1 Introduction

Livestock grazing is the largest agricultural land use in Australia, occupying approximately 432 M ha or 56% of the continent (Trewin 2002). On the North-West Slopes of New South Wales (NSW), natural pastures occupy 70% of the agricultural land or 2.03 M ha (Lodge *et al.* 1984; Lodge *et al.* 1991) and support sheep and cattle grazing enterprises. Native warm season perennial grasses dominate the species composition of these pastures. Natural pastures tend to have low levels of green leaf, which leads to low protein content, low digestibility and poor animal performance (Lodge and Whalley 1983). Many of these pastures tend to accumulate dead standing material that is caused by frosting in winter (Lodge and Roberts 1979). To accommodate this, stocking strategies commonly incorporate continuous grazing at low levels of intensity. The mean stocking rate of these pastures ranges between 3.7 and 5.2 dry sheep equivalents per hectare (DSE/ha, Lodge *et al.* 1991).

Natural pastures are generally less productive than they once were and sown pastures show a rapid decline in productivity soon after establishment (Kemp and Dowling 2000). A change in species composition with a loss of perennial species causes this decline and previous experiments assessed the impact of grazing management in manipulating the composition of perennial species (Mason and Kay 2000). Maintaining perennial species in the pasture sward was expected to result in fewer weeds, higher water use and lower soil acidification rates, and so more sustainable production (Kemp *et al.* 2000).

Grazing at higher intensity may lead to a decline in herbage mass (e.g. Langlands and Bennett 1973; Gill *et al.* 1998), while rotational grazing at the same intensity with periods of rest may lead to an increase in herbage mass. High intensity-short duration grazing systems may lead to a depletion of herbage mass during the grazing phase (Weltz *et al.* 1989), but with sufficient rest, herbage mass recovers. The amount of litter in a pasture is an index of grazing pressure (Willms *et al.* 1993) and provides a simple measure to ascertain system health (McCormick and Lodge 2001). Grazing at any intensity will reduce the amount of litter in a pasture, with lowest amounts under highest grazing intensity (Johnston *et al.* 1971; Gill *et al.* 1998; Molinar *et al.* 2001).

Previous studies have examined the effect of grazing management on various components of the hydrological balance or factors that may affect each component. Greenwood (1996) reported the effect of grazing on soil-physical properties for sown pastures on the Northern Tablelands of NSW. With increased grazing intensity, the pore size distribution changes leading to significantly lower pore continuity and lower infiltration (Greenwood and McKenzie 2001). The effect of grazing management on infiltration rate, particularly in regard to intensive rotational grazing or time control grazing, has been reported extensively (Gifford and Hawkins 1978; Warren *et al.* 1986; Weltz *et al.* 1989).

Ground cover is an important component of a pasture system that can be manipulated with grazing management, and is an indicator of pasture productivity and sustainability (McCormick and Lodge 2001; Lodge and Murphy 2002*a*). In a long-term study of surface runoff from a natural tussock grass pasture near Gunnedah NSW, Lang (1979) reported that ground cover was highly effective at reducing the frequency and magnitude of runoff events. However, for these tussock grass pastures, ground cover and herbage mass are not always correlated (Lodge and Murphy 2002*a*) so ground cover may more adequately predict the generation of runoff. In a survey of the North-West Slopes, Emery (1975) reported that 80% of agricultural and grazing lands were eroded, caused by excessive surface runoff. Subsequently, Lang and McCaffrey (1984) demonstrated that soil erosion and sediment loss were reduced when adequate levels of ground cover were maintained.

Evapotranspiration is the largest component of the hydrological balance for pastures on the North-West Slopes (e.g. Simpson *et al.* 1998; Lodge *et al.* 2002). Some studies have reported that litter in pastures can reduce bare soil evaporation by up to 400% and increase transpiration by 50%, resulting in a net decrease in evapotranspiration of 5-10 % (Gonzalez-Sosa *et al.* 1999, 2001). Grazing management in rangeland was also recognised for its role in maintaining litter levels to improve surface soil structure and infiltration and so reduce soil erosion (Molinar *et al.* 2001).

Excessive deep drainage is accepted as the cause of water table rise and salinisation of areas of south-eastern Australia (Walker *et al.* 1999). Considering that pastures occupy such a large proportion of the landscape, deep drainage from them has substantial implications. For the high rainfall zone (> 600 mm annual rainfall), various studies have shown that annual pastures use 25-40% less water than perennial pastures (Scott and Sudmeyer 1993; Ridley *et al.* 1997; Simpson *et al.* 1998; Dolling 2001; Heng *et al.* 2001; Ridley *et al.* 2001). Simulation studies have indicated that grazing management may have a minimal impact on water use of grass based pastures and so deep drainage, compared with the effect of alternative plant species (Simpson *et al.* 1998).

A major national research program was initiated in 1997 to devise more profitable and sustainable grazing systems for the high rainfall zone of southern Australia. The Sustainable Grazing Systems National Experiment (SGS NE, Mason and Andrew 1998) was divided into five key theme areas of research including soil nutrients, biodiversity, pastures, animals and water. The water theme focussed on determining the impact of grazing management on the amount and pathways of water movement in a pasture landscape. These have a fundamental influence on the production capacity and sustainability of a grazed pasture. The development of sustainable grazing management strategies requires a thorough understanding of how grazing impacts upon the hydrological balance of a pasture (Thurow 1991).

The research presented in this thesis was primarily conducted at a field scale grazing experiment located at Springmount on the North-West Slopes of NSW. At Springmount, five grazing treatments were implemented in a replicated design, and their impact on pasture characteristics and associated impact on various components of the hydrological balance were documented. Investigation of surface runoff also included data from additional grazing experiments conducted as part of the SGS NE at Eloura and Winchfield (also on the North-West Slopes). A separate experiment was implemented at NSW Agriculture's Tamworth Centre for Crop Improvement to investigate the effect of herbage mass, litter mass, ground cover and soil water content on actual evapotranspiration.

The objective of this thesis was to assess the potential to improve the productivity and sustainability of pastures on the North-West Slopes of NSW through improved grazing management and its effect on components of the hydrological balance. Scope exists to improve the sustainability of grazed pastures through an improved hydrological balance that has less surface runoff, increased water use and lower soil evaporation.

The research presented in this thesis begins with a review of literature that is relevant to the impact of grazing management on the hydrological balance of pastures (Chapter 2). The literature review examines the extent of grazed pastures on the North-West Slopes and the factors that influence the sustainability of those pastures, which identifies management of the hydrological balance as a key issue.

Two methods, namely visual estimation of ground cover and use of electrical resistance sensors to measure surface soil water content, were common to research reported in several chapters of the thesis. The development and validation of each of these techniques is described in Chapter 3, together with a description of each study site.

The effect of a range of grazing treatments on pasture herbage mass, litter mass and ground cover were documented in Chapter 4, together with the influence of climatic conditions. The grazing treatments were designed to manipulate these pasture characteristics so that ensuing changes to components of the hydrological balance might be quantified. Surface runoff was measured on a series of plots located within grazing treatments and it was determined if ground cover and canopy cover greater than 70 and 40%, respectively, could prevent runoff (Chapter 5). Also, it was determined if greater herbage mass, litter mass, and larger soil water deficit might decrease the amount of runoff for these pastures (Chapter 5).

A study was conducted to determine the effect of herbage mass, litter mass, ground cover and soil water content on actual evapotranspiration from small-scale plots (Chapter 6). Specifically, it was determined whether high litter mass reduced soil evaporation and if evapotranspiration might increase with greater plant density and soil water content. Similarly, the effects of plant density and ground cover types on albedo and the net radiant energy balance were also determined.

The dynamics of profile stored soil water were quantified for a four year period in relation to grazing management, climatic conditions and wetting and drying cycles to determine if grazing management might increase the extraction of stored soil water (Chapter 7). Further, the ability of subterranean clover to increase soil drying was also tested.

In Chapter 8, a simulation model was used to determine the effect of contrasting grazing treatments on pasture production and components of the hydrological balance, both for the duration of the experiment and for a longer term (31 years).

The general discussion and conclusion highlights key findings of each component of the research and explores the implications for grazing management of these pastures (Chapter 9). In conclusion, the ideal physical characteristics are described for a pasture that might provide the most productive and sustainable use of water within the hydrological balance, and how grazing management might be used to create such a pasture.

The appendices provide additional detail for daily evapotranspiration values, analyses of stored soil water, parameter sets used in the simulation modelling, and copies of publications arising from this research.

2 Sustainability, grazing management, and the hydrological balance

"…ecologically sound grazing tactics require a clear understanding of the interaction of grazing on hydrologic processes." (Thurow 1991)

2.1 Natural pastures and their sustainability

Livestock grazing is the largest agricultural land use in Australia, occupying approximately 432 M ha, which includes around 23.8 M ha of sown pastures and grasses (Trewin 2002). In the financial year 1999-2000, gross value of direct products from grazing was $11.1 B AUD, with livestock populations of around 27.6 and 118.6 M head of cattle and sheep, respectively (Trewin 2002). On the North-West Slopes of NSW, native and natural pastures occupy 70% of the agricultural land (Lodge *et al.* 1991) supporting sheep and cattle grazing enterprises.

Natural pasture constitutes the major area of the North-West Slopes, covering 2.03 M ha (Lodge *et al.* 1984). The species composition of these pastures is usually dominated by warm season perennial grasses (e.g. redgrass *Bothriochloa macra* (Steud) S. T. Blake, wiregrass *Aristida ramosa* R. Br. bluegrass *Dichanthium sericeum* S.T. Blake, kangaroo grass *Themeda australis* (R. Br.) Stapf, *Eragrostis leptostachya* Steud., windmill grass *Chloris truncata* R. Br., slender rat tail grass *Sporobolus elongatus* R. Br.). Unless actively managed, these species tend to dominate the pasture swards. Natural pastures tend also to have low levels of green leaf, which leads to low protein contents, low digestibility and poor animal performance (Lodge and Whalley 1983). The crude protein level of the warm season grasses ranges between 5 and 17%, varying little between summer and winter (Lodge and Whalley 1983). However, these grasses are usually more digestible in spring and summer (60 to 80%) compared with autumn and winter (50 to 60%, Lodge and Whalley 1983). Some yearlong green species such as wallaby grasses (*Austrodanthonia spp.* H.P. Linder) have consistently higher levels of digestibility being > 60% at all times of the year (Lodge and Whalley 1983). However, many of these pastures tend to accumulate standing dead material caused by frosting in winter (Lodge and Roberts 1979). To accommodate this, stocking strategies usually include continuous grazing at low levels of intensity. The average stocking rate of these pastures is around 4.3 DSE/ha, but ranges from 3.7 to 5.2 DSE/ha for Manilla and Nundle Shires, respectively (Lodge *et al.* 1991).

The production of natural pasture species may be improved with the addition of fertilisers, and various species respond better than others do. In a pot trial, Lodge (1979) reported that the yield of some warm season grasses (redgrass, windmill grass, bluegrass) significantly increased with the addition of phosphorus (P), sulphur (S) and nitrogen (N) fertilisers. Other species such as wiregrass and slender rat tail grass did not respond as favourably. Using the estimates of improved herbage mass production, Lodge and Roberts (1979) indicated that natural pastures have potential carrying capacities of up to 4.8 DSE/ha.

2.1.1 Pasture improvement

For the area of grazing lands in Australia, only 5.5% include sown species (Trewin 2002), and so natural pastures are very important for most grazing enterprises. For the North-West Slopes, there exists a general understanding that natural pastures need to be replaced in order to achieve productivity gains. The low level of green leaf in winter creates a feed and energy gap that limits year round production (Lodge *et al.* 1984). Many farms on the North-West Slopes with natural pastures have undertaken various pasture improvement strategies in an attempt to increase year round productivity. In a survey of graziers in the area, Lodge *et al.* (1991) reported that around 75% of those surveyed had implemented some form of improvement, with sowing species (48%), aerial application of fertiliser (22%) and aerial application of seed and fertiliser (18%) being the most common approaches. Introduced species, such as lucerne *Medicago sativa* L. (97%), subterranean clovers *Trifolium subterranean* (Katzn. *et* Morley) Zohary and Heller (60%), and ryegrasses *Lolium perenne* Gaudin (54%) were the most commonly sown (Lodge *et al.* 1991).

2.1.2 Pasture sustainability

Declining productivity and loss of perennial species in both sown and natural pastures led to the formation of the Temperate Pastures Sustainability Key Program (TPSKP, Mason and Kay 2000) in the high rainfall zone (> 600 mm annual rainfall) of south-eastern Australia. Natural pastures are less productive than they once were and sown pastures showed rapid decline in productivity soon after establishment (Kemp and Dowling 2000). A change in species composition with a loss of perennial species was identified as one of the key causes of this decline and experiments were conducted to assess the impact of grazing management in manipulating the composition of perennial species (Mason and Kay 2000). Maintaining perennial species in the pasture sward was expected to result in fewer weeds, higher water use and lower soil acidification rates, and so more sustainable production (Kemp *et al.* 2000). The TPSKP established that most of the perennial grasses that were studied were sensitive to grazing at some particular growth stage (e.g. tillering, stem elongation, or flowering) and that targeted management at these times could manipulate species composition. Continuous grazing particularly resulted in either a decline in perennial species or no net benefit to those species (Kemp *et al.* 2000). Targeted resting of pastures was critical to maintain certain species, and to increase growth and survival of those species. Management of species during drought and dry periods was also critical to the survival of perennial species and when herbage mass was maintained above critical thresholds, survival was enhanced. Depending on the species, critical herbage mass levels ranged from 500 to 1500 kg DM/ha and that by maintaining a higher herbage mass level, pastures were considered more sustainable (Kemp *et al.* 2000).

A further critical aspect affecting sustainability of pastures is their water use. The hydrological balance of grazed pastures in Australia is often different to that of native woody perennial vegetation (Johnston *et al.* 1999). Essentially, in much of the high rainfall zone, grass based pastures do not use as much water, or at the same times of the year as native vegetation (Walker *et al.* 1999). In some areas, excess water has contributed to ground water recharge and caused a rise in water tables, and so soil salinity. However, for grazing lands on the North-West Slopes, the timing and magnitude of these losses are not well understood. Also, pasture management that results in low ground cover may cause excessive surface runoff and soil erosion (Lang 1979). Other studies have reported that in grazed pastures, soil evaporation may be as much as 80% of total evapotranspiration, which leads to lower productivity (Simpson *et al.* 1998). Therefore, great scope exists to improve the sustainability of grazed pastures through an improved hydrological balance that has less surface runoff, increased water use and lower soil evaporation.

2.1.3 Soil structure, soil health, and soil organic matter

Soil structure and soil health are vital components of a sustainable grazing system, but tend to be less well studied. The effect of grazing on soil-physical properties was reported for sown pastures on the Northern Tablelands of NSW by Greenwood (1996). That study reported that as grazing intensity increased the effect on soil physical properties increased. Particularly, soil pore size distribution reduced and bulk density increased. These effects were long lasting and natural amelioration through wetting and drying cycles, root growth, and soil biota took at least 2.5 years (Greenwood *et al.* 1998). In a review of the effect of grazing intensity on soil infiltration, Gifford and Hawkins (1978) reported that recovery times following intensive grazing were up to 13 years.

Soil biota and microbes are an important component of healthy soils. They breakdown pasture residues and aid incorporation of soil organic matter into the soil. After studying pastures on the Northern Tablelands, King and Hutchinson (1976) reported that grazing could impact upon the amount of soil biota through effects on food availability, soil water and temperature regimes, and the soil pore size distribution (or biota living space). Increased grazing intensity has the potential to remove herbage mass, litter mass and ground cover, thereby impacting upon the physical environment required by soil biota (King and Hutchinson 1983). In a study of the population of soil biota, Hutchinson and King (1980) reported that increasing grazing intensity led to a lower mass of large soil invertebrates. In grazed pasture systems, soil biota can dominate the nutrient and energy cycles (Hutchinson and King 1982) and their mass may equal or exceed that of livestock grazing the pasture (Hutchinson and King 1980). Thus, increased grazing intensity may reduce soil biota populations, nutrient and energy cycling and so pasture productivity (King and Hutchinson 1983). Nutrient cycling by soil biota may be more important in natural pastures than in sown and fertilised pastures, as it is through breakdown of organic matter that nutrients are released for plants to use.

Soil organic matter (derived from both plant and animal residues) is important to maintain soil structure and chemical and physical fertility in many Australian soils (Charman and Roper 1992). Generally, soil organic matter content tends to be higher in undisturbed soils, whether they are under natural pasture, sown pasture, or native vegetation Soil disturbance of any kind leads to breakdown of organic matter and the bonds that it forms between the soil particles. In the long-term, continued disturbance will lead to a loss of soil structure (Charman and Roper 1992). Many soils rely upon organic matter to maintain structural stability, aggregation, resistance to erosion, and resistance to compaction. Organic matter and residues (such as polysaccharides) that are released by soil biota, assist in binding soil particles together to form stable aggregates (Harte 1992).

In grazed pasture systems, the organic matter content may increase with the regular addition of plant litter brought about through grazing and growth and senescence of pasture plants. Depending upon the residual herbage mass and grazing intensity, soil organic matter may increase through trampling and incorporation by grazing animals (Schuman *et al.* 1996). However, depending on the level of utilisation, the response is not always consistent. Periods of overgrazing and removal of litter is likely to reduce soil organic matter (Lull 1959). Many of the red chromosol soils (Isbell 1996) of the North-West Slopes have had an extensive cultivation history, which has led to structural decline of the surface soil and exacerbation of their hard-setting characteristics (Emery 1975). Owing to the decline of cereal cropping on these soils, many of these areas are now natural pasture, which show poor surface structure and infiltration capacity.

After long-term grazing by sheep near Armidale NSW, Greenwood (1996) investigated soil physical properties under pastures, and found that infiltration capacity generally declined with higher stocking rates. However, the study also found that the effect of grazing at low rates, tended to equal that of higher rates with time. Other studies have also found that infiltration declines with increased stock trampling (e.g. Warren *et al.* 1986). Studies using simulated rainfall have shown that infiltration and sediment production increase with higher levels of stocking. Surface soil is susceptible to compaction by animal traffic and an increase in bulk density especially in wet conditions (Weltz *et al.* 1989). With increased grazing intensity, pore size distribution may be restricted, and pore continuity may decline significantly, leading to lower infiltration (Greenwood and McKenzie 2001). In a review of hydrology and erosion in grazing lands, Thurow (1991) provided a simple table showing the relationships between infiltration rate, soil and pasture physical attributes and grazing intensity (Table 2-1).

Table 2-1. General relationships between infiltration rate, soil and pasture attributes and grazing intensity. For example, infiltration rate increases with higher aggregate stability, but under increased grazing intensity, aggregate stability decreases, and so infiltration (after Thurow 1991).

	Infiltration rate	Grazing intensity
Soil attributes		
Aggregate stability	↑	↓
Bulk density	↓	↑
Pasture attributes		
Herbage mass / litter mass	↑	↓
Ground cover / litter cover	↑	↓

2.2 Grazing management

A grazing management system is a tool that can be used to manipulate the pasture through the control of intensity and timing of grazing. The objectives of grazing management may be many and varied, but can be simplified to managing plant density and species composition to maintain or increase long-term productivity (Wilson *et al.* 1984). Such changes should be performed to address goals of each livestock enterprise (Bell and Allen 2000).

A pasture that is not grazed beyond its natural production level does not require a grazing management system, as species composition and herbage mass may well be sustained. However, the resilience to grazing of each pasture is dependent on a range of factors, necessitating the careful evaluation of each grazing system. With a successful grazing system, pasture stability will be maintained at stocking rates that would otherwise be deleterious in the long-term (Wilson *et al.* 1984).

Grazing management systems can be broadly classified into three groups; continuous, rotational, and deferred grazing. In continuous grazing, livestock are uniformly distributed across the pasture such that species composition and herbage mass are maintained through most seasons. At higher grazing intensity and where species are not resilient to continuous grazing, continuous systems tend to favour annual species. As such, stocking rate is usually conservative so that grazing intensity can be maintained year round (Lodge *et al.* 1991). In rotational grazing, livestock are grazed in one paddock at a time, while other paddocks are rested for periods dependent upon the number of paddocks in the system. In these systems, short term livestock production may not increase, but higher long-term productivity and stability are likely. Cell-grazing, mob-stocking, time control and short duration-high intensity grazing are all forms of rotational grazing methods. In deferred grazing, one paddock is rested from grazing while livestock graze the remainder. This system provides a short period of rest for each paddock before livestock return. The success of each of these systems relies upon tactical decisions of grazing intensity and duration to achieve the desired pasture outcomes.

2.2.1 Pasture species composition

Change in the composition of a pasture may be a desirable outcome of a grazing management system and such change may improve the productivity of the pasture. Species composition change may be achieved by targeting species at different phenological stages. To achieve change, the aim is to target an undesirable species with high grazing pressure when it is vulnerable, while reducing pressure when a desirable species is growing and flowering (Garden and Dowling 1997). Grazing management can only bring about composition change if the target species has a different characteristic, for example, winter versus summer growth response, perennial versus annual, sensitive versus tolerant to grazing, or tussocky versus rhizomatous growth (Garden *et al.* 2000). Lodge and Whalley (1985) reported a successful grazing strategy to reduce the incidence of wiregrass in pastures on the North-West Slopes of NSW. That strategy involved targeting wiregrass with heavy grazing during its main growing and flowering season followed by rest in winter when wallaby grass was preparing to flower and establish seedlings. In that study, herbage mass and basal cover of wiregrass declined and that of wallaby grass increased. Alternatively, species composition change may be achieved through sowing of species such as subterranean clover.

2.2.2 Pasture herbage mass production

Grazing management systems attempt to maximise herbage mass production to meet livestock requirements. However, herbage mass accumulation is the balance of pasture growth, senescence, decay, animal trampling, and animal intake. Grazing at higher intensity will lead to a decline in herbage mass (e.g Langlands and Bennett 1973; Gill *et al.* 1998), while rotational grazing at the same intensity with periods of rest will lead to an increase in herbage mass. High intensity-short duration grazing systems may lead to a depletion of herbage mass during the grazing phase (Weltz *et al.* 1989), but with a period of sufficient rest, herbage mass will recover. However, in natural pastures of the North-West Slopes, under utilisation in each grazing phase may lead to accumulation of unproductive dead material that has low digestibility and productivity (Lodge and Whalley 1983). For each grazing management system, pasture production should be linked with the requirements of the livestock enterprise, so that adequate green leaf with high digestibility and protein content is available to meet the requirements of the livestock (Bell and Allen 2000).

2.2.3 Pasture litter mass

Pasture litter has variously been defined depending upon the focus of particular studies that have examined it. Other studies have defined litter as 'all dead organic matter not incorporated with the mineral soil, and occurring above soil mineral horizons' (e.g. Naeth *et al.* 1991*b*). Alternatively, another definition is 'dead plant material', with no distinction between standing, attached, or lying on the soil (e.g. Willms *et al.* 1993). Here, litter is defined as 'unattached plant material lying upon the soil surface'. The important distinction here is between soil organic matter (defined as material directly derived from plants and animals, Charman and Roper 1992) that is *within* the soil, and plant material that is *on* the soil surface.

In grazed pastures, litter has long been recognised as an important component of the system. Early studies indicated that litter was important for soil moisture conservation, surface runoff prevention and encouraging pasture growth (Beutner and Anderson 1943). As litter is a source of food for soil biota, it was recognised as being important for encouraging microbial activity in the surface soil (White 1946) and as a living space for soil biota (King and Hutchinson 1983). Similarly, litter provides valuable protection against raindrop impact, preventing breakdown of soil aggregates at the soil surface (Thurow 1991). Other benefits that litter provides include increased infiltration, reduced surface runoff, and reduced soil evaporation (Bond and Willis 1969; Naeth *et al.* 1991*a*; Ji and Unger 2001; Murphy and Lodge 2001*a*). Uncertainty exists about the amount of litter and ground cover required to prevent excessive surface runoff and erosion across the diverse range of topography and soil types that pastures exist (Meeuwig 1970). In a study of volunteer pastures, Gonzalez-Sosa *et al.* (1999, 2001) investigated the effect of pasture litter on soil evaporation and pasture transpiration, and reported that litter could reduce soil evaporation by up to 400% and increase transpiration by up to 50%.

The amount of litter in a pasture is an index of grazing pressure (Willms *et al.* 1993) and provides a simple measure to ascertain system health (McCormick and Lodge 2001). Grazing at any intensity will reduce the amount of litter in a pasture, with lowest amounts under highest grazing intensity (Johnston *et al.* 1971; Gill *et al.* 1998; Molinar *et al.* 2001). While it may be difficult to define a satisfactory amount of litter for pasture systems, maximum production might be achieved with maximum litter quantity (Willms *et al.* 1993).

Any grazing management strategy that reduces long-term herbage mass will also reduce litter mass (Thurow 1991). Grazing management can have an impact on litter accumulation in pastures, with higher grazing intensity leading to a reduction in litter particle size and amount (Naeth *et al.* 1991*b*). However, where initial herbage mass is high, short periods of grazing at high intensity may result in trampling of the pasture and hence litter accumulation. Hormay (1970) discussed the importance of resting pastures from grazing so that litter may accumulate between bases of plants and so resting may be an important tool in litter management. The effect of grazing management strategies on litter accumulation in natural pastures of the North-West Slopes is poorly understood and further investigation is required.

2.2.4 Ground cover

Ground cover is an important component of a pasture system that can be manipulated with grazing management and is an indicator of pasture productivity and sustainability (McCormick and Lodge 2001; Lodge and Murphy 2002*a*). Ground cover has been defined as any non-soil material on or near the soil surface (McIvor *et al.* 1995) and that definition is adopted here. The dominant components of ground cover are usually plants and residues derived from them. Various studies have reported relationships between herbage mass and ground cover for a range of species (e.g. Lang 1998). For natural pastures on the North-West Slopes, Lodge and Murphy (2002*a*) reported that herbage mass accounted for 68-78% of the variation in values of ground cover, while litter mass also accounted for 15-60%. Ground cover is a simple parameter to estimate (Murphy and Lodge 2002) and its level can be an indicator of many processes that occur within the pasture.

Runoff control

On the North-West Slopes the need to maintain ground cover in natural pastures has long been recognised as a crucial management tool for controlling surface runoff and reducing soil erosion in a predominantly summer rainfall environment. White (1946) identified that '…close grazing and tracking brings disaster to the soil…' and suggested that herbage cover provided an effective defence against erosion. Similarly, Mau (1946) reported that extensive soil erosion in the Tamworth district of NSW was brought about by poor land use and indicated that if soil could be kept '…well covered with vegetable matter, dead or alive, soil erosion could be controlled…'.

Standing herbage (or foliar cover) is an important component of ground cover (McIvor *et al.* 1995) and it reduces raindrop impact and surface movement of water (Lang 1979). In a long-term study of surface runoff from a natural pasture near Gunnedah NSW, Lang (1979) reported that ground cover was highly effective at reducing the frequency and magnitude of runoff events. Lang and McCaffrey (1984) also demonstrated that soil erosion and sediment loss were reduced when adequate levels of ground cover were maintained. Many studies have reported threshold values of ground cover (ranging from 40 to 75%) for runoff control, with the value being influenced by a variable range of parameters including rainfall characteristics, pasture type, soil type and location (Lang 1979; Costin 1980; Gifford 1985; van Rees and Boston 1986; McIvor *et al.* 1995).

Evaporation control

Ground cover and its various components have been reported to modify the surface energy budget of both pasture and cropping systems with a corresponding impact on the amount of evaporation and transpiration (Bristow 1988; Farahani and Ahuja 1996; Gonzalez-Sosa *et al.* 1999). Particularly, litter mass provides the soil surface with insulation from radiant energy, resulting in lower evaporation (van Doren and Allmaras 1978). Similarly, ground cover and litter reduces both soil heating during the day (Otterman 1977) and cooling at night (Charney *et al.* 1975). While specific weights of litter or residues have been indicated to control evaporation (e.g. 3000 kg DM/ha, Murphy and Lodge 2001*a*), ground cover and litter mass may be directly related through empirical relationships (e.g. Lodge and Murphy 2002*a*).

Microbial activity

Soil biota and decomposer organisms, particularly invertebrates, require living space, which in a pasture system is provided by ground cover (herbage mass and litter mass, King 1997). Under low ground cover conditions soil biota have less food and a less desirable physical environment (King and Hutchinson 1983). Lower energy flux into the soil also makes conditions more favourable for soil biota by reducing extremes of temperature (King 1997). With high ground cover, soil temperature and moisture regimes are likely to be more favourable for soil biota.

Measurement techniques

The literature presents a range of techniques used for estimating ground cover in pastures and rangelands. Depending on the study objectives and required accuracy, those techniques have included point quadrat (Goodall 1952; Cunningham 1975), line intercept (Andrade and Ocumpaugh 1979; Brady *et al.* 1995), and visual estimation and digital image analysis (Zhou *et al.* 1998). For studies of surface runoff or soil erosion, a range of techniques has been used. The point quadrat method and variations of it including point frame, line intercept and ocular telescope methods have been used in many studies (Lang 1979; Freebairn and Boughton 1981; Lang and McCaffrey 1984; Eldridge and Rothon 1992; Bari *et al.* 1995). Several authors have applied photographic techniques incorporating either point quadrat methods (Freebairn and Boughton 1981; McIvor *et al.* 1995) or digital techniques (Zhou *et al.* 1998; Vanha-Majamaa *et al.* 2000). Direct visual estimation incorporating reference to calibrated photographic standards has been used extensively (Costin and Gilmour 1970; Dadkhah and Gifford 1980; Freebairn and Boughton 1981; Scanlan *et al.* 1996). Of these methods, visual estimation appears to be the simplest and fastest requiring no specialised equipment or training. Hatton *et al.* (1986) reported the nature of errors involved in the visual estimation method, and suggested that multiple observers may be required. In a study comparing a range of estimation methods, Murphy and Lodge (2002) concluded that the visual estimation technique compared with other objective methods had sufficient accuracy to be used in ground cover monitoring programs.

2.2.5 Depth and distribution of plant roots

The root system of pasture plants has great importance for plant-soil water relations. Plants with deeper and more extensive root systems may have the opportunity to access greater amounts of stored soil water (Lolicato 2000). In studies of the hydrological balance of pastures, plant root depth is an important factor that may help define water loss through transpiration (Lodge *et al.* 2001). The effect of grazing management on root systems of pasture plants is not clear (Greenwood 1996). It tends to be confounded by change of botanical composition, time of the year, growth stage of the plants and soil physical characteristics. However, Thurow (1991) suggested that a reduction in above ground herbage mass will eventually translate into a loss of below ground root mass.

Some studies have reported that total root mass declines with intensity of grazing (e.g. Langlands and Bennett 1973), while others have reported that root mass near the soil surface increases with grazing (e.g. Milchunas and Lauenroth 1993). The severity and frequency of defoliation of pasture plants may reduce the depth of roots and alter the distribution of the roots so that proportionally more roots are near the soil surface (Chaieb *et al* 1996). In addition, root development has been shown to change under the influence of defoliation. For wallaby grass (*Austrodanthonia caespitosa* H.P. Lindner), both root extension and branching were reduced and these effects occurred within 1 h of defoliation (Hodgkinson and Baas Becking 1977). In a comparison of root characteristics under pastures that were grazed at three intensities, Greenwood and Hutchinson (1998) reported that under higher intensity there were a greater proportion of roots near the soil surface and that these roots were finer. Also, in ungrazed pasture, there were less fine roots, but greater root length and volume at depth (c. 70 cm depth). Little information is available that describes the root distribution of natural or sown pastures for the North-West Slopes, but for a natural pasture, Lodge and Murphy (2002*b*) reported that mean root depth was around 115 cm, ranging from 30 to 170 cm depth.

2.3 The hydrological balance of pastures

The development of sustainable grazing management strategies requires a thorough understanding of how grazing impacts upon the hydrological balance of a pasture (Thurow 1991). Conservation of mass principles indicate that water within a grazed pasture cannot be created or destroyed, merely transformed. Hence, water entering the system must also leave the system by one of many pathways. Grazing of pasture by livestock can affect the amount of water detained within or lost from the pasture, and as such has an important role in defining a sustainable grazing system.

The hydrological cycle, describes how water moves around the earth through various pathways (Figure 2-1). The amount of water within a pasture system will vary from location to location according to the rates at which water enters, moves through and leaves the system. Using the principle of conservation of mass, and for any period, the hydrological balance of a pasture can be defined using the following equation;

$$P = R_o + ET + D_d + \Delta S \qquad \textbf{Equation 2-1.}$$

where P is precipitation, R_o is surface runoff, ET is evapotranspiration, D_d is deep drainage, and ΔS is change in stored soil water. Evapotranspiration includes, evaporation from canopy interception, litter mass, and bare soil surfaces, and transpiration from plants.

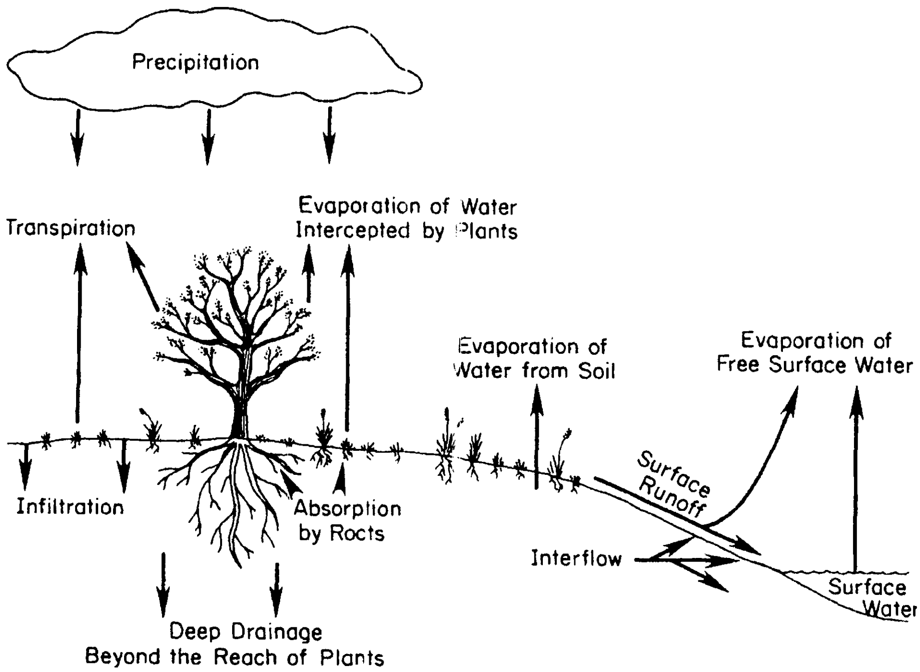

Figure 2-1. The hydrological cycle showing the major processes and pathways of water movement through a system (after Thurow 1991).

Grazing management has the potential to manipulate many of these processes by changing the physical structure and species composition of pastures. The two most important processes that grazing management can manipulate are surface runoff and evapotranspiration. Factors contributing to surface runoff include ground cover, infiltration capacity and surface detention. Previous long-term simulation studies of the hydrological balance for natural pastures on the North-West Slopes estimated that annual rainfall was accounted for by evapotranspiration (89-95%), runoff (2.5-3.0%), and deep drainage (2.3-8.4%) (Table 2-2).

Table 2-2. Annual hydrological balance for natural perennial pastures on the North-West Slopes estimated using simulation analysis.

Pasture	P (mm)	ET (mm)	R_o (mm)	D_d (mm)	Reference
Perennial	708	659	21	25	Simpson *et al.* (1998)
Wallaby grass + subclover (low fertility)	708	671	19	16	Simpson *et al.* (1998)
Wallaby grass + subclover (high fertility)	708	661	20	26	Simpson *et al.* (1998)
Redgrass	663	589	17	56	Lodge *et al.* (2002)

2.4 Surface runoff (R_o)

In a dictionary of soil conservation terms, Houghton and Charman (1986) defined runoff as '...that portion of precipitation not immediately absorbed into or detained upon the soil and which thus becomes surface flow'. The rate at which rain is absorbed depends upon the surface infiltration capacity, while the surface roughness and pasture structure determine the amount of surface detention.

Rainfall on the North-West Slopes is summer dominant and storms of high intensity occur regularly in the warmer months exacerbating the effect of low ground cover. Large summer rainfall events are usually derived from low-pressure (cyclonic) systems or troughs, which originate in the tropical north and move in a southerly direction into northern New South Wales west of the Great Dividing Range (Anon. 1970). Such systems direct warm, moisture-laden air from the north and rainfall is triggered by atmospheric instability from local troughs or cold fronts that approach from the south-west. Daily rainfall totals may be extreme with 221 mm recorded for a 24 h period at Bective near Tamworth during such an event (Anon. 1970). A review of major floods in the Namoi Valley on the North-West Slopes showed that similar weather systems triggered the major floods of 1955, 1971, 1974 and 1976 (Anon. 1980). For the event of 1955, two moisture laden tropical air masses, one from the north-west of the continent and the other from the north-east converged over northern New South Wales and southern Queensland during February. At Upper Manilla (8 km south of Springmount study site), records showed that in two 5 day periods, 55 and 217 mm of rainfall were received (13-18 and 23-28 February, respectively, Anon. 1980). The initial falls wet the soil profile and the latter fall triggered substantial runoff and widespread flooding within the catchment.

Logan (1965) studied rainfall pluviograph records for Gunnedah and Inverell to determine rainfall intensity, duration, and recurrence intervals for storms on the North-West Slopes. To interpolate rainfall intensity and recurrence values for the Springmount study site, intensity and duration graphs in that paper were used (Table 2-3). It is predicted that Springmount may experience a rainfall event having a 30 minute intensity of 75 mm/h once in 5 years. Similarly, for the same duration, an event having an intensity of 105 mm/h may occur once in 20 years (Table 2-3).

Table 2-3. Probable rainfall intensity (mm/h), recurrence interval (years), and duration values (minutes) for Springmount, interpolated from Logan (1965).

Recurrence Interval	Duration (minutes)									
	5	**10**	**20**	**30**	**40**	**50**	**60**	**80**	**100**	**120**
5 year	188	132	94	75	58	50	41	37	30	24
10 year	221	147	108	88	70	60	51	42	34	32
20 year	249	168	127	105	83	70	60	47	41	36

The generation of runoff has implications at both local paddock scales and further a field. Locally, it represents a loss of water that otherwise may have been available for pasture growth and maintaining moist soil conditions. Also, runoff water often transports sediment, organic matter, and nutrient, resulting in a loss of resources for the pasture. As runoff water concentrates and collects, it gains velocity and energy, creating an erosive force that can result in severe gully erosion, destabilization of stream banks, and ultimately sedimentation of rivers and water storage reservoirs. However, runoff is a natural process and is very important for ecosystem function, providing a valuable water resource to river systems. While runoff may be a natural phenomenon, the location and method of its generation are critical in determining the concentration of sediment and nutrient load transported within the water. Hence, grazing management may play a critical role in controlling not only the amount of runoff generated but also the quality of that water.

2.4.1 Generation of surface runoff

Rainfall depth, intensity, and duration have major influences on the process of runoff generation. When the intensity of rainfall is greater than the infiltration capacity of the soil, excess rainwater accumulates on the soil surface. Upon exceeding the soil surface detention capacity, water then begins to move down slope as overland flow. Soil physical properties determine the infiltration capacity. Runoff generated by this process is defined as infiltration excess flow or Horton overland flow (Horton 1933). When normal infiltration fills the storage capacity of the 'A' horizon, runoff will occur if the hydraulic conductivity of the 'A' horizon is greater (often up to one or two orders of magnitude) than that for the sub-soil, as in texture contrast soils. While rainwater may readily infiltrate through the 'A' to reach the 'B' horizon, the impedance from the sub-soil creates a restriction, causing the upper soil to saturate. Hydraulic conductivity of the sub-soil then effectively limits that of the soil surface and while rainfall intensity remains high, runoff will generate at the soil surface that is, saturation excess flow. Soil water content together with grazing management via its effect on ground cover and infiltration may influence which of these processes occur in a pasture system.

2.4.2 Infiltration and soil physical properties

Many soil physical properties influence the infiltration rate of a soil. Initial infiltration is usually higher and a function of the sorptivity of the soil. Thus, soil water content and mineralogy, rather than physical structure, largely affect initial infiltration. As rainfall continues, infiltration usually declines in a roughly exponential fashion, reducing to a value approximating the hydraulic conductivity of the soil. At higher soil water content, the pore size distribution within the soil controls infiltration, with higher rates associated with an increased abundance and continuity of macropores near the soil surface (i.e. > 1.2 mm diameter, Greenwood *et al.* 1997). Surface soil is susceptible to compaction by animal traffic and an increase in bulk density particularly in wet conditions (Weltz *et al.* 1989). Increased bulk density is usually associated with higher soil strength, which can impede root development and the opportunity for macropores to develop (Cornish 1987). Around the base of grass tussocks, macropores are usually associated with increased biological activity, particularly where invertebrate activity is high and root decay provides pathways for infiltration. With increased grazing intensity the pore size distribution is restricted leading to significantly lower pore continuity, and lower infiltration (Greenwood and McKenzie 2001).

2.4.3 Infiltration and grazing management

The effect of grazing management on infiltration rate has been extensively studied, particularly in regard to intensive rotational grazing, or time control grazing (Gifford and Hawkins 1978; Warren *et al.* 1986; Weltz *et al.* 1989). This type of grazing management uses short periods of grazing at high intensity followed by long periods of rest to allow for pasture recovery. In a study of the effect of flash grazing by cattle on hydrologic parameters, Weltz *et al.* (1989) reported that even with short duration grazing (14 h), bulk density increased significantly and infiltration rate was reduced. Amelioration was slow and after 110 d of rest, infiltration was < 50% of the rate prior to grazing. Greenwood *et al.* (1998) studied the effect of excluding grazing on hydraulic conductivity and bulk density of soils under grazed pasture. Values after excluding grazing for 2.5 years were similar to those from an area that was not grazed for 27 years. Biological activity, wetting and drying cycles, and root growth and decay provide the best form of amelioration, although change can be slow (Greenwood and McKenzie 2001).

Residual herbage mass after grazing was reported to be important for runoff control through its effect on infiltration (Bari *et al.* 1995). The importance of grazing management for erosion and runoff control was recognised on the North-West Slopes by Mau (1946), who highlighted the danger of grazing too heavily in summer, exposing the soil to excessive risk of erosion. Costin (1980) reported that pasture managed for constant ground cover, regardless of stocking rate reduced the likelihood of runoff and erosion. For grazing lands in Ethiopia, Mwendra *et al.* (1997) demonstrated that increased grazing intensity resulted in higher rates of runoff and sediment transport through an associated decrease in ground cover and infiltration rate.

2.4.4 Infiltration and raindrop impact

One consequence of declining ground cover is the exposure of more surface area to the effect of raindrop impact. Raindrops have a high kinetic energy that transfers to the soil upon impact. When raindrops fall upon pasture or litter, the dry matter dissipates the energy through deformation or bending of resilient components. On a bare soil, energy dissipates through the shattering of soil aggregates into component particles (Rosewell *et al.* 1992). Aggregates of surface hard-setting soils are further susceptible to slaking and dispersion into constituent particles that can clog and seal surface pores (Johns *et al.* 1984), resulting in a rapid decline in infiltration. Surface crusts formed through the action of raindrop impact have very low permeability and restrict infiltration (Bradford *et al.* 1987*a*). Grazing management that reduces ground cover exposes more surface area to raindrop impact, which is likely to reduce infiltration capacity.

2.4.5 Ground cover

Many studies have investigated the importance of ground cover for controlling surface runoff. On the North-West Slopes, Lang (1979) conducted experiments to explore the effect of ground cover on runoff and found that it affected both runoff frequency and magnitude. McIvor *et al.* (1995) concluded that ground cover directly influenced both runoff and soil movement in the semi-arid tropics of Queensland. On the Southern Tablelands of NSW, Costin (1980) found that runoff and soil loss were inversely proportional to ground cover. Scanlan *et al.* (1996) reported that areas of low ground cover produced high rates of runoff and soil erosion. Many studies have reported a threshold value of ground cover that is required to reduce runoff. These thresholds were influenced by combinations of local rainfall characteristics, pasture type, soil type and soil water content (Table 2-4). Many techniques have been used to estimate the percent area of ground cover, ranging from point quadrat methods, to visual estimation and lately, digital techniques. Ground cover is an easily estimated parameter (Murphy and Lodge 2002) and can be a useful indicator to determine pasture health and condition (McCormick and Lodge 2001). From the information presented in previous studies (Table 2-4), management of grazed pastures to maintain ground cover > 70% and canopy cover > 40% may be adequate to control surface runoff on the North-West Slopes.

Table 2-4. A range of ground cover threshold values to control surface runoff reported by other studies.

Land Use	Location	Study Types	Threshold Value	Reference
Grazing	Gunnedah, NSW	Surface runoff	75%	Lang (1979)
Grazing	Gunnedah, NSW	Erosion from runoff plots	50-75%	Lang and McCaffrey (1984)
Grazing	Ginninderra, NSW	Rainfall simulator and runoff plots	60%	Costin (1980)
Rehabilitation	Texas, USA	Small catchments	50-70%	Wright *et al.* (1982)
Grazing	Utah, USA	Rainfall simulator	50%	Dadkhah and Gifford (1980)
Grazing	North-East Qld	Runoff plots	40-50%	Scanlan *et al.* (1996)
Grazing	North Qld	Runoff plots	40%	McIvor *et al.* (1995)
Grazing	Central Qld	Small catchments	35-40%	Ciesiolka (1987)
Grazing	Zimbabwe	Runoff plots and erosion studies	30%	Elwell and Stocking (1976)
Grazing	Kenya	Simulated rainfall and erosion studies	20%	Moore *et al.* (1979)
Feral animal grazing	Yathong, Western NSW	Rainfall simulator	No correlation	Eldridge and Rothon (1992)
Native animal grazing	Bogong High Plains, Vic.	Rainfall simulator	No correlation	van Rees and Boston, (1986)

2.5 Evapotranspiration (*ET*)

Evapotranspiration is the process through which water is returned to the atmosphere via vaporisation. In a pasture system, rainfall may be intercepted by plant canopies, and subsequently evaporate before entering the soil profile. Similarly, water may be stored by litter on the soil surface, and subsequently evaporate. Where the soil is bare, water may accumulate and pond leading to evaporation or water may simply evaporate from the soil water store. Water returned to the atmosphere through plants is called transpiration and is subject to availability of stored soil water and green leaf area. Hence, depending on the source of the water, the balance of evaporation and transpiration components may vary widely between grazing systems.

2.5.1 Annual and daily evapotranspiration for pastures

Separate simulation studies of the hydrological balance of pastures on the North-West Slopes have estimated that evapotranspiration accounts for 89-95% of annual rainfall (Simpson *et al.* 1998; Lodge *et al.* 2002). Mean potential evapotranspiration exceeds rainfall for all months, with daily values ranging from 1.5 to 14 mm/d, in winter and summer, respectively (Clewett *et al.* 1999).

Daily values of actual evapotranspiration for pastures have been rarely reported, supposedly due to the difficulty and accuracy of its measurement. Precise weighing lysimeters and micrometeorological techniques (e.g. Bowen 1926) have been used in various studies of pasture water use and energy balance. Rosset *et al.* (1997) used the Bowen ratio method when studying alpine grasslands in Switzerland and reported evapotranspiration rates of up to 5.0 mm/d. In a study of kangaroo grass pasture near Canberra Australia, Dunin and Reyenga (1978) used a combination of precise weighing lysimeters and Bowen ratio methods to investigate controls on the process of evapotranspiration and reported maximum daily rates of 5.4 mm/d and peak hourly rates of 0.75 mm/h. A review by Kelliher *et al.* (1993) reported that maximum daily evapotranspiration values from pastures were in the order of 4.8 to 5.0 mm/d. McLeod *et al.* (1998) reported daily rates of evapotranspiration of around 1.1 mm/d for three pasture types (degraded annual, phalaris, and phalaris-white clover (*Trifolium repens* L.)) on the Northern Tablelands of NSW in July. Few measurements exist of actual evapotranspiration rates for pasture or grassland environments in Australia, and none are available for the North-West Slopes.

2.5.2 Factors that influence evapotranspiration

Evapotranspiration represents a continuum of water movement through soil and plant from the subsoil store to the atmosphere. As such, many factors influence the rate and movement of water including, soil water content, movement of water within the soil pores and root interfaces, conductivity through plant tissues and stomata, vapour pressure deficit of the atmosphere, and net radiant energy flux (Ward 1971). Hence, it is difficult to assess the effect of these factors in isolation, as there are also many interactions between them. In respect to a grazed pasture, some factors are more relevant than others and may help to understand how grazing management practices might influence pasture evapotranspiration. These factors include albedo and net radiant energy, herbage mass and canopy interception, green leaf area, the amount of litter and its effect on bare soil evaporation, and soil water content within the root zone and surface layers.

The latent heat of vaporisation of water ranges between 2450 and 2260 kJ/kg for temperatures between 20 and 100 °C, respectively (Giancoli 1985) and as such, radiant energy is the basic driver of evaporation of water. Higher net radiant energy (i.e. radiant energy retained by the pasture system) has the potential to generate higher latent heat flux, given that water is available in the soil and plants, and the vapour pressure deficit allows it. Availability of stored soil water is fundamental to evapotranspiration. As a soil dries, the rate of evapotranspiration also declines. Some studies have reported linear relationships between decreasing soil water content and evapotranspiration (e.g. Scotter *et al.* 1979), or that evapotranspiration was not impeded until the soil approached wilting point (-1500 kPa, Sauer *et al.* 2002). Thus, the distribution of water within the soil profile in relation to plant root zone is important, with the surface layers being critical for bare soil evaporation.

The amount of herbage mass may have implications for rainfall intercepted by grass canopies (Dunkerley 2000). In some instances, a substantial proportion of rainfall may be intercepted by vegetation and the water returned to the atmosphere through evaporation (e.g. 32% for Mitchell grass *Astrebla lappacea* (Lindl.) Domin., Dunkerley and Booth 1999). Intercepted rainfall does not enter the soil water store and so is not available for transpiration or movement within the soil profile.

The effect of litter (variously defined as mulch and crop residues) on bare soil evaporation within cropping systems has been studied with particular emphasis on energy balance and temperature regimes. For fallow lands in the sub-tropics, Bristow (1988) reported that mulch architecture influenced the energy balance, albedo and evaporation rate. Farahini and Ahuja (1996) modelled the effect of partial litter cover on evaporation in pasture and reported that litter influenced the rate of evaporation particularly when soils were wet. For grassland and pasture systems, litter has long been recognised as an important component for moisture conservation, herbage production and erosion control (Beutner and Anderson 1943). Grazing management in rangeland has also been recognised for its role in maintaining litter levels to decrease soil erosion and improve surface soil structure, infiltration and herbage production (Molinar *et al.* 2001). In addition, Gonzalez-Sosa *et al.* (1999, 2001) reported a detailed modelling study of volunteer pasture that showed litter reduced bare soil evaporation by up to 400% and increased transpiration by 50% resulting in a net decrease in evapotranspiration of 5-10%. Generally, litter may reduce the rate of evaporation, but its effect in natural pastures and grasslands on the North-West Slopes is unclear.

2.5.3 Net radiant energy balance

Net radiant energy is a key driver of the evapotranspiration process. Albedo is a measure of the proportion of short wave radiant energy that is reflected by a surface and it may influence evapotranspiration by up to 20% (Farahini and Ahuja 1996). The implication for evaporation and transpiration is that energy is not available for latent heat flux and so the amount of water that can be evaporated is reduced. Removal of vegetation and litter cover may lead to an increase in the local albedo, resulting in less heating of the soil surface and less latent and sensible heat flux (Otterman 1977). Similarly, bare soil surfaces tend to cool more at night compared with those that have ground cover (vegetation and litter) and so reduce the sensible heat (Charney *et al.* 1975). In a pasture situation, albedo may change in response to pasture type, litter type, mass and age, ground cover, soil water content, and sun angle (Farahini and Ahuja 1996; Rosset *et al.* 1997; Bristow 1998; Song 1998). For calculations of reference evaporation (E_o, e.g. Smith *et al.* 1996), albedo is usually set at 0.23 for a defined crop type, but it should be altered to suit local conditions (Meyer *et al.* 1999). For grazed pastures on the North-West Slopes, albedo and net radiation values are unknown.

2.5.4 Techniques to measure actual evapotranspiration

In investigating the rate of actual evapotranspiration, the researcher is faced with a range of techniques and methods based around three approaches: (a) theoretical modelling of the entire soil-plant-atmosphere continuum taking into account energy balance and vapour transfer principles; (b) measuring the soil water balance for a known volume of soil, in which evapotranspiration is apportioned to the difference between inflow and outflow; and, (c) measurement of vapour flux above the evaporation surface (Ward 1971).

An example of the first approach includes the combination formulae method developed by Penman (1948) and Monteith (1965, 1981) where it is adapted for local coefficients (e.g. Meyer *et al.* 1999). Variations of the second approach have included estimation of evapotranspiration from stored soil water records (Dunin 1969*b*; McGowan and Williams 1980), simple water balance (Scotter *et al.* 1979), and macro and micro lysimeters (Puckridge 1978; Boast and Robertson 1982; Reicosky 1983). The third approach has seen the development of micrometeorological methods such as Bowen ratio (e.g. Rosset *et al.* 1997), and evaporation chamber techniques (Reicosky and Peters 1977; McJannet *et al.* 1996). In recent years with advanced microelectronics and data logger capacity, techniques have been developed that estimate evaporation based on small changes in surface soil temperature (Qiu *et al.* 1999). However, a limitation of micrometeorological techniques like Bowen ratio is that they are suitable for large plots with wind fetch lengths > 200 m where evapotranspiration is integrated over the entire fetch (Heilman *et al.* 1989).

2.6 Change in stored soil water (ΔS)

2.6.1 Pasture water use

Management of stored soil water within the root zone has the potential to alleviate deep drainage losses. Across southern Australia, considerable effort has been expended to compare the drying ability of different crop and pasture sequences for the purpose of dryland salinity mitigation and management, and to further understand the dynamics of herbage mass production.

For the high rainfall zone, various studies have shown that annual pastures use less water than perennial pastures (Ridley *et al.* 1997; Simpson *et al.* 1998; Heng *et al.* 2001; Ridley *et al.* 2001). With high rainfall, perennial species use around 25-40% more water than do annuals (Scott and Sudmeyer 1993; Dolling 2001). In a study of stored soil water use of a range of perennial pastures in southeast Australia, Lolicato (2000) reported few differences, except for lucerne (summer active), which had a deeper root system. Snaydon (1971) reported that there was little difference between winter active and summer active perennial pasture species in terms of drying the soil profile.

although, perennial pasture used more soil water than annual pastures. However, rarely have stored soil water dynamics been reported for grazed natural pastures.

Lucerne being a deep-rooted perennial species is ideal for high water use and deep drainage control in many landscapes. The water use of lucerne has been reported for a variety of situations and climatic conditions (e.g. Crawford and MacFarlane 1995; Lolicato 2000; Ridley *et al.* 2001). As annual rainfall declines, lucernes' ability to prevent drainage is more tree-like, and is likely to be an economic alternative. However, a limitation to the application of lucerne across the landscape includes its low tolerance to acidic and saline soils (Humphries and Auricht 2001). To effectively increase water use and reduce deep drainage, the deepest-rooted perennial species needs to be chosen that is at least as profitable as the system that it replaces. Depending on soil type, location, and climate, the optimal configuration of cropping, pastures and trees needs to be determined (Stirzacker *et al.* 2002).

2.6.2 Techniques to measure stored soil water

To gain an understanding of plant water use, an estimate of stored soil water within the profile is required. Preferably, measurements should be made through time and depth so that seasonal changes can be documented. However, it is virtually impossible to measure the flux of soil water in a profile and so the researcher is left to repeatedly measure the state of stored soil water, and infer flux over intervening time periods. Measurements of stored soil water can be obtained using a variety of techniques ranging from physical sampling (soil cores), tensiometers (soil water potential), electrical resistance sensors, time domain reflectometry, and neutron scattering techniques. In a study of pasture systems, direct estimates of volumetric water content are preferable as they can be compared directly with rainfall measurements. As such, the neutron scatter technique is highly suitable (Greacen *et al.* 1981).

The neutron scatter technique has been extensively studied, including calibration (Greacen *et al.* 1981), sources of error (Sinclair and Williams 1979), comparison of instruments (O'Leary and Incerti 1993), and application to stored soil water issues in pastures (e.g. McGowan and Williams 1980; Lolicato 2000). As such, the neutron scatter technique is considered suitable to obtain repeated measurements of stored soil water beneath grazed pastures.

2.7 Deep drainage (D_d)

With development of agriculture in south-eastern Australia, a substantial amount of its native perennial woody vegetation was cleared and replaced with either annual cropping or pasture systems.

These systems use less of the annual rainfall and in a different pattern to the native vegetation, resulting in higher amounts of deep drainage below the root zone (Johnston *et al.* 1999). Excessive deep drainage leading to ground water recharge is accepted as the cause of water table rise and land and river salinisation (Walker *et al.* 1999). For the high rainfall zone, various studies have shown that annual pastures use less water than perennial pastures on an annual basis (Ridley *et al.* 1997; Simpson *et al.* 1998; Heng *et al.* 2001; Ridley *et al.* 2001).

Considering the areal extent of grazed pastures on the North-West Slopes of NSW, the risk of potential land salinisation is high (Beale *et al.* 2000). However, potential evapotranspiration is higher and annual rainfall is summer dominant compared with more southern areas, which lessens the potential for regular deep drainage events taking place (Simpson *et al.* 1998). Further, deep drainage may recharge aquifers that supply irrigation and town water supplies elsewhere (e.g. Weltz and Blackburn 1995). The magnitude and timing of deep drainage events below grazed natural pastures is not well known and the impact of grazing management is thought to be small (Simpson *et al.* 1998).

Deep drainage is notoriously difficult to measure directly, particularly because of low flux rates at units of scale that are practical. Two common approaches used to estimate deep drainage for pasture systems include simple soil water balance (e.g. Ridley *et al.* 1997) and biophysical modelling (e.g. Simpson *et al.* 1998). The latter has appeal due to the complex nature of interactions between the plant and soil and climatic conditions.

2.8 Biophysical simulation modelling

2.8.1 Why use a model

Models that accurately replicate biophysical systems have great potential to help improve the understanding of processes within and management effects on such systems. These models allow analysis of data sets and exploration of interactions in a manner not possible in experimental studies. For example, hypothetical treatments, such as stocking rates that are beyond economic thresholds, may be simulated to ascertain likely impacts on pasture. Similarly, where variables are difficult to measure quantitatively (e.g. deep drainage), simulation models may indicate likely outcomes from various grazing management strategies (e.g. Simpson *et al.* 1998).

Models also offer the opportunity to extend experimental results to longer time frames. Where trends are evident in experimental data sets, these trends can be tested over the long-term using a model, to ascertain the continuation of those trends. The value of this approach is to safeguard experimental results that might have been collected in an abnormal run of seasons, so that they might be safely extrapolated.

Importantly, biophysical process based models can be used to challenge our understanding of how particular systems may be operating and analyse experimental data (Thornley and Johnson 2000). For example, many complex interactions exist in pasture systems, involving climate, soil, plant and animal components. In an experiment, it is impossible to quantify all of the interactions that occur between the various components, but a biophysical model allows us to explore some of these interactions in a relative way. Further, experimental data may suggest that a particular process might be happening, such as the proportion of evaporation and transpiration components within evapotranspiration, and a model can help to explore the interactions that direct the partitioning. Biophysical modelling should not be seen as an exercise in fitting experimental data, rather as an opportunity to further explore and challenge experimental data.

Many different models have been created for a variety of applications. In essence, a model simply captures our level of understanding of a process in terms of mathematical equations. Simple empirical models are useful for predicting a response from the interaction of a few variables with few parameters, and are generally quite robust (Thornley and Johnson 2000). Mechanistic deterministic models tend to be much more complex and involve numerous interacting components, and require many parameters to be defined. Such models are often used in applied research to aid the understanding of systems and the complex interactions that take place between various components (Thornley and Johnson 2000). However, the response can be quite unpredictable and less than robust. Thus, the choice of which model to use depends upon the application. Where a reliable prediction from a few variables is required, an empirical model that describes processes that are well understood would be appropriate. However, where it is desired to further understand the interactions between numerous components and hence generate likely responses, a mechanistic model might be appropriate.

2.8.2 Examples of biophysical models used in pasture research

The literature presents a plethora of models and they are gaining increasing popularity as prediction tools. Such models are usually developed to address specific research questions and applications. For example, HYDRUS-2D (Simunek *et al.* 1999) simulates water and solute movement in the unsaturated zone of soil profiles. This model relies upon the empirical relationships that predict water movement through porous media using the Richards equation (e.g. Campbell 1985) derived from Darcy's Law. Water retention characteristics are described by the van Genuchten equation (van Genuchten 1980). However, while HYDRUS-2D may simulate water movement through the profile very well, it does not include interactions with soil health and plant uptake.

In a study that investigated the impact of management of ground cover on surface runoff from small catchments in central Queensland, Connolly *et al.* (1997) applied the ANSWERS model (Beasley and Huggins 1981). The ANSWERS model successfully aided understanding of the interaction between the management of ground cover and surface runoff generation in a spatially diverse catchment. Important processes were identified and incorporated into the model, including the relationship of increasing infiltration rate with higher ground cover. However, the ANSWERS model simulated runoff generated via Hortonian overland flow processes only (Horton 1933) and did not replicate surface runoff generated by long duration, low intensity rainfall.

A more complex model that incorporated components of the atmosphere, plant and soil system is the WAVES model (Zhang and Dawes 1998). This model recognised the complex series of interactions in the soil-vegetation system and enabled feedback responses between the components. Soil water infiltration and movement through the soil profile was described using the Richards equation. Surface runoff was described within the model under Hortonian overland flow processes according to the infiltration capacity of the surface soil. Plant growth was based on carbon and water availability with limitations due to nutrient deficiency. By using the WAVES model Zhang *et al.* (1999) successfully simulated pasture and crop production and described the episodic nature of deep drainage in the Mallee landscape of NSW and Victoria. The authors reported that the success of the WAVES model was that it accurately incorporated specific canopy interception and soil water movement processes. However, the interface of this model is not particularly user friendly, and requires the handling of several parameter and input data files.

The APSIM (Agricultural Production Systems Simulator) software system (McCown *et al.* 1996) allows various sub-models to be incorporated under one operating system to dynamically simulate the soil, vegetation, and management system. A central 'engine' coordinates the various modules that are dynamically linked. For example wheat production may be simulated using the CERES-wheat model (Ritchie *et al.* 1988), while the SWIM model (Ross 1990*a*) describes water movement in the profile. A key feature of the APSIM system is that it allows the soil resource to change through time in response to climate, vegetation and management interactions, with the underlying assumption that the soil forms the basis for all production. The APSIM system has been developed using a Windows® format for ease of application and use.

One key feature of all of the models described above is that they were created to answer specific research questions. Each simulation model has specific idiosyncrasies that developed in response to their developers' understanding of the system. However, for any biophysical model, accurate fitting of experimental data does not necessarily indicate that the model is representing processes taking place within the physical system. Most experimental data measures the state of variables, which is a balance of fluxes through the system. Hence, good agreement may occur between simulated and observed data due to the incorrect balance of fluxes achieving the correct outcome. Therefore, use of a biophysical model should be limited to aiding the understanding of processes within the system.

2.9 Conclusion

Natural pastures are a key resource of the livestock grazing industry in Australia, particularly for the North-West Slopes of NSW. However, their productivity and sustainability are being limited. Productivity of these pastures is limited by the species composition, with some species being less palatable and digestible than others are. Similarly, annual production is often limited by low availability of green leaf year round, particularly in winter when the warm season grasses are inactive. The TPSKP identified that productivity could be increased and species composition maintained or improved through strategic grazing. Sustainability of these pastures also appears to be limited through the effect of grazing management on the hydrological balance, with high amounts of surface runoff and bare soil evaporation leading to low levels of plant available water.

Grazing management affects both the plant and soil resources of the pasture system. Specifically, with higher grazing intensity, herbage mass, litter mass, and ground cover are likely to be less, resulting in poor soil structure and soil health. Livestock trample the soil surface leading to compaction, lower porosity and lower infiltration rates. Similarly, the soil biota suffers from a lack of food and a suitable environment in which to live, resulting in lower incorporation of soil organic matter and ultimately poorer soil structure. Higher grazing intensities increase the rate at which soil and plant characteristics are changed.

Herbage mass, litter mass, and ground cover have important roles in manipulating the hydrological balance of pastures and so grazing management might affect the pathways of water movement within the pasture system. Ground cover is important for surface runoff control, erosion control and reducing bare soil evaporation. Similarly, litter prevents raindrop impact, impedes surface flow, increases infiltration and reduces soil evaporation. Herbage mass provides green leaf for intake by livestock, intercepts rainfall, prevents raindrop impact, and absorbs radiant energy before it reaches the soil surface. Also, with long-term grazing, the amount of herbage mass is also likely to reflect the amount of root mass, and so the opportunity for water uptake by plants. Grazing may influence both the amount of roots and their distribution within the profile.

Evapotranspiration is the largest component of the hydrological balance (85-95% of annual rainfall) and of the components offers the greatest opportunity for manipulation through grazing management. On the North-West Slopes, soil evaporation is the dominant component of evapotranspiration and increasing levels of litter mass and ground cover may reduce it. By slowing the rate of soil evaporation, stored soil water may be accessed by plant roots for transpiration, and thereby increasing pasture production. Similarly, the amount of green leaf in the pasture may influence the amount of transpiration. However, the net radiant energy balance of natural pastures is unknown, and albedo may vary according to ground cover and litter mass.

Excessive deep drainage is a key concern across much of south-eastern Australia, but few experimental data are available for grazed pastures on the North-West Slopes. Deep drainage is particularly difficult to measure and biophysical modelling offers the opportunity to evaluate the effect of alternative grazing management in manipulating it. Biophysical modelling also provides a framework to analyse experimental results and expand trends to longer time frames.

Various grazing management strategies may manipulate the amounts of litter mass, herbage mass, and ground cover, thereby influencing the relative proportions of surface runoff, canopy interception, soil evaporation, stored soil water and deep drainage, and so the sustainability of the system. The interactions between the grazing animal and the pasture and soil resource require further investigation for the North-West Slopes for a range of simple, contrasting, grazing management systems.

3 Study sites and common methodology

3.1 Introduction

The current research is an attempt to document he impact of grazing management on the hydrological balance of a grazed pasture on the North-West Slopes of NSW. To do this, various studies were performed at four separate sites. The major component of this research was performed at Springmount, while two other sites were used for runoff studies (Eloura and Winchfield), and another used for evapotranspiration studies (Tamworth Centre for Crop Improvement). A description of each site including their location, soil type, and dominant pasture species is provided in this Chapter.

At Springmount, the effects of five grazing management strategies including both continuous and rotational grazing approaches, on pasture characteristics and components of the hydrological balance were investigated. These treatments are described here together with the core measurements and data sets that were collected.

Two methodologies were developed and evaluated so that they could be used in various components of the research. Ground cover was core data in studies of herbage mass, surface runoff and evapotranspiration, and a visual estimation technique was used to measure it. The visual estimation technique is validated in this Chapter. Surface soil water content was measured in studies of surface runoff, evapotranspiration and profile stored soil water. A technique that used electrical resistance sensors to measure surface soil water content in real time was developed and it also is described in this Chapter.

3.2 Study sites

3.2.1 Springmount

Location

The core study site was located 22 km north of Manilla, NSW, on the property "Springmount" (30°34'15"S, 150°38'25"E, 510 m a.s.l.). The study site was part of the Sustainable Grazing Systems National Experiment (Mason and Andrew 1998; Lodge *et al.* 2003*b*). In total area, the study site occupied approximately 10 ha and was fenced separately from the other grazing paddocks on Springmount. The site was located at the foot of the Nandewar Range and had a gentle slope (3.4%) and a south-easterly aspect. The soil was a deep (> 2 m deep) red chromosol (Isbell 1996), derived from colluvial deposits, and it had a hard setting surface. The hard setting surface was attributed to the cropping history of the site and low level of organic matter (1.9% total carbon, Lawson 1998).

The history of the study site included phases of intensive cropping in the 1960s and the early 1980s. Wheat was last grown in the paddock in 1984 and it was under-sown with lucerne, which persisted until 1989. Subsequently, native grass species recolonised the site, and were dominated by redgrass, wallaby grasses (*Austrodanthonia richardsonnii* (Cashmore) H.P. Linder and *A. bipartita* (Link (H.P. Linder) and wiregrass. The community was typical tussock grassland, with tufted grasses interspersed with areas of bare soil. Annual legumes were rare in the pasture with small proportions (< 5% by dry weight) of *Medicago spp.*L. and *Trifolium spp.* L. Since the end of cropping, the pasture had been continuously grazed at a stocking rate of around 4-5 sheep/ha.

Soil description

Intact soil cores (45 mm diameter) were obtained and the field texture, approximate clay content (Northcote 1974), and soil colour (Munsell 1994) were described for each soil depth layer (Table 3-2). To determine soil bulk density, a soil pit was excavated by a backhoe to a depth of 2.1 m. Bulk density samples were taken from the side wall of the pit using the core method of Blake and Hartge (1986). After bulk density was determined for each sample, the weight and volume of gravel (> 2 mm diameter) was determined by the displacement method (Cresswell and Smiles 1995). Gravel occupied from 1.0 to 10.4% of the sample volume depending on depth (Table 3-2). Initial soil bulk density values were adjusted to account for the weight and volume occupied by gravel, which was assumed to be impervious to water. The soil water retention characteristic was determined using tension table and pressure plate apparatus (Cresswell and Smiles 1995), and the values for field capacity (-10 kPa) and wilting point (-1500 kPa) were used to illustrate the characteristic down the soil profile (Table 3-2). The concentration of total phosphorus and nitrate was determined down the soil profile at each site (Table 3-6).

Grazing treatments

Five grazing treatments across three replicates were implemented at Springmount and treatments were allocated randomly to plots (~0.5 ha each) in each replicate (Figure 3-1). The treatments were designed to provide a range of pasture herbage mass, litter mass, and ground cover conditions so that impact on surface runoff, evapotranspiration and stored soil water might be determined (Table 3-1). Treatments were designed taking grazing management of local producers into account and district average stocking rates (Lodge *et al.* 1991). Prior to stocking the treatments, initial pasture herbage mass data were analysed using analysis of variance (ANOVA) to check that any differences between treatments were not significant ($P \geq 0.05$). All pasture herbage mass, litter mass and ground cover data were statistically analysed to determine significant differences at the 0.05 probability level as commonly done in Australian agricultural studies (e.g. Orchard *et al.* 2000). Three treatments were continuously grazed while the others were rotationally grazed.

Treatment 1 (T1C4): continuous grazing at 4 sheep/ha without fertiliser. The stocking rate was based on the district average of 3.5 to 4.0 DSE/ha for native perennial grass pastures in Parry Shire on the North-West Slopes (Lodge *et al.* 1991).

Treatment 2 (T2C6): continuous grazing at 6 sheep/ha without fertiliser. This treatment represented the near upper limit of district stocking rate, as in a survey of producers no respondent stocked above 7 DSE/ha (Lodge *et al.* 1991), and was intended to reduce herbage mass, litter mass and ground cover to low levels.

Treatment 3 (T3FERT8): continuous grazing at 8 sheep/ha with fertiliser and subterranean clover. This treatment was intended to increase herbage mass, litter mass and ground cover, while maintaining a higher stocking intensity to maximise livestock production.

Treatment 4 (T4GR4): rotational grazing at 4 sheep/ha representing one paddock of a simple two paddock rotation. Plots were grazed for 4 weeks at an intensity of 8 sheep/ha and then rested for 4 weeks in a continual cycle. While the plots were being rested, sheep were grazed on an adjacent area of pasture similar to the treatment area.

Treatment 5 (T5GR12): rotational grazing at 4 sheep/ha, representing one paddock of a four paddock rotation. Plots were grazed for 4 weeks at an intensity of 16 sheep/ha and then rested for 12 weeks in a continual cycle. The 12 week rest was intended to allow pasture plants adequate time for regeneration before the next grazing and represented an approximate season (3 months). Again, while plots were being rested, sheep were grazed in an adjacent area of similar pasture.

Merino wether sheep were used in each grazing treatment. Although some treatment plots contained 2 or 8 sheep (Table 3-1), there were no visible signs of abnormal animal behaviour such as tracking or walking fence lines for companionship. Sheep for each treatment were selected from a larger mob of the same age and type so that there were no initial weight differences. Sheep were systematically allocated into three groups (animal order through a race) and ear tagged (red, green or blue tags for the three replicates) with unique numbers. Animals in each colour group were then distributed into different treatments so that mean weight was similar for each. The initial mob of sheep was 17 month old and was used in the experiment for 12 months. A second mob (15 month old initially) was used for the remainder of the experiment (October 1998 to October 2001). Sheep were crutched in early autumn, shorn in spring and treated to prevent fly strike in early summer. Live weight and condition fat score (0-5 arbitrary scale) were measured at approximately 4 week intervals to monitor animal health and condition (data not presented). Livestock in this study were used as a tool to manipulate the pasture, and livestock production issues are not reported here. The impact of grazing management on livestock performance at Winchfield, Springmount, and Eloura were reported by Lodge *et al.* (2003*a*, *b*, and *c*, respectively).

Table 3-1. Grazing treatment descriptions for Springmount, including definition, description, plot allocations, sheep per plot, and annual stocking rate.

Treatment	Short Description	Plots	Sheep/Plot	Annual Stocking Rate (sheep/ha)
T1C4	Continuous graze, low intensity	2, 7, 12	2	4
T2C6	Continuous graze, high intensity	1, 8, 15	3	6
T3FERT8	Continuous graze, fertiliser + subterranean clover	3, 6, 11	4	8
T4GR4	Rotational graze, 2 paddock	4, 9, 13	4	4
T5GR12	Rotational graze, 4 paddock	5, 10, 14	8	4

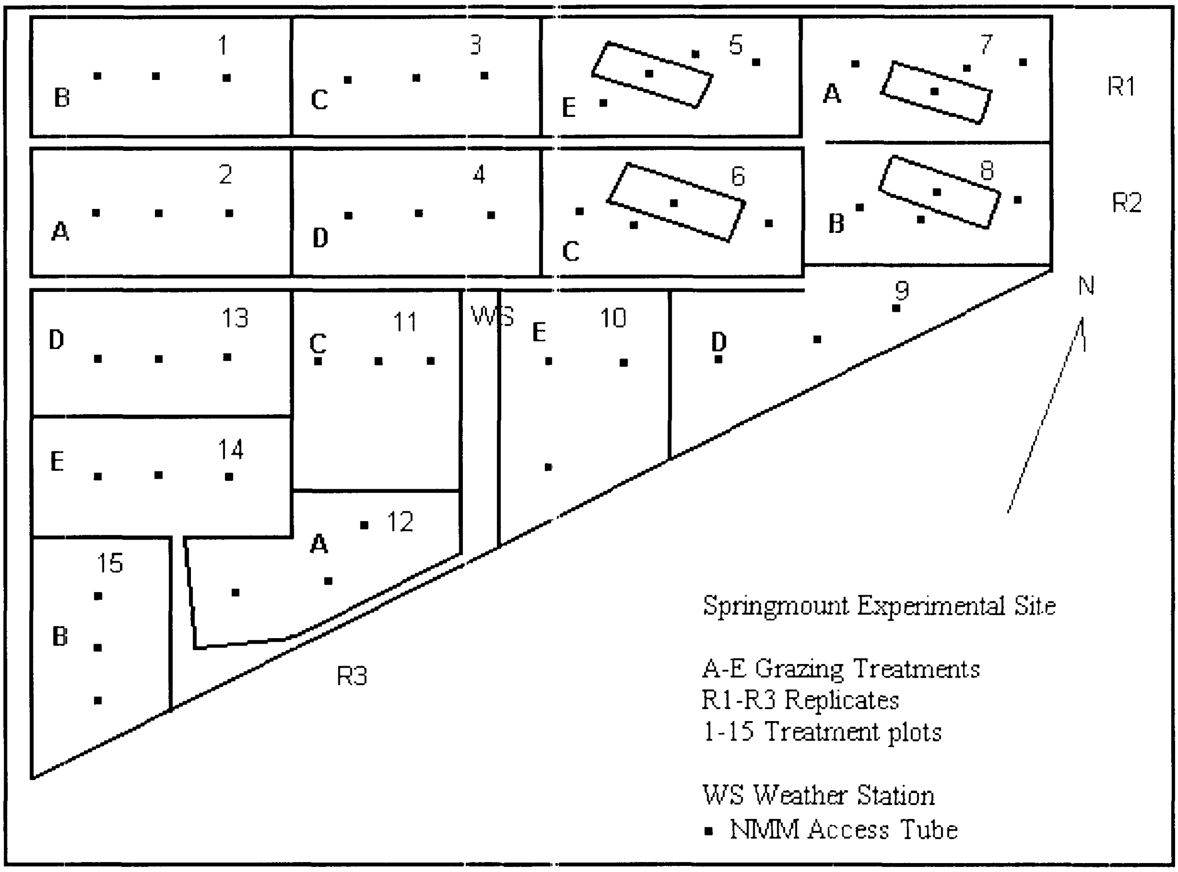

Figure 3-1. Approximate layout of Springmount, showing allocation of grazing treatments to plots, where 'A' is T1C4, 'B' is T2C6, 'C' is T3FERT8, 'D' is T4GR4 and 'E' is T5GR12. Each plot was approximately 0.5 ha. (Replicate 1 is plots 1-5, replicate 2 is plots 6-10, replicate 3 is plots 11-15).

Supplementary feeding of sheep

When herbage mass of grazing plots was low (< 500 kg DM/ha) or sheep body fat score was < 1, to maintain animal health, sheep were fed either a by-pass protein supplement (cottonseed meal pellets, 24% protein at 0.2-0.4 kg/head.d) or lupins (~28% protein at 0.15 kg/head.d). Initially sheep were fed on the experimental plots, but were later removed to an adjacent area to minimise overgrazing of the treatment plots. Sheep in the T2C6 treatment were fed on three occasions throughout the experiment: autumn-winter 1998, winter-spring 2000, and late winter 2001. Sheep in the T1C4 treatment were supplemented in the same periods in 1998 and 2000. Sheep in other treatments did not require supplementary feeding at any time.

Application of seed and fertiliser

Only treatment three (T3FERT8) had subterranean clover and it was oversown at rates of 12 and 6 kg/ha in 1997 and 1998, respectively (equal mix of three cultivars: Clare, Seaton Park, and York). Plots were sown in May by broadcasting seed onto the undisturbed soil surface. The second sowing was used to bolster the plant population of subterranean clover. Single superphosphate fertiliser (8.8% P, 11% S) was applied at 125 kg/ha at time of sowing and sulphur-fortified fertiliser (7.2% P, 26.5% S) was applied in May 2000 at 125 kg/ha

3.2.2 Eloura and Winchfield

Eloura and Winchfield were used to provide surface runoff data. A short description of each site and grazing treatments that were implemented is presented here.

Eloura

The Eloura study site was 11 km west of Manilla, NSW, on the property "Eloura" (30°49'05"S, 150°42'25"E, 475 m a.s.l.). The site was very gently sloping (1.7%) with a northerly aspect. There were two soil types on the site, with the western part dominated by brown vertosol and the eastern part dominated by red chromosol. The brown vertosol had a typically cracking to self-mulching surface. The red chromosol was hard setting where ground cover was low. The site had an intensive cropping history prior to 1977, with the last crop of barley sown in 1980 and undersown with lucerne that persisted until 1985. No fertiliser was applied and crop performance was poor. Since that time the site was used for grazing cattle and native grass species recolonised. Pastures were dominated by redgrass, wallaby grass, wiregrass and speargrass (*Austrostipa scabra* (Lindl.) H.P. Linder) on the red chromosol soil and bluegrass on the brown vertosol. A small amount of annual legume (*Medicago* L. and *Trifolium* L. spp.) was present on both soil types.

Five grazing treatments were implemented at Eloura, replicated three times, in 15 plots of 0.65 ha each. The treatments were designed similarly to Springmount. Two treatments were continuously grazed (3.1 or 6.2 sheep/ha), two were rotationally grazed (3.1 sheep/ha, 2 or 4 paddock rotation), and one was over sown with subterranean clover and grazed continuously at 9.2 sheep/ha. In a study describing the impact of grazing management on pasture herbage mass, litter mass, animal production, and stored soil water, Lodge *et al.* (2003*c*) provide detailed descriptions of the site, treatments, and key findings. The colour, clay content, gravel content, bulk density, and water holding capacity were described for each soil type at Eloura (Table 3-3).

Winchfield

The Winchfield study site located 5 km north of Nundle, NSW, on the property "Winchfield" (31°24'30"S, 151°07'30"E, 590 m a.s.l.) The site had a moderate slope of 6.8% with a north-easterly aspect, with shallow yellow podosols on the upper slope and deeper yellow sodosols on the lower slopes (Isbell 1996). Rock outcrops were evident immediately upslope testifying to the shallow soils over parts of the trial site. In 1992, the pasture was sown to phalaris (*Phalaris aquatica* L. cv. Sirosa), subterranean clover (cv. Seaton Park) and lucerne (cv. Aurora). Annual ryegrass (*Lolium rigidum* Gaudin) and barley grass (*Hordium leporinum* Link) dominated the winter growing annual grass species. The site had not been cropped. Management of the site prior to the experiment aimed to conserve pasture herbage mass and litter mass. Hence, the soils on the site had a high level of organic matter (3.20% total carbon, Lawson 1998).

Winchfield had four grazing treatments, replicated three times in 12 plots of 0.48 ha each. Two treatments were continuously grazed at 6 and 12 sheep/ha, respectively. In the two other treatments, the base stocking rate was 12 sheep/ha, but in spring and autumn it was reduced to either 0 or 4 sheep/ha, to encourage persistence of the phalaris. In a study investigating the response and persistence of phalaris pasture to grazing management, Lodge *et al.* (2003*a*) provide detailed description of the site, treatments, and key findings. The colours, clay content, gravel content, bulk density, and water holding capacities were described for the major soil type (yellow sodosol) at Winchfield (Table 3-4).

3.2.3 Tamworth Centre for Crop Improvement

An evapotranspiration study was performed at NSW Agriculture's, Tamworth Centre for Crop Improvement (TCCI), Tamworth, NSW (31°09'S, 150°59'E; elevation 434 m a.s.l.). The experimental plots were located 50 m north of the meteorological lawn where climate data were collected. TCCI has an average annual rainfall of 677 mm (Clewett *et al.* 1999). The soil type was a brown chromosol (Isbell 1996, Table 3-5) and it had been used extensively for cereal crop production. The 12 treatments were designed to provide a range of herbage mass, litter mass and ground cover conditions that might affect evapotranspiration (Chapter 6).

Table 3-2. Soil profile physical description for Springmount (red chromosol).

Depth (cm)	Horizon	Field Texture	Clay Content (%)	Munsell Colour	Bulk Density (Mg/m^3)	Gravel Volume (%)	Field Capacity (θ_{vol}%)	Wilting Point (θ_{vol}%)
0-5	Surface	Clay loam	30 to 35	Reddish Brown	1.40 ± 0.028	3.3	31.1	12.3
5-10	A_1	Clay loam	30 to 35	Reddish Brown	1.40 ± 0.060	3.1	31.0	12.2
10-30	B_1	Light/medium clay	40 to 45	Reddish Brown	1.46 ± 0.033	5.5	32.4	12.8
30-50	B_2	Medium clay, FS	45 to 55	Reddish Brown	1.64 ± 0.004	5.0	35.6	19.4
50-70	B_2	Medium clay	45 to 55	Yellowish Red	1.67 ± 0.005	8.9	36.3	19.8
70-90	B_2	Medium clay	45 to 55	Yellowish Red	1.62 ± 0.058	1.0	42.1	23.6
90-110	B_2	Medium clay	45 to 55	Yellowish Red	1.55 ± 0.105	4.3	40.1	22.5
110-130	B_2	Medium clay	45 to 55	Reddish Brown	1.57 ± 0.090	2.5	40.8	22.8
130-150	B_2	Medium clay	45 to 55	Dark Red	1.66 ± 0.036	4.9	43.2	24.1
150-170	B_2	Medium clay	45 to 55	Yellowish Red	1.66 ± 0.030	9.6	43.2	24.2
170-190	B_2	Medium clay	45 to 55	Yellowish Red	1.66 ± 0.049	10.4	40.4	23.5
190-210	B_2	Medium clay, FS	45 to 55	Yellowish Red	1.63 ± 0.036	7.0	39.9	23.2

Table 3-3. Soil profile physical description for the brown vertosol and red chromosol at Eloura.

Depth (cm)	Horizon	Field Texture	Clay Content (%)	Munsell Colour	Bulk Density (Mg/m^3)	Gravel Volume (%)	Field Capacity (θ_{vol}%)	Wilting Point (θ_{vol}%)
				Brown vertosol				
0-5	Surface	Light/medium clay	40 to 45	Dark Brown	1.48 ± 0.012	0.7	30.7	16.8
5-10	A_1	Light/medium clay	40 to 45	Dark Brown	1.48 ± 0.040	0.1	30.8	16.9
10-30	B_1	Medium/heavy clay	> 50	Dark Yellow Brown	1.48 ± 0.065	0.4	39.4	24.0
30-50	B_1	Medium/heavy clay	> 50	Dark Yellow Brown	1.51 ± 0.036	0.5	40.3	24.6
50-70	B_1	Medium/heavy clay	> 50	Dark Yellow Brown	1.59 ± 0.063	2.7	42.3	25.8
70-90	B_2	Medium/heavy clay	> 50	Dark Brown	1.62 ± 0.063	1.2	45.7	30.8
90-110	B_2	Medium/heavy clay	> 50	Dark Brown	1.64 ± 0.007	2.0	46.5	31.3
110-130	B_2	Medium/heavy clay	> 50	Dark Brown	1.60 ± 0.027	6.9	45.1	30.4
130-150	B_2	Medium/heavy clay	> 50	Dark Brown	1.48 ± 0.030	0.6	41.9	28.2
150-170	B_2	Medium/heavy clay	> 50	Reddish Brown	1.48 ± 0.016	1.2	41.8	28.1
170-190	B_2	Medium/heavy clay	> 50	Reddish Brown	1.52 ± 0.086	0.5	46.7	33.5
190-210	B_2	Medium/heavy clay	> 50	Yellowish Red	1.64 ± 0.018	1.6	50.5	36.2
				Red Chromosol				
0-5	Surface	Clay loam	30 to 35	Dark Brown	1.45 ± 0.036	2.3	31.4	12.8
5-10	A_1	Clay loam	30 to 35	Dark Brown	1.46 ± 0.053	1.1	31.5	12.9
10-30	A_2	Light clay	35 to 40	Yellowish Red	1.43 ± 0.056	1.6	31.0	12.6
30-50	B_1	Medium clay	45 to 55	Yellowish Red	1.57 ± 0.043	1.9	39.9	20.1
50-70	B_1	Medium clay	45 to 55	Yellowish Red	1.64 ± 0.026	3.0	41.9	21.0
70-90	B_1	Medium clay	45 to 55	Yellowish Red	1.61 ± 0.065	1.2	47.5	26.5
90-110	B_1	Medium clay	45 to 55	Yellowish Red	1.50 ± 0.074	1.1	44.3	24.8
110-130	B_1	Medium clay	45 to 55	Yellowish Red	1.51 ± 0.014	1.1	44.4	24.8
130-150	B_2	Medium clay	45 to 55	Dark Red	1.51 ± 0.047	2.4	44.4	24.8
150-170	B_2	Medium clay	45 to 55	Dark Red	1.51 ± 0.047	2.4	44.4	24.8
170-190	B_2	Medium clay	45 to 55	Dark Brown	1.43 ± 0.079	8.9	58.0	36.5
190-210	B_2	Light clay	35 to 40	Brownish Yellow	1.46 ± 0.021	2.2	59.3	37.2

Table 3-4. Soil profile physical description for Winchfield (yellow sodosol).

Depth (cm)	Horizon	Field Texture	Clay Content (%)	Munsell Colour	Bulk Density (Mg/m^3)	Gravel Volume (%)	Field Capacity (θ_{vol}%)	Wilting Point (θ_{vol}%)
0-5	Surface	Fine sandy loam	10 to 25	Dark Yellow Brown	1.34 ± 0.016	1.7	31.7	8.7
5-10	A_1	Loam	25	Dark Yellow Brown	1.39 ± 0.022	2.6	32.8	9.0
10-30	A_1	Sandy clay loam	20 to 25	Brown	1.42 ± 0.025	3.4	33.7	9.3
30-50	A_2	Sandy clay loam to light/medium clay	20 to 45	Brownish yellow	1.44 ± 0.053	3.6	29.5	16.6
50-70	B_1	Light to medium clay	40 to 55	Yellowish Brown	1.68 ± 0.025	5.8	34.3	19.3
70-90	B_1	Light to medium clay	40 to 55	Yellowish Brown	1.58 ± 0.058	10.9	28.4	18.1
90-110	B_1	Light to medium clay	40 to 55	Yellowish Brown	1.65 ± 0.065	9.3	29.6	18.8
110-130	B_1	Sandy to medium clay	35 to 55	Yellowish Brown	1.71 ± 0.008	1.5	30.6	19.5
130-150	B_1	Sandy to medium clay	35 to 55	Yellowish Brown	1.66 ± 0.020	6.7	44.1	25.0
150-170	B_2	Sandy to medium clay	35 to 55	Yellowish Brown	1.69 ± 0.025	2.7	44.8	25.4
170-190	B_2	Sandy to medium clay	35 to 55	Yellowish Brown	1.56 ± 0.032	4.8	44.8	25.4
190-210	C	Sandy to medium clay	35 to 55	Greyish Brown	1.58 ± 0.032	5.1	45.5	24.9

Table 3-5. Soil profile physical description for TCCI (brown chromosol).

Depth (cm)	Horizon	Field Texture	Clay Content (%)	Munsell Colour	Bulk Density (Mg/m^3)	Gravel Volume (%)	Field Capacity (θ_{vol}%)	Wilting Point (θ_{vol}%)
0-5	A_1-A_2	Clay loam	30 to 35	Brown	1.38 ± 0.038	NA	NA	NA
5-10	B_1	Clay loam	30 to 35	Yellowish Brown	1.47 ± 0.032			
10-30	B_1	Clay loam	30 to 35	Yellowish Brown	1.37 ± 0.010			
30-50	B_{21}	Medium clay	45 to 55	Yellowish Brown	1.38 ± 0.030			
50-70	B_{21}	Medium clay	45 to 55	Yellowish Brown	1.37 ± 0.030			
70-90	B_{21}	Medium clay	45 to 55	Yellowish Brown	1.42 ± 0.056			
90-110	B_{22}	Medium clay	45 to 55	Strong Brown	1.48 ± 0.026			
110-130	B_{22}	Medium clay	45 to 55	Strong Brown	1.59 ± 0.034			
130-150	B_{22}	Medium clay	45 to 55	Strong Brown	1.50 ± 0.025			
150-170	B_{22}	Medium clay	45 to 55	Strong Brown	1.58 ± 0.050			
170-190	B_{22}	Medium clay	45 to 55	Strong Brown	1.59 ± 0.053			
190-210	B_2/C	Sandy clay	40 to 45	Yellowish Brown	1.63 ± 0.087			

NA = Not assessed.

Table 3-6. Mean soil profile concentration of phosphorus (P) and nitrogen (NO3) for each of the sites Springmount, Eloura and Winchfield.

	Springmount		Eloura		Winchfield	
Depth (cm)	**P (mg/kg)**	**NO_3 (mg/kg)**	**P (mg/kg)**	**NO_3 (mg/kg)**	**P (mg/kg)**	**NO_3 (mg/kg)**
0-10	595	1.1	398	2.6	425	3.8
10-20	520	1.0	308	0.5	310	1.7
20-40	478	0.3	245	0.3	305	1.4
40-60	393	0.6	235	0.3	415	1.0
60-80	470	0.4	235	0.4	425	0.8
80-100	488	0.3	270	0.6	445	0.8
100-120	445	0.9	310	1.1	475	0.7

3.3 Core measurements and data sets

To quantify the effect of grazing management on the pasture and the hydrological balance, measurements were taken in several theme areas including climate, pasture and litter, surface runoff, evapotranspiration, and stored soil water. For future reference, the specific data sets collected in each of these areas, including the units, frequency, and the start and end of measurement is presented in Table 3-7. Similar data sets were collected at Winchfield and Eloura and Lodge *et al.* (2003*a*, and 2003*c*, respectively), reported these.

Table 3-7. **Key data sets collected at Springmount, including the units, sample frequency and start and end dates of measurement.**

Theme	Data set	Units	Frequency of measurement	Start – End of measurement
Climate	Rainfall	mm	30 minute interval	November 1997 to September 2001
	Rainfall intensity	mm/h	1 minute interval, 4 minute duration	
	Air temperature	^oC	30 minute interval	
	Relative humidity	%	30 minute interval	
	Solar radiation	$MJ/m^2.d$	30 minute interval	
	Wind speed (3 m)	m/s	30 minute interval	
Soil description	Clay content	%	Initial	To 2 m depth
	Colour	Hue/Chroma	Initial	
	Bulk density	Mg/m^3	Initial	
	Gravel volume	m^3/m^3	Initial	
	Gravel percent	%	Initial	
	Wilting point	m^3/m^3 at -1500 kPa	Initial	
	Field capacity	m^3/m^3 at -10 kPa	Initial	
Pasture	Herbage mass	kg DM/ha	12 weeks, 6 weeks in spring	September 1997 to September 2001
	Litter mass	kg DM/ha	12 weeks, 6 weeks in spring	
	Ground cover	%	12 weeks, 6 weeks in spring	
	Percent green leaf	% by dry weight	12 weeks, 6 weeks in spring	
	Species composition	% by dry weight	12 weeks, 6 weeks in spring	
Surface runoff	Rainfall	mm	1 and 30 minute interval	November 1997 to September 2001
	Rainfall intensity	mm/h	4 minute interval	
	Rainfall duration	minutes		
	Surface runoff	mm	1 and 4 minute interval	
	Sediment concentration	mg/L	Per runoff event	
	Nitrogen concentration	mg/L	Per runoff event	
	Phosphorus concentration	mg/L	Per runoff event	
	Ground cover	%	Monthly	
	Canopy cover	%	Monthly	
	Stored soil water (0-20 cm depth)	mm	4 minute intervals	

Theme	Data set	Units	Frequency of measurement	Start – End of measurement
Evapotranspiration	Evapotranspiration	mm	Hourly and daily, in each season	April 2000 to May 2001
	Net radiation	MJ/m^2	5 minute intervals	
	Albedo	dimensionless	5 minute intervals	
	Pasture mass	kg DM/ha	Each sampling date	
	Litter mass	kg DM/ha	Each sampling date	
	Ground cover	%	Each sampling date	
	Canopy cover	%	Each sampling date	
	Pasture height	cm	Each sampling date	
	Stored soil water (0-20 cm depth)	mm	Daily	
Stored soil water	Stored soil water (0-210 cm)	mm	Monthly, 20 cm depth intervals	November 1997 to September 2001
	Stored soil water (0-10 cm)	mm	Each sampling date	
	Plant available water (0-210 cm)	mm		
	Change in stored soil water	mm	For major wetting and drying events	

3.4 Visual estimation of ground cover

Ground cover is an important component of a pasture system that can be manipulated with grazing management and it is an indicator of pasture productivity and sustainability (McCormick and Lodge 2001; Lodge and Murphy 2002*a*). The need to maintain ground cover in native pastures on the North-West Slopes of NSW has long been recognised as essential for controlling surface runoff and reducing soil erosion (Mau 1946). Ground cover and its various components have been reported to modify the surface energy budget of both pasture and cropping systems with a corresponding impact on the amount of evaporation and transpiration (Bristow 1988; Farahani and Ahuja 1996; Gonzalez-Sosa *et al.* 1999). Ground cover components (herbage mass and litter) are also an important living space for soil biota (King 1997).

Ground cover and canopy cover were key data sets for a large proportion of the current study and were measured during BOTANAL assessments (20 estimates per plot per sampling, see Chapter 4), for runoff plots (10 estimates per runoff plot per month, see Chapter 5), and during evapotranspiration studies (12 plots, see Chapter 6). Hence, a rapid and reliable technique was required that could be performed simply and efficiently at multiple sampling's.

The literature presents a range of techniques used for estimating ground cover in pastures and rangelands and these were reviewed in Chapter 2 (e.g. point quadrat, line intercept, digital image analysis, visual estimation). Of the methods, visual estimation appears to be the simplest and fastest, and requires no specialised equipment. Hatton *et al.* (1986) reported on the nature of errors involved in the visual estimation method, indicating that human observers had difficulty in distinguishing the amount of cover when shapes were complex and they had the most difficulty when cover was within the mid-range (30-70%). Visual estimation is a rapid technique, but required verification of its accuracy, repeatability, and applicability to the tussocky pastures in the current study. To ascertain how readily this technique could be learnt and with what accuracy, inexperienced observers were studied together with experienced observers. Both groups were tested by comparing their estimates with those of accepted objective methods to ascertain the veracity of the technique.

3.4.1 Methods

Data were collected from Springmount and Eloura study sites. At each site, 30 quadrats (40 by 40 cm) were arbitrarily selected with a wide range of ground cover levels. For each quadrat, total ground cover (including standing herbage, litter, animal dung and stones) was estimated by four methods, visual, mapped area, digital image analysis, and photo point quadrat technique. Canopy cover (foliar grass cover > 5 cm in height), was estimated by only the visual and mapped area methods since it could not be determined using photographic or digital techniques. Litter (unattached plant material in contact with the soil surface) and standing herbage were harvested separately in each quadrat and dried at 80°C in a forced draught dehydrator for 48 h before weighing.

Mean herbage mass and litter mass of quadrats was 1375 and 165 kg DM/ha, respectively. Herbage mass of quadrats was highly variable (1-5090 kg DM/ha) with Eloura having the higher mean (1430 kg DM/ha). Native perennial grasses dominated pastures at both sites. Litter mass was equally variable (1-1825 kg DM/ha) with Eloura having the highest mean (205 kg DM/ha). For total mass (herbage and litter mass), Eloura had the highest mean (1630 kg DM/ha) and Springmount the largest range (1-5100 kg DM/ha).

Visual estimation

At each site, four observers independently estimated percent ground cover and canopy cover for each quadrat. Two of the observers (experienced, observers 1 and 2) had visually estimated ground cover in these pastures since 1997 (approximately 6000-10 000 estimates each); the other two had not previously estimated ground cover or canopy cover (inexperienced, observers 3 and 4). Inexperienced observers were trained immediately before undertaking visual estimation of ground and canopy cover. At each site, one of the experienced observers selected five quadrats that had a range of ground cover conditions (ground cover 3-100%; canopy cover 0-90%). Each of the four observers independently estimated the five reference quadrats, and then discussed and compared their percentage estimates in relation to photographic standards (e.g. McCormick and Lodge 2001).

Mapped area

One of the experienced observers mapped ground cover, canopy cover and bare ground of each quadrat onto a data map (scale 1:2.5) using a 5 cm steel mesh grid as a drawing aid. This grid was suspended above the quadrat on an adjustable height frame. To avoid squashing the grass tussocks and distorting the estimate, the height of the grid was adjusted between 10 and 40 cm. The ground cover components were drawn onto data maps that had a 2 by 2 cm grid as a guide. Mapped cover components were cut out and measured in an electronic area meter (Lycor LI-3100 Area Meter) to estimate the percentage area of ground cover and canopy cover in each quadrat.

Digital image analysis

A colour photograph was taken in natural light conditions of each quadrat using a 35 mm single lens reflex camera from a fixed vertical height of 1.6 m with the objective lens at 60 mm focal length (Kodak print film, ISO 400). The photographs were centred on the middle of the quadrat to avoid distortion of the image (the centre was defined by cross wires tied at the midpoint on each side of the quadrat). The quadrat image filled the viewfinder of the camera resulting in a photographic print reproduction of approximately 9 by 9 cm. Photographic prints were digitally scanned at 600 d.p.i. in 32-bit, real colour and Paint Shop-Pro® (Version 5) was used to manually classify pixel colours corresponding to bare ground. Each photograph was classified manually due to variation in colour saturation and contrast. Colour was reduced to 2-bit density with white pixels corresponding to cover components and black to bare ground. White pixels were counted digitally using Delta T-Scan® (Kirchoff and Pender 1993) to estimate the percentage area of ground cover.

Photo point quadrat

This technique was applied to the colour photographic prints produced for the digital analysis, with ground cover intercepts determined for 100 points per quadrat. A grid (9.4 by 9.4 mm grid squares) on a transparency was placed over each colour print and the intersection points used to record presence or absence of ground cover. Transparency grid lines were less than 0.2 mm wide and when scaled to actual quadrat size were equivalent to physical points of approximately 1 mm diameter, which allowed sufficient resolution to accurately distinguish the presence or absence of ground cover at the intercept points.

Statistical analyses

Data were pooled between sites to provide the widest range of ground cover estimates and a high number of observations (n=60) and were examined using regression analysis. Experienced and inexperienced observer estimates of ground cover and canopy cover were tested for significant difference ($P \leq 0.05$) between means. The slope and intercept of the regression describing the relationship between estimates by each observer and the mean of all observer estimates for ground and canopy cover were tested to determine differences between observers. Similarly, estimates of ground cover by the objective methods were tested for significant differences between them. The overall relationship between mean observer visual estimate and mean objective estimate of ground cover and canopy cover was also examined. The variation in visual estimates was assessed by plotting the standard deviation of ground cover and canopy cover estimates against the mean of observer estimates for each quadrat.

3.4.2 Results

Relationships between visual estimates by observers

Ground cover

Visual estimates of ground cover ranged from 3 to 100%. Estimates by each observer for all quadrats (n=60) were compared with the mean estimate for all observers. For observer 4, the mean visual ground cover estimate was lower but not significantly different to those of the other observers

(Table 3-8). However, the regression intercept was lower for observer 4 compared with observer 3 ($P<0.05$, Table 3-8). The regression slope was also lower ($P<0.05$) for observer 1 compared with observer 2 and for observer 3 compared with observers 2 and 4 (Table 3-8). The means of experienced and inexperienced observer estimates were not significantly different (Table 3-8). Since there were no significant differences among means, visual estimates of ground cover were averaged among observers for each quadrat to compare with values from the other methods.

Canopy cover

Estimates of canopy cover ranged from 0 to 100%. Mean estimated canopy cover for each observer was not significantly different (Table 3-9). The regression intercept values were also not significantly different, but the slope was lower ($P<0.05$) for observer 2, compared with observers 1 and 3 (Table 3-9). Again, since mean estimated visual canopy cover was not significantly different among observers, canopy cover was averaged for each quadrat to compare with estimates from the mapped area method.

Table 3-8. Mean estimated visual ground cover (%, ± se) for each of the four observers for both sites combined (n=60), together with the linear regression equation (Y = observer visual estimate ground cover %, X = mean visual ground cover %).

Observer	Mean	Equation
	Experienced	
Observer 1	74.0 (± 5.02)	Y = 0.98X (± 0.024) + 1.90 (± 1.893)
Observer 2	74.4 (± 5.12)	Y = 1.03X (± 0.025) - 1.58 (± 1.932)
	Inexperienced	
Observer 3	75.7 (± 5.19)	Y = 0.97X (± 0.025) + 3.92 (± 1.956)
Observer 4	70.9 (± 4.83)	Y = 1.02X (± 0.021) - 4.25 (± 1.821)

Table 3-9. Mean estimated visual canopy cover (%, ± se) for each of the four observers for both sites combined (n=60), together with the linear regression equation (Y = observer visual estimate canopy cover %, X = mean visual canopy cover %).

Observer	Mean	Equation
	Experienced	
Observer 1	33.1 (± 5.78)	Y = 1.04X (± 0.026) – 3.06 (± 1.190)
Observer 2	34.1 (± 6.25)	Y = 0.96X (± 0.028) + 0.67 (± 1.286)
	Inexperienced	
Observer 3	37.5 (± 6.90)	Y = 1.03X (± 0.031) + 1.79 (± 1.419)
Observer 4	34.0 (± 2.92)	Y = 1.00X (± 0.050) + 3.54 (± 2.238)

Estimates of ground and canopy cover using objective methods

Ground cover

Estimates by objective methods ranged from a low of 5.3% for the mapped area method to 100% for all methods. For digital image analysis the lowest estimate of ground cover was 19% compared with 5 and 6% by the other methods for the same quadrat. Digital image analysis was less sensitive to low levels of ground cover as exemplified in three quadrats where estimates of cover were higher than the other methods with 5, 28 and 26% (mapped area), 6, 29 and 35% (point quadrat) and 19, 40 and 51% (digital image analysis), respectively.

Mean ground cover estimate of each objective method was not significantly different (mapped area, 82.0 ± 2.6%; point quadrat 84.7 ± 3.4%, and digital image analysis 82.7 ± 4.7%). However, the intercept for the mapped area method (-10.14 ± 1.4%) was lower (P<0.05) than that of the point quadrat (4.60 ± 1.8%) and digital image analysis (5.53 ± 2.6%). Similarly, the mapped area method had a higher (P<0.05) slope (1.11 ± 0.01) than the other methods (point quadrat, 0.96 ± 0.02; digital analysis, 0.93 ± 0.03).

For each quadrat (n=60), the mean visual estimate of ground cover was compared with the estimate from each of the other methods (mapped area, digital analysis and point quadrat, Figure 3-2*a*, *b* and *c*). Data relationships between visual and objective estimates were non-linear (second order polynomial, Figure 3-2) with 92, 87 and 91% of the variation in mean visual estimate explained by the variation in the mapped area cover (Figure 3-2*a*), digital image analysis cover (Figure 3-2*b*) and photo point quadrat cover (Figure 3-2*c*) estimates, respectively. Mean visual estimate of ground cover was lower than that estimated by each of the objective methods indicating that observers underestimated ground cover, particularly in the mid-range (20-80% ground cover, Figure 3-2). Visual estimates were more scattered in the mid-range but had less variation towards the extremes of cover (0 and 100%).

The overall relationship between mean visual estimate and mean objective estimate of ground cover was non-linear (second order polynomial) with 93% of the variation in visual estimates being explained by variation in the objective estimates (Figure 3-3). This indicated that ground cover estimated by the visual method was highly correlated (r=0.96) with the mean of objective measures, but the relationship indicated that observers tended to underestimate cover in the mid-range. Mean visual estimate of ground cover (all quadrats and observers) was 73.7 ± 3.5% compared with the mean objective estimate of 83.7 ± 2.7%.

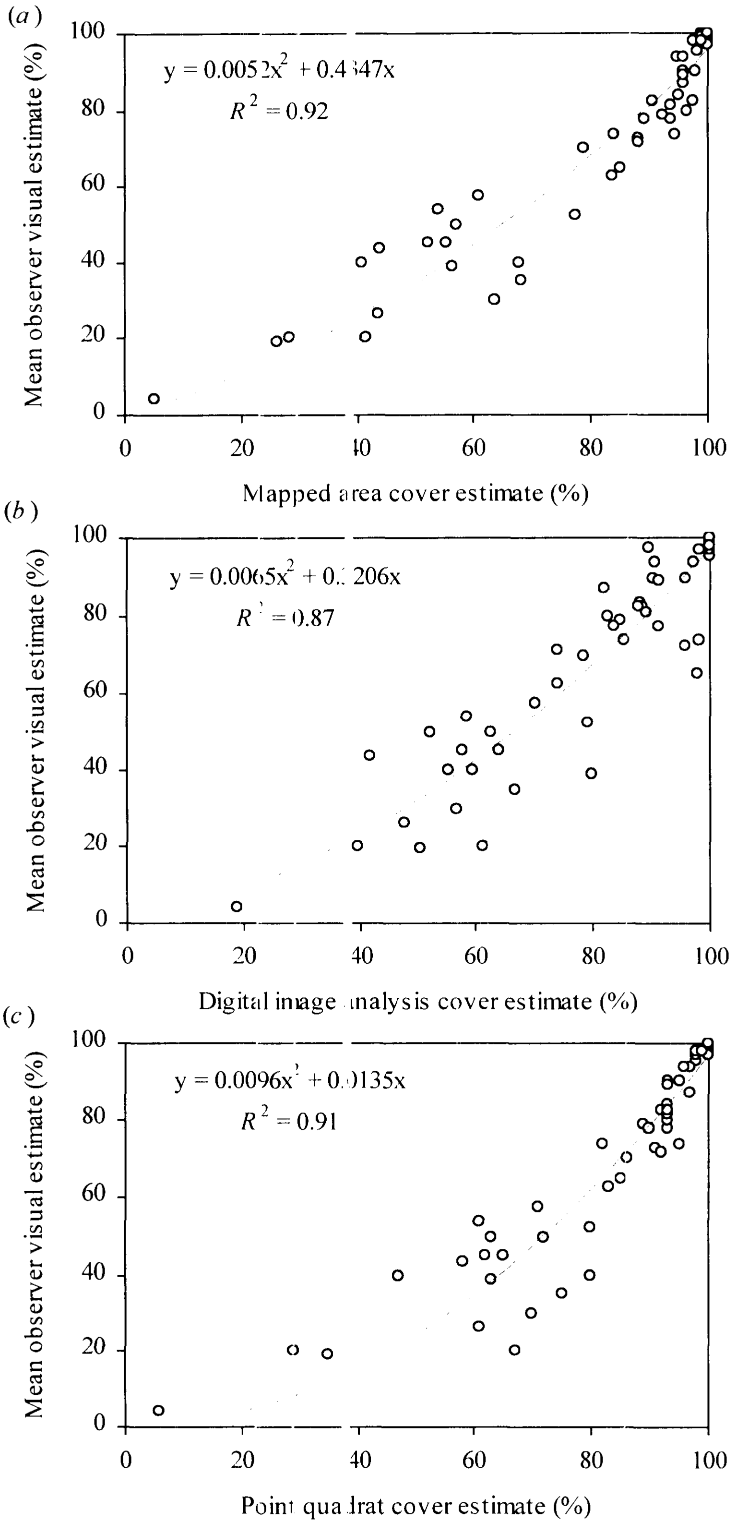

Figure 3-2. Relationship between mean observer visual estimate of ground cover (%) and each of the objective estimates of ground cover (%) for (*a*) mapped area estimate, (*b*) digital image analysis, and (*c*) point quadrat methods.

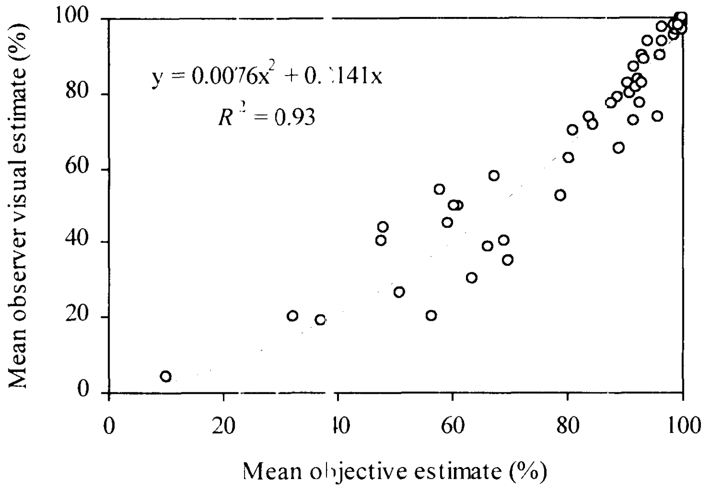

Figure 3-3. Relationship between mean observer visual estimate of ground cover (%) and mean objective estimate of ground cover (%).

Canopy cover

Mean visual estimate of canopy cover was highly correlated (r=0.95) with that of the mapped area method and was best described by a linear regression relationship (R^2=0.90, Figure 3-4). However, the mapped area method gave markedly lower estimates of canopy cover in two quadrats compared with the visual estimate (53 *vs*. 86%; 6 *vs*. 33%, Figure 3-4). Both of these quadrats contained wiregrass tussocks and had a diffuse canopy structure that was difficult to map. Hence, for these two quadrats, the visual estimate of canopy cover was probably more representative than that estimated by the mapped area method. Overall, the mean visual estimate of canopy cover (34.6 ± 3.7%) was similar to that for the mapped area method (34.3 ± 3.9%, n=60).

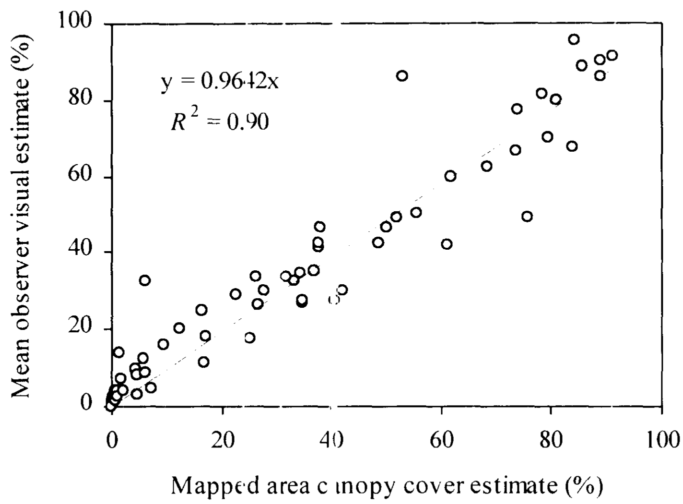

Figure 3-4. Relationship between mean visual estimate of canopy cover (%) and mapped area estimate of canopy cover (%).

Variance of visual estimates

For mean ground cover, the highest variation occurred in the mid-range, between 20 and 80% as shown by the quadratic regression relationship (R^2=0.71, n=60, Figure 3-5*a*). As ground cover approached the extremes of 0 and 100%, variation around the mean reduced, indicating that observers estimated cover with more accuracy. Plots of variation of mean visual estimates of canopy cover were similar, but the data relationship was not as strong, with more variation across the range of canopy cover values (R^2=0.43, n=60, Figure 3-5*b*). Again, the greatest variation around the mean was in the mid-range.

Time required completing assessment per quadrat

Each of the estimation techniques required a different length of time to complete assessments, in both the field and the laboratory. In the field, time requirements per quadrat ranged from 0.5 minute for the visual method to 5 minutes for the mapped area method (Table 3-10). While in the laboratory, the visual technique had no time requirements and the digital analysis method took a further 20 minutes per quadrat to complete (Table 3-10).

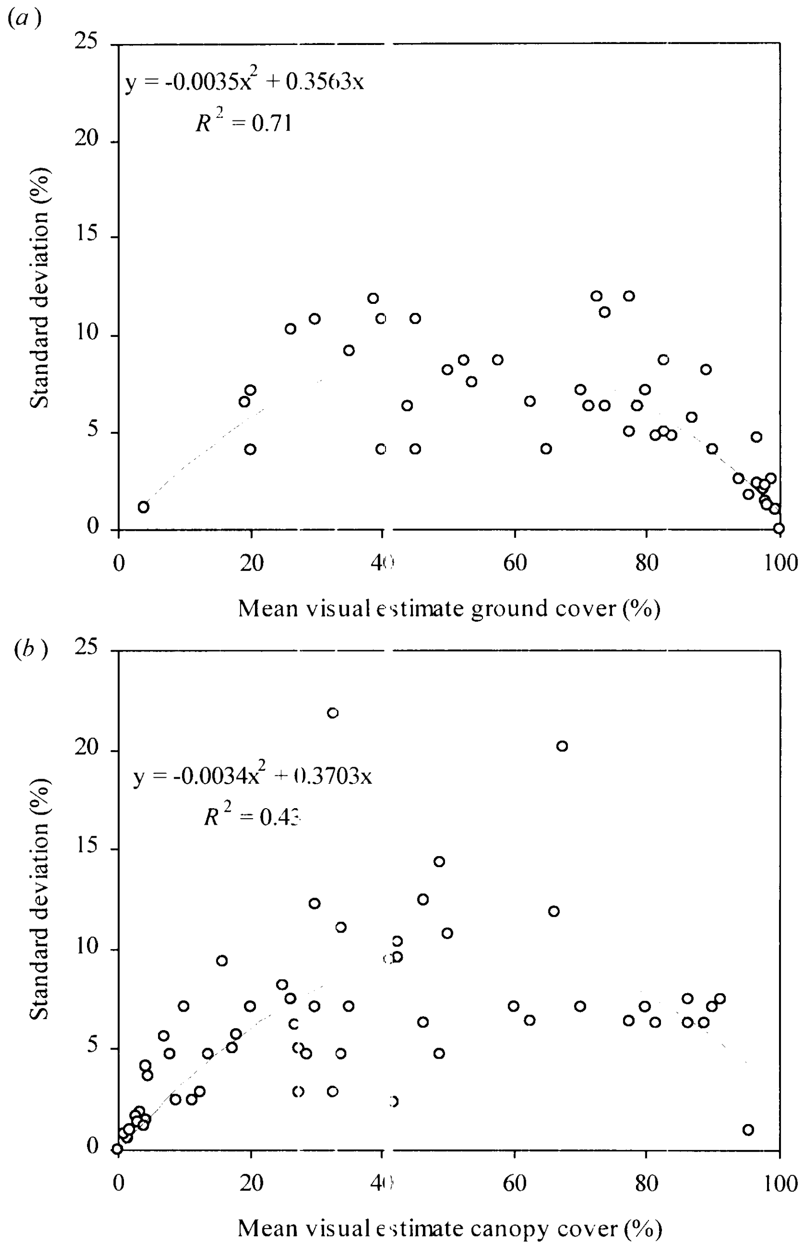

Figure 3-5. Standard deviation compared with the mean of observer estimates of each quadrat for (*a*) ground cover (%), and (*b*) canopy cover (%).

Table 3-10. Approximate time required (minutes per quadrat) to perform ground cover assessments using each of the estimation methods.

Estimation Technique	**Field**	**Laboratory**
Visual estimation	0.5	0
Mapped area	3-5	10
Digital image analysis	2	20
Photo point quadrat	2	2

3.4.3 Discussion

After simple training, inexperienced observers were easily able to estimate ground cover by visual means. Further, their estimates of ground cover and canopy cover were similar to those of experienced observers and they could readily distinguish ground cover ranging from < 5 to 100%. This indicates that the visual method is easily learnt and could be readily used to estimate ground cover within broad categories of low (< 40%), medium (40-70%) and high (> 70%) as used in management tools such as the Pasture Health Kit (McCormick and Lodge 2001). Therefore, it is reasonable to conclude, that inexperienced observers could identify an important threshold of ground cover, such as that suggested by Lang (1979).

Mean visual estimates of total ground cover and canopy cover by inexperienced observers were within 1.4 and 2%, respectively, of the experienced observers' estimates. While there was reasonably good agreement between experienced and inexperienced observer estimates in this study, they may be further improved by the use of visual aids, such as photographic standards of ground cover, as used in the Pasture Health Kit (McCormick and Lodge 2001). In these studies, both the inexperienced and experienced observers underestimated cover in the mid-range to about the same degree. Again, reference to photographic standards may assist in overcoming such underestimation.

As noted previously, all observers tended to underestimate ground cover compared with the objective methods. This was probably related to the ability of the human eye to look 'through' pasture to delineate areas of bare ground, subsequently overestimating its proportion. Conversely, the objective methods tended to amalgamate areas of cover, overestimating its proportion. This was evident in the mapped area method, which had the strongest non-linear relationship with visual estimates. This method however, was least sensitive at recording diffuse cover since the complex patterns of cover components were difficult and time consuming to map. Inevitably, small discrete areas of cover were mapped as areas of bare ground because of the time required to record them accurately.

The higher levels of variation in the visual estimates of canopy cover compared with those of ground cover were probably associated with the process of estimating canopy cover. Firstly, the observers had to determine which, if any components of the pasture were higher than 5 cm, and secondly estimate their percentage area. Since each is subject to variation in observer perception, the variation around the mean tended to be broader for canopy cover compared with ground cover.

Under laboratory conditions, Hatton *et al.* (1986) investigated the variation of visual estimates of cover using artificial maps and concluded that estimates within the mid-range had the largest variation. This resulted from the difficulty of integrating boundary effects in complex cover patterns. Similar to the current study, they suggested that if observers were required to identify ranges of cover, they were able to distinguish small changes in cover class at the extremes but were less able through the mid-range.

For the current data, there were more quadrats representing high rather than low ground cover. The eight quadrats with the lowest values had a substantial influence on the relationship between mean visual estimate and each of the objective methods. Observer estimates for these quadrats were in the range of 4-40% but objective method estimates were higher (6-80%). These quadrats were all visually challenging with complex patterns of ground cover and bare ground that were difficult to delineate.

Digital image analysis overestimated ground cover in some low cover quadrats compared with the mapped area and point quadrat methods. When photographic prints were scanned, bare ground, dry pasture and litter had the potential to be assigned very similar colours when cover was low. This difficulty of identifying unique pixel colours corresponding to either cover or bare ground led to an overestimate of cover. The digital method could be improved by scanning at a higher colour saturation and pixel resolution to increase the definition of each ground cover component. However, this would considerably increase the time and computing resources required. Also, in a study that compared cover estimates using digitised photographs, Vanha-Majamaa *et al.* (2000) recommended that to maintain the spectral accuracy of the image, the original film should be scanned rather than a paper print.

3.4.4 Conclusion

Visual estimation was relatively quick and gave estimates of ground cover that were within 10% of those obtained by using objective methods. It is therefore suited to land management research that requires estimates of cover within this level of accuracy because of its speed, simple equipment and minimal specialised training. Vanha-Majamaa *et al.* (2000) also concluded that the visual estimation technique provided reliable cover estimates quickly and cheaply. The mapped area method was the slowest in the field, required considerable laboratory processing time (cutting out ground cover areas and measuring with an electronic area meter) and accumulated errors at each stage. Digital image analysis took only 2 minutes in the field but considerably more time in the laboratory, and it required photographic equipment, a digital scanner and specialised computer software to identify ground cover, making the method laborious and expensive. The point quadrat method was the fastest of the objective methods in the field, but still required some processing after photography. The key benefit of the visual method was its speed. The technique may be used to collect large sample numbers in a relatively short period with suitable accuracy. The data from this study indicated that the visual estimation technique for assessing ground and canopy cover, gave results that were comparable with other objective measures, and due to the speed of the technique, is suitable for monitoring ground cover in field scale pasture studies.

3.5 Installation and calibration of Watermark electrical resistance sensors

In pasture systems, surface soil water content is an important factor that can influence plant growth, surface runoff, and evapotranspiration. However, estimation of surface soil water content is often problematic in hard setting soils (e.g. with time domain reflectometry, TDR), labour intensive (e.g. physical sampling), or intermittent (e.g. neutron moisture meter). Nevertheless, data obtained in real time are essential to understanding the dynamics of surface soil water content (Murphy and Lodge 2001*b*). Electrical resistance sensors, when coupled with automatic data loggers, have the potential to provide such real time data.

Watermark electrical resistance sensors were used to provide stored soil water data in surface runoff studies (see Chapter 5), evapotranspiration studies (see Chapter 6) and stored soil water measurements (see Chapter 7). The data were collected at various time intervals that ranged from 4 minutes to monthly in runoff studies and stored soil water measurements, respectively. The following section details the installation and calibration of the electrical resistance sensors to provide these real time data.

3.5.1 Methods

Resistance sensors

The type of resistance sensor used in these studies was a 'Watermark 200® soil moisture sensor' manufactured by Irrometer Co., Riverside California USA (22 mm diameter, 80 mm long). The resistance sensor is similar to a 'gypsum block' in that it consists of two electrodes embedded in a porous matrix. However, unlike gypsum blocks the matrix is enclosed in a perforated stainless steel casing with a synthetic membrane lining that protects the matrix from deterioration. A gypsum tablet buffers soil water against soil salinity. before the water can access the electrodes (Proulx *et al.* 1999). The manufacturer indicated that these sensors measured the full range of soil water potential assuming that the potential of the sensor was in equilibrium with that of the surrounding soil. In addition, the sensors required no maintenance or individual calibration, and had a long service life. They were promoted for use in irrigated horticulture applications for the scheduling of irrigation requirements. In a study comparing a range of soil moisture sensors, Proulx *et al.* (1999) provided a general description of the sensor and its operation.

Resistance sensors were connected to automatic data loggers (Tain Electronics 'Micropower Mark III' 8 or 16 channel data loggers) and were interrogated by an alternating current to prevent polarisation (Fowler and Lopushinsky 1989). The sensor and logger systems provided calibrated soil water potential data between 0 and -207 kPa at intervals of 4 or 30 minutes. Tain Electronics provided a polynomial function specific to the Watermark sensor that described the electrical resistance response in relation to the water potential of the sensor and so the surrounding soil water potential.

Arrays of sensors were installed at Springmount (2.5, 5, 7.5, 10, 15 and 20 cm depth) in summer 1997-98 in four surface runoff plots (see Chapter 5) and at TCCI (2.5, 7.5 and 15 cm depth) in winter 2000 in each of 12 treatments (see Chapter 6). Before installing the sensors, they were saturated with water for 24 h so that the sensors would equilibrate to the surrounding soil when installed. A narrow trench was excavated and pre-wetted sensors were inserted horizontally at each depth into undisturbed soil on the sidewalls, and sensors were located diagonally across the sidewall so that they were not vertically above one another. To ensure good contact between the surrounding soil and each sensor, they were installed individually and firmly packed, so that the water potential of the sensor was equal to the soil and that rainwater tracking down the array was limited. Sensors are normally installed vertically (at depths > 20 cm), but to detect soil water content change in narrow layers they were installed horizontally (Mitchell and Shock 1996). Intact soil sods and plants were placed over the disturbed area to recreate soil surface conditions similar to those prior to installation. Sensors were connected to each logger with cable lengths of < 2 m to avoid capacitance affects within the cable. Sensors were in continuous operation from summer 1997-98 to end of spring 2001 and from winter 2000 to end of summer 2001-02, at Springmount and TCCI, respectively.

Calibration

Soil water potential readings estimated by each sensor were calibrated for volumetric soil water content for each soil type and depth of installation. Before calibration data were collected, the sensors were allowed to equilibrate with the soil profile, going through several wetting and drying cycles. Electrical resistance sensors typically exhibit hysteresis effects, but Watermark sensors generally respond quickly and consistently compared with gypsum blocks (Hanson *et al.* 2000*a*). Immediately after rain, soil samples were taken (approx. 125 g dry soil) from undisturbed soil adjacent to the sensors at depths, corresponding to each sensor and this collection was repeated until the soil was dry. Soil water content was determined gravimetrically (θ_g%, g/g) and converted to volumetric content (θ_{vol}%) using bulk density data (ρ_s Mg/m^3, Table 3-2). A natural log transformation [$\log_n(\psi_s)$] was applied to soil water potential data giving a linear regression relationship ($\theta_{vol}\%$ = a (X) + b; where X = $\log_n(\psi_s)$) for each site and depth. Regression slope and intercept coefficients were then tested for significant differences.

Surface runoff studies (Chapter 5)

Sensors were used to provide soil water content data at short time intervals (4 minutes) associated with surface runoff events. These data were used in the interpretation of runoff generation processes and to further understanding about the interaction between rainfall, soil water content and runoff. Stored soil water of the profile between 0 and 20 cm was calculated as the addition of the stored soil water (mm) for the layers represented by each sensor ($\theta_{vol}\%$ x depth in mm).

Evapotranspiration studies at TCCI (Chapter 6)

Resistance sensors recorded daily surface stored soil water to assist in the interpretation of evapotranspiration studies conducted on experimental plots with a range of pasture conditions. Specifically, the data were used to define the stored soil water between 0 and 20 cm depth of each plot in relation to evapotranspiration rate. Also, stored soil water data recorded at 09:00 h were used to monitor rate of drying over extended periods.

Surface stored soil water (Chapter 7)

In this study, resistance sensors were used to provide representative estimates of stored soil water of the surface layer (0 to 10 cm) and complemented measurements made using a neutron moisture meter (10-210 cm) for each grazing treatment. On each sampling day, soil water content data was obtained at 09:00 h from the resistance sensors (0-5 cm and 5-10 cm depths) and complemented data obtained using the neutron moisture meter (10-30 cm). Values were used at this time of the day to minimise temperature effects between heating and cooling of the soil surface and the sensors.

3.5.2 Results

Calibration of the Watermark resistance sensors

Soil samples were collected with soil water content between 3 and 46%, and were compared with water potential values estimated by the resistance sensors (-207 and -3 kPa, Figure 3-6). The linear regression relationships for each depth were tested for significant differences between slope (a) and intercept (b) coefficients. Slope coefficients for depths 2.5, 5.0 and 7.5 cm were significantly different at Springmount (Table 3-11), while values for depths 7.5 and 10 cm were similar, as were values for 15 and 20 cm. For TCCI, all slope coefficients were significantly different (P<0.05). For Springmount, the intercept values for soil depths of 7.5 and 10 cm were not significantly different, while values for all other depths were different (P<0.05) from each other (Table 3-11). Intercept values for all depths at TCCI were significantly different (Table 3-11). Differences among depths, for slope and intercept coefficients, were attributed to the range of soil water contents estimated at each depth. Samples collected closest to the surface tended to have a wider range of soil water content values because of unrestricted soil wetting and evaporative drying, respectively. These differences in slope and intercept were sufficient to warrant the use of individual calibrations for each depth.

Table 3-11. Mean volumetric soil water content (θ_{vol}%) of calibration data for each site and depth together with the linear regression relationship coefficients ($\theta_{vol}\% = a(\log_n(\psi_s)) + b$) for each site and depth that watermark sensors were installed.

Depth (cm)	θ_{vol}%	a	b
	Springmount		
2.5	22.0^{a}	-9.3^{a}	55.9^{a}
5.0	19.8^{a}	-6.9^{b}	44.9^{b}
7.5	19.5^{a}	-5.1^{cd}	38.1^{c}
10	20.2^{a}	-4.8^{d}	37.1^{c}
15	21.0^{a}	-4.1^{e}	34.7^{d}
20	21.1^{a}	-3.8^{e}	32.9^{e}
	TCCI		
2.5	23.6^{a}	-4.3^{a}	37.9^{a}
7.5	25.4^{a}	-3.1^{b}	34.6^{b}
15	23.9^{a}	-2.1^{c}	29.0^{c}

NB: Values in each column for each site with the same superscript were not significantly different ($P>0.05$).

3.5.3 Discussion

The resistance sensors were calibrated in the field for volumetric soil water content. Previously, some attempt was made to calibrate resistance sensors for soil water content under laboratory conditions (Yoder *et al.* 1998; Proulx *et al.* 1999). In those studies, soil bulk density and water content were controlled, which enabled accurate calibration. Here, under field conditions, a higher level of variability was encountered, which led to different calibration equations for each soil type and depth that resistance sensors were installed (Table 3-11). The range of wetting and drying experienced by each sensor generated significantly different regression equations that best described the relationship between soil water content and sensor matric potential at each depth.

Resistance sensors are usually calibrated for soil water potential to monitor soil water status (McCann *et al.* 1992; Spaans and Baker 1992; Thomson *et al.* 1996). For any particular type of resistance sensor, the relationship between its water content and electrical resistance is an empirical one, and can be defined under laboratory conditions. For irrigation scheduling in horticultural production, calibration of the sensors for soil water potential may be satisfactory. However, in studies that require the total amount of soil water (e.g. stored soil water, mm), resistance sensors need to be calibrated for soil water content, which requires knowledge of the relationship between soil water content and soil water potential for that soil (Proulx *et al.* 1999). This relationship is difficult to obtain, since it requires specialist equipment that is often beyond simple agronomic research (e.g. pressure plate and tension table apparatus). However, by calibrating matric potential from the resistance sensor with *in situ* soil water content, a surrogate water retention curve was developed over the response range of the sensor.

Some studies have shown that electrical resistance sensors can operate over a wider range of soil water potential (e.g. 0 to -2000 kPa, Yoder *et al.* 1998; Johnston 2000) than was possible in the current study (0 to -207 kPa). The narrow range in the current study was limited by the sensitivity of the data logger configuration, which is 0.37 to 29 kΩ (or 0 to -207 kPa). This limitation was particularly pronounced when soils were dry. As the soil dried so that maximum electrical resistance within the sensor was attained (29 kΩ at -207 kPa), further drying could not be measured. At a soil water potential of -207 kPa, the soil water content obtained from soil samples ranged from 4 to 12% (Figure 3-6), indicating that the resistance sensors were unable to respond when soils were very dry. A wider electrical response would give a greater range over which soil water content could be monitored. The crux of this issue is the need for a data logger with suitable sensitivity that could interrogate the resistance sensors over a wider range of electrical resistance. Similarly, when sensors that were located within 10 cm of the soil surface were wet (i.e. < -3 kPa), the corresponding values of soil water content ranged between 28 and 46% (Figure 3-6). This indicated both the variability of surface soil water content conditions and the difficulty of obtaining samples that were representative of where the sensors were located. In addition, few calibration points were obtained when soil water potential was between -3 and -15 kPa, giving the appearance of a gap in data when plotted on the natural log scale. Watermark sensors were reported to show hysteresis effects during wetting rather than drying (Jovanovic and Annandale 1997) and so may explain the range of values recorded when sensors were wetting up.

Each Watermark sensor cost $85 AUD (September 2001), which was cheap compared with other sensor types such as TDR waveguides (e.g. $170 AUD per waveguide, Campbell Scientific Australia, personal communication). In addition, installation of delicate TDR waveguides at study sites that had a hard setting soil surface would have required substantial disturbance. The resistance sensors, in comparison with manometers or tensiometers, gave continuous data over various time scales. While automatically sensed tensiometers are available, they need regular inspection that would make them unsuitable for remote installations. Also, tensiometers would not have been suitable during extended dry periods (Aggelides and Londra 1998) that are regularly experienced by pastures in the current study. In a study comparing the effectiveness of tensiometers and resistance sensors, Hanson *et al.* (2000*b*) found that resistance sensors had greater reliability and responded over a wider range of soil water potential. The resistance sensor system used here was relatively easy to install, calibrate and maintain, and was considerably cheaper than competing technology.

3.5.4 Conclusion

Site and depth specific calibration equations were derived that relate soil water content and matric potential within the Watermark sensor. These sensors provide a technique that is suitable to collect calibrated measurements of stored soil water for the surface layers of runoff plots and evapotranspiration plots in real time. These sensors are also suitable to provide estimates of surface stored soil water for incorporation with profile estimates of deeper stored soil water using the neutron moisture meter.

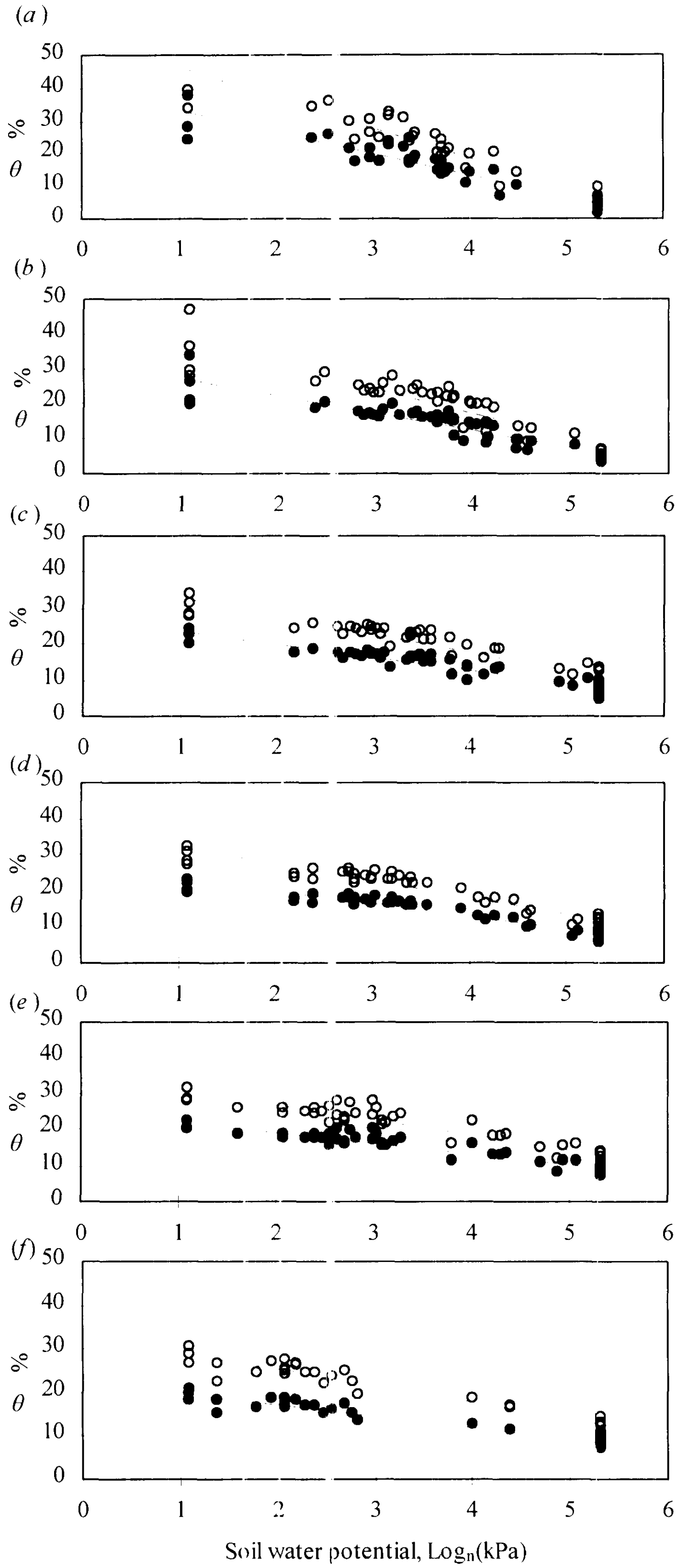

Figure 3-6. Linear relationships between water content (● θ_g%, ○ θ_{vol}%) and soil water potential [Log_n(kPa)] of electrical resistance sensors at Springmount for each installation depth (*a*) 2.5 cm, (*b*) 5.0 cm, (*c*) 7.5 cm, (*d*) 10 cm, (*e*) 15 cm, and (*f*) 20 cm.

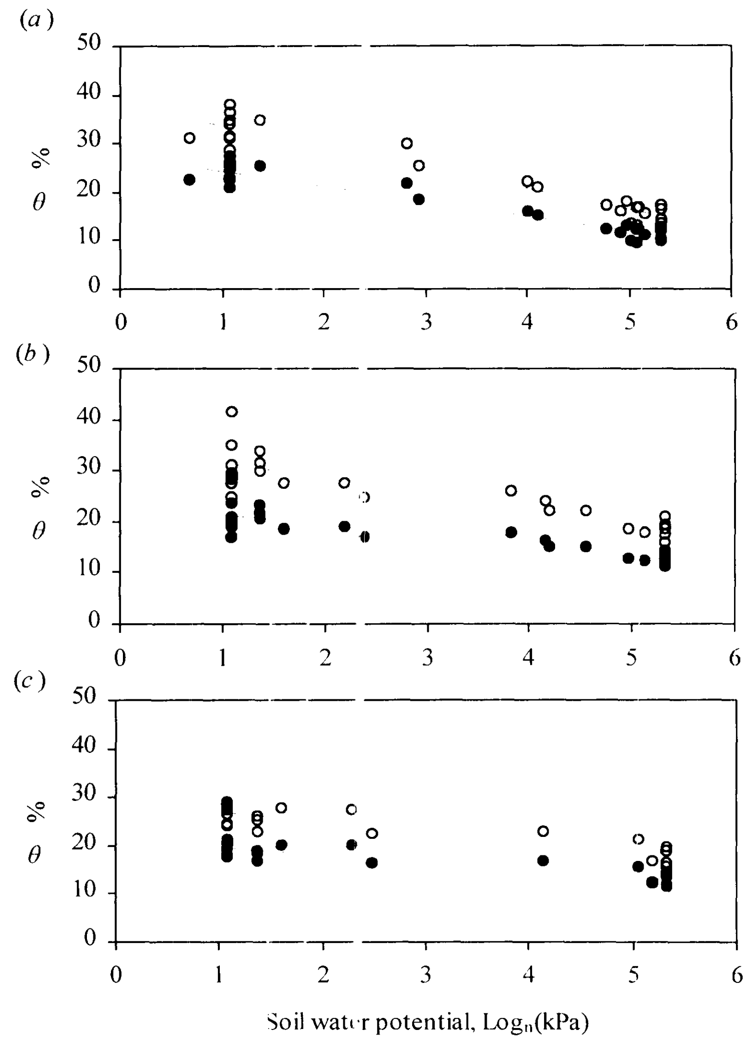

Figure 3-7. Linear relationships between water content (● θ_g%, ○ θ_{vol}%) and soil water potential [Log_n(kPa)] of electrical resistance sensors at TCCI for each installation depth (*a*) 2.5 cm, (*b*) 7.5 cm, and (*c*) 15 cm.

4 The effects of climate and grazing management on herbage mass, litter mass, ground cover and species composition

"***Natural pastures are generally dominated by warm season perennial grasses, which determine the general structure and productivity of the pasture communities.***" (Lodge *et al.* 1984)

4.1 Introduction

The North-West Slopes of NSW is a summer rainfall dominant environment with 35% of annual rainfall received between December and February (Clewett *et al.* 1999). The species composition of natural pastures is dominated by warm season caespitose species such as redgrass, wiregrass and bluegrass (Lodge 1983; Garden *et al.* 2000). These species grow during the warmer months when temperatures and rainfall are usually higher.

Seasonal rainfall is the main driver of herbage accumulation with sporadic periods of growth when rainfall and stored soil moisture are adequate (Simpson *et al.* 1998). Grasses such as redgrass have the ability to go dormant during periods of low rainfall, conserving carbohydrate reserves until conditions more favourable for growth eventuate. Herbage accumulation (or depletion) is the result of the simple difference between herbage growth rate and intake or decomposition. Lodge (1983) reviewed the effect of grazing management on natural pasture on the North-West Slopes, particularly continuous, rotational and deferred rest grazing strategies. Stocking rate and timing of grazing in combination with climatic influence were the most important determinants of herbage mass dynamics in these grazed pastures.

Higher grazing intensity reduces herbage mass compared with lower intensity. In a study of the effect of grazing intensity on pasture production on the Northern Tablelands, Langlands and Bennett (1973) showed that herbage mass declined with increased intensity. A challenge that faces many graziers is the difficult task of assessing pastures to match stocking intensity with pasture growth, percent green leaf, legume content and digestibility, as it requires the successful integration of pasture characteristics with livestock requirements (Bell and Allan 2000).

Residual herbage mass and litter mass after grazing are important for reasons relating to the hydrological balance. In separate reviews, both Gifford and Hawkins (1978), and Greenwood and McKenzie (2001) explored the important relationship between grazing intensity and infiltration, showing that higher grazing intensity decreased the rate of infiltration. Often, a critical factor associated with lower infiltration is the loss of herbage mass or ground cover. Warren *et al.* (1986) investigated the effects of short duration high intensity grazing on soil physical properties, infiltration and runoff response and concluded that such practice damaged soil structure and reduced herbage mass leading to increased runoff and erosion. In terms of the amount of water used by pastures, Dunin (1969*b*) indicated that the composition of pasture might influence the rate of evapotranspiration. Sowing subterranean clover and the application of phosphate fertiliser on natural pasture on the North-West Slopes is a management practice that is increasing and has greatly improved production (Lodge *et al.* 1991). Such practice may also alter the timing and magnitude of water use by these pastures.

In recent years, pasture litter appears to have been largely ignored in the pasture and grazing literature, suggesting that its role in pasture systems has been forgotten. Beutner and Anderson (1943) discussed the importance of managing grazing so that litter mass was maintained. They thought that litter mass was important for soil moisture conservation, surface runoff prevention and encouraging pasture growth. Although there were no physical methods for measuring microbial activity at that time, White (1946) indicated that litter was important for encouraging microbial activity in the surface soil. However, both Gill *et al.* (1998) and Molinar *et al.* (2001) recently reported that increased grazing intensity led to lower litter mass. Grazing management that encourages litter accumulation (e.g. trampling of pasture by grazing at higher intensity to increase leaf fall) may also benefit populations of soil organisms (King and Hutchinson 1983). Hormay (1970) discussed the importance of resting pastures from grazing so that litter may accumulate between plant bases and so resting may be an important tool in pasture management.

The objective of this experiment was to evaluate the impact of a range of grazing management treatments on a redgrass dominant pasture at Springmount. The specific aims were:

a) to determine the effect of grazing management (continuous, short and long rotation grazing) and seasonal conditions on herbage mass, litter mass, and ground cover;
b) to determine the effect of applied subterranean clover and fertiliser on herbage mass, litter mass and ground cover compared with other treatments;
c) to monitor the percent green leaf of pasture; and
d) to monitor pasture species composition for any change with different grazing management.

Treatment effects on animal production, including live weight change and wool production were not considered within the current study, but were reported by Lodge *et al.* (2003*b*). Relevant findings included that sheep live weight in the treatment with subterranean clover and fertiliser applied (T3FERT8) was significantly higher compared with the continuously grazed treatment (T1C4).

Wool cut per head in the subterranean clover treatments (T3FERT8) was significantly greater than all other treatments (Lodge *et al.* 2003*b*).

4.2 Methods

4.2.1 Climate

Weather data were recorded at 30 minute intervals from an automatic weather station (Tain Electronics 'Micropower Mark III', 16 channel automatic data logger). Daily data (sensors and units of measurement in Table 4-1) were used to calculate potential evapotranspiration (mm) using the methods of Penman-Monteith (Smith 1992) and Priestly-Taylor (Priestly and Taylor 1972). The weather station was located centrally to the study site and was fenced to exclude stock. The enclosure was mown regularly to maintain a low lawn, but was not irrigated.

Rainfall was measured with two 'Monitor Sensors' tipping bucket pluviometers that measured 0.2 mm rainfall depth with each tip. Rainfall intensity (mm/h) was recorded at 1 minute intervals and averaged for 4 minute duration, while total rainfall was recorded at 30 minute intervals. Air temperature and relative humidity sensors were housed in a Stevenson Screen. Global solar radiation flux (W/m^2.s) was measured with a silicon cell pyranometer (peak response at 700 µm, 70% response limits of 500-900 µm) mounted 2 m above the soil surface and values were transformed into radiant energy in MJ/m^2.d. Average wind speed (m/s) was measured with an anemometer mounted 3.0 m above ground level, and converted to wind run in km/d. Soil temperature was measured at 2.5 and 5.0 cm depth below the soil surface. A small hole was excavated to place each temperature sensor in, with minimal disturbance to the surrounding area.

Table 4-1. Data recorded by the automatic weather station at 30 minute intervals, including sensor type and units of measurement.

CHANNEL	DATA	SENSOR	UNIT
1	Rainfall	Pluviometer (0.2 mm)	mm
2	Relative humidity	Mirror resistor	%
3	Solar radiation (2 m height, 500-900 μm)	Silicon cell pyranometer	MJ/m^2
4	Air temperature (screen)	Thermistor	°C
5	Soil temperature (2.5 cm)	Thermistor	°C
6	Soil temperature (5.0 cm)	Thermistor	°C
7	Wind speed (3 m height)	Cup anemometer	m/s

4.2.2 Herbage mass, litter mass, percent green leaf, ground cover and species composition

The BOTANAL technique (Tothill *et al.* 1992) was used to estimate pasture herbage mass (kg DM/ha), litter mass (kg DM/ha) and species composition (as a percentage of herbage mass) every 12 weeks at the beginning of each season, that is March (autumn), June (winter), September (spring), and December (summer). An extra sampling was performed in October (mid-spring) when growth rates were high. A dry-weight rank method was used to class species contributions to total herbage mass (Mannetje and Haydock 1963). Multiplier values for tied and cumulative ranks were applied following Jones and Hargreaves (1979). The comparative yield method of Haydock and Shaw (1975) was used to calibrate observer estimates of herbage mass. Species composition was determined by the dry weight rankings and each species was assigned an herbage mass value as a proportion of total herbage mass of each quadrat.

The technique was a non-destructive, quadrat based, visual, repeatable method suitable for small grazing plots. Each grazing plot had two permanently marked transects (22 m long) located centrally and starting at least 10 m from fence lines. Two observers independently assessed one of the two transects in each plot. A 40 by 40 cm quadrat was used to assess pasture at 2 m intervals along each transect, totalling 20 sample points per plot. In each quadrat observers estimated herbage and litter mass on a scale of 0 to 5, while ranking contribution (1 to 3) of individual species to total herbage mass. Percent green leaf and ground cover was estimated visually, using the technique described in Chapter 3 and by Murphy and Lodge (2002).

Prior to each sampling, observer estimates of herbage and litter mass and percent green leaf were calibrated for each observer. Thirty calibration quadrats were selected across grazing treatment plots so that the range of expected conditions was sampled. In each quadrat, each observer ranked herbage and litter mass on an arbitrary scale of 0 to 5 and percent green leaf (%) was estimated. Approximately 10 quadrats were selected that had either low or high herbage and litter mass so that the calibration quadrats were representative of the range of conditions within the treatment plots. In each calibration quadrat, litter was collected separately by hand and then the herbage mass was harvested to ground level using electric shears. Litter samples were sorted to remove any non-litter components such as animal dung, soil and rocks, and green leaf. Harvested herbage material was sorted into green and dead components and oven dried at 80 °C for 48 h before weighing to give percent green leaf by weight and total herbage mass. Regression was used to determine the relationship between actual and estimated values from the calibration quadrats for herbage mass, litter mass and percent green leaf for each observer. The regression equations were then used to predict herbage, litter and percent green leaf from estimated values for quadrats in each treatment plot. Correlation coefficients (*r* values) ranged from 0.7 to 0.95 for herbage mass, 0.6 to 0.8 for percent green leaf and 0.5 to 0.7 for litter mass.

4.2.3 Data analysis

Rainfall data (monthly and annual) were compared with the long-term average conditions to ascertain the representativeness of climate conditions throughout the study. Percentiles of rainfall were obtained for the nearest official recording station at Barraba, which had 117 years of record (Clewett *et al.* 1999).

GENSTAT (Payne *et al.* 1988) was used to determine treatment differences in herbage mass, litter mass, ground cover and percentage of green leaf at each sampling date using analysis of variance (ANOVA). A covariate term was used each spring (the conditions at the previous spring or start of experiment) to account for the effect of previous conditions on current conditions. Species composition determined by the dry weight of perennial grass was monitored throughout the grazing study.

4.3 Results

4.3.1 Climate

The long-term average annual rainfall for Barraba is 694 mm (Clewett *et al.* 1999) with 241 mm (or 34.7%) of the total received in summer (Figure 4-1). Annual rainfall during the study was above average in 1998 (724 mm), near average for 1999 (666 mm), and below average in 2000 (602 mm), and 2001 up until September (402 mm, Figure 4-1). Rainfall in summer was below average in 1998-99 (-107 mm) and 1999-00 (-119 mm). Rainfall in summer 1997-98 was average and that of 2000-01 was slightly below average. Winter of 1998 was the third wettest winter on record at Barraba (328 mm, Clewett *et al.* 1999) and at Springmount 275.5 mm was recorded, followed by a wet spring with a further 217 mm. Spring rainfall in 1999 and 2000 was also well above average with 256 and 217 mm, respectively. Potential evapotranspiration calculated from weather data collected at the site generally exceeded rainfall for most months (Figure 4-1). The only periods that rainfall exceeded potential evapotranspiration were June to September 1998, and for the months of October 1999 and July 2001. Maximum daily rainfall was 54 mm on 26 June 1998, and the peak intensity was 123 mm/h on 13 December 2000. The minimum and maximum temperatures were -4.5 and 38.6 °C, recorded on 7 June 2000 and 28 November 1997, 20 January 2000 and 15 January 2001, respectively. The mean daily minimum temperature was 2.1 °C for August 2001 and the mean daily maximum was 33.1 °C for November 1997 (Figure 4-2). Daily solar radiation flux density usually peaked in December or January (~30 $MJ/m^2.d$) and was lowest in June or July (~10 $MJ/m^2.d$) (Figure 4-2).

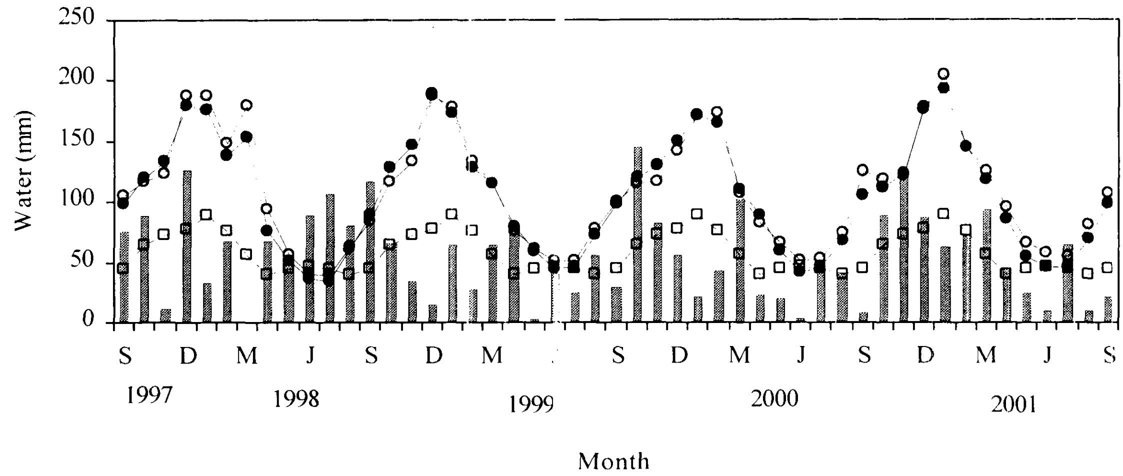

Figure 4-1. Monthly rainfall (mm, vertical bars) and potential evapotranspiration (mm, Penman Monteith - O and Priestly Taylor - ●) at Springmount with long-term mean monthly rainfall (mm - □) for Barraba (117 years of record, Clewett *et al.* 1999).

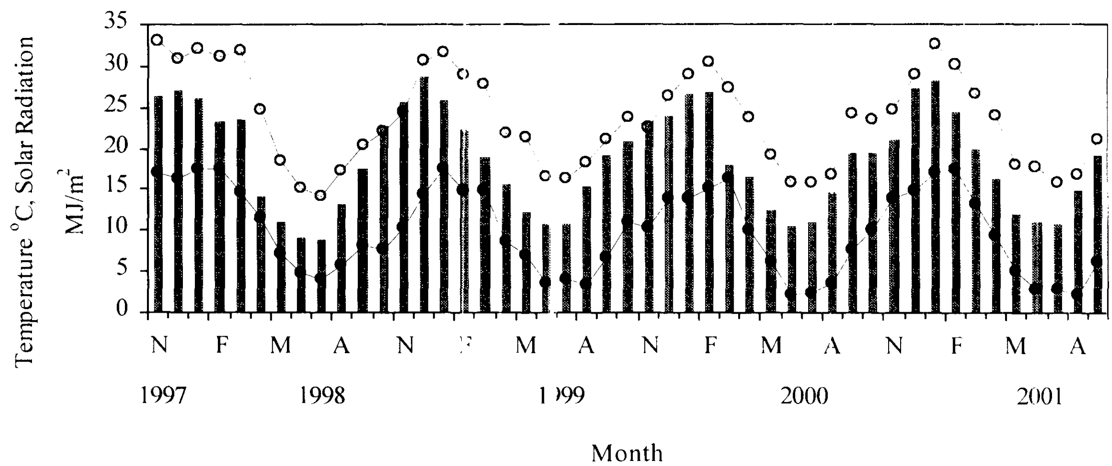

Figure 4-2. Mean monthly minimum (●) and maximum (O) temperature (°C) and the mean daily solar radiant energy flux (MJ/m², vertical bars) recorded at Springmount between November 1997 and September 2001.

4.3.2 Herbage and litter mass

Herbage mass was similar among treatments at the start of the experiment in September 1997 (mean herbage mass ~3600 kg DM/ha, Figure 4-3). By autumn 1998, treatment effects on herbage mass were significant ($P<0.05$), with the rotational treatments maintaining > 3200 kg DM/ha, while the other treatments declined to 2300 kg DM/ha (Figure 4-3). Herbage mass in the continuously grazed plots without fertiliser declined steadily to mean values of 1800 and 1500 kg DM/ha for T1C4 and

T2C6, respectively, and was significantly lower ($P<0.05$) than in the rotationally grazed treatments from September 1998 to September 2001. Both rotational grazing treatments maintained herbage mass as predominantly standing dead material, with the 4 week rotation having a mean of 3275 kg DM/ha and the 12 week rotation, 3581 kg DM/ha (Figure 4-3). From December 1999, the fertiliser and subterranean clover treatment also had significantly higher ($P<0.05$) herbage mass than the continuously grazed treatments. The preceding spring herbage mass was not significant as a covariate in any spring comparison.

The minimum treatment herbage mass was 593 kg DM/ha for T2C6 in October 1999 after a dry winter (Figure 4-1, Figure 4-3). At that time, sheep were removed from the grazing plots of this treatment and were supplementary fed. The maximum herbage mass was recorded in the long rotation treatment with 5829 kg DM/ha in March 1999 following the record rains of the previous winter and spring and summer pasture growth.

Initial litter mass was low in all treatments (due to prior management of the study site), with a mean mass of 47 kg DM/ha and no differences among treatments (Figure 4-4). Litter mass varied throughout the grazing experiment according to time of year and seasonal conditions, with greater amounts in spring (Figure 4-4). Litter accumulation was slow in all plots but the response was greatest in the rotationally grazed plots and those with fertiliser and subterranean clover. Mean litter mass in the subterranean clover plots (242 kg DM/ha) was double that in the continuously grazed treatments without fertiliser (112 kg DM/ha). The rotationally grazed treatments accumulated litter more readily in favourable seasons compared with the continuously grazed treatments. A minimum litter mass of < 15 kg DM/ha was recorded in T2C6 in October 1999, and a maximum of 780 kg DM/ha was recorded in T3FERT8 in March 1999. After December 1998, litter mass was significantly higher ($P<0.01$) in the subterranean clover and rotational grazed plots compared with the continuously grazed plots (Figure 4-4). The preceding spring litter mass was not significant as a covariate term in any spring comparison.

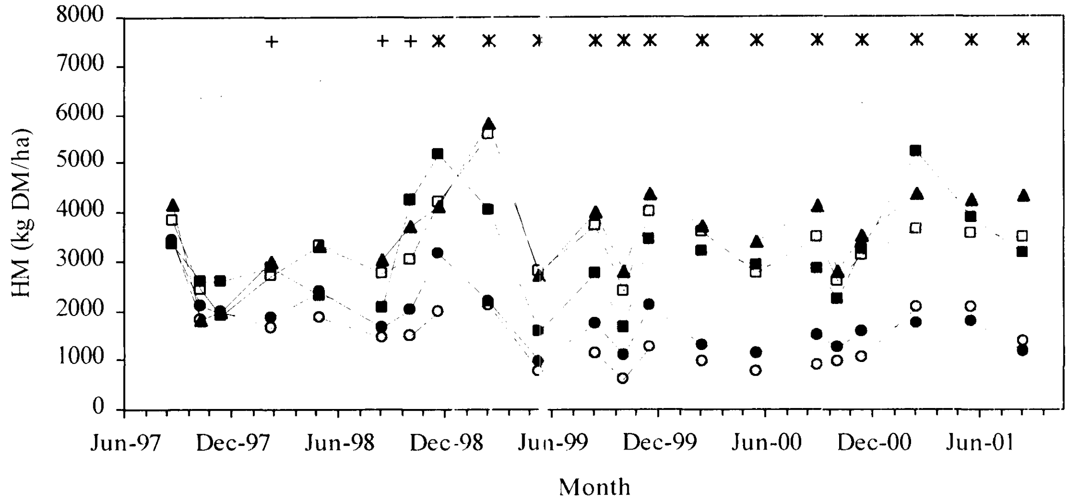

Figure 4-3. Herbage mass (HM kg DM/ha) estimated during BOTANAL assessments for each grazing treatment at Springmount (T1C4 - ●, T2C6 - O, T3FERT8 - ■, T4GR4 - □, and T5GR12 - ▲). Vertical bars indicate one standard error of the difference between herbage mass means. Significant differences are indicated by + (*P*<0.05) and * (*P*<0.01).

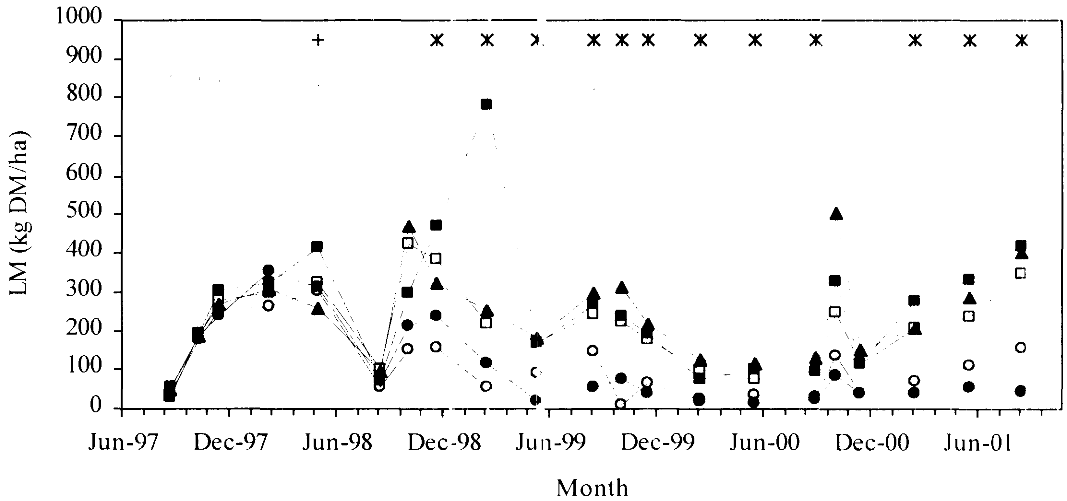

Figure 4-4. Litter mass (LM kg DM/ha) estimated during BOTANAL assessments for each grazing treatment at Springmount (T1C4 - ●, T2C6 - O, T3FERT8 - ■, T4GR4 - □, and T5GR12 - ▲). The vertical bars indicate one standard error of the difference between litter mass means. Significant differences are indicated by + (*P*<0.05) and * (*P*<0.01).

4.3.3 Ground cover

Ground cover of grazing treatments was similar when treatments were started in September 1997 with a mean of 66% (Figure 4-5). By December 1998, differences in ground cover had developed and these were maintained to the end of the experiment. The continuously grazed treatments (T1C4 or T2C6) without fertiliser had lower ($P<0.05$) ground cover than the rotation or subterranean clover treatments between December 1998 and September 2001 (Figure 4-5). The covariate term was not significant in any analyses of ground cover. The two continuous grazing treatments developed the lowest mean ground cover (73% T1C4, 70% T2C6) compared with the two rotation treatments with mean values of 83 and 85% for T4GR4 and T5GR12, respectively. The minimum ground cover of any treatment was 54% for T2C6 (May 1999). Ground cover in the fertilised subterranean clover treatment increased with seasonal growth flushes, peaking in October 1998 with a maximum cover of 98%. This treatment also had the maximum mean ground cover (90%).

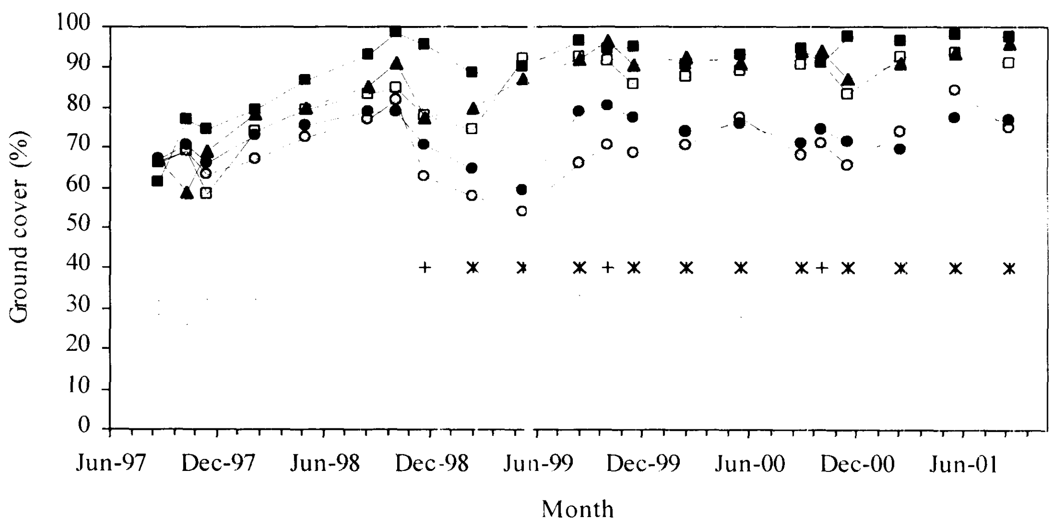

Figure 4-5. Ground cover (%) estimated during BOTANAL assessments for each grazing treatment at Springmount (T1C4 - ●, T2C6 - O, T3FERT8 - ■, T4GR4 - □, and T5GR12 - ▲). Vertical bars indicate one standard error of the difference between ground cover means. Significant differences are indicated by + ($P<0.05$) and * ($P<0.01$).

4.3.4 Percent green leaf

Grazing treatment affects on percent green leaf were rare (Figure 4-6). Each year, peak green content was recorded in September and October in response to spring rainfall and growth of perennial grasses (mainly redgrass). The rotationally grazed treatments generally had a lower proportion of green leaf due to the accumulation of standing dead (frosted) material within the pasture. In comparison, the continuously grazed treatments tended to attain higher maximum values of green with 81, 92, and 99% green leaf for T1C4, T2C6 and T3 FERT8, respectively, in October 1998. The fertiliser and subterranean clover treatment had the highest value of green leaf due to the presence of a large amount of subterranean clover (2880 kg DM/ha) at that time. Low green leaf content was recorded after prolonged dry periods in autumn or winter with just 3% green for T3FERT8 in June 2000 and 4% green for T2C6 T4GR4 and T5GR12 in August 2001. Mean percent green leaf ranged from 28% (T5GR12) to 37% (T3FERT8). Percent green leaf values were significantly lower (P<0.05) for the rotationally grazed treatments in September and December 1998, December 1999, December 2000, and March 2001, compared with the continuously grazed treatments (Figure 4-6).

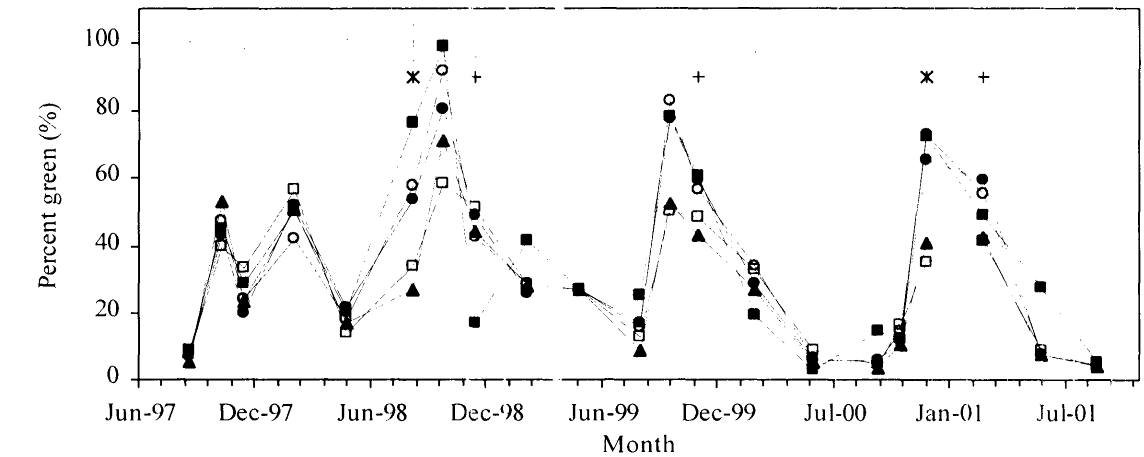

Figure 4-6. Pasture percent green leaf (% by dry weight) for each grazing treatment at Springmount (T1C4 - ●, T2C6 - O, T3FERT8 - ■, T4GR4 - □, and T5GR12 - ▲). Vertical bars indicate one standard error of the difference between percent green means. Significant differences are indicated by + (P<0.05) and * (P<0.01).

4.3.5 Species composition

During the spring of 1997, forbs (tarvine *Boerhavia diffusa* L. and kidney weed *Dichondra repens* Forster & G. Forster) were common in all treatments, due to the extended rest from grazing prior to the start of the experiment. Native perennial grasses (redgrass, wallaby grass, wiregrass) dominated all grazing treatments (perennial grass > 85% by dry weight). Redgrass was the dominant species with total herbage mass > 75% of dry weight. Perennial grass content was most variable in the subterranean clover treatment, ranging between 16 and 99% in October 1998 (clover 2880 kg DM/ha) and March 2001, respectively (Figure 4-7). In spring 1998, subterranean clover and naturalised legumes (woolly burr medic *Medicago minima* (L.) Bart and clustered clover *Trifolium glomeratum* L.) were abundant, accounting for up to 26% of mean herbage mass.

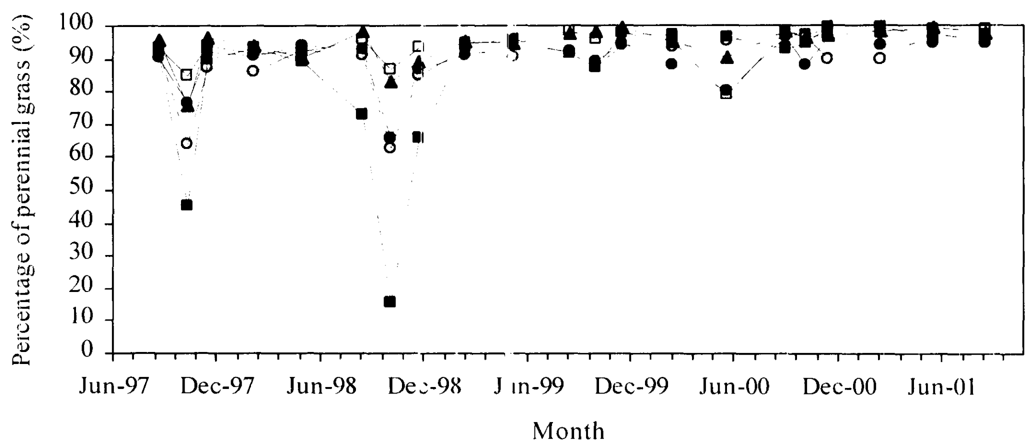

Figure 4-7. The proportion of perennial grass by dry weight (%) within the sward for each grazing treatment at Springmount (T1C4 - ●, T2C6 - ○, T3FERT8 - ■, T4GR4 - □, and T5GR12 - ▲).

4.4 Discussion

Annual rainfall throughout the experiment was near average with a minimum of 602 mm (2000). Data for Barraba showed that at least 622 mm of rain is expected in 60% of years (Clewett *et al.* 1999). However, the distribution of rainfall was important for herbage mass accumulation. Few consecutive seasons had rainfall equal to or exceeding average, which led to low herbage accumulation, with the exception of winter-spring 1998 (492 mm). In three of the four summer seasons, rainfall was below the long-term average and considering that maximum potential evapotranspiration was around 8 mm/d (Figure 4-1), stored soil moisture was likely to be rapidly depleted, leading to low pasture growth. Associated with below average summer rainfall was a lower incidence of storms, which usually bring high intensity rainfall. Due to low summer rainfall, plots that were grazed continuously without applied fertiliser showed a decline in herbage leading into winter each year, which in turn led to sheep being supplementary fed (e.g. T2C6).

Pasture herbage accumulation was related to sporadic flushes of growth when rainfall coincided with temperatures suitable to the native perennial grasses. From a long-term simulation study, Simpson *et al.* (1998) concluded that pasture growth on the North-West Slopes was likely to be sporadic in response to seasonal rainfall and available stored soil moisture. In their simulations, the pasture sward was dominated by C4 grass species with warm-season growth characteristics, and herbage accumulation by these species was limited to summer periods with above average rainfall. Within the current study, herbage mass accumulated within the rotationally grazed and subterranean clover treatments due to the carryover of frosted dead material that was mainly warm-season grasses (Figure 4-3, Figure 4-6). Unpalatable frosted material has a low digestibility and nutritive value, but is an inherent characteristic of these pastures (Lodge and Whalley 1983). However, this material is often considered by graziers to be an essential reserve of dry feed for livestock.

The percent green leaf content of the pasture was generally low (the maximum treatment mean was 37% for T3FERT8) and responded to seasonal rainfall and periods of pasture growth. Subterranean clover and other legumes contributed substantially to higher levels of green in the T3FERT8 treatment, particularly in spring (e.g. 2880 kg DM/ha in 1998). Redgrass in this treatment may also have responded to the applied fertiliser and fixed nitrogen from the subterranean clover. Redgrass gave the appearance of having a higher proportion of green leaf for longer periods than the same species in other treatments. Other studies have shown that in native pastures dominated by redgrass, wallaby grass, and wiregrass, the proportion of green leaf may increase with the application of fertiliser (Lodge 1979). However, the response was highly dependent on seasonal conditions. The rotationally grazed treatments had a significantly lower percentage of green leaf in spring due to the carry over of standing dead material. Conversely, the continuously grazed treatments without fertiliser had lower amounts of standing dead material and so had higher percentage of green leaf at those times.

While the continuous grazing treatments were unable to sustain grazing intensity (4 and 6 sheep/ha) throughout the current study, others (Lodge and Roberts 1979) have reported that similar pastures may be continuously stocked at rates of 4.8 DSE/ha by applying high amounts of fertiliser (S 54 kg/ha, P 15 kg/ha). Garden *et al.* (2000) reported that a wiregrass-redgrass dominant pasture carried about 4-6 DSE/ha in a 4 year study despite below average rainfall. Those results were dependent on adequate summer rainfall that led to herbage accumulation sufficient to carry livestock through the winter, which further highlights the importance of the annual distribution of rainfall on pasture production. In the current study summer rainfall was below the long-term average for three of the four summer seasons (Figure 4-1), which when coupled with continuous grazing, prevented herbage mass accumulating before winter and so the necessity of supplementary feeding livestock in those treatments. Grazing needs careful management during dry summers so that herbage mass might be maintained. During such seasons, inappropriate management may have a long-term impact on the productivity of these redgrass pastures, which the use of simulation modelling may determine.

Higher litter mass developed in treatments grazed rotationally and that with fertiliser and subterranean clover, but total mass was never greater than 780 kg DM/ha. Residual litter mass is a function of the rate that it is laid down and the rate which it is consumed by soil micro-organisms or livestock. For litter to be laid down, it must first be available as residual herbage mass or annual herbage that has senesced (e.g. subterranean clover), and then through some mechanical action be separated from the plant base and fall to the soil surface. The fertiliser and subterranean clover treatment had high residual herbage mass from the perennial grasses (mean > 3000 kg DM/ha) combined with flushes of annual herbage mass from the subterranean clover. The high grazing intensity (8 sheep/ha) then led to the highest amount of litter mass being laid down on the soil surface (mean > 250 kg DM/ha).

Decomposition rates for subterranean clover litter are much higher than that of litter derived from dead leaf and stem material of native grass, which leads to rapid turnover and incorporation into the soil (G.M. Lodge and S.R. Murphy, unpublished data). The rotationally grazed treatments (T4GR4 and T5GR12) also had high residual herbage mass and high grazing intensity during grazing periods (8 and 16 sheep/ha) allowing standing dead material to be trampled to the soil surface. In these treatments, the majority of the litter was dead stem from the native grasses, which decomposed slowly and laid on the soil surface for a long period. To achieve high litter mass for evaporation control (e.g. 1500-3000 kg DM/ha, Murphy and Lodge 2001*a*), other methods might be required to increase the rate of litter transfer to the soil surface such as slashing with a tractor or trampling with higher stock density.

Compared with continuous grazing treatments, ground cover was higher in the rotationally grazed treatments and the subterranean clover and fertiliser treatment, and generally increased with herbage and litter mass. Lodge and Murphy (2002*a*) investigated ground cover and herbage mass in a study at the Springmount and Eloura study sites and found that a polynomial regression best described the relationship between them. High ground cover occurred with both high and low amounts of herbage mass while litter was also an important component of cover. However, in the current study at Springmount, redgrass plants were very resilient to grazing and changed their growth habit in response to increasing intensity. The continuously grazed treatment T2C6 was expected to develop a very low amount of cover (< 40%) in response to the high grazing intensity but this did not happen. Individual plants tended to develop a prostrate habit with larger, flatter bases, thereby maintaining ground cover but with low herbage mass and pasture height.

Pasture species composition was dominated by native perennial grasses in all grazing treatments throughout the experiment (mean > 85% by dry weight). The herbage mass of legumes and other annual forbs occasionally achieved substantial levels following above average rainfall (e.g. winter-spring 1998), but these were generally of short duration. On the Northern Tablelands, Roe *et al.* (1959, quoted in Lodge 1983) stated that no differences were found between rotational and continuous grazing management in their effects on botanical composition and productivity of redgrass pasture. Lodge *et al.* (2003*b*) reported the basal cover of the major perennial grasses in the current study and showed that redgrass remained dominant throughout and the area occupied by other species remained relatively constant. Calendar based management systems were shown previously to be unlikely to induce species composition change (Lodge and Whalley 1985). Hence, the calendar based grazing treatments employed in the current study (by not specifically targeting species phenological differences), had no effect on species composition.

4.5 Conclusion

The maximum annual rainfall at Springmount over the experimental period (September 1997 to September 2001) was 724 mm (1998), which included record totals for winter and spring. For all other years, annual rainfall was below average, and summer rainfall particularly was below average in 1998-99, 1999-00 and 2000-01. The low summer rainfall had significant implications for pasture accumulation in those treatments grazed continuously. The highest daily rainfall total was 54 mm on 26 June 1998 and the maximum rainfall intensity was 123 mm/h on 13 December 2000.

The continuously grazed treatments had less herbage mass, litter mass and ground cover than the treatments that were rotationally grazed or with subterranean clover and fertiliser applied. A minimum herbage mass of 590 kg DM/ha was recorded in treatment T2C6 in October 1999 and this treatment also had the minimum mean herbage mass (1500 kg DM/ha), but it was not different from the T1C4 treatment (1800 kg DM/ha). Greater accumulation of herbage mass was recorded in the rotationally grazed treatments with a maximum of 5829 kg DM/ha in T5GR12 in March 1999. The maximum mean herbage mass of 3581 kg DM/ha was also recorded in this treatment. Mean herbage mass in the subterranean clover and fertiliser treatment was not different to that of the rotationally grazed treatments. Initial mean litter mass was < 50 kg DM/ha, but it generally increased throughout the experiment. The rotationally grazed and subterranean clover treatments accumulated more litter than the continuously grazed treatments. Maximum litter mass (780 kg DM/ha) was recorded in the subterranean clover treatment in March 1999, while the minimum (12 kg DM/ha) was recorded in the T2C6 treatment in October 1999. The continuously grazed plots had significantly lower ground cover between December 1998 and September 2001 compared with the rotationally grazed plots or those with subterranean clover and fertiliser. Mean ground cover in the continuously grazed treatments was 73 and 70% (T1C4 and T2C6, respectively) while the two rotationally grazed treatments and the subterranean clover treatment had mean values of 83, 85, and 90%, respectively.

Seasonal conditions and species composition determined the percent green leaf of pasture in treatment plots. Maximum green leaf content (99%) was recorded in the subterranean clover treatment in spring 1998 following heavy rainfall and prolific subterranean clover growth. Green content was lowest in winter when the perennial grasses were frosted. Added fertiliser and fixation of nitrogen by the subterranean clover may have influenced the amount of green leaf in those plots, as the perennial grasses appeared to remain greener for longer periods than in other plots. Accumulation of dead standing material in the rotationally grazed plots led to lower estimates of green leaf as a proportion of dry weight. No change in species composition occurred in any treatment. Native perennial grasses were the dominant component of the pasture in all treatments (mean > 85% by dry weight) with occasional prolific growth of annual legumes and forbs in response to cool season rainfall.