennial pastures on the North-West Slopes. Simpson *et al.* (1998) and Lodge *et al.* (2002) reported simulation studies indicating mean annual evapotranspiration of 659-671 mm (or 93-95% of average annual rainfall) and 589 mm (or 89% of average annual rainfall), respectively. Examination of the evapotranspiration term showed that nearly 80% was contributed from bare soil evaporation. However, with such a large proportion of water being lost through soil evaporation, the proportion of evaporation and transpiration might be affected by changes in pasture herbage mass, litter mass and ground cover.

Grazing management can manipulate the pasture herbage mass, litter mass and ground cover as was reported in Chapter 4. Continuous grazing led to lower ground cover, herbage and litter mass, while rotational grazing and improvement with subterranean clover increased levels of these factors. Logically, pasture that has higher green content and herbage mass might increase transpiration due to greater leaf area, and conversely, reduce the amount of bare soil evaporation due to higher ground cover. In addition, the amount of litter on the soil surface might limit evaporation, conserving soil moisture for transpiration (Murphy and Lodge 2001*a*). Increased water for transpiration might then lead to increased pasture growth and potentially, a higher grazing intensity.

The North-West Slopes environment is dominated by summer rainfall, with infrequent but large downpours through the warmer months when evaporative demand is high (Logan 1965, Chapter 5). Immediately after these events, the evaporative demand can deplete stored soil water very rapidly with mean daily pan evaporation rates of 9.5, 9.3, and 8.4 mm/d for December, January, and February, respectively (Clewett *et al.* 1999). Managing the pasture structure and litter mass to minimise evaporative losses following rainfall, might conserve soil water, enabling pasture plants to use it for transpiration and growth. In addition, Gonzalez-Sosa *et al.* (1999, 2001) reported a detailed modelling study of volunteer pasture that indicated litter could reduce annual bare soil evaporation by up to 400% (reduced from 400 to 104 mm) and increase transpiration by 50%

(increased from 457 to 670 mm) resulting in a net decrease in evapotranspiration of 5-10% (reduced by 39 to 89 mm). Generally, litter may reduce the rate of evaporation, but its affect in natural pastures for the North-West Slopes is not clear.

Solar energy is a key driver of the evapotranspiration process. Albedo (α) of the incident surface (short wave radiant energy reflectance) through its effect on net radiant energy can influence evapotranspiration by up to 20% (Farahani and Ahuja 1996). Meyer *et al.* (1999) indicated that for calculation of reference evaporation (e.g. Smith *et al.* 1996) and crop evapotranspiration, local coefficients are necessary and direct albedo estimates are required. Albedo for pastures on the North-West Slopes is unknown. Similarly, the vapour pressure deficit (e_s - e_a, where e_s is the saturation vapour pressure, and e_a is the partial vapour pressure of air) has a major influence on the evapotranspiration process (Linsley *et al.* 1988). The vapour pressure deficit changes seasonally and diurnally with air temperature and relative humidity. Net radiant energy and vapour pressure deficit are likely to influence evapotranspiration of pastures at both seasonal and hourly time scales.

A review of methods to measure actual evapotranspiration from pastures was provided in Chapter 2. Each method may have its advantages in certain situations, but the evaporation dome described by McJannet *et al.* (1996) has the most appeal. This technique provides fast, repeatable, direct measurements of evapotranspiration with relatively low cost. The technique may also be used on small-scale plots, which may have unique surface characteristics.

Very little information is available in regard to the actual evapotranspiration of native grasses and grazed pastures. Such values are of particular importance for inclusion in modelling studies (e.g. Lodge *et al.* 2001; Murphy and Lodge 2001*a*) and for accurate assessment of the hydrological balance where deep drainage is determined by mass balance (Johnson *et al.* 2002). The objective of this experiment was to identify important factors that influence actual evapotranspiration (i.e. net radiant energy, vapour pressure deficit, albedo, soil water content, herbage mass, green leaf area, proportion of green leaf, litter mass, ground cover, and season) from small scale contrived plots of native grass and from plots in grazed natural pasture. The specific aims were:

a) to determine the effect of plant density, litter mass, soil water content, and ground cover on hourly and daily actual evapotranspiration rates for small scale plots;
b) to test the hypothesis that increasing litter mass (kg DM/ha) will reduce the rate of bare soil evaporation;
c) to test the hypothesis that evapotranspiration will increase with greater plant density;
d) to test the hypothesis that evapotranspiration will increase with higher soil water content;

e) to investigate the range of seasonal evapotranspiration rates from grazed native pastures; and

f) to determine the effect of plant density and ground cover types on albedo and the net radiant energy balance.

6.2 Methods

6.2.1 Evapotranspiration experiments

Actual evapotranspiration rate was measured on small plots for a range of plant density, litter mass, and ground cover conditions with dry and wet soil surfaces for specific months through out the year. A dry soil surface was defined as the antecedent soil water content and wet conditions were created by irrigating with approximately 25 mm (depth) of water. Pasture conditions at field sites are too heterogeneous and diverse to measure evapotranspiration from discrete areas, so small plots were established with a range of pasture conditions that might be expected in a grazed pasture situation. Plots were sown to different plant densities of a native perennial grass, and litter levels were adjusted to mimic conditions that may be achievable in a grazed paddock. The evaporation dome technique was used to measure actual evapotranspiration on an hourly basis and values were integrated to provide daily totals. Solar and net radiant energy fluxes were measured over a 5 minute period coinciding with each measurement of evapotranspiration. Also, the soil water content of each plot was estimated at the beginning of each sampling day to ascertain the importance of soil moisture in limiting evapotranspiration.

6.2.2 Study site at Tamworth Centre for Crop Improvement

The evapotranspiration experiment was performed at NSW Agriculture's Tamworth Centre for Crop Improvement (TCCI, Chapter 3). Climatic data were used to calculate the daily potential evapotranspiration rate (ET_{oPM}) using the modified Penman-Monteith technique (Doorenbos and Pruitt 1975) and provided an indication of evaporative demand on each day that measurements were taken (Table 6-1). Similarly, hourly evaporation was measured from a Class A pan evaporation tank by recording the change in water level using vernier callipers. The evaporation tank was located in the meteorological lawn and hourly values were summed to provide daily totals (Pan E, mm, Table 6-1).

Meteorological conditions

Measurements were taken on five occasions (1 dry and 1 wet on each occasion) within a 13 month period, beginning with autumn 2000 and ending in autumn 2001 (Table 6-1). Weather conditions for each sample day varied considerably, but an attempt was made to take measurements on days that were likely to be fine with little or no cloud cover. Fine days were preferable so that consistent solar radiation was available. Measurements often began under fine conditions early in the morning, but cloud coverage changed at various times throughout the day.

Table 6-1. Sample dates for evapotranspiration measurements at TCCI, showing the daily temperature range, reference evapotranspiration (ET_0), pan evaporation (Pan E), solar radiation (MJ/m^2) and relative humidity (RH).

Date	Dry or wet surface	Temperature max. (°C)	Temperature min. (°C)	ET_0 (mm)	Pan E (mm)	Solar Rad. (MJ/m^2)	RH (%)
3 Apr 2000	Dry	29.4	15.6	4.2	4.4	16.7	71
4 Apr 2000	Wet	29.4	17.6	2.2	5.3	11.6	73
3 Jul 2000	Dry	16.6	5.0	2.2	3.8	6.8	60
7 Jul 2000	Wet	17.5	7.0	1.5	2.0	7.2	81
6 Nov 2000	Dry	25.9	11.6	5.3	5.3	21.4	66
7 Nov 2000	Wet	21.0	11.4	5.6	5.3	20.3	64
6 Feb 2001	Dry	31.0	21.1	4.2	7.4	11.7	67
7 Feb 2001	Wet	31.2	18.1	6.2	5.0	22.7	67
8 May 2001	Wet	22.5	9.5	2.1	1.8	10.8	88
9 May 2001	Dry	21.4	8.5	2.0	1.4	10.6	85

Treatments

Twelve treatments were allocated randomly to plots and represented a continuum of plant density (plants/m^2), litter mass (kg DM/ha) and ground cover (%), ranging from a bare soil surface to 100% pasture and litter cover (Table 6-2). Each plot was 2 by 2 m and positioned in a single row along a north-south axis. This orientation was used to minimise one treatment shading another, either early or late in the day. Shading was not encountered in the middle of the day as the sun was near its zenith, which reduced shadow length. A range of evaporation and transpiration rates was expected through the combination of different pasture herbage mass, litter mass, ground cover and wet and dry soil surface conditions. Maximum evaporation was expected from the bare soil surface, while high transpiration with little evaporation was expected from plots with high plant density and high litter levels.

To prevent plant roots growing from one plot to another, a plastic barrier sheet was used to separate them (e.g. Boschma and Scott 2000). A trench 10 cm wide and 90 cm deep was cut between plots using a chain digger, and a sheet of heavy duty plastic was placed in the trench before back filling. Only neighbouring plots that had contrasting plant density were protected, such as all bare soil plots (Plots 5, 8, and 11) and low plant density plots neighbouring high plant density plots (Plots 7 and 10).

The range of plant densities was achieved by establishing wallaby grass (*Austrodanthonia richardsonii* (Cashmore) H.P. Linder cv. Taranna) plants at different spacings. Wallaby grass was an ideal plant for these evapotranspiration studies, as it remained green year round given adequate water and nutrient. Seedlings were germinated and established in "Jiffy-Pellets" in a glasshouse prior to planting into the plots on 1 June 1999. The pellets were made from compressed peat moss encased in nylon net and ensured successful establishment. At planting, a 10 by 10 cm steel grid was used as a guide to attain the correct spacings, with spacings of 50 by 50 cm, 30 by 30 cm, and 20 by 20 cm for low, medium and high density planting, respectively (Table 6-2).

Litter mass (Table 6-2) was chosen to represent typical (500 kg DM/ha), high (1500 kg DM/ha) and maximum levels (3000 kg DM/ha) encountered in grazed pastures on the North-West Slopes (Lodge *et al.* 2003*a*). Litter was applied to each plot at the allocated level 3-4 d prior to undertaking evapotranspiration measurements. Fresh litter was used on each occasion, which was obtained from grazed native pastures so that it was representative of the size, colour and quality of litter for a grazed pasture.

Pasture characteristics

The leaf area index (mm^2/mm^2) of each treatment plot was estimated using an electronic leaf area meter (Lycor LI-3100 Area Meter). For each plot one or two plants were harvested to ground level with electric shears and the material was sorted into green and dead components. The leaf area index was estimated by passing green material through the leaf area meter. The sorted material was oven dried (80°C) to estimate the percent green material (%) and the dry weight (g). Values were converted to herbage mass (kg DM/ha) using the plant density ($plants/m^2$) of each plot. Pasture characteristics for individual plots were used in the data analysis.

Plot measurements

Evapotranspiration measurements were taken from each plot every hour between sunrise and sunset on each sampling day. The plots were sampled at 5 minute intervals (12 plots/h) and net radiant energy flux was measured in the intervening period.

Plot maintenance

Weeds were controlled to ensure that only wallaby grass provided green leaf on each plot. Non-selective glyphosate herbicide (1% by volume of active ingredient applied at 100 L/ha) was used on the plots without wallaby grass, while broad-leaf selective 2,4-DB herbicide (2.5% by volume of active ingredient applied at 100 L/ha) was used within the grass plots. Grass weeds were controlled within wallaby grass plots by chipping. All plots were irrigated equally, using a soaker hose controlled by automatic timer. To maintain plant health and encourage green leaf production, a general fertiliser was applied to plots with wallaby grass each spring and autumn (17, 4, and 6 kg/ha of N, P, and K, respectively).

Table 6-2. Treatment description of evaporation plots located at TCCI, including plant density, litter mass and target ground cover conditions.

Plot	Treatment	Plant density (plants/m^2)	Litter mass (kg DM/ha)	Target ground cover (%)
1	Medium plants, no litter	12	0	75
2	Low plants, low litter	4	500	60
3	Medium plants, medium litter	12	1500	95
4	High plants, high litter	25	3000	100
5	Medium litter	0	1500	90
6	High plants, low litter	25	500	95
7	Low plants, high litter	4	3000	100
8	Bare Soil	0	0	0
9	High plants, no litter	25	0	95
10	Low plants, no litter	4	0	25
11	High litter	0	3000	100
12	Low litter	0	500	30

6.2.3 Measurement of actual evapotranspiration with the evaporation dome

Actual evapotranspiration rates were measured using the evaporation dome technique outlined by McJannet *et al.* (1996) and McLeod *et al.* (1998). The evaporation dome that was used in the current study was developed and used by McLeod *et al* (1998) and McLeod (2002) in studies of evapotranspiration of grazed pastures on the Northern Tablelands of NSW.

Evaporation dome construction

A clear hemispherical perspex dome 680 mm in diameter and 400 mm deep from the base to the apex was supported by a lightweight steel frame, which had three wheels for easy transportation and manoeuvrability (Figure 6-1). A canti-lever handle on the side of the frame raised and lowered the dome as needed. The base of the dome was lined with a skirt of medium density foam rubber (5 by 5 cm) that sealed it onto the soil surface. A tray on the top of the frame contained batteries, a data interface and a palm-top computer.

On the inside of the dome, two micro-fans were used to thoroughly mix the internal atmosphere during evapotranspiration measurements. These fans were similar to those used for internal cooling in desktop computers. They were mounted on opposite sides of the dome and pushed air in a circular direction. A rheostat control allowed the fan speed to be adjusted. Temperature and humidity was monitored inside the dome with a Vaisala HMP 35A combination temperature and relative humidity sensor. The operational range for relative humidity (RH) was 0-100% (0-90 ± 2%

RH, and 90-100 ± 3% RH,) with a 90% response time of 15 s. The settling time for humidity readings was just 1 s, and the fastest of commercially available instruments. The temperature response range was -20 to 60°C. Readings were logged at 1 s intervals and recorded via a TAIN Electronics 'TechFour' data interface to a SHARP PC3100 palm top computer. A custom data capture program was developed by Mr Steve Howard (TAIN Eelectronics, Melbourne) to record each data set in a space delimited text file, marked with time and date. The file format allowed simple conversion to Microsoft Excel® format for later analysis.

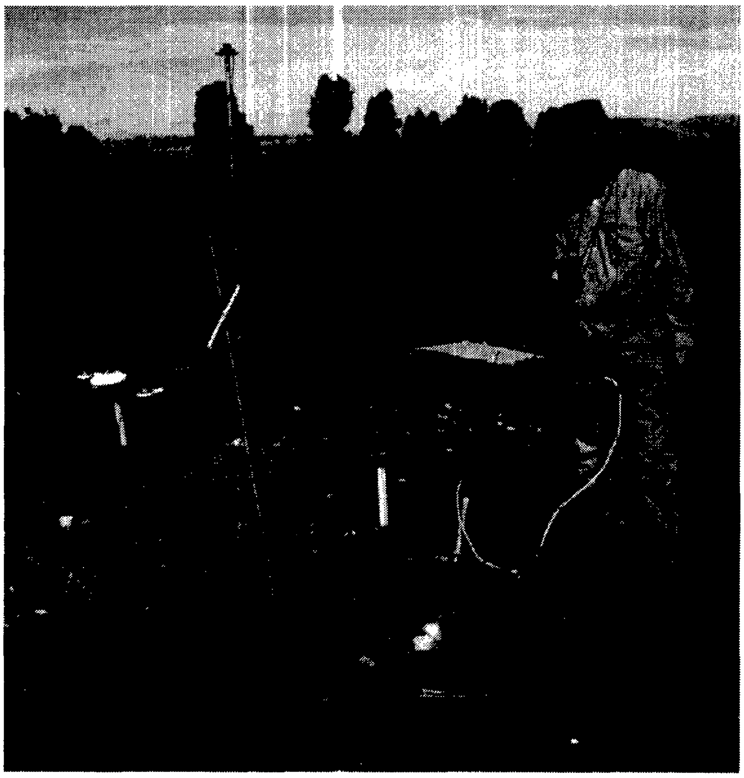

Figure 6-1. Evaporation dome equipment was used to measure actual evapotranspiration. A steel frame, which was equipped with tray for a micro-computer and wheels for movement, supported the clear perspex dome. For each measurement, the dome was placed on the same area as indicated by the marker in front of the dome.

Measurement procedure

The evaporation dome was calibrated by McLeod *et al.* (1998) in a previous experiment using the method outlined by McJannet *et al.* (1996). A portion of the water vapour that accumulates inside the dome is absorbed by the internal surface of the dome and foam rubber seal, reducing the response of the Vaisala sensor and hence evaporation estimates. The calibration procedure involved placing the dome over a beaker of boiling water and simultaneously recording the rate of generation of water vapour by a decrease in weight, and the accumulation of water vapour pressure inside the dome recorded by the Vaisala sensor. A calibration factor (C) was developed by calculating the ratio between accumulating water vapour inside the dome and the generation of vapour from the beaker (McJannet *et al.* 1996).

To take an evaporation measurement, the dome was firstly wheeled into position near the target plot. The fans and data capture programs were started and the dome moved over the plot. Data recording commenced when the dome was lowered onto the ground surface. Readings were taken at 1 s intervals for a period of approximately 45 to 60 s. Prior investigation showed that as the atmosphere inside the dome neared saturation vapour pressure, movement of water vapour was reduced.

Field data were transferred to a desktop computer for calculation of evaporative flux using the procedure detailed by McJannet *et al.* (1996) which was a three-stage process. Firstly, the saturation vapour pressure (e_s, in Pa) was calculated according to the temperature inside the dome:

$$e_s = 6.11213 \times f(P)\exp\left(\frac{17.5043t}{241.2+t}\right) \qquad \textbf{Equation 6-1}$$

where t is temperature (°C), and $f(P)$ is a constant related to atmospheric pressure ($f(P) = 100.4718$). Secondly, the vapour density (ρ_v, in g/m^3) of water inside the dome was calculated using:

$$\rho_v = \left(\frac{0.622e}{R_d T}\right) \times 1000 \qquad \textbf{Equation 6-2}$$

where R_d is the gas constant (287.04 J/kg.K), T is the absolute temperature (K), and e is the partial pressure of water vapour in Pa, calculated from:

$$e = \frac{Ue_s}{100} \qquad \textbf{Equation 6-3}$$

where U is the relative humidity (RH%).

The vapour density was plotted against time for each data set and linear regression was used to determine the slope (M) over a 15 s period between 8 and 23 s after placing the dome on the plot surface (Figure 6-2). A large number of these graphs (144) were obtained on each sample day and this process was automated in a spreadsheet to speed up data analyses and reduce the chance of manual error.

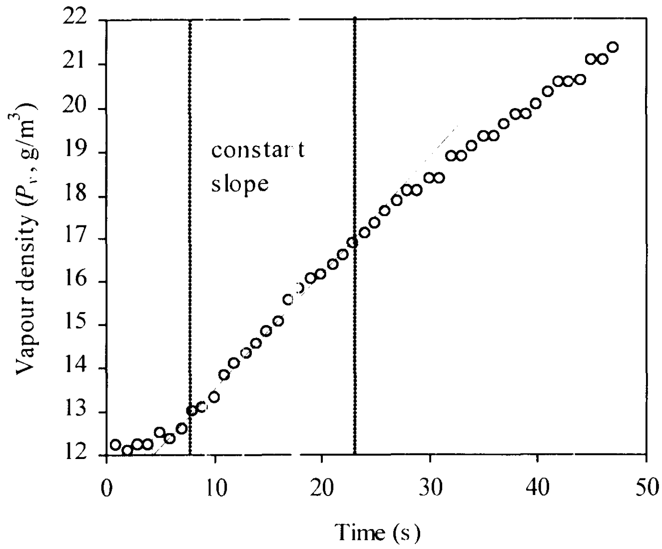

Figure 6-2. A typical plot of vapour density (ρ_v, g/m^3) against time that shows the region of maximum slope between 8 and 23 s. The slope (*M*) was used to determine the weight of water evaporated from each plot.

Thirdly, the rate of vapour density accumulation was converted to a loss of evaporated water E (kg/m^2.s) using:

$$E = \frac{\left(\frac{MCV}{A}\right)}{1000}$$ **Equation 6-4**

where M is the slope of the vapour density accumulation curve, C is the dome calibration factor (2.206), V is the volume of the dome (0.1041 m^3), and A is the surface area covered by the dome (0.3632 m^2).

6.2.4 Effect of wind speed on measured evaporation

The evaporation dome was equipped with fans to mix the atmosphere within the dome and to simulate the effect of air moving across the ground surface. The fan speed was fully adjustable using a rheostat control. However, McJannet *et al.* (1996) in a study of litter and soil evaporation in Mountain Ash forest in Victoria, Australia, concluded that the simulated wind speed might have a significant effect on the measured evaporation within the dome. To test this, hourly measurements were taken on 6 April 2000 from a wet bare soil surface using three simulated wind speeds; 0.75, 1.36, and 3 m/s (Figure 6-3). Consecutive measurements using the three wind speeds were taken over a 5 minute period, with the dome being removed from the plot between measurements. This was done to avoid retarding the evaporation rate through saturation of the atmosphere within the dome. The process was repeated at hourly intervals throughout the day (Figure 6-3). A *t*-test was used to determine significant differences between readings obtained using each fan speed.

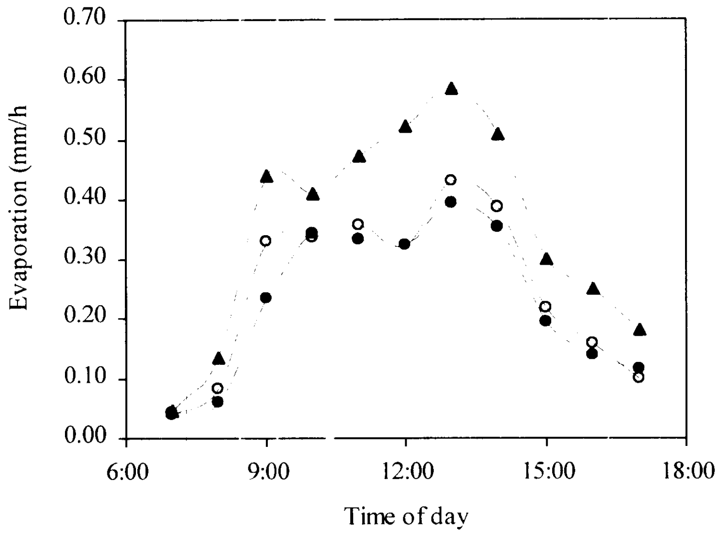

Figure 6-3. The effect of three simulated wind speeds, low (0.75 m/s, ●), medium (1.36 m/s, O), and high (3 m/s, ▲) on hourly evaporation for a wet soil surface on 6 April 2000.

The maximum hourly evaporation rates (0.39, 0.43, and 0.58 mm/h) were recorded at 13:00 h and increased with fan speed (Figure 6-3). A *t*-test showed that the 11 hourly values were significantly different ($P<0.05$, n=11) for each of the three fan speeds. Daily values (sum of the 11 hourly values) also increased with fan speed with totals of 2.5, 2.8 and 3.8 mm respectively, for the three speeds. In other studies using an evaporation dome, both McJannet *et al.* (1996) and McLeod *et al.* (1998) concluded that a lower fan speed provided uniform mixing of air within the dome without unduly disturbing the boundary layer of humid air that lies close to the soil surface. Thus, for all evapotranspiration measurements reported in the remainder of this Chapter, the lowest fan speed of 0.75 m/s was used.

6.2.5 Measurement of net radiation (R_n) and albedo (α)

The net radiation (R_n) balance can be described by:

$$R_n = (R_{si} - R_{so}) + (R_{li} - R_{lo})$$ **Equation 6-5**

where R_{si} is the flux of incoming short wave radiation ($W/m^2.s$), R_{so} is the flux of outgoing short wave radiation ($W/m^2.s$), R_{li} is the flux of incoming long wave radiation ($W/m^2.s$), and R_{lo} is the flux of outgoing long wave radiation ($W/m^2.s$).

Net radiation flux and albedo were estimated at 30 s intervals for a five minute period on each plot immediately after evapotranspiration was measured. Net radiation was measured using a Middleton net pyrradiometer (CN1-R), an instrument that was suitable for measuring radiation flux (solar, terrestrial and atmospheric) downward and upward through a horizontal surface (Figure 6-4). The net pyrradiometer measured a combination of long and short wave radiation flux that had wavelengths between 0.3 and 60 μm (95% response time of 45 s) using separate thermopile sensors. Short wave radiation components were measured separately using a Middleton pyrano-albedometer (EP-16), an instrument for measuring the ratio of incoming and outgoing total solar global radiation (Figure 6-6). The albedometer measured short wave radiation flux between the wavelengths of 0.3 and 3 μm and incoming and outgoing flux were recorded separately (99% response time of < 40 s) so that albedo (α) could be calculated. Radiation sensors were supported 50 cm above the ground surface on a portable stand that was custom made (Figure 6-5).

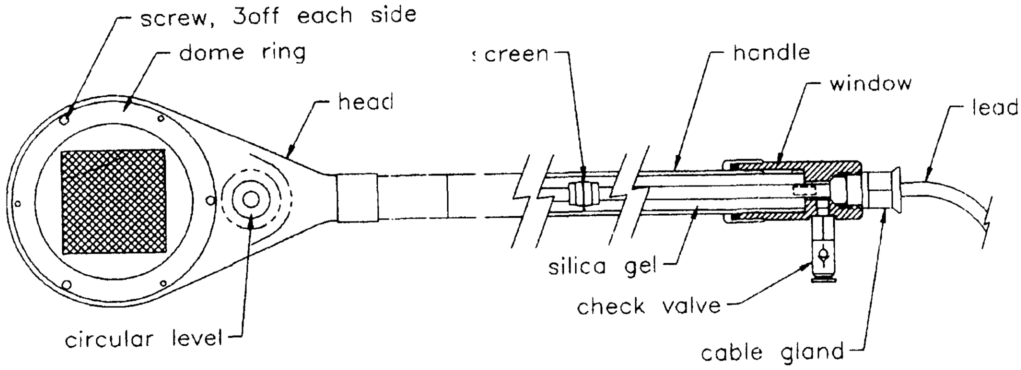

Figure 6-4. A diagram (top view) of a net pyrradiometer (CN1-R) that shows its general construction and the square theromopile sensor area (crosshatched).

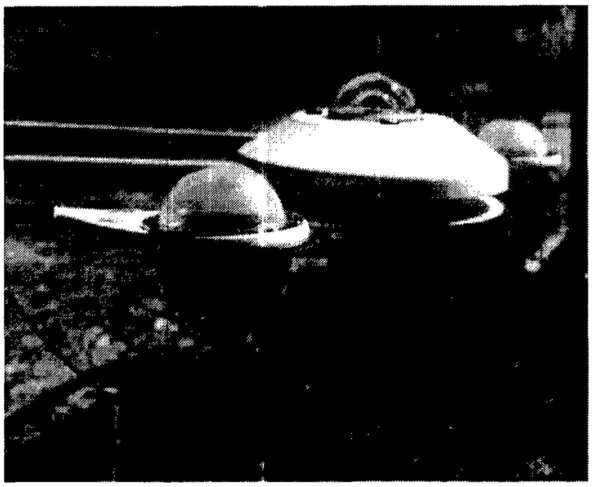

Figure 6-5. CN1-R net pyrradiometer used for measuring net radiation (foreground) and EP-16 pyrano-albedometer for measuring albedo (background).

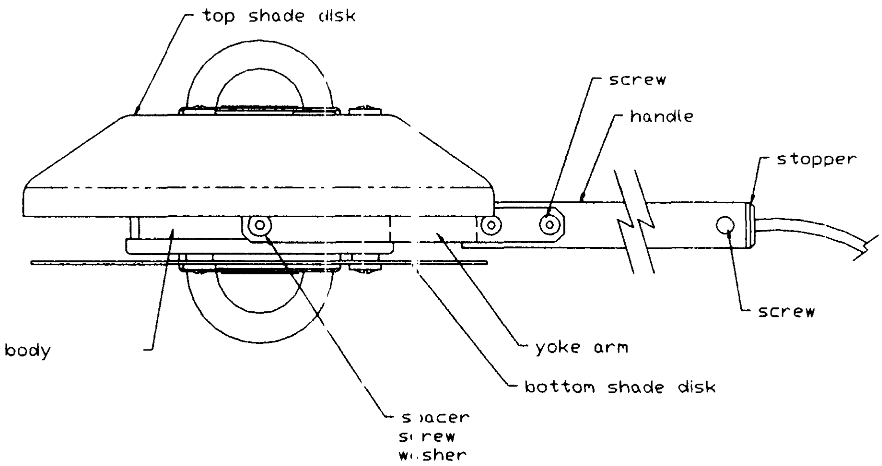

Figure 6-6. EP-16 pyrano-albedometer schematic diagram (side view) showing upper and lower hemispherical glass domes and general construction.

6.2.6 Measurement of soil water content

Surface soil water content ($\theta_{vol}\%$) was estimated in three layers (0-5, 5-10, and 10-20 cm) of each treatment plot using Watermark resistance sensors installed at depths of 2.5, 7.5 and 15 cm. The resistance sensors were installed and calibrated by using the method detailed in Chapter 3. Stored soil water (mm) was calculated for each layer and recorded at 7:00 h on the day of evapotranspiration measurements.

Also, long term stored soil water data was used to examine drying rate under different litter and plant density conditions. Two periods were selected following irrigation or natural rainfall. Stored soil water (mm) was monitored for contrasting plots with differing plant density (2 and 25 plants per m^2) and bare soil with zero or high litter mass (3000 kg DM/ha). Stored soil water was estimated daily at 9:00 h using the Watermark resistance sensors and recorded by Tain data loggers. Total water loss (mm of stored soil water) and rate of water loss (mm/d) of each plot was compared for those periods.

6.2.7 Measurement of actual evapotranspiration at Springmount

A separate evapotranspiration experiment was established at Springmount to quantify rates of evapotranspiration for grazed natural pasture. To assess variation throughout the year, evapotranspiration rates were measured on four occasions; summer (February), autumn (May), winter (July) and spring (November). Four, paired study areas were established within two grazing treatment plots (T4GR4, Plot 4 and T3FERT8, Plot 6) in close proximity to the weather station. Each study area consisted of two adjacent sub-plots (each 2 by 2m) that had similar herbage and ground cover characteristics. The study areas were selected with a range of ground cover, herbage mass and litter mass conditions that were representative of the range across all treatment plots at the site (Table 6-3). The pair with high herbage mass was trimmed to a height of approximately 40 cm before measurements were taken with the material removed consisting mainly of dry seed heads. One plot of each pair was irrigated with 25 mm of water to create wet soil conditions. Those plots were irrigated on the afternoon before evapotranspiration measurements were conducted, and covered with plastic to maintain water content over-night. All study areas were available to sheep for grazing as part of the larger treatment plot and as such pasture characteristics varied slightly at each sampling time and their range is shown in Table 6-3. The same study areas were used each season so that soil and plant differences remained relatively constant between each sampling.

Table 6-3. Description of the study areas used for evapotranspiration measurements at Springmount.

Study area	Plot	Soil surface	Ground cover (%)	Herbage mass (kg DM/ha)	Litter mass (kg DM/ha)
Bare soil	1	Dry	< 5	0	0
	2	Wet			
Low cover and herbage	3	Dry	60-75	< 100	<50
mass	4	Wet			
Medium cover and herbage	5	Dry	75-85	750-1000	100-200
mass	6	Wet			
High cover and herbage	7	Dry	100	3000-5000	300-500
mass	8	Wet			

Weather data recorded at the Springmount weather station (Table 6-4) showed that conditions were similar to those for measurements at TCCI (Table 6-1), except for a considerably higher solar radiation value for February.

Table 6-4. Weather data for each day of evapotranspiration measurements at Springmount, with temperature range, calculated reference evapotranspiration (Penman-Monteith ET_{oPM}, Priestly-Taylor ET_{oPT}), solar radiation and relative humidity (RH).

Date	Temperature max. (°C)	Temperature min. (°C)	ET_{oPM} (mm)	ET_{oPT} (mm)	Solar Rad. (MJ/m^2)	RH (%)
9 Feb 2001	30.7	16.2	6.4	6.7	31.2	62
10 May 2001	18.8	6.7	2.4	2.5	15.8	81
5 Jul 2000	16.4	3.8	1.9	1.9	13.1	68
9 Nov 2000	23.1	10.5	4.0	3.9	20.9	56

Daily potential evapotranspiration was estimated using data collected by the weather station using both the Penman-Monteith and Priestly-Taylor equations; sub-daily routines were not available. Components of the net radiation balance were measured using the same procedure as at TCCI.

Gravimetric soil water content was estimated at the beginning of each sample day from samples taken in the layers 0-5 and 5-10 cm. Wet weights were determined and then samples were oven dried at 105°C for 24 h before re-weighing. Bulk density values (Chapter 3) were used to calculate volumetric soil water content and hence stored soil water for each layer.

Pasture characteristics of each plot were described and included ground cover (% estimated visually), herbage mass (kg DM/ha), litter mass (kg DM/ha), and percentage of green leaf by dry weight (%). Pasture samples were cut from standard quadrats (40 by 40 cm) and sorted into green and dead components before oven-drying to determine dry weight and proportion of green, as for the

TCCI plots in section 6.2.2. Leaves of redgrass are prone to curling after harvesting, so leaf area index was not assessed for these plots.

6.2.8 Data analysis

Hourly data were graphed to investigate variation through out the day, for a range of litter and plant density treatments. Hourly values were summed to daily values and the range of seasonal values was investigated for wet and dry soil surfaces. Students *t*-test was used to determine differences between values measured from wet and dry soil surfaces. The effect of litter mass on evaporation and plant density on evapotranspiration was explored by graphing daily values. Values of net radiation from wet and dry soil surfaces were tested for significant differences using the *t*-test.

Net radiation and vapour pressure deficits are known to be the major driving variables in evapotranspiration processes through out the year (Ward 1971; Linsley *et al.* 1988). In winter, radiant energy is low, air temperature is low, and relative humidity is often higher, creating less evaporative demand. In summer, radiant energy is high, air temperature is high, humidity is often low, and so evaporative demand is high. However, in the current study the effect of other factors including ground cover, herbage mass, litter mass, and soil water content on evaporation and evapotranspiration were important. These variables might change through grazing management (e.g. Lodge *et al.* 2003*a*) and so might influence evapotranspiration.

The importance of a range of variables in explaining variation in daily evaporation and evapotranspiration was examined using a series of linear regression models (S-Plus, MathSoft 1999) for data from both TCCI and Springmount. The influence of litter mass and soil water content on bare soil evaporation only was examined by analysing data from plots at TCCI without plants.

Net radiation and herbage mass accounted for most of the variation in evapotranspiration data, and after the inclusion of soil water content and litter mass and their interactions, other variables such as vapour pressure deficit, albedo and their interactions with herbage mass or radiation were added if they were significant. The decision to add a term was based on the *F*-value and the proportion of variation explained. Leaf area index and percent green leaf of pastures did not further improve the explanation of variation and so were not included.

The derived models and the coefficients for each variable were used to predict the difference in evapotranspiration due to litter for a range of herbage mass conditions with either wet or dry soil. This was done to isolate the effect of litter mass on evapotranspiration for both wet and dry soil conditions. Wet and dry soils were defined as having soil water content either greater than or less than the median soil water content measured at TCCI (i.e. above or below 30.6%).

6.3 Results

6.3.1 Hourly evapotranspiration rate

Hourly evapotranspiration ranged from 0.02 to 0.82 mm/h. Minimum values were recorded immediately after sunrise on several occasions for several plots. The maximum value was recorded for several plots around midday in February and November.

The daily pattern of evapotranspiration was starkly different for the range of treatments, with bare soil plots having lower hourly rates than those with high plant density (Figure 6-7*a*, *b*). The maximum hourly values for high plant density ranged from 0.29 to 0.66 mm/h in July and February, respectively (Figure 6-7*a*). For a bare dry soil, the maximum hourly value was 0.3 mm/h (Figure 6-7*b*). Values recorded in May and July were usually the lowest, while those recorded in February were the highest.

The longest period over which evapotranspiration was recorded was 12 h, starting at 6:30 and ending at 18:30 h for February, while in May and July, the period was only 10 h (7:30 to 17:30 h). The data recorded in February for Plot 4 (high plant density and high litter) showed that evapotranspiration was actively taking place when the last measurement was taken at 18:30 h (0.45 mm/h, Figure 6-7*a*). The data trend suggests that evapotranspiration may have continued into the evening beyond the time of the last measurement. A similar trend was also apparent for the data collected in November, with the last measurement at 17:30 h showing a rate of 0.22 mm/h. For the bare dry soil surface, final measurements were less than 0.1 mm/h suggesting that evaporation might not have continued into the evening.

6.3.2 Seasonal variation in daily evapotranspiration rate

Daily evapotranspiration ranged from 0.6 to 5.6 mm/d (Appendix 1 provides all daily values). When the surface soil was wet, Plot 11 (bare soil with high litter mass) had the minimum value on all occasions and was among the lowest when soils were dry. Mean daily evapotranspiration values ranged from a maximum of 4.5 mm on 7 February 2001 with a wet soil surface to a minimum of 1.1 mm on 7 July 2000 also with wet soil conditions (Figure 6-8). A *t*-test showed that evapotranspiration rates recorded with dry soil surface conditions were significantly different ($P<0.05$, n=60) to those from wet soil surface conditions, except for a cluster where values were less than 2 mm/d (Figure 6-9*a*). Values of evapotranspiration for wet and dry soil recorded in May and July (Figure 6-9*b*) showed little deviation from the 1:1 ratio. Stored soil water in May and July for the wet and dry measurements was not significantly different (*t*-test, $P>0.05$, n=60). For these samples, evapotranspiration was not limited by soil water content, but was limited by available energy.

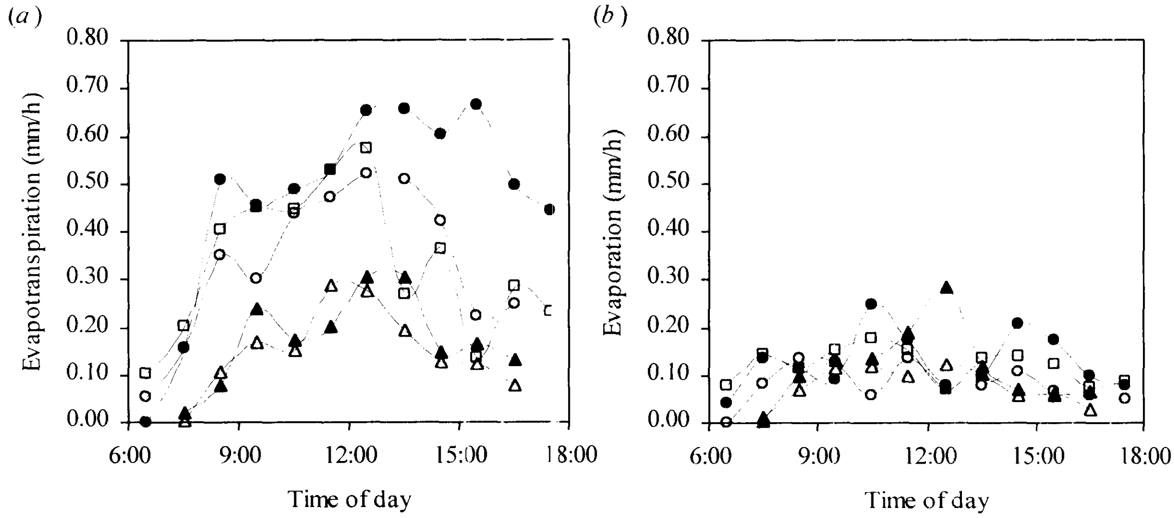

Figure 6-7. Hourly evapotranspiration (mm/h) for February (●), April (○), May (▲), July (△) and November (□) for (*a*) high plant density and litter mass (25 plants/m² and 3000 kg DM/ha, Plot 4), and (*b*) bare dry soil (Plot 8).

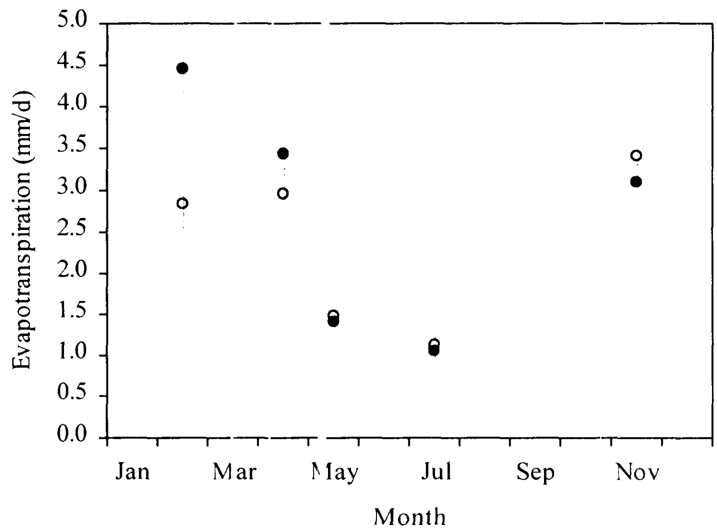

Figure 6-8. Mean daily evapotranspiration (mm) recorded for wet (●) and dry (○) surface soil conditions between February and November. Vertical bars indicate one standard error of the mean for daily evapotranspiration.

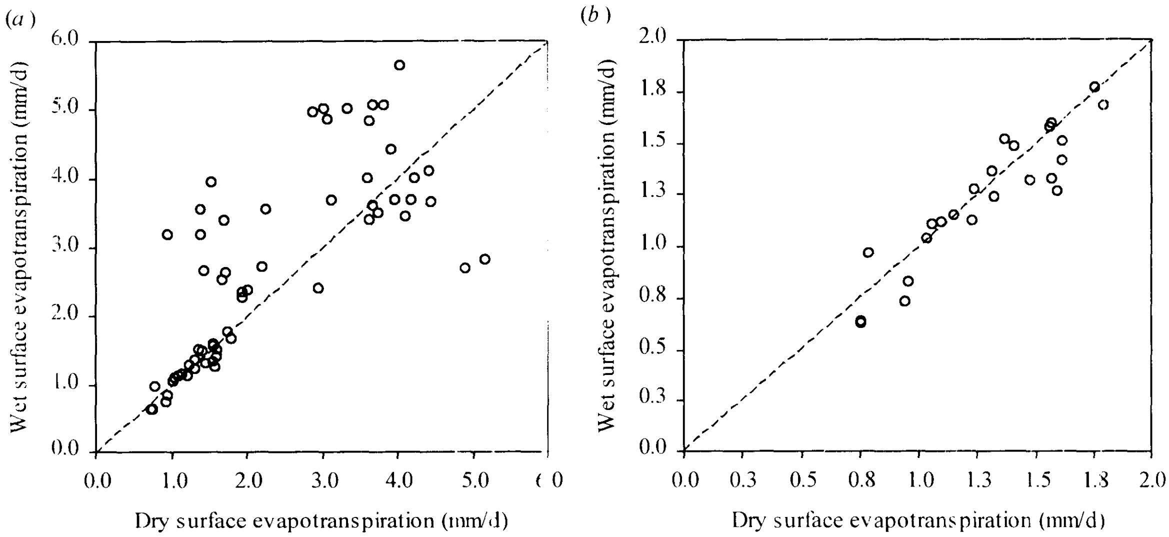

Figure 6-9. Comparison of daily evapotranspiration (mm/d) from plots with a dry soil surface with those having a wet soil surface for (*a*) all values, and (*b*) values recorded in May and July (dashed line shows the 1:1 ratio).

6.3.3 Effect of litter mass on soil evaporation

Daily evaporation ranged from 0.6 to 3.9 mm/d in July and February, respectively (Figure 6-10*b*). With high litter mass (3000 kg DM/ha), the maximum rate was 2.5 mm/d in February. Maximum daily evaporation for February, April, May and November was from a plot that had a wet soil surface (Figure 6-10*a*, *b*). In July, values were similar regardless of soil water content and evaporation was likely limited by energy demand as opposed to available soil water. For plots with dry soil surfaces, the effect of increasing litter mass on the rate of evaporation was inconsistent, but a plot with litter generally showed the maximum value (Figure 6-10*a*). The higher rate of evaporation from plots with litter in these circumstances was related to residual stored soil water held below the litter layer as indicated by the Watermark sensors.

For plots with a wet surface soil, evaporation generally declined with increasing litter masses and was consistent for all months. The minimum on each occasion was recorded from the plot with the highest litter mass (Figure 6-10*b*). Evaporation from either plots with 1500 or 3000 kg DM/ha of litter was always lower than evaporation from the bare soil (Figure 6-10*b*).

For wet soil conditions, mean hourly evaporation rate showed that increasing litter mass restricted evaporation, particularly in the middle part of the day (Figure 6-11). The maximum mean hourly rate for a bare soil surface was 0.35 mm/h at 11:30 h, but for a litter mass of 3000 kg DM/ha it was 0.20 mm/h at 7:30 h (Figure 6-11). Values for the plot with high litter mass were lower during the middle part of the day compared with at the beginning or end. The plots with litter mass of 500 and 1500 kg DM/ha had maximum mean hourly rates of 0.28 and 0.25 mm/h at 10:30 and 12:30 h, respectively (Figure 6-11).

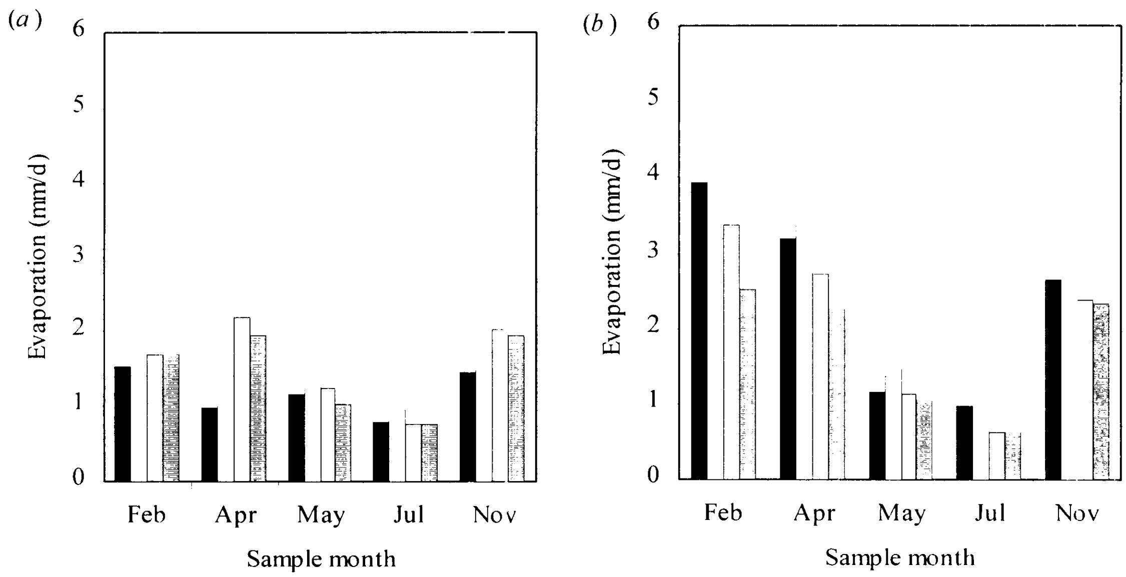

Figure 6-10. Daily soil evaporation (mm/d) from plots with different litter mass (0 - black bars, 500 - light grey, 1500 - medium grey, and 3000 kg DM/ha - dark grey) for (*a*) dry soil surface conditions, and (*b*) wet soil surface conditions.

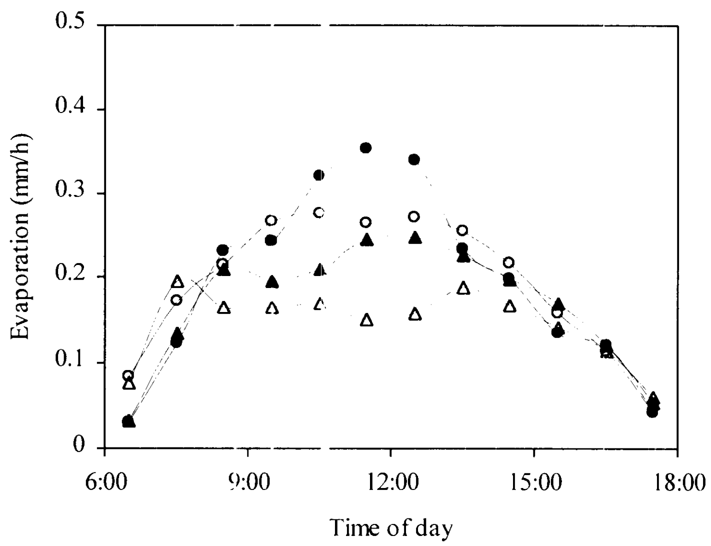

Figure 6-11. The effect of litter mass (kg DM/ha) on mean hourly soil evaporation (mm/h) for bare soil (●), 500 (O), 1500 (▲) and 3000 kg DM/ha of litter (△).

6.3.4 Effect of plant density and soil water content on evapotranspiration

Although plots were planted at various densities (4, 12 and 25 plants/m^2), the characteristics of individual plants in plots of each density were very different. During the experiment, mean herbage mass accumulated from 1293 kg DM/ha in April 2000 to 2500 kg DM/ha in February 2001, and 3500 kg DM/ha in May 2001. However, the green leaf percentage and leaf area index did not follow the same pattern. The minimum mean green percentage (31%) was recorded in May 2001 and the maximum (82%) was recorded in November 2000. Mean leaf area index was minimum in February 2001 and maximum in November 2000 with a value of 0.37 and 0.88, respectively. Although plants were actively managed to encourage green leaf production, they still responded to seasonal conditions, with green leaf percentage and leaf area reaching maximum levels following a wet spring in 2000 (Chapter 4).

The amount of evapotranspiration increased with plant density for both dry and wet soil surfaces (Figure 6-12). Values recorded from plots with dry soil conditions tended to be lower than those recorded from wet soil surfaces and for dry soils there were larger differences between low and high plant density plots (up to 1.6 mm in April, Figure 6-12*a*). For dry surface conditions, plots with plants appeared to extract water from deeper in the soil profile. Wet surface conditions tended to equalise the response of the plots, with low density plots showing similar values (< 0.5 mm difference) compared with those with high plant density (Figure 6-12*b*). Plots with low plant density had lower ground cover and hence more wet soil exposed to radiant energy, allowing the evaporation component to increase. Plots with high plant density rarely had the maximum daily evapotranspiration value (e.g. November with dry soil surface, and July with wet soil surface, Figure 6-12) despite having higher percent green and leaf area.

6.3.5 Net radiation (R_n) and albedo (α)

Mean albedo from plots with dry surfaces was 0.193, compared with 0.185 from wet soil plots. A *t*-test showed that the two samples were different (P<0.05, n=60). Albedo for plots with dry soil ranged from a minimum of 0.164 (Plot 1, medium plants, no litter) to a maximum of 0.229 (Plot 4, high plants, high litter). For plots with a wet soil surface, albedo ranged from 0.130 (Plot 8, bare soil) to 0.223 (Plot 11, high litter). These data show that a bare soil with a wet surface reflects less short wave radiation, while a surface with high litter is more reflective. Similarly, the mean daily value of net radiation measured from plots with a dry soil surface was 9.6 MJ/m^2 and values were different to those from plots with a wet soil surface (mean 10.6 MJ/m^2, P<0.05, n=60, *t*-test). Net radiation varied with time of the year and ranged from 3.6 to 20.1 MJ/m^2 in July and February, respectively.

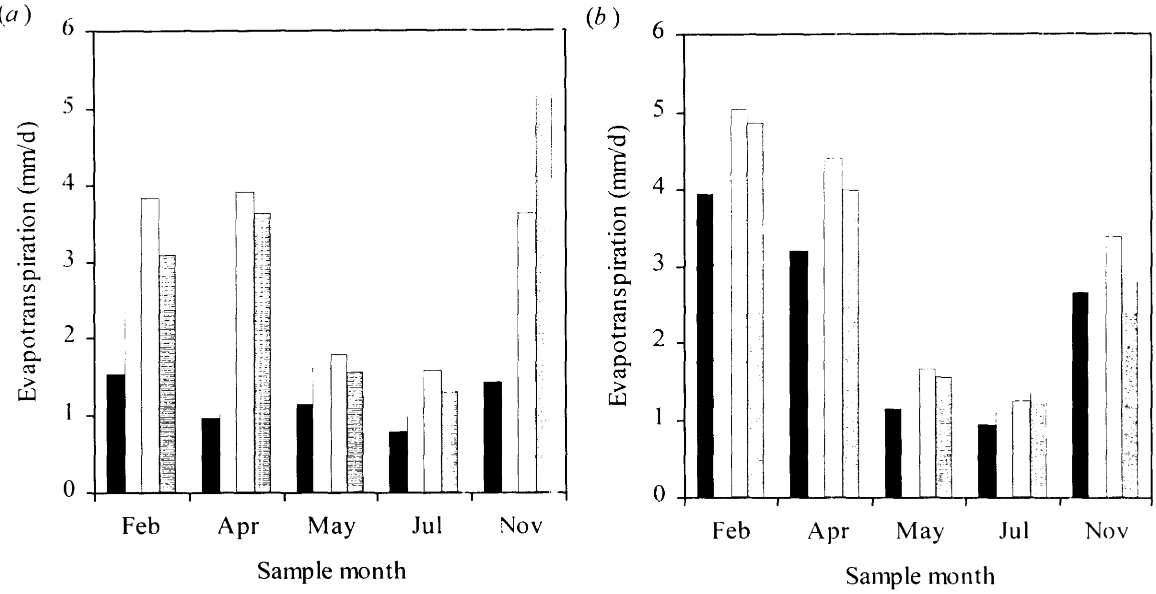

Figure 6-12. Daily evapotranspiration (mm/d) of plots with different plant densities and no litter, 0 (black bars), 4 (light grey), 12 (medium grey) and 25 (dark grey) plants/m^2 for (*a*) dry surface conditions, and (*b*) wet surface conditions.

6.3.6 Linear regression analysis of evapotranspiration at TCCI

Evaporation

A linear model accounted for 77.4% of the variation in evaporation with a residual mean square error of 0.20 mm (df=39, Table 6-5). The *F*-values indicated that net radiation (49.5% of variation), vapour pressure deficit (14.1%), soil water content (5.0%), and an interaction between soil water content and litter mass (5.5%) were important variables in explaining the variation in evaporation. However, after accounting for the contribution by main variables, the ranking changed with vapour pressure deficit (14.1% of variation), net radiation (7.9%), soil water content (5.3%), and litter mass (2.4%) being the most important. Albedo did not account for a significant proportion of the variation in evaporation values.

Evapotranspiration

A linear model accounted for 93.2% of the variation in evapotranspiration with a residual mean square error of 0.15 mm (df=119, Table 6-6). The *F*-values indicated that net radiation (51.9% of variation), herbage mass (17.3%), and vapour pressure deficit (14.6%) were important variables in explaining the variation in evapotranspiration. Several interactions also explained significant proportions of the variation (9.2% in total) and included herbage mass and net radiation (4.1%), and vapour pressure deficit and soil water content (1.9%). However, after accounting for contributions from all main effects, the importance of variables changed, with herbage mass (17.0% of variation), vapour pressure deficit (14.7%) and net radiation (5.1%) being the most important.

Table 6-5. The F-value, probability and the percentage of variation accounted for by each variable including litter mass in a linear regression model describing daily evaporation (mm) at TCCI (R^2 = 77.4, RMS = 0.20 mm on df=39).

Variable	F-value	Pr(F)	Percentage of variation (%)	Percentage of variation after main effects (%)
Net radiation	74.3	<0.001	49.5	7.9
Soil water content	7.5	<0.01	5.0	5.3
Litter mass	5.0	<0.05	3.3	2.4
Vapour pressure deficit	21.2	<0.05	14.1	14.1
Soil water content : litter mass	8.2	<0.01	5.5	

Table 6-6. The F-value, probability and the percentage of variation accounted for by each variable including litter mass in a linear regression model describing daily evapotranspiration (mm) at TCCI (R^2 =93.2, RMS = 0.15 mm on df=119).

Variable	F-value	Pr(F)	Percentage of variation (%)	Percentage of variation after main effects (%)
Herbage mass	125.2	<0.001	17.3	17.0
Net radiation	752.4	<0.001	51.9	5.1
Vapour pressure deficit	211.6	<0.001	14.6	14.7
Soil water content	2.3	0.13	0.2	0.1
Litter mass	0.1	0.72	0.0	0.1
Soil water content : litter mass	12.5	<0.001	0.9	

Effect of high litter mass on evapotranspiration

The linear regression models were used to investigate the likely difference in evapotranspiration with and without litter for wet and dry soils. Predicted daily evapotranspiration was lower (-0.05 to -1.04 mm) for wet soils with high litter mass compared with no litter mass (Table 6-7). However, for dry soils daily evapotranspiration was higher (0.19 to 0.50 mm) with high litter mass than with no litter mass (Table 6-7). These changes indicate that high litter reduces evaporative loss when soils are wet, but when soils are dry, those with litter are likely to have stored soil water for evaporation and so values are higher.

Table 6-7. The effect of litter (3000 compared with 0 kg DM/ha) on daily evapotranspiration (mm/d) for wet (> 30.6%) and dry (< 30.6%) soil for a range of different herbage mass conditions.

Herbage mass conditions	Wet soil	Dry soil
Evaporation only	-1.04	0.19
Nil herbage mass	-0.95	0.43
Medium herbage mass (800 kg DM/ha)	-0.41	0.50
High herbage mass (3000 kg DM/ha)	-0.05	0.28

6.3.7 Evapotranspiration and stored soil water through time

12 November to 13 December 2000

This period included a substantial amount of rainfall (152 mm) in 10 d from 12 November that uniformly wet the soil surface of all plots (Figure 6-13). The rainfall filled the surface soil to capacity, providing adequate stored soil water to be non-limiting for evapotranspiration. Stored soil water did not change for 2 d following the rainfall (21 November) and then dried through to 30 November (Figure 6-13). It is this 9 d period that showed water was removed from the surface soil of plots at contrasting rates. Plot 11 (bare soil with high litter) dried by 8.8 mm over this period (0.98 mm/d), while Plot 8 (bare soil surface) dried by 10.2 mm or 1.13 mm/d. A similar trend was shown for plots with contrasting plant density, with Plot 7 (low plant density) drying by 18.7 mm (2.08 mm/d) while Plot 4 (high plant density) dried by 20.5 mm or 2.28 mm/d. Further rainfall on 30 November and 7 December showed partial wetting of the surface and recurrence of a similar pattern of drying.

1 February to 12 March 2001

This period began with a small amount of rainfall (8.2 mm) on 1 and 2 February, followed by some drying to 6 February. Evapotranspiration measurements were taken with the evaporation dome on 7 February after further irrigation (~12 mm) to create a wet soil surface. The period of drying that followed through to 21 February showed that plots removed stored soil water at contrasting rates (Figure 6-14). Plot 11 (bare soil with high litter) dried by 13.4 mm over this period (0.95 mm/d), while Plot 8 (bare soil surface) dried by 18.6 mm or at 1.33 mm/d. A similar trend was shown for plots with contrasting plant density, with Plot 7 (low plant density) drying by 23.4 mm (1.67 mm/d) while Plot 4 (high plant density) dried by 26.3 mm or 1.88 mm/d. The plots without plants took a further 10 d to dry completely before it rained on 10 March.

Loss of stored soil water increased with plant density and decreased with litter mass. More water was removed from the surface layer of soil and at a higher rate in plots with high plant density compared with those with bare soil. The same pattern was reproduced for other periods of drying, with faster rates for plots with high compared with low plant density, and plots with low compared with high litter mass.

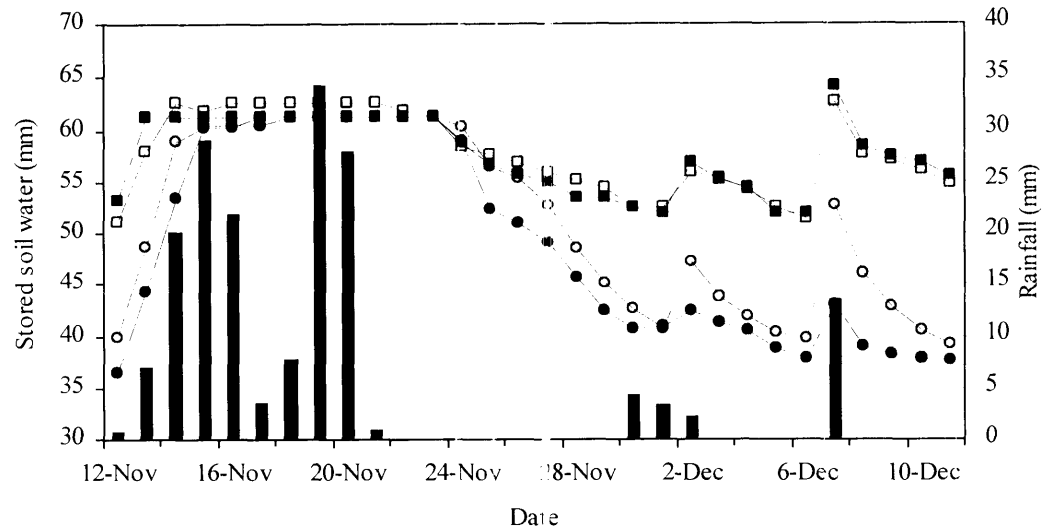

Figure 6-13. Rainfall (mm, black bars) and stored soil water (mm, 0-20 cm layer) for the period 12 November to 12 December 2000 for treatments with different plant density and litter mass: Plot 4 (25 plants/m^2 + 3000 kg DM/ha, ●), Plot 7 (4 plants/m^2 + 3000 kg DM/ha, O), Plot 11 (0 plants/m^2+ 3000 kg DM/ha, ■), and Plot 8 (0 plants/m^2+ 0 kg DM/ha, □).

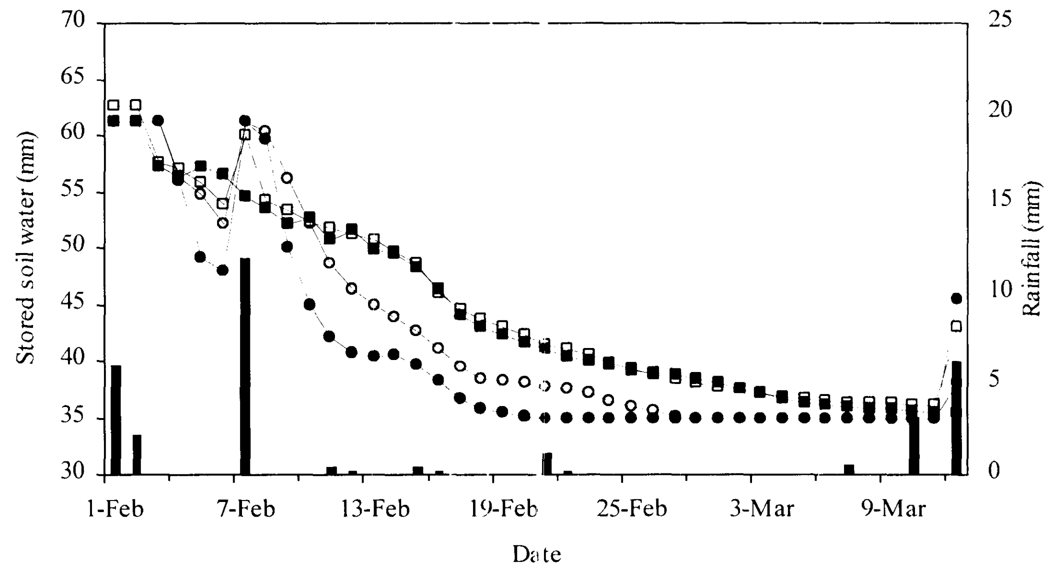

Figure 6-14. Rainfall (mm, black bars) and stored soil water (mm, 0-20 cm layer) for the period 1 February to 12 March 2001 for treatments with different plant density and litter mass: Plot 4 (25 plants/m^2 + 3000 kg DM/ha, ●), Plot 7 (4 plants/m^2 + 3000 kg DM/ha, O), Plot 11 (0 plants/m^2 + 3000 kg DM/ha, ■), and Plot 8 (0 plants/m^2+ 0 kg DM/ha, □).

6.3.8 Evapotranspiration at the Springmount study site: seasonal and daily effects

Seasonal variation in evapotranspiration

Daily evapotranspiration at Springmount ranged from 0.2 to 7.6 mm/d in July and February, respectively (Figure 6-15*a*, *b*. Appendix 1 provides all daily values). Of all the measurements, those taken from a bare dry soil surface returned the lowest daily values, as that plot had antecedent soil water contents of 5-8%. With the addition of irrigation water, bare, low and medium cover plots responded with an increase in evapotranspiration of up to 2.3 mm/d (e.g. medium cover, February) compared with values measured from dry surfaces (Figure 6-15*b*). Evapotranspiration values from plots with high herbage mass showed little difference between values from wet and dry surfaces, and these plots gave consistently lower values than other plots with pasture cover (Figure 6-15*a*, *b*). However, a *t*-test showed that evapotranspiration values from bare soil plots with wet and dry surfaces were significantly different ($P<0.05$, n= 22).

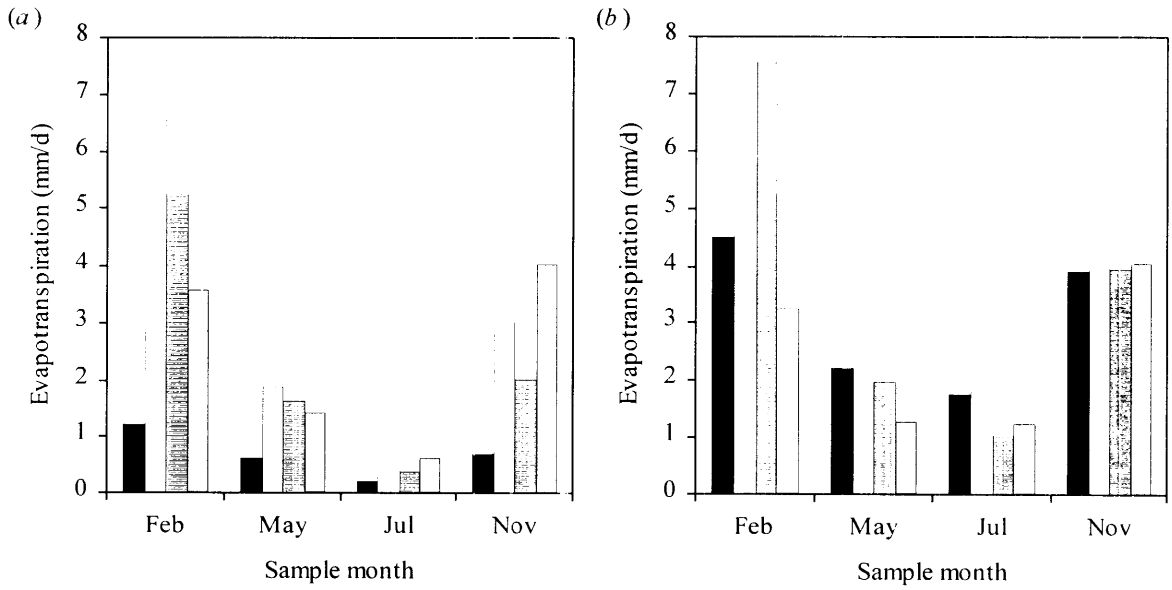

Figure 6-15. Daily evapotranspiration (mm/d) for plots at Springmount with different herbage mass and ground cover, bare soil (black bars), low (light grey), medium (medium grey), and high (dark grey) herbage mass and ground cover, respectively, for (*a*) dry soil surfaces, and (*b*) wet soil surfaces.

High herbage mass and ground cover

The plots with high herbage mass showed little response to irrigation and a wet soil surface. This was examined more closely by investigating the hourly evapotranspiration rates for February and November, when temperature and solar radiation were not limiting. Hourly values from wet and dry soil surfaces showed a similar pattern through the day (Figure 6-16). The maximum value was

0.62 mm/h for the wet surface in February, while the dry surface had a maximum of 0.60 mm/h for the same month (Figure 6-16). A *t*-test showed that there was no difference between hourly values ($P>0.05$, n=12) for either February or November. The lack of response between wet and dry surface conditions might have been caused by the restriction of air movement within the dome by the pasture height.

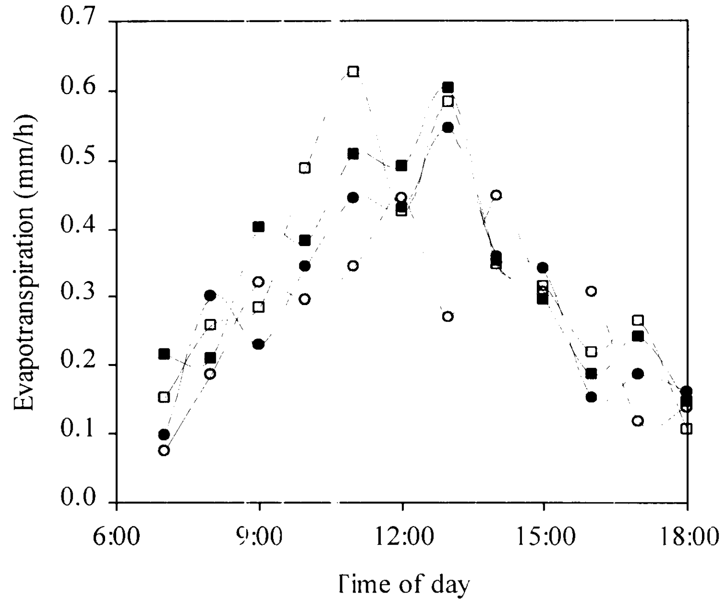

Figure 6-16. Hourly evapotranspiration (mm/h) for plots with high herbage mass at Springmount, showing little difference between February (●, O) and November (■, □) for dry (●, ■) and wet (O, □) soil surface conditions

Bare soil evaporation

The bare soil plots at Springmount illustrated the expected difference in evaporation rate between wet and dry soil surfaces. Hourly values in February and November showed that evaporation from the dry soil surface was relatively constant between 0.08 and 0.15 mm/h with a slight peak in the middle of the day (Figure 6-17). However, with a wet soil surface the maximum evaporation rate of 0.66 mm/h was recorded at 10:00 h (Figure 6-17), rather than around midday when available energy was greatest. By 9:30 h, approximately 30% (by visual estimation) of the soil surface appeared dry and within 2 hours the entire soil surface was dry and the evaporation rate was declining.

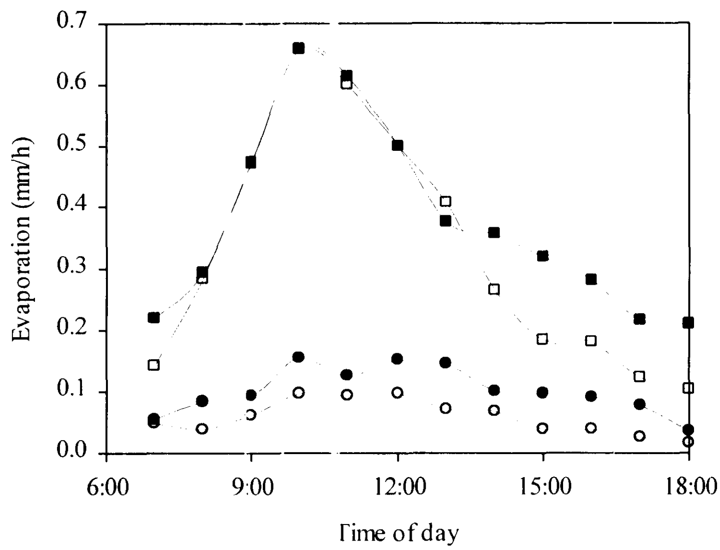

Figure 6-17. Hourly bare soil evaporation (mm/h) for dry (●, O) and wet (■, □) soil surfaces in February (●, ■) and November (O, □) showing a rapid decline in evaporation after 10:00 h for the wet surface.

Net radiation (R_n) and albedo (α)

The range of net radiation values at Springmount were similar to those recorded at TCCI, with a minimum of 6.4 MJ/m^2 and a maximum of 19.9 MJ/m^2. There was no difference between the values recorded from plots with wet or dry soil surfaces (P>0.05, n=22, t-test) and the mean value of daily net radiation was 11.9 MJ/m^2.

Albedo values recorded at Springmount were less than those for TCCI and ranged from a minimum of 0.134 a maximum of 0.208. There was no difference between values from wet and dry soil surfaces (P>0.05, n=22, t-test) and the mean value was 0.172.

Linear regression analysis of evapotranspiration at Springmount

A linear model accounted for 93.9% of the variation in evapotranspiration with a residual mean square error of 0.37 mm (df=31, Table 6-8). The F-values indicated that net radiation (59.9% of variation), soil water content (7.9%), herbage mass (6.8%), and albedo (4.7%) were important variables in explaining the variation in evapotranspiration. Several interactions also explained significant proportions of the variation, included those between herbage mass and net radiation (8.2%), and soil water content and litter mass (3.0%). However, after accounting for contributions from all other main effects, the importance of variables changed, with net radiation (33.8%), herbage mass (12.5%), and soil water content (8.6%) being the most important.

Table 6-8. The *F*-value, probability and the percentage of variation accounted for by each variable including litter mass in a linear model describing daily evapotranspiration (mm) at Springmount (R^2 =93.9, RMS = 0.37 mm on df=31).

Variable	*F*-value	Pr(*F*)	Percentage of variation (%)	Percentage of variation after main effects (%)
Herbage mass	12.4	<0.001	6.8	12.5
Net radiation	217.6	<0.001	59.9	33.8
Albedo	17.2	<0.001	4.7	3.4
Soil water content	28.8	<0.001	7.9	8.6
Litter mass	12.3	<0.01	3.4	3.4
Soil water content : litter mass	10.8	<0.01	3.0	

6.3.9 Summary of results

At TCCI, hourly evapotranspiration values ranged from 0 to 0.82 mm/h and higher values were recorded around midday. The maximum value for a bare wet soil (0.68 mm/h) was recorded in February. Daily evapotranspiration ranged from 0.6 mm in July to 5.6 mm in February. Mean daily values were lowest in July (1.1 mm/d) and highest in February (4.5 mm/d) reflecting the variation in radiant energy and vapour pressure deficit. For all data combined, values recorded from plots with wet soil surfaces were higher than values collected from plots with dry soil surfaces. However, for May and July there were no differences between wet and dry plots, reflecting the low radiant energy and non-limiting stored soil water.

On bare soil plots with a wet surface, evaporation decreased with greater litter mass, with maximum rates of 3.9 and 2.5 mm/d for a bare plot and for a plot with a high litter mass of 3000 kg DM/ha, respectively. For plots with a dry surface, the opposite occurred as plots with higher litter mass had residual stored soil water, which continued to evaporate through the litter. Evapotranspiration increased with plant density, from 0 to 12 plants/m^2, but lower values were recorded for plots with the highest density (25 plants/m^2). The higher plant density and associated herbage mass appeared to restrict air circulation within the evaporation dome leading to lower estimates of evapotranspiration.

Mean albedo for plots with a wet soil surface was lower (0.185) than plots with a dry soil surface (0.193). The minimum albedo (0.130) was recorded from a plot with bare wet soil surface, while the maximum (0.229) was recorded from plot with high herbage and litter mass. Values of net radiation followed this trend with dry surface plots having a lower mean net radiation (9.6 MJ/m^2) than plots with a wet surface (10.6 MJ/m^2).

At TCCI, the linear regression analysis accounted for 93.2% of the variation in daily evapotranspiration data (R^2 = 93.2%, RMS = 0.15 mm, df=119) and showed that herbage mass, vapour pressure deficit and net radiation were important variables. Using these models, predicted daily evapotranspiration was lower (-0.05 to -1.04 mm/d) for wet soils with high litter mass compared with no litter mass. However, for dry soils daily evapotranspiration was higher (0.19 to 0.50 mm/d) with high litter mass compared with no litter.

Stored soil water of plots was monitored through periods of soil drying and showed that plots with high plant density dried more rapidly than plots with low plant density. Similarly, plots with high litter mass dried more slowly compared with plots that had no litter mass.

At Springmount, daily evapotranspiration rate ranged from 0.2 to 7.6 mm/d in July and February, respectively. The maximum value was higher than at TCCI due to higher solar radiation on those days (31.2 MJ/m^2 vs. 22.7 MJ/m^2). Rates recorded from plots with wet soil surfaces were higher than those from plots with dry soil surfaces were, as was recorded at TCCI. For plots with high herbage mass, there was no difference in evapotranspiration whether soil surfaces were wet or dry, particularly for the months of February and November. The pasture height may have restricted air movement within the evaporation dome, leading to lower estimates of evapotranspiration from these plots.

Albedo at Springmount ranged from 0.134 to 0.208 with a mean of 0.172. These values reflected the lower percentage of green leaf in the pasture and the higher amount of standing dead material. Net radiation values ranged from 6.4 to 19.9 MJ/m^2 for July and February, respectively. There was no difference between values from wet and dry surfaces.

At Springmount, the linear regression model analysis accounted for 93.9% of the variation in daily evapotranspiration data (R^2 = 93.9%, RMS = 0.37 mm, df=31) and showed that net radiation, herbage mass and soil water content were important variables.

6.4 Discussion

6.4.1 Seasonal and daily variation in evapotranspiration at TCCI

Actual evapotranspiration was successfully measured from a series of small plots that varied in plant density, leaf area and litter mass. Hourly evapotranspiration ranged from 0.02 mm/h at sunrise in April to 0.82 mm/h at midday in February. Maximum hourly values were recorded around midday when available energy was usually highest and the sun near its zenith. Under dry soil surface conditions, the plots with high herbage mass and leaf area index had higher hourly rates (e.g. 0.82 mm/h, Plot 9, November), and water was likely being retrieved from below the soil surface (Sauer *et al.* 2002). Under wet conditions, the bare soil plots had higher hourly values that were comparable to those from plots with high herbage mass (e.g. 0.68 mm/h Plot8 and 0.65 mm/h Plot 4 at 12:30 h in February). However, the rate declined for bare soil plots once evaporation was limited by available soil water. The values recorded in the current study were comparable to values reported in other studies (e.g. 0.74 mm/h by Dunin and Reyenga 1978, and Rosset *et al.* 1997; 0.2 mm/h by McLeod *et al.* 1998).

The latest measurement of evapotranspiration occurred between 17:30 and 18:30 h depending on the season and was scheduled to finish as close to sunset as possible. Plots with high herbage mass and leaf area index despite rapidly declining net radiant energy showed a substantial rate of evapotranspiration at that time (e.g. up to 0.4 mm/h). Plants were actively transpiring and appeared as though they would continue to do so well past sunset. Both Rosset *et al.* (1997) and Malek (1992) reported overnight evaporation of 1.24 and 1.05 mm, respectively. In both cases, the authors suggested that strong winds (advection) throughout the night provided adequate energy that allowed evaporation to continue. Malek (1992) also showed that a negative sensible heat flux and negative soil heat flux provided energy for evaporation at night.

In the current study, no measurements were made with the evaporation dome beyond sunset due to the lack of radiant energy and the concern that the fans inside the dome would create artificial advection and so false evaporation values. At night, hourly values would be very low and any positive effect of fan speed (e.g. < 0.02 mm/h, McJannet *et al.* 1996) would be substantial. However, McJannet *et al.* (1996) used the evaporation dome throughout the night when measuring soil and litter evaporation over 24 h periods below canopies of Mountain Ash forest. They found that evaporation rate over night was relatively constant, and I suspect that it was due to turbulence created by the electric fans inside the dome. To measure evaporation at night, alternative methods such as weighing lysimeters (Sharma 1976) or Bowen ratio (Malek 1992; Sauer 2002) might be more suitable. However, evaporation at night could represent a significant proportion of the daily evapotranspiration flux. Malek (1992) reported that evaporation at night amounted to between 1.7 and 14% of 24 h evapotranspiration and so a significant proportion of the annual total.

Daily values of evapotranspiration ranged from 0.6 mm in winter to 5.6 mm/d in summer. These values are comparable to those reported by a number of authors for grasslands of different types. Using an evaporation dome in winter, McLeod *et al.* (1998) reported mean daily values of evapotranspiration between 0.87 and 1.03 mm/d over a 6 d period. Those estimates were taken from degraded sown pastures and phalaris pastures on the Northern Tablelands of NSW and were in good agreement with values from winter in the current study (mean daily values of 1.06 and 1.12 mm/d recorded in July for wet and dry soil surfaces, respectively). McLeod *et al.* (1998) also noted that evapotranspiration was limited by radiant energy rather than soil water content at that time of the year and that the maximum hourly rate was approximately 0.2 mm/h. In a study of energy balance of alpine pastures at differing altitudes in Switzerland, Rosset *et al.* (1997) used the Bowen ratio method to estimate evapotranspiration and reported maximum daily values between 4.8 and 5.0 mm/d. The authors reported that the rate of evapotranspiration was strongly correlated with the available energy flux, which varied with altitude; the maximum hourly rate was 0.74 mm/h. Elsewhere, Dunin and Reyenga (1978) used a combination of lysimeter and Bowen ratio methods to estimate evapotranspiration of kangaroo grass (*Themeda australis* S.T. Blake) grassland near Canberra, Australia. In that study, daily evapotranspiration rates ranged from 0.45 to 4.7 mm/d for August and November, respectively, with peak hourly rates of 0.74 mm/h. Sauer *et al.* (2002) used the Bowen ratio method to estimate evapotranspiration in the seasonal water balance of tall fescue (*Festuca arundinacea* Schreb.) grassland in Arkansas USA and reported values of around 2 mm/d in winter and nearly 8 mm/d in summer.

Daily evapotranspiration was greater from plots with wet soil surfaces than from plots with dry soil surfaces, indicating that stored soil water was limiting evapotranspiration on most days. When stored soil water was available, meteorological conditions (available energy) rather than plant stomatal resistance governed the rate of evapotranspiration (Dunin and Reyenga 1978). Also, for grasslands with non-limiting stored soil water, evapotranspiration was controlled by net radiation rather than vapour pressure deficit (Rosset *et al.* 1997). Sauer *et al.* (2002) reported that while soil water content was greater than wilting point (ψ_s, -1500 kPa) the evapotranspiration rate was likely to be near that of potential. Therefore, for plots with exposed wet soil and wet litter or wet herbage, higher rates of evapotranspiration were likely, as water was freely available. On some occasions, plots with high plant density and leaf area index showed no increase in evapotranspiration with irrigation, suggesting that plant roots retrieved soil water from below the surface and it was adequate to meet energy demands (Sauer *et al.* 2002). However, in May and July, there was no difference in evapotranspiration between plots with wet or dry surface conditions. This was due to two factors; antecedent stored soil water was sufficient to avoid water limited evapotranspiration from the 'dry' runs and available energy was so low that moisture limitation was not encountered during either run (McLeod *et al.* 1998).

Litter significantly reduced the rate of evaporation from plots with bare wet soil (Figure 6-10). This effect was strongest for high litter mass as was reported by Gonzalez-Sosa *et al.* (2001). Bristow (1988) studied the effect of litter and its architecture on soil temperatures and concluded that litter significantly influenced the energy and surface soil water balance, tending to slow the rate of evaporation. As litter dried, it became a more efficient insulator with lower convective energy transfer and hence reduced the amount of available energy for latent heat flux. Similarly, Farahini and Ahuja (1996) modelled the effect of partial litter cover on evaporation and reported that, upon drying, the litter provided a layer of higher evaporative resistance leading to lower rates of vapour transfer. In the current study, Plot 11 (bare soil plot with high litter mass) showed no increase in hourly evaporation rate during the middle of the day, possibly due to high evaporative resistance through the litter.

In a long-term energy balance study of a pasture in France, Gonzalez-Sosa *et al.* (1999) found that litter had low thermal conductivity that kept the soil cool and this property increased with its dryness, reducing the evaporative demand at the soil surface. They showed that litter reduced evaporation by 200-400%, but transpiration increased by 30-50% due to subsequently higher surface soil water content, resulting in an overall net decrease in evapotranspiration of 5-10%. Results from the current study, however, showed that with dry surface conditions, evaporation increased with litter mass for three of the five sample dates (Figure 6-10). The soil water content data showed that on these occasions, the plots with higher litter mass had higher antecedent stored soil water due to previously lower rates of evaporation in the period leading up to the sample date. The linear regression models indicated that a high litter mass may reduce evaporation from wet soil surfaces by up to 1.04 mm/d, and for dry surfaces, evaporation would increase by 0.50 mm/d.

Another possible effect of a litter layer may be that of increased dewfall, particularly in the cooler months. In the current study, plots with higher litter mass tended to have increased rates of evaporation during the morning when the litter was wet with dew. On an energy balance basis, a significant proportion of the net radiant energy would be used to evaporate the dewfall before being used to evaporate water from the soil store. In this manner, Sharma (1976) showed that dewfall in winter months amounted to 0.56 mm/d and accounted for > 22% of the net radiant energy exchange in its evaporation. Litter is a good thermal insulator (discussed previously) and at night the temperature of the litter surface is colder than the underlying soil surface, leading to increased dewfall with a negative vapour pressure gradient (Sharma 1976). Hence, litter may encourage dewfall, and its subsequent evaporation would use a proportion of the available radiant energy thereby reducing the demand upon the stored soil water.

The leaf area index of plots in the current study ranged from 0.15 to 1.52 in direct proportion to the sown plant density and herbage mass. Evapotranspiration was expected to increase with leaf area index as reported by Rosset *et al.* (1997). However, evapotranspiration was usually highest for plots with an intermediate plant density and leaf area index. Several factors may have contributed to the findings in the current study. Firstly, plots with high herbage mass had lower antecedent soil water content due to previous extraction. Second. the canopy of the herbage may have created a strong boundary layer effect preventing transfer of vapour. Last, the high herbage mass may have prevented air movement within the evaporation dome leading to non-uniform mixing and lower evapotranspiration. A larger evaporation dome might be more suitable for measuring evapotranspiration from pastures with high herbage mass and height (e.g. Reicosky 1983).

Net radiation quantifies the amount of energy available for latent heat and sensible heat flux, and its value can be influenced by the albedo of the surface. Albedo is an important component of the energy balance and can influence net radiant energy by up to 20% (Farahini and Ahuja 1996). Many agricultural studies do not measure albedo, as it requires specialised sensors, so its value is largely not documented for paddock situations. Albedo in the current study ranged between 0.13 for a wet bare soil surface and 0.23 for high plant density, leaf area and litter mass. Farahini and Ahuja (1996) stated that albedo of litter has a strong effect on net radiant energy and it varies with type, water content, age, and geometry of the litter. In grassland situations, the leaf area, bare soil area and the maximum sun angle also influence albedo (Rosset *et al.* 1997). Typical values for albedo reported in the literature include 0.14 for a bare wet soil and 0.20 for litter (Bristow 1988), 0.2 to 0.6 for various litter types (Farahini and Ahuja 1996), 0.14 and 0.24 for grassland with low and high herbage mass, respectively (Rosset *et al.* 1997). These values are directly comparable with those values recorded in the current study.

Hourly albedo values showed an asymmetric diurnal pattern (data not shown); similar to that reported by Song (1998), who studied albedo of grass pastures. In that study, albedo was higher at the beginning and end of the day due to the orientation of the pasture sward in relation to the sun angle. Strong winds were thought to change the pasture orientation. Wet pasture and litter surfaces created by dewfall may also reduce albedo early in the morning and these changes might have important implications for the radiation balance in hydrological modelling (Song 1998). Hence, when using a meteorological approach to estimate evapotranspiration of various pasture types and conditions, local coefficients for values such as albedo are essential (Meyer *et al.* 1999).

Monitoring the stored soil water through time with Watermark sensors (e.g. Figure 6-13) showed that plots with high plant density extracted water more rapidly compared with plots that had lower plant density or bare soil. Also, litter mass reduced the rate of evaporation from bare soil but by only 0.1 - 0.4 mm/d. However, the daily rates of evapotranspiration calculated this way, were lower than daily values measured using the evaporation dome (c. 1.9 vs. 4.1 mm/d). The evaporation dome measured the rate of water vapour accumulation above the soil surface, while the Watermark sensors recorded a net change in stored soil water. A limitation of the Watermark technique is that water can redistribute within the profile as water is removed by evapotranspiration. The 2 d period that stored soil water did not change following rainfall in November (Figure 6-13) is evidence that water redistributed in the profile. Negative water potential gradients may allow water to redistribute within the profile, particularly over night, leading to a lower net loss of water over any 24 h period. In a study of grassland hydrological balance, Sauer *et al.* (2002) alluded to a similar process that retrieved water from below the plant root zone. Hence, using the water balance of the surface soil to estimate the rate of evapotranspiration may be misleading, but it could prove useful if it incorporated estimates of the profile stored soil water (e.g. to 200 cm depth with a neutron moisture meter) to ascertain if water was being redistributed. Similarly, nested tensiometers might indicate the neutral flux zone within the profile, and so determine if water is being redistributed in an upward (evapotranspiration) or downward (through drainage) direction (Salve and Tokunaga 2000).

6.4.2 Seasonal and daily variation in evapotranspiration at Springmount

The range of daily evapotranspiration values measured at Springmount was greater than at TCCI, with a minimum of 0.2 mm/d and a maximum of 7.6 mm/d. The minimum value was recorded from a dry bare soil surface in July when radiant energy was lowest. Evaporation was kept low by an extremely dry soil surface (θ_{vol} of 5% or near air dry ψ_s, -15,000 kPa), showing that little water was available at that time. Maximum evapotranspiration rates were generally higher at Springmount than at TCCI and higher levels of radiant energy compared with TCCI explained this. For the February sample day, solar radiant energy at Springmount peaked at 31.2 MJ/m^2 compared with 22.7 MJ/m^2 at TCCI.

In addition, soil physical properties (e.g. pore connectivity) may have aided evapotranspiration at Springmount. Plots at Springmount that had high ground cover also had excellent surface soil structure, which was porous and friable. Good surface porosity is favourable for water infiltration enabling water to enter the profile. Pore connectivity and capillary rise allow water to return to the surface for evaporation (Greenwood 1996). In contrast, the plots at TCCI were constructed for the experiment and although an attempt was made to minimise soil disturbance, a degree of compaction was inevitable. Lower pore connectivity may have limited evapotranspiration, as it is not only constrained by meteorological conditions but also by supply of water through the soil to the evaporating surface (Farahini and Ahuja 1996).

As was recorded at TCCI, evapotranspiration rates under dry and wet soil conditions at Springmount were markedly different with up to 2.3 mm/d more water being removed from wet surfaces. Antecedent stored soil water was very low at Springmount (5-10%, θ_{vol}), leading to lower evapotranspiration values on dry plots. Under wet soil conditions, available soil water combined with high radiant energy and good soil surface structure, probably led to increased evapotranspiration, magnifying the difference between the two. However, the plots with the highest herbage mass (Plots 7 and 8) showed no difference between dry and wet surface conditions. As at TCCI, the pasture height at Springmount (despite being cut back to 40 cm height) may have led to the formation of a strong boundary layer at the canopy surface and a physical restriction of mixing humid air. However, in a grazed paddock situation, this effect may be beneficial in that the strong boundary layer prevents rapid evapotranspiration, conserving soil water for use by the plants over a longer period.

The plots with bare soil surfaces (Plots 5 and 6) clearly demonstrated the effect of first and second stage evaporation processes (Figure 6-17). The soil surface of these plots was severely sealed, which led to very low infiltration rates (e.g. < 28 mm/h. Lawson 1998) and made it difficult to irrigate, resulting in low stored soil water (e.g. February Plot 6, 20.8% 0-5 cm; 16.4% 5-10 cm). The hourly evaporation rate from the wet surface showed a sharp decline around 10:00 h, prior to the peak in radiant energy flux. This indicated that the surface of evaporation had started to recede below the soil surface and capillary conductance could no longer supply adequate water to the surface to meet demand (Farahini and Ahuja 1996). At this time, the surface of the plot began to 'dry' showing distinct patches of dry soil and the evaporation rate declined rapidly.

Albedo values recorded for the plots at Springmount ranged from 0.13 to 0.21 and were slightly lower than values recorded at TCCI. Causes for different albedo values were discussed previously, and at Springmount, the large amounts of dry, standing dead herbage mass and low percent green may have contributed to the lower values. Lower values of albedo indicated that more short wave radiant energy was absorbed by the surface and was available for latent heat and sensible heat flux. The mean value of 0.17 was well below the accepted standard of 0.23 used in calculations of reference evapotranspiration (e.g. Smith *et al.* 1996).

6.5 Conclusion

The evaporation dome technique was successfully used to measure actual evapotranspiration from contrived pasture plots at TCCI and grazed pasture at Springmount. The fan speeds used within the dome had a significant effect on evapotranspiration values. Thus, the lowest speed was used for all measurements and it provided adequate mixing of the air within the dome on all occasions, except when herbage mass was high.

At TCCI, daily evapotranspiration ranged from 0.6 to 5.6 mm/d with minimum values recorded in July and maximum values in February, reflecting the magnitude of radiant energy and vapour pressure deficit at these times. At Springmount, daily evapotranspiration ranged from 0.2 to 7.6 mm/d in July and February, respectively. The maximum hourly rate of evapotranspiration was 0.82 mm/h and the maximum bare soil evaporation rate was 0.68 mm/h, both recorded around midday when radiant energy was highest. For plots with higher herbage mass there was some indication that evaporation continued into the early evening beyond sunset, indicating that evaporation at night was likely in this environment.

On bare soil plots with a wet surface, evaporation decreased with greater litter mass, with maximum rates of 3.9 mm/d and 2.5 mm/d, for a bare plot and for a plot with a high litter mass of 3000 kg DM/ha, respectively. For plots with a dry surface, the opposite occurred as plots with higher litter mass had residual stored soil water, which continued to evaporate through the litter. Evapotranspiration increased with plant density, from 0 to 12 plants/m^2, but lower values were recorded for plots with the highest density (25 plants/m^2). The higher plant density and associated herbage mass appeared to restrict air circulation within the evaporation dome leading to lower estimates of evapotranspiration.

Linear regression models indicated that net radiation, vapour pressure deficit, herbage mass, litter mass and soil water content were important variables in accounting for up to 93.2 and 93.9% of the variation in evapotranspiration data at TCCI and Springmount, respectively. These same models were used to estimate the effect of high litter mass on evapotranspiration and they indicated that for wet soil surfaces, litter may decrease evapotranspiration may by up to 1.04 mm/d, but for dry surfaces, evapotranspiration may increase by 0.50 mm/d. The increase for 'dry' surfaces accounts for the evaporation of residual soil water held below the litter compared with surfaces that have already dried.

Albedo varied with soil water content, litter and herbage mass, ranging from 0.13 to 0.23 for a bare wet soil and for a plot with high herbage and litter mass, respectively. Similarly, net radiation ranged from 3.6 to 20.1 MJ/m^2.d and at TCCI mean values were higher on plots with wet soil surfaces.