University of Alberta

SOIL WATER REGIME AND SURFACE RUNOFF PATTERNS OF PASTURES UNDER MANAGED INTENSIVE GRAZING IN CENTRAL ALBERTA

by

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DEDICATION

This thesis is dedicated to Les Bradshaw and Lawrence Biswanger - two beloved farmers, whose love of the land influenced me to pursue an agriculturally based project. I hope I made them proud.

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1.1 Background

The Aspen Parkland ecoregion of Alberta contains over 800,000 ha of cropland pasture, approximately 36% of the provincial total, and over 1.2 million ha of natural land for pasture, approximately 18% of the provincial total (Statistics Canada 2001). Existing and potential pasture space is limited in this region (Engstrom 1997), but Aspen Parkland pastures were occupied by 70% of the Alberta cowherd as of 1996. Existing pastures must be managed in a sustainable manner to protect soil, water and atmospheric resources, while increasing productivity. In view of recent beef industry crises, Alberta beef producers are not able to sell their yearling calves and cull cows for a profit as normal. Therefore, many Alberta beef producers need to find a profitable, yet sustainable, grazing method that will enable them to keep a larger than normal beef herd through the market downturn. If such methods are not employed, beef producers will likely not be able to provide enough pasture for their entire herd, and they may be forced to sell portions of it at an economic loss.

1.1.1 Managed Intensive Grazing

One grazing management option that is growing in popularity is managed intensive grazing (MIG). This management practice encompasses any grazing system in which forage utilization is managed to control forage availability and quality (Barnhart et al. 1998). Generally, managed intensive grazing, also sometimes referred to as short-duration intensive grazing (SDIG or SDG), involves grazing livestock at a high intensity, typically a high stocking rate in a small area, for a short duration of time. The management is "intensive" in that additional inputs of resources, labor, and/or capital are required to improve forage production and utilization (Barnes et al. 2003). Grazing paddocks are typically divided into numerous, smaller paddocks, allowing livestock to be easily and frequently rotated among them. Stocking rate, density, and duration are calculated using forage availability and quality in addition to rate of consumption and regrowth. Paddocks are not always grazed in the same order, and the system can be adjusted to accommodate varying rates of forage maturation, periods of slow forage growth or recovery, occasional hay harvest, or supplemental feeding. Livestock are given unlimited access to water, mineral, and salt, with the stations permanently located within each paddock, moved from paddock to paddock with the livestock, or centrally located. (Barnhart et al. 1998)

Managed intensive grazing has many advantages. It has the potential to increase forage production and quality, which generally improves livestock performance and can increase weight gain per acre (Barnhart et al. 1998). In areas with a shorter grazing season, such as the Aspen Parkland ecoregion of Alberta, managed intensive grazing may allow for better management of many cool-season grasses, given that over 60% of their growth occurs prior to July 1 (Baron et al. 1993; Barnhart et al. 1998). The flexibility of managed intensive grazing can enable immediate utilization during this rapid growing period, or the choice to stockpile all or some of it for use during the period of depressed forage productivity in July and August, typical of cool-season grasses in Alberta. In other words, managed intensive grazing is a method for extending the grazing season, since the low productivity of perennial forages during late summer and fall typically limits livestock productivity (Baron et al. 1993). Another advantage of managed intensive grazing is better manure distribution and nutrient recycling within each grazing paddock, since frequent rotation of livestock prevents establishment of permanent bedding areas that can become inundated with excess urine and feces (Barnhart et al. 1998).

All grazing systems have their disadvantages, and managed intensive grazing is no different. Managed intensive grazing will require a large amount of temporary or permanent fencing and watering equipment, which entails a sizable initial investment. Barnhart et al. (1998) estimate that this cost can be recovered in 1 or 2 years from improved animal performance, or slightly longer for facilities that are more substantial. In addition to the initial cost, time is required to maintain the fences, monitor the growth and consumption rates, and move livestock to the next paddock at the correct time (Barnhart et al. 1998). Above all, the greatest disadvantage is the requirement of skills and expertise to make the system work. Producers would have to commit to learning how to properly evaluate forage resources, and many of these skills can only be learned through first-hand experience (Barnhart et al. 1998).

1.1.2 Annual Forages in Pasture Rotations

Pasture land in Alberta has traditionally consisted of perennial forage species, such as grasses and legumes. Perennial forages prevent soil erosion by maintaining permanent ground cover and improving soil structure (Mapfumo et al. 2003). In contrast, annual species have traditionally been grown for cereal, silage, or green-feed crops, yet in other areas of the world they have been grown as an alternative pasture forage (Twerdoff et al. 1999). Annuals are primarily chosen to extend the grazing season, which can be a very beneficial management practice for livestock producers (Entz et al. 2002). Baron et al. (1993) stated that cereal production normally occurs within a 4-month period, followed by a 2-month period of fallow or stubble prior to winter. They suggested that the proper crop mixture of spring and winter cereals both planted in the spring, adjacent to traditional perennial pastures, could dramatically extend the grazing season. In such a system, spring cereals would provide substantial early grazing, and winter cereals would provide late-summer and fall pasture, as they are able to tolerate intermittent frosts and low temperatures (Baron et al. 1993). The majority of central Albertan pasture lands consist of cool-season grasses, which typically decrease their growth during the high temperatures of mid-summer. Hence, annual forages can also be stockpiled to supplement feed gaps in perennial pastures, such as during mid-summer (Entz et al. 2002).

1.1.3 Grazing and the Hydrologic Regime

In general, grazing of any type impacts the hydrologic regime, although the degree of impact varies by management practice. Climate, vegetation, soil, and grazing regime all interact to impact the hydrological regime. Therefore, grazing impacts a number of hydrologic processes including infiltration, water retention, percolation, and evapotranspiration (Gifford and Hawkins 1978; Mapfumo et al. 2002).

These processes ultimately influence pasture soil water and runoff. Additionally, grazing often increases the surface bulk density of soil, through the hoof action of grazing animals. In turn, this also impacts infiltration, and hence soil water and runoff. Grazing also recycles nutrients to the soil, as they are not removed off-site as they would be in a hay system (Entz et al. 2002). However, increased concentrations of nutrients that are mobile in the soil may leach into groundwater, causing environmental contamination and degradation (Havlin et al. 1999). Overall, these hydrologic relationships are not simple, as many factors contribute to each process, some factors having a greater influence than others.

1.1.4 Existing Research

Although managed intensive grazing has its disadvantages, it can be a valuable tool to livestock producers and grazing managers through its potential economic advantages and environmental benefits. Including annual forages in pasture rotations can also be very advantageous to livestock producers. However, little information exists on the impacts of managed intensive grazing on the hydrologic regimes of perennial and annual pastures in semi-humid areas of Alberta. The impacts of grazing on hydrologic processes have traditionally been researched on arid and semi-arid rangelands and pasturelands throughout the Western United States and Canada (Warren et al. 1986; Abdel-Magid et al. 1987; Dormaar et al. 1989; Naeth and Chanasyk 1995). Hydrologic studies conducted on the semi-humid rangelands and pasturelands of Alberta have focused on various stocking rates, rather than specifically on managed intensive grazing and its impacts on different forage species (Twerdoff et al. 1999; Mapfumo et al. 2003).

1.2 General Research Hypotheses

The global objective of this study is to characterize the soil water regime and surface runoff patterns of annual and perennial pastures under managed intensive grazing. Therefore, the general hypotheses of this study are:

i. Soil parameters would be affected at the surface rather than at depth, by managed intensive grazing.

ii. Annual treatments would have greater soil water than perennial treatments.

iii. Annual treatments would have a higher leaching potential than perennial treatments.

iv. Annual treatments would produce more surface runoff than perennial treatments.

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2 RESEARCH SITE OF A MANAGED INTENSIVELY GRAZED PASTURE IN THE ASPEN PARKLAND ECOREGION OF ALBERTA

2.1 Site Description

The research site is located at Agriculture and Agri-Food Canada's Lacombe Research Station, Lacombe, Alberta, (52°27' N, 113°45' W) approximately 130 km south of Edmonton, Alberta. Intensive, short duration rotational grazing, referred to as managed intensive grazing (Barnhart et al. 1998; Barnes et al. 2003), began on grazed 1.2-ha paddocks (Figure 2.1) in summer 1999.

The research site is located within the aspen parkland ecoregion of Alberta, which represents a "climatical and ecological transition zone between boreal forest and grassland environments" (Strong and Leggat 1992). The climate of the area is continental prairie with a sub-humid moisture regime, characterized by long, cold winters, and short, cool summers, and low annual rainfall (Phillips 1990; National Research Council of Canada 1998).

The long-term mean annual precipitation is 446.0 mm, with an average 360.6 mm from rainfall and an average 95.9 mm from snowfall (Environment Canada 2003). The mean annual temperature is 2.6 °C, with a January average mean temperature of -12.3 °C and a July average mean temperature of 15.4 °C (Environment Canada 2003).

The underlying bedrock is from the Paskapoo formation, a freshwater deposition resulting in "soft, grey, clayey and calcareous sandstones, and soft shales and clays" (Bowser et al. 1951). The soil parent material ranges from sandy loam to clay loam to calcareous, originating from glacio-lacustrine and/or alluvial aeolian depositions (Bowser et al. 1951). The soil is an Orthic Black Chernozem, ranging from a Peace Hills fine sandy loam/Penhold fine sandy loam on the northern edge of the site to a Ponoka loam on the remaining area of the site (Bowser et al. 1951; Twerdoff 1996). All of these loam soils developed on materials deposited in slowly moving water (alluvial lacustrine). Peace Hills fine sandy loams and Penhold fine sandy loams have calcareous parent material, whereas Ponoka loams have sandy loam to clay loam parent material that can contain gravel lenses. Peace Hills fine sandy loams consist of fine sand and are characterized by having well to somewhat excessively drained soils, and are recognized in the field by a deep black sandy surface horizon, a thin lighter colored B horizon and a loose sandy subsoil. Penhold fine sandy loams are well drained soils, and can be identified by a thick black surface horizon, a bright yellow brown subsurface horizon, breaking sharply to a light brown chalky subsoil. (Bowser et al. 1951)

The topography is level and undulating to gently rolling (Bowser et al. 1951) with most of the slopes between 1 and 6% (Twerdoff 1996). The elevation at the handling facility in the middle of the study site is 867 m above sea level (Land Information Services Division 1991).

Historically, the entire research site was old perennial grassland, and a portion of it (now Block 1) was converted into barley silage, and then into summerfallow in fall 1996. In 1997, the summerfallow area was divided into 18 paddocks and seeded accordingly in mid-June. The first production year for the meadow bromegrass/alfalfa and alfalfa paddocks was 1998, which was also when this area and the remaining old perennial grass area were separately fenced into 24 paddocks, forming 2 blocks. The first block (Block 1) was comprised of 3 forage treatments replicated 3 times, and the second block (Block 2) was comprised of the old grass treatment replicated twice, which had never been cultivated or disturbed (Figure 2.1). Each rectangular-shaped paddock (replicate) is approximately 1.2 ha, ranging between 192 and 366 m in length, and between 35 and 67 m in width. In Block 1, the land slopes west to east in Replicate 2, north to south in Replicates 1 and 3. In Block 2, the old grass area, the land is a series of slopes that alternate in direction.

Six annual treatment paddocks were seeded with annual ryegrass (*Lolium multiflorum* Lam.) (Moss 1994) in 1998, then from 1999 to 2003 with a mixture of "AC Mustang" oat (*Avena sativa* L.) (Kibite 1997) and "Bobcat" winter triticale (*X Triticosecale* Wittmack) (Salmon et al. 2000) (Table 2.1). Crop residues (all above ground plant material remaining after the last grazing of the previous season) were left over winter, as the annual treatments were spring seeded each year with a zero-till seeder. Annual forage crops, such as oats, fall rye, barley, and spring and winter wheat have been successfully used for grazing (AAFRD 1998).

Six perennial paddocks were seeded with "Spreador 2" alfalfa (*Medicago sativa* L.) (Moss 1994) in 1997 (Table 2.1). Alfalfa is the most used pasture legume in Alberta due to its hardiness and yield (AAFRD 1998). The alfalfa species has four types of roots (tap, branch, rhizomatous, and creeping), allowing it to tolerate a wide range of climatic and soil conditions (AAFRD 1998). In sandy soils with a high water table, alfalfa roots can grow as deep as 3 to 5 m (AAFRD 1998). Therefore, this medium-lived perennial is able to utilize more of the soil profile to obtain water than most other pasture plants.

The second perennial treatment, also seeded in 1997, consisted of a mixture of meadow bromegrass (*Bromus riparius* Rehm.) (Knowles et al. 1993) and "Spreador 2" alfalfa (*Medicago sativa* L.) (Moss 1994) paddocks (50/50 mix by seed number) (Table

2.1). Over time, this meadow bromegrass/alfalfa pasture has become predominantly meadow bromegrass, so it is hereinafter referred to as the meadow bromegrass treatment. Meadow bromegrass is a long-lived perennial bunchgrass, which provides good soil protection (AAFRD 1998). It is an early season pasture plant that has strong regrowth characteristics, providing good summer and fall growth, and thus is one of the most useful forage plants in the black soil zone of Alberta (AAFRD 1998).

The final treatment area was a perennial mixture of quack grass (*Elytrigia repens* L.) (Moss 1994), smooth bromegrass (*Bromus inermis* Leyss.) (Moss 1994), and Kentucky bluegrass (*Poa pratensis* L.) (Moss 1994) (hereinafter referred to as the old grass treatments), seeded sometime prior to 1970 (Table 2.1). This old grass area, similar to that of unbroken land, represented the common grazing management practice in the area, and provided a long-term pasture comparison with the other pasture treatments (Mapfumo et al. 2003; Young 2003). These pastures typically have thick accumulations of fallen litter, thus often suffering from low infiltration. Additionally, Kentucky bluegrass requires a considerable amount of moisture and responds to hot, dry weather by going dormant (AAFRD 1998). Therefore, these pastures are expected to be quite hardy, tolerating drought and cold winters, but will likely have lower soil moisture levels compared to the other perennial forages.

The paddocks were lightly grazed in summer 1998 (first production year) to keep the pastures in shape and to prepare them for research in 1999. Beginning in 1999, half of the paddocks were rotationally grazed during the summer. The other half were stockpiled, where the forage is saved for fall and winter grazing after cold weather has stopped forage growth, and then rotationally grazed (Barnes et al. 2003). With the exception of Paddock 19 in the old grass area, all the summer-grazed paddocks were monitored during this study.

In both 2002 and 2003, each summer grazed paddock was given one of two fertilizer treatments: no nitrogen fertilizer or nitrogen at 100 kg/ha N as ammonium nitrate (NH_4NO_3). The meadow bromegrass/alfalfa mixture, old grass mixture, and annual paddocks received the nitrogen fertilizer, whereas alfalfa was not nitrogen fertilized (Table 2.1). All four forage crops received 30 kg/ha phosphorus (P_2O_5) and 30 kg/ha potassium (K_2O) (Table 2.1).

Yearling beef heifers (cattle) were rotationally grazed, in a managed intensive grazing fashion, within each treatment/paddock using electric fencing during the summer months, from June 1 to September 15. A "put and take" (variable) stocking method (Bransby 1989) of grazing was employed based on forage availability, which in turn determined stocking rates. The paddocks were divided into numerous grazing strips, running across the paddocks and separated by portable electric fencing. The cattle were sequentially grazed from strip to strip, from one end of the paddock to the other, and then rotated back to the starting point to graze the strips again. The grazing strips were individually sized within each paddock to provide for the same number of grazing days for each treatment.

In order to determine available forage, plant samples were collected from 6 quadrats (0.25 m^2) within the paddocks. The samples were bulked and dried for 3 days at 80 °C, and the dry weights used in combination with the area sampled to calculate dry matter yield. The target rate of grazing was to graze each 1.3 ha paddock 3 times in 100 days. Thus, each rotation across the paddock was approximately 33 days, meaning that the cattle needed to graze 0.04 ha per day. However, since it would have been too labor intensive and disruptive to move the cattle every day, a 4-day average grazing period was selected. Therefore, for each 4-day grazing period, the average size of a grazing strip within the paddocks was 0.16 ha, where the width generally ranged from 20 to 30 m.

A stocking rate of 5% consumption, where the individual animal consumes 5% of their body weight in dry matter, was derived from past grazing trials at Lacombe; a consumption rate of 3% resulted in lower cattle performance, whereas 6% resulted in too much residue being left in the pastures. Therefore, if the cattle were assumed to weigh 365 kg, at a consumption rate of 5%, they would need to eat 73 kg in 4 days. The sampled dry matter yield was used to derive the amount of available forage in 0.16 ha, and the number of animals that could be supported on that forage was calculated. For example, if 2500 kg/ha of forage was available, in 0.16 ha, there was 400 kg of forage. Divided amongst 73 kg/heifer, each grazing strip could support 5 heifers for 4 days. The number of heifers in each pen was adjusted every 2 weeks to reflect changes in the amount of available forage and changes in the cattle weights. Since the cattle were weighed monthly, the rate of weight gain was assumed to be 1 kg/day for all of the cattle, and adjustments were made accordingly.

Pasture treatments were applied to 2 blocks of land. The first contained 3 pasture treatments, alfalfa, meadow bromegrass and alfalfa mixture, and annual mixture, randomized in 3 replicates. The second block, which was adjacent to the first, contained the old grass mixture in 3 replicates. All pasture treatments were grazed as previously described.

2.2 Materials and Methods

2.2.1 Instrumentation

Meteorological parameters at the research site were recorded year round with an automated portable weather station, located in the northwest corner of Paddock 24 (Figure 2.1). Air temperature (maximum and minimum) and relative humidity were measured with a Vaisala HMP45C sensor; total rainfall was measured with a Texas Instruments TE525 rain gauge; soil temperature was measured with a Campbell Scientific 107B probe; and wind speed and direction was measured with a R.M. Young 05103-10 wind monitor. Rainfall intensity was recorded on a 5-min basis. A Campbell Scientific CR10 data logger scanned the sensors every 60 s, and hourly and daily averages were stored after being calculated by the data logger.

Aluminum access tubes (tubes) were installed in May 2002 within Block 1 (Paddocks 1, 3, 4, 13, 14, 15), and Block 2 (Paddocks 21, 24) to depths ranging from 160 cm to 200 cm at 3 locations along a transect perpendicular to each paddock gate (Figure 2.1). After installing these tubes and collecting soil moisture data for a month, it became obvious that coarse soil conditions existed in Rep 3 of Block 1, unlike those in Rep 1. Additional access tubes were installed in Rep 2 of Block 1 on Paddocks 7, 9, and 12 in July 2002, using the same methods as previously mentioned. The three soil access tubes in each paddock were generally located 20 m from the far side of the exclosure (if the reference point is an observer standing at the paddock gate, looking into the paddock away from the gate). The exclosures were located anywhere from 45 to 150 m from the paddock gates. Within each paddock, the access tubes were 30 m apart; the access tube closest to each exclosure was labeled Tube 1, the access tube furthest from each exclosure was labeled Tube 3, and the access tube in between these two was labeled Tube 2. Therefore, each access tube was numbered in the following manner: Paddock-Tube. For example, access tube # 15-3 could be found in Paddock 15, furthest away from the exclosure relative to the other tubes in this paddock. The distances between tubes varied slightly on Paddocks 7, 9, and 14 due to difficult soil augering conditions at the time of installation. The access tubes were used for neutron moisture probe readings to measure the soil moisture content at depths up to 2 m, and for measurements of in-situ bulk density.

2.3 Statistical Analyses

The experimental design was a randomized complete block in which treatments were randomized into two experimental areas. It was assumed, a priori, that differences between any of the treatments in the two experimental areas were due to treatment effects rather than inherent differences in soil properties or microclimatic conditions between study areas. Three of the treatments (short-term intensive systems: annual, meadow bromegrass, and alfalfa) were randomly assigned into Block 1. The remaining treatment (old grass mixture) was assigned to Block 2. In Block 2, the old grass system was assigned to two experimental units (paddocks). The short-term intensive systems were replicated three times and the old grass system was replicated two times. Randomization of the treatments was restricted to the short-term intensive and old grass experimental areas. All experimental units were subject to one summer grazing management technique: managed intensive grazing (MIG).

Statistical analyses were done on the following response variables: surface bulk density; bulk density at 15 cm; penetration resistance; select total soil water (TSW) values (TSW40, TSW80, TSW120, TSW160, TSW120–160); bare ground and canopy cover percentages of the vegetation in the runoff frames; snowmelt and rainfall runoff volumes; and select water quality parameters (alkalinity, chlorine, electrical conductivity, nitrate, nitrite, pH, and potassium).

Data were subjected to an analysis of variance with the PROC MIXED procedure of SAS (Littell et al. 1996). The effect of replicate nested within experimental areas was considered random, and the effects of treatment (Trt), and date, where applicable, were considered fixed for all analyses. When the date by treatment interaction (Date*Trt) was statistically significant, contrasts were used to determine the date(s) for which the treatment effect was significant. The preceding model was configured (parameterized) four different ways to find a model with the best fit. Also, model parameterization was varied to account for repeated measurements across dates within the growing season. One parameterization considered variability among the replicate by treatment combinations nested within experimental areas as a random effect, as follows:

$$y_{ijk} = \mu + \alpha_i + \gamma_j + (\alpha\gamma)_{ij} + \delta_k + \varepsilon_{ik} + \varepsilon_{ijk}$$

and the second parameterization considered this same variability as a subject within the repeated statement of PROC MIXED with a suitable covariance structure (Structure) to account for variations across dates, as follows:

$$y_{ijk} = \mu + \alpha_i + \gamma_{ij} + (\alpha\gamma)_{ij} + \delta_k + \varepsilon_{ijk}$$

where α represents the ith level of 'Trt', and γ represents that jth level of 'date', and δ represents the kth level of 'rep' within the experimental areas. The first model has two error terms; specifically, ε_{ik} representing the between block (replicate by experimental area combination) variation, and ε_{ijk} representing the between experimental unit variation. The first model parameterization assumes that the error term for testing the treatment effect is the same for all environments and the second parameterization assumes between subjects (replicate by treatment combinations nested within experimental areas) and within subjects (subsampling and measurements across dates) variances are unique. The covariance structure used with the repeated statement parameterization was a compound symmetry (all dates were equally correlated with each other) or first-order autoregressive (correlations were greatest for closest dates). (Stevenson 2004)

For each of the two preceding models, variance estimates were kept constant or allowed to vary across experimental areas (Group). Accounting for contrasting variance estimates would allow for the possibility that unique attributes for the two experimental areas ultimately resulted in contrasting levels of variation. The preceding model parameterizations were compared using the corrected Akaike's Information Criterion (AICC). (Stevenson 2004)

A confidence level of 95% was chosen ($\alpha = 0.05$) to identify statistically significant effects and interactions. Significance or non-significance is appropriately noted within each chapter, and a complete set of results for each analysis is included in the Appendix (Table 7.9). The *P* values for contrasts testing the treatment effect at each sampling date are also included in the Appendix (Table 7.10).

Table 2.1 Description of forage treatments at Lacombe, Alberta

Treatment Name	Forage Mixture	Seeding Rate per species (kg/ha)	Date Seeded	Fertilizer (kg/ha)	Paddock # *
Annual	Oat	78	Annually	100 N	4
	Winter Triticale	101		30 P_2O_5	9
				30 K_2O	15
Meadow Bromegrass	Meadow bromegrass	13	1997	100 N	3
	Alfalfa	5		30 P_2O_5	12
				30 K_2O	13
Alfalfa	Alfalfa only	11	1997	30 P_2O_5	1
				30 K_2O	7
					14
Old Grass	Quack grass	Unknown	Prior to 1970	100 N	21
	Smooth bromegrass	Unknown		30 P_2O_5	24
	Kentucky bluegrass	Unknown		30 K_2O	

* Refer to Figure 2.1

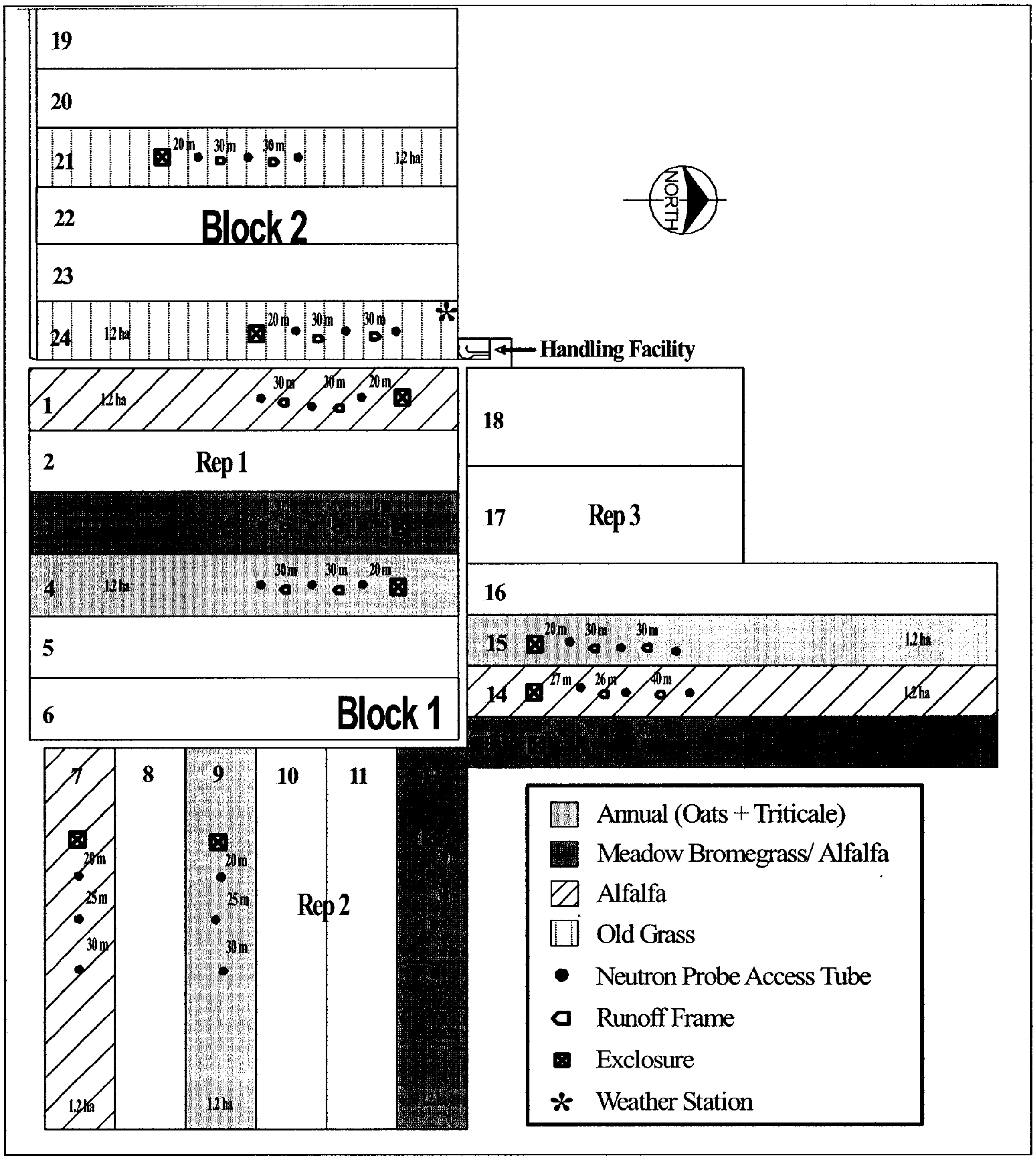

Figure 2.1 **Plot plan of Lacombe managed intensive grazing (MIG) research study.**

Only shaded or patterned paddocks were monitored for this study. The remaining plots were stockpile grazed. Block 1 encompasses the short-term intensive system, comprised of Reps 1, 2, and 3. Block 2 encompasses the old grass system. *Not drawn to scale.*

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3 SOIL PROPERTIES OF MANAGED INTENSIVELY GRAZED PASTURES IN THE ASPEN PARKLAND ECOREGION OF ALBERTA

3.1 Introduction

Orthic Black Chernozems in the prairie regions of Western Canada, such as those at the research site, have an A-horizon that is at least 10 cm thick, a B-horizon at least 5 cm thick, and a C-horizon that is enriched with carbonates. These soils have dark surface horizons with accumulations of organic matter, containing 1 to 17% organic carbon. The dominant exchangeable cation in these soils is calcium, and since they are non-saline, they do not have naturally high levels of sodium, chlorine, or sulfate salts. (National Research Council of Canada 1998)

Basic soil properties, such as texture, organic matter, bulk density, soil strength, and chemical composition are major factors in determining the effect that grazing management strategies have on hydrologic processes. To accurately evaluate these effects, soil physical and chemical properties must be analyzed and considered.

3.1.1 Soil Physical Properties

Soil texture influences the infiltration rate, water retention capacity, soil fertility, and porosity of the soil (Donahue et al. 1983). The relative percentages of soil separates (clay, sand, and silt) define soil texture (Tan 2000). Fine-textured soils, those dominated by clay particles, hold more water than coarse-textured soils, such as those dominated by sand particles (Chanasyk and Naeth 1995).

Organic matter influences many biological, chemical, and physical characteristics that determine soil productivity and quality (Havlin et al. 1999). Organic matter improves aggregation of soil particles, thus improving water and air flow through the soil; it increases the soil's cation exchange capacity; improves soil fertility; and improves the buffering capacity of the soil, adsorbing pollutants and detoxifying the soil (Donahue 1983; Tan 2000). Additionally, in conjunction with clay content, the amount of soil organic matter determines the water retention properties of the soil (Baron et al. 1999). Moreover, soil organic matter is very responsive to external influences, such as climate, vegetation, and land management practices like tillage, so it is a very important indicator in determining the overall quality of a soil (Krzic et al. 1999; Tan 2000). Cultivation of a virgin soil has the greatest impact on organic matter. Organic matter decreases rapidly during the first 10 years after cultivation; then it decreases slowly for several decades until equilibrium is reached (Havlin et al. 1999).

Soil bulk density is an important indicator of the physical condition of the soil, as it is dependent on soil texture and organic matter content (Donahue et al. 1983; Tan 2000). It can affect plant root penetration, water content, air content, and biological activity (Havlin et al. 1999). However, since bulk density can vary with soil water, it should not be used to evaluate the effects of grazing on soil compaction, unless data from both grazed and ungrazed areas are compared. Otherwise, increases in bulk density from soil drying could be inaccurately linked to grazing (Chanasyk and Naeth 1995).

Bulk density is commonly used to evaluate soil compaction (Twerdoff et al. 1999). Grazing has caused compaction on a variety of soil textures in North America, including sand (Bauer et al. 1987), sandy loam (Krenzer et al. 1989), loam (Lodge 1954; Klemmedson 1956; Van Haveren 1983), silt loam (Lodge 1954; Orr 1960; Twerdoff et al. 1999), and clay loam (Tanner and Mamaril 1959; Chanasyk and Naeth 1995) textured soils. However, other studies have found that grazing did not compact sandy loam (Abdel-Magid et al. 1987) or loam (Orr 1960) textured soils. Water content of the soil at the time of grazing is also a determining factor in the degree of soil compaction (Tanner and Mamaril 1959; Van Haveren 1983).

Generally, increases in bulk density due to grazing are observed primarily at the soil surface (0-10 cm) (Naeth and Chanasyk 1993). Other studies have found that grazing increases surface bulk density, resulting in soil compaction in the uppermost 2.5, 10.0, 5.0, and 7.5 cm, respectively (Alderfer 1947; Lodge 1954; Orr 1960; Naeth et al. 1990). Additionally, Van Haveren (1983) found that grazing intensity significantly increased bulk density on fine-textured soils, but not on coarse-textured soils. Lull (1959) also found that coarse-textured soils are less susceptible to compaction due to their lower clay contents.

Numerous studies have found that wet soils are more easily compacted than dry soils (Orr 1960; Van Haveren 1983; Krenzer et al. 1989). Orr (1960) concluded that soils are subject to maximum compaction at moisture contents halfway between wilting point and field capacity. Since soils with higher clay and organic matter content have increased water retention properties, it follows that these soils would be most vulnerable to compaction when wet (Baron et al. 1999). Therefore, fine-textured soils will be more susceptible to compaction if grazed when wet (Chanasyk and Naeth 1995).

Penetration resistance is commonly used to quantify soil strength and mechanical impedance to root growth. Soil strength is an inherent soil property that enables root systems to mechanically support plants, and allows the soil to maintain pore space, protecting it from collapse under the weight of the overlying soil, vegetation, and animal or machine traffic (Bennie 1991). Under compactive forces, the pore space can decrease, increasing soil strength to the point where it begins to impede root penetration, eventually reducing root growth (Krenzer et al. 1989; Bennie 1991; Tan 2000).

Penetration resistance is influenced by soil moisture content, bulk density, soil type, soil strength, and the cone characteristics of the selected penetrometer (Perumpral 1987). However, at high moisture contents, bulk density had a minimal effect on soil penetration resistance, and at low moisture contents, bulk density had a large effect on penetration resistance (Perumpral 1987). A penetration resistance of 2.0 MPa is the accepted threshold that limits root growth (Chanasyk and Naeth 1995). Root elongation declined rapidly at resistances between 0.8 and 1.2 MPa (Bennie 1991). Coarse-textured soils do not experience as much soil impedance as fine-textured ones, because of the large quantity of macro-pores through which plant roots can grow (Tan 2000). Clay-textured soils can have mechanical impedance 8 times larger than sandy soils because they are more cohesive (Bennie 1991).

Compaction can negatively impact pasturelands by reducing infiltration rates (e.g., Gifford and Hawkins 1978; Proffitt et al. 1993), and thus increasing runoff. Compaction on pastures is most commonly caused by animal traffic due to grazing (Twerdoff et al. 1999), but can also be caused by frequent traffic of vehicles or heavy farm machinery (Tanner and Mamaril 1959). It is interesting to note that soil pressure from sheep hooves may be as high as 200 kPa, whereas the pressure from a tractor can range from 30 to 150 kPa (Proffitt et al. 1993). Organic matter content, texture, structure, water holding capacity, plant rooting depth, amount and type of vegetation, and freezethaw and wetting-drying cycles affect soil bulk density and penetration resistance, and thus compaction (Naeth et al. 1990).

3.1.2 Soil Chemical Properties

Soil chemistry is an indicator of soil quality, and tends to vary both spatially and temporally in pasturelands (Krzic et al. 1999). Forage plants and other pasture vegetation rely on mineral elements in the soil as a source of nutrients (Dormaar et al. 1977). Although plant available water is the most limiting factor for maximum yield potential, sufficient soil fertility is the second most limiting factor (Havlin et al. 1999).

Analysis of soil chemistry typically includes soil pH; electrical conductivity (EC), which is a measure of salinity; sodium adsorption ratio (SAR), which is a measure of the relative concentration of sodium ions in relation to calcium and magnesium ions; and various anions and cations. Soil pH, salinity, ammonium, nitrate, phosphate, potassium, chlorine, and sodium are the chemical parameters most affected by urine and feces from grazing (Dormaar et al. 1977; Haynes and Williams 1993). Potassium is predominantly excreted in urine, phosphorus is excreted mainly in feces, whereas ammonium, nitrate, sodium, and chlorine are excreted in both urine and feces (Haynes and Williams 1993). While pH can be decreased by grazing (Dormaar et al. 1977) or only minimally affected (Baron et al. 1999), salinity and nutrient concentrations often increase (Maulé and Fonstad 2000).

Soil sodicity, as expressed by SAR, generally occurs in wetter areas where there may be a high water table or buried zone of lateral flow (Chaikowsky 2003). The greatest problem of the nonsaline-sodic soils is that they disperse and deflocculate, resulting in low permeability to water and air (Bernstein 1975). However, the high salt concentrations in saline-sodic soils actually promote flocculation, alleviating the otherwise low permeability (Bernstein 1975).

Soil salinity is caused by increased concentrations of chloride, sulfate, carbonate, sodium, calcium, or magnesium ions, or rarely, nitrate or potassium ions (Bernstein 1975). Increased soil salinity, as expressed by EC, will decrease germination and plant growth (Bernstein 1975).

Calcium and magnesium naturally occur in soil, originating from weathering of soil parent material, including rocks and various minerals. Magnesium is also found in secondary clay minerals. Both of these cations can leach from soils, depending on the concentration of each in the soil, the rate of weathering, amount of water flux, and uptake by plants. These cations can also be lost with the soil particles to which they are adsorbed, during erosion due to wind or runoff. (Havlin et al. 1999)

A relatively low soil pH can decrease soil microbial activity, reducing or even suppressing nitrification, denitrification, or potassium fixation, or accelerating phosphorus precipitation (Havlin et al. 1999; McKenzie 2003). A relatively high soil pH can reduce the growth of plants or restrict plant uptake of phosphorus and some micronutrients (Havlin et al. 1999). Increased pH can also reduce phosphorus adsorption by iron/aluminum oxides in the soil, thus reducing the retention of phosphorus in the soil (Havlin et al. 1999).

High concentrations of nitrate and sulfate can be hazardous to the environment, since they are both highly mobile and can be readily leached with movement of soil water (Havlin et al. 1999). Additionally, soluble salts can be leached through the soil profile.

If the potential for leaching increases, the potential for groundwater contamination is subsequently increased (Maulé and Fonstad 2000).

High concentrations of ammonium, phosphate, and potassium are more environmentally hazardous to surface water supplies than groundwater since they are not very mobile in the soil (Havlin et al. 1999). Furthermore, phosphorus is only present in feces and thus does not enter the soil profile under normal grazed pasture conditions (Haynes and Williams 1993). Phosphorus adsorption is greater in fine-textured than coarse-textured soils (Havlin et al. 1999), so fine-textured soil particles carried by runoff or erosion will likely carry more phosphorus, increasing the potential for surface water contamination. However, sandy soils have low cation exchange capacity, allowing both ammonium and potassium to leach into the subsoil, becoming a risk to groundwater contamination (Havlin et al. 1999; Maulé and Fonstad 2000). Leaching of potassium can also occur in soils that are prone to flooding; ammonium can be leached if it is converted into nitrate through the process of nitrification; and phosphorus can move out of water-soluble phosphorus fertilizer granules, although initial movement away from the fertilizer application site rarely exceeds 3 to 5 cm (Havlin et al. 1999).

In conclusion, the potential for nutrient leaching depends on two factors: the concentration of nutrients in the soil solution, and the water flux transporting these nutrients into lower layers (Brye et al. 2001). However, mineralization rates and microbial activity are greatly affected by soil water content and temperature (Krzic et al. 1999), impacting the amounts of ammonium and sulfate in the soil.

3.2 Research Hypotheses

The null hypotheses for the soil properties characterization component of the study are:

i. Physical properties (e.g., bulk density and penetration resistance) do not vary by forage treatment.
ii. Organic matter does not vary by forage treatment.
iii. Chemical properties (e.g., pH, EC, SAR, cations, and anions) do not vary by forage treatment.

3.3 Materials and Methods

3.3.1 Data Collection

Soil samples were collected for physical and chemical analysis in August 2002 using "Dutch" hand augers and a Gator™ mounted hydraulic soil sampler. Samples were taken approximately 3 m away from the three access tube locations within each paddock. In Paddocks 1, 3, 4, 13, 14, 15, 21, and 24, the soil samples were taken 3 m to the east of each access tube, and 3 m to the south of each tube in Paddocks 7, 9, and 12. Samples were taken at depth intervals of 20 cm to a total depth of 200 cm.

Surface (0-10 cm) volumetric moisture and bulk density measurements were taken on July 10, 2003 at 2 locations within 1 m of each neutron access tube, with a Campbell Scientific MC-3 Portaprobe® (surface moisture/density gauge). The probe was inserted into a small 10-cm deep hole, within 1.0 m of each access tube, and a 16-sec count was taken. Using a manufacturer's equation for density and a locally derived equation for soil moisture, the counts were converted into wet bulk density and volumetric moisture content. Bulk density was determined by difference between these latter two parameters.

Soil samples for laboratory measured bulk densities were taken on September 24, 2003 from three locations within each paddock with a Uhland corer whose cores were 7.6 cm in diameter and 7.6 cm in height. The soil surface was cleared of vegetation and litter, and the corer was tapped into the soil surface within 1.0 m of each of the aluminum access tubes. These soil cores were then extracted and cut horizontally with a small saw blade into soil slices that were 2.5 cm in height (7.5 cm in diameter), resulting in a volume of 110.45 cm^3. Each 2.5-cm slice represented one of three depth intervals: 0 – 2.5 cm, 2.5 – 5.0 cm, and 5.0 – 7.5 cm. These soil samples were oven dried at 105 °C for 24 h and weighed to determine the bulk density for the three depth intervals.

Field bulk density measurements were taken with two Campbell Scientific 501DR Depth Moisture/Density Gauges in 2002, using 16-s counts. After analyzing the moisture and density data, it was determined that one gauge had not provided reliable data. Therefore in 2003, 15 of the 33 aluminum access tubes were reread with the "reliable" 501DR gauge, to provide missing bulk density data. Six of these tubes were reread for cross calibration purposes, to gauge any differences between readings in 2002 to 2003.

Penetration resistance measurements (Bengough and Mullins 1990) to a 10-cm depth were taken early in the growing season on May 14, 2003, and then in the middle of the growing season on July 24, 2003. Penetration resistance was recorded with a hand-pushed, manually read 13-mm diameter penetrometer at 5 depths (0.0, 2.5, 5.0, 7.5, and 10.0 cm) and a 21-mm diameter penetrometer at the ground surface (0.0 cm depth) for approximately 30 locations in each forage treatment. Measurements were taken with both the small cone (13-mm diameter; 1.327 cm^2) and large cone (21-mm diameter; 3.464 cm^2) penetrometers in May. However, drier soil conditions in July made pushing the large cone into the surface impossible, so only small cone measurements were taken. Early season measurements were not taken on the annual paddocks since they were being cultivated and seeded at this time, likely resulting in only minimal resistance in the loose soil conditions.

3.3.2 Data Analyses

Throughout the discussion in this thesis, the soil profile was considered to be the entire profile of monitored soil, specifically between 0 and 180 cm. For discussion purposes, the rooting zone was considered to be between 0 and 80 cm, and occasionally up to 100 cm. The depth interval below the rooting zone was considered to be between 80 and 180 cm, and occasionally between 100 and 180 cm.

Wet bulk densities at the surface and at depth, as measured by the MC-3 Portaprobe® and the 501DR Depth Moisture/Density Gauges, were determined by the difference between wet density and volumetric moisture content. Specifically:

$$D_b = D_b wet - \left(\frac{VMC}{100} \right)$$

where D_b is bulk density, D_b wet is the wet bulk density at a particular depth, and VMC is the volumetric moisture content at that depth, as determined by the same gauge at the time of density measurement. Surface bulk density measurements were averaged for each tube, and then averaged for each forage treatment. Similarly, bulk density measurements at depth were averaged at each depth by paddock, and then averaged for each forage treatment.

Laboratory measured near-surface bulk densities, as sampled with the Uhland corer, were determined in the following manner:

$$D_b = \frac{M_{dry}}{V_{slice}}$$

where D_b is the bulk density, M_{dry} is the mass of the oven-dried soil slice for a particular depth interval, and V_{slice} is the volume of the soil slice (2.5 cm height x 7.6 cm diameter; volume = 110.45 cm^3) for one 2.5 cm depth interval. Both the near-surface bulk densities and volumetric moisture contents were averaged for each paddock and for each forage treatment by depth interval.

Large cone (13-mm diameter) field penetration resistance measurements at the ground surface were converted from psi into MPa in the following manner:

$$MPa = psi \times \frac{6.894kPa}{1psi} \times \frac{1MPa}{1000kPa}$$

Small cone (13-mm diameter) field penetration resistance measurements at 5 depths were converted from psi into MPa in the following manner:

$$MPa = psi \times \frac{6.894kPa}{1psi} \times \frac{1MPa}{1000kPa} \times \frac{3.464cm^2}{1.327cm^2}$$

where 3.464 cm^2 is the area of the large cone, and 1.327 cm^2 is the area of the small cone. The penetration resistance measurements from each cone size were averaged for each depth, and then averaged by forage treatment.

Soil samples, in depth intervals of 20 cm, from the 2002 sampling were analyzed by Enviro-Test Labs in Edmonton, Alberta for various chemical parameters. Samples were dried and ground in preparation for the following laboratory analyses. The laboratory methods used followed procedures generally based on nationally or internationally accepted methodologies. Unless otherwise stated, analyses were conducted on each soil depth interval between 0 and 200 cm for each paddock.

Soil samples were pre-treated with Calgon and percentage sand, silt, and clay were determined via the hydrometer method of particle size analysis (Carter 1993). Organic carbon and organic matter were determined on the top 3 depth intervals of 20 cm each (0-60 cm) by dichromate oxidation with external heat for complete oxidation of organic matter (Carter 1993). Electrical conductivity (EC) and pH were determined through the saturated paste method (Carter 1993). The sodium adsorption ratio (SAR) was calculated from Ca, Mg, K, and Na ions in a saturated paste extract (Carter 1993). Available nitrate (NO_3^-) nitrogen was extracted with 0.001M $CaCl_2$ to determine the N availability index, and available ammonium (NH_4^+) nitrogen was extracted with 2N KCl (Carter 1993). Total Kjeldahl nitrogen ("total soil nitrogen"), which includes most of the organic forms of N in addition to NH_4^+ and NO_3^-, was analyzed by digestion (Carter 1993). Available phosphorus (PO_4^-) was extracted with the modified Kelowna extract of 0.25N HOAc, 0.0115N NH_4F, and 0.025N NH_4OAc at pH 4 (Qian et al. 1994). Sulfate (SO_4), and chloride were analyzed in a saturated paste (APHA 2002).

3.3.3 Statistical Analyses

Refer to Chapter 2 for detailed description.

3.4 Results and Discussion

3.4.1 Physical Soil Properties

3.4.1.1 Soil Texture

Soil texture varied across the research site. Soil textures within each paddock are shown in the Appendix (Table 7.1). At the upper (west) end of Block 2 (Paddock 21), the soil texture was sandy loam throughout the profile, having a sand content between 52 and 73%, and a clay content between 8 and 19% (Table 7.1). As the elevation decreased, moving from west to east in this block, the top portion of the profile (0-80 cm) remained as sandy loam, but the bottom depths of the profile (80 cm to 200 cm) changed to loamy sand, loam, and finally clay loam. The elevation decreased slightly again from Block 2 into Rep 1 of Block 1, where the texture was generally loamy sand or clay loam in the upper portion of the profile, and clay (10 to 26% sand; 39 to 57% clay) in the bottom portion of the profile. This trend continued in Rep 2, at the eastern side of the research area. Sandy clay loam and sandy loam soils dominated the upper profile, while clay dominated the lower profile depths. At the northern side of the research area, Rep 3 was dominated by sandy loam and loam in the upper portions of the profile, clay in the middle of the profile, and silt clay loam (e.g., 16% sand, 35% clay) and silt loam (e.g., 9% sand, 23% clay) in the bottom of the profile.

The average soil texture for the annual treatments was sandy loam near the surface (0-60 cm), loam in the middle of the profile, and clay loam and clay at the bottom of the profile (Table 3.1). The average soil texture for the meadow bromegrass treatments at the near-surface depths (0-80 cm) was sandy clay loam, clay in the middle of the profile, and silty clay at the bottom (180-200 cm). The alfalfa treatments had an average soil texture of sandy loam in the top half of the profile (0-100 cm), clay in the lower half of the profile (100-180 cm), and silt clay loam at the bottom (180-200 cm). In contrast, the old grass treatments were sandy loam throughout the profile (0-160 cm), with the exception of the bottom of the profile (160-200 cm), which was loam textured. (Table 3.1)

Based on field observations at various locations around the research site, the general texture of the soil in Reps 1 and 2 of Block 1 ranged from sandy loam to clay loam between 0 and 100 cm, and was often clay between 100 and 200 cm. In contrast to the other reps, areas in Rep 3 had a gravel-like lens in the middle of the soil profile, between 100 and 120 cm.

In general, Block 2 (old grass area) had the most sand and the least clay at all depths, while the percentage of sand was very similar within Block 1. However, the percentage of clay varied below 100 cm; within Block 1, Rep 3 had the least amount of clay, and Rep 1 had the most.

3.4.1.2 Soil Organic Matter

Soil organic matter (OM) generally decreased by depth in all treatments, ranging from 1.1 to 13.0% (Table 7.1). On average, the organic matter near the surface (0-20 cm) was 8.0%, whereas in the middle of the rooting zone (40-60 cm), the average was 3.1% (Table 3.1). This trend concurs with Alderfer and Robinson's (1947) finding that organic matter content was often greatest in the 0 to 2.5 cm layer.

The overall soil organic matter ranking by forage treatment in the top 40 cm was: meadow bromegrass > alfalfa > annual > old grass (Table 3.1), although this relationship was not tested statistically. Between 40 and 60 cm, the non-statistical ranking was: alfalfa > annual > meadow bromegrass > old grass. The average OM in the meadow bromegrass treatments ranged from 10.8 to 3.0%, between 0 and 20 cm, and 40 and 60 cm, respectively. In contrast, the average OM in the old grass treatments ranged from 4.7 to 1.9% in the same depth intervals. These OM percentages were consistent with the typical ranges for the black soil zone in Alberta; OM in virgin soil ranged between 6 and 10%, and OM in cultivated soil ranged between 4 and 6% (Lickacz and Penny 2000).

In general, the soil organic matter levels in the surface soil (0-20 cm) at the research site were very high, as organic matter contents of 3 to 8% or higher are considered optimum for crop production (Donahue et al. 1983). A 1956 study on subalpine grasslands in Colorado, also found that organic matter was higher in soils from good condition ranges than from fair and poor condition ranges (Klemmedson 1956).

3.4.1.3 Surface Soil Moisture

Average surface (0-10 cm) volumetric soil moisture contents (VMC), as measured by the MC-3 Portaprobe®, were quite low, ranging between 4.4 and 10.9% (Figure 3.1). As expected, the annual treatment had the highest surface VMC, likely due to the shallower root systems and greater percentage of bare ground, resulting in greater storage of soil moisture in these treatments. Also as expected, old grass had the lowest surface VMC, likely due to a combination of large root mass and greater plant density, resulting in restricted infiltration and increased soil water uptake, both of which decrease soil water levels. The overall ranking of the surface VMC for the forage treatments was: old grass < alfalfa < meadow bromegrass < annual, although this was not tested statistically.

3.4.1.4 Surface Bulk Density

The average surface (0 to 10 cm) bulk densities, as measured by the MC-3 Portaprobe®, for the meadow bromegrass, annual, and old grass treatments were very similar, ranging from 1.15 to 1.17 Mg/m^3, respectively (Figure 3.2). The alfalfa treatments had a slightly higher average surface bulk density, at 1.25 Mg/m^3. Overall, the surface bulk densities of the four forage treatments as measured by this method were very similar.

In contrast, the surface bulk densities measured in the laboratory from the Uhland core samples were significantly different (Table 7.9) amongst treatments for the three depth intervals sampled (Figure 3.3). Old grass treatments had the lowest average bulk density for the 0.0-2.5 cm interval (0.80 Mg/m^3), which was significantly different from the other forage treatments, likely due to the large quantity of crowns and roots in the sub-surface litter. However, at the 2.5-5.0 cm depth interval, the old grass treatments had the highest bulk densities, approximately 1.28 Mg/m^3, which was significantly higher than the annual and meadow bromegrass treatments. Similarly, at the 5.0-7.5 cm depth interval, the bulk density for the old grass treatments (1.40 Mg/m^3) was significantly higher than the annual and meadow bromegrass treatments. The elevated bulk densities in these last two intervals were likely due to years of near-surface compaction from livestock and machinery. In 1947, Alderfer and Robinson also found low bulk densities (1.09, 1.36, and 1.34 Mg/m^3) under an ungrazed Kentucky bluegrass pasture in 5-cm increments in the uppermost 15 cm.

Annual and meadow bromegrass treatments had similar bulk densities at approximately 1.00, 1.11, and 1.15 Mg/m^3, for the three respective depth intervals, and were not significantly different from each other. Since the annual treatments were cultivated and seeded each year, it was expected that they would have low bulk densities. Meadow bromegrass is a bunchgrass and has moderately spreading roots, therefore like the annual treatments it has more open ground compared to the old grass treatments. However, the spreading rhizomes of quack grass and smooth bromegrass in the old grass treatments failed to alleviate compaction, as a high bulk density was observed between 2.5 and 7.5 cm.

Alfalfa treatments, on the other hand, had the highest bulk density at the surface (0.0-2.5 cm) at 1.09 Mg/m^3, although it was only significantly different from the old grass treatments. Alfalfa treatments had the second highest bulk densities for the remaining depths (1.21 and 1.23 Mg/m^3, respectively), which were not significantly different from any other treatments. Alfalfa treatments had more bare ground than did the other treatments (Table 5.2). This may have made these pastures more susceptible to surface crusting from raindrop impacts and/or surface compaction from cattle and machinery. Although the high organic matter Chernozems typically do not crust, the surface soil in the alfalfa treatments had a hard surface layer that may have acted like a crust. The very low soil moisture levels in the alfalfa treatments are hypothesized to contribute to this hard layer, despite the high organic matter contents (8.8% on average).

Results from a previous study adjacent to the site were that surface (0-10 cm) bulk density increased with high animal traffic under heavy grazing (Twerdoff et al. 1999). These researchers surmised that vegetation removal by grazing decreased ground litter, resulting in less cushioning of the soil surface, making it more susceptible to compaction. Other studies also found that significant increases in bulk density due to compaction were only in the surface soil, often in the top 10 cm (e.g., Naeth et al. 1990; Donkor et al. 2002).

3.4.1.5 Bulk Density at Depth

Average soil bulk density varied by treatment in the rooting zone, but little at depths below the rooting zone (Figure 3.4). At 15 cm, the old grass treatments had the highest bulk densities (approximately 1.00 Mg/m^3), followed by the alfalfa treatments (approximately 0.95 Mg/m^3), the annual treatments (approximately 0.90 Mg/m^3), and finally, the meadow bromegrass treatments (approximately 0.70 Mg/m^3), although these differences were not significant. This trend generally continued to 35 cm, but by 45 cm, the annual treatments had the lowest bulk density. Below 65 cm, the bulk densities did not vary much between forage treatments. However, the differences in bulk density below the rooting zone (>80 cm) likely reflect differences in soil texture rather than forage treatment. In a southern Alberta grazing intensity study, bulk density increased with depth to 65 cm with increasing grazing intensity (Naeth and Chanasyk 1993).

Overall, bulk densities at depth were very low at the research site, averaging 1.04 Mg/m^3 (data not shown). A grazing intensity study conducted on Chernozemic soil in southern Alberta also found low bulk densities regardless of treatment, related to the well aggregated and well structured, porous nature of Chernozems (Naeth and Chanasyk 1993).

3.4.1.6 Penetration Resistance

Penetration resistance measurements taken during "wet" soil conditions in spring 2003 (May 14), were highest in old grass treatments and lowest in the alfalfa treatments at all depths (0.0, 2.5, 5.0, 7.5 and 10.0 cm), ranging between 1.27 and 2.22 MPa, and 0.53 and 1.42 MPa, respectively (Figure 3.5 a), although these differences were not statistically significant. Even though the loose soil conditions in the annual treatments prevented measurements from being taken, it was likely that they had the lowest penetration resistance relative to the perennial forages. The overall ranking for penetration resistance in forage treatments under "wet" soil conditions was: annual < alfalfa < meadow bromegrass < old grass, although they were all similar statistically. This was likely because the old grass treatments had a thick fallen litter layer and large volume of roots in the top 10 cm of the soil profile, which decreased bulk density. Alternatively, the alfalfa plants were likely not able to use all the water from snowmelt by the measurement date, so the surface soil was quite moist, resulting in low penetration resistance values. Perumpral's (1987) literature review suggests that at high moisture contents, bulk density had a minimal effect on penetration resistance, but that the reverse was true at low moisture contents.

Penetration resistance was considerably greater during "dry" soil conditions in mid-summer 2003 (July 24). Chanasyk and Naeth (1995) also found that penetration resistance increased between "wet" and "dry" dates at all depths for all treatments, likely due to a decrease in soil water. Similar trends were observed for the old grass treatments, in that they had the highest penetration resistance at all depths measured (5.40 MPa for all depths) (Figure 3.5 b), and likely for similar reasons previously mentioned in addition to the very low surface (0-10 cm) volumetric moisture contents measured 2 weeks prior (Figure 3.1). Unlike the May 14th readings, the alfalfa treatments had the second highest penetration resistance at all depths measured (ranging between 2.26 and 4.44 MPa), possibly due to dry soil conditions (Figure 3.1). Perumpral's (1987) review concluded that penetration resistance increased as soil moisture content decreased. Meadow bromegrass treatments had the third highest penetration resistance at all depths, ranging between 1.80 and 3.43 MPa. The annual treatments, which had not been measured previously, had relatively low penetration resistance at all depths (ranging from 0.25 to 2.80 MPa), likely due to the loose, low-density soil conditions typical of annual crops. Bennie (1991) stated that cultivated soils normally have low penetration resistance, likely due to their low bulk density.

The overall ranking of "dry date" penetration resistance for the forage treatments was: annual < meadow bromegrass ≤ alfalfa < old grass. These relationships were statistically significant at 2.5, 5.0, and 7.5 cm, and varied slightly at 0 and 10 cm (Figure 3.5 b). These relative penetration resistances were inversely related to the surface (0-10 cm) volumetric moisture contents, measured 14 days prior to these readings (Figure 3.1). Additionally, almost all of the penetration resistances measured in the "dry" soil conditions exceeded the generally accepted threshold value of 2.0 MPa, beyond which root growth is potentially limited (Chanasyk and Naeth 1995).

The "dry date" penetration resistances were significantly greater than the corresponding penetration resistances for the "wet date" (Table 7.9). Overall, the old grass treatments were significantly different from alfalfa and meadow bromegrass treatments at 0, 2.5, and 5 cm, and significantly different from meadow bromegrass treatments at 7.5 and 10 cm. The relative ranking of the forage treatments was very similar for both dates. Old grass had the highest resistance to penetration for both dates, and annual the lowest, even though it was not directly measured for the first date, and these differences were not statistically significant for the "wet" date. Meadow bromegrass had a higher penetration resistance for the "wet date" than alfalfa, but this relationship was reversed for the "dry date", likely due to a greater use of soil water by alfalfa. It should also be noted that there were significant differences in penetration resistance at all depths for the measurement date/forage treatment interaction.

3.4.2 Soil Chemistry

3.4.2.1 Basic Chemical Indicators

The average pH of the soil at the research site did not vary much between forage treatments, with the exception of a few depth intervals in the annual treatments (Table 3.2, Table 7.2), although these differences were not tested statistically. In the uppermost 60 cm, the annual treatments had a slightly higher pH than the other treatments, ranging between 6.0 and 7.2, and between 80 and 160 cm, these treatments had a slightly lower pH, ranging between 6.4 and 6.8. However, these pH values are not unusual, as they are consistent with the range given by Bowser et al. (1951) for a Ponoka loam or Peace Hills fine sandy loam/Penhold fine sandy loam. When comparing average pH by rep, there was a small difference in the soil near the surface (20 cm), as Rep 3 of Block 1 was the most acidic at a pH of 5.3, and Rep 2 the most neutral, at a pH of 6.2 (data not shown). On average, pH increased in all forage treatments with depth, which is consistent with a 1993 to 1996 study at an adjacent site (Baron et al. 1999).

At the research site, the sodium adsorption ratios (SARs) were generally low, below 4, and often below 1 (Table 7.2). The highest SARs, of 3.3 and 3.4, were found in the mid-profile (100 to 140 cm) in Paddock 7 (alfalfa treatment), although these differences were not tested statistically. This may be due to a high water table or buried zone of lateral flow, as other studies have found that the greatest sodicity is found in the wettest areas (Chaikowsky 2003). Although these SARs were the highest on site, they are not high enough to cause sodicity concerns.

Electrical conductivity (EC) at the research site was also low (<2 dS/m), and was often below 1 dS/m (Table 7.2), which was expected as the parent material of Ponoka loams is low in salt content (Bowser et al. 1951). Soils with EC between 0 and 2 dS/m have negligible salt effects, so salinity is not a concern at the research site (Bernstein 1975; AAFRD 2003).

3.4.2.2 Soil Nitrogen

Three forms of soil nitrogen were analyzed: available ammonium (NH_4^+) nitrogen; available nitrate (NO_3^-) nitrogen; and total Kjeldahl nitrogen, but treatment differences were not tested statistically. The complete data set for each of these values is in Table 7.2. Since soil samples were collected at the end of the growing season in 2002, all three forms of nitrogen were generally quite low.

On average, the available NH_4^+ levels were very similar between the alfalfa and old grass treatments throughout the soil profile (Table 3.2). The average available NH_4^+ levels in the meadow bromegrass treatments between 80 and 200 cm were slightly elevated (4.5 to 6.5 mg/kg), but were still very low (Table 3.2). In fact, all of the available ammonium-N (NH_4^+) was ≤ 10 mg/kg, excluding one annual treatment where 21.2 mg/kg was found in the surface soil (Table 7.2). However, it should be noted that these results are likely due to spatial variability in pastures, rather than forage treatment differences. According to Marx et al. (1999), 2 to 10 mg/kg of ammonium-N is typical, and >10 mg/kg is common in areas that have fertilizer residue. Due to row spacing and the large quantity of bare ground in annual pastures, it is quite possible that the annual crop had not utilized the ammonium-N in the surface soil.

Available nitrate-N (NO_3^-) levels were generally higher than ammonium-N, ranging from 1.2 to 68.4 mg/kg (Table 7.2). The highest levels were found in the top 60 cm in one of the old grass treatments (ranging between 30-50 mg/kg), and in the surface soil of the annual treatments (ranging between 25-70 mg/kg) (Table 7.2). Two unique high values were found in the surface soil of a meadow bromegrass treatment (58.8 mg/kg), and at the bottom of the root zone in another meadow bromegrass treatment (42.8 mg/kg) (Table 7.2). Keyes et al. (2002) provides guidelines for evaluating residual nitrate-N in the surface 60 cm: 20 mg/kg is deficient to marginal; 40 mg/kg is marginal to optimum; and 60 mg/kg is the upper limit of optimum, bordering on excessive. Therefore, this research site does not have any areas with very high levels of nitrate, decreasing the potential hazard of nitrate leaching into groundwater resources. The highest nitrate levels were measured in the surface soil of an annual treatment (68.4 mg/kg) (Table 3.2). It is likely that the smaller number of plants in this treatment compared to perennial treatments were not able to take up as much nitrate by the time of sampling.

3.4.2.3 Soil Phosphorus

Available phosphate ($H_2PO_4^-$/ HPO_4^{2-}) phosphorus ranged from <1 to 140 mg/kg (Table 7.2), averaging 15 mg/kg. The surface soil (0-20 cm) of the meadow bromegrass treatments had the highest levels, averaging 120 mg/kg (Table 3.2), although these differences were not tested statistically. The highest phosphate levels were found in the surface 20-cm of soil, in 9 of the 11 paddocks tested ranging between 61 and 140 mg/kg, which were above the optimum range of 25 to 60 mg/kg (Keyes et al. 2002) (Table 7.2). These high phosphate areas did not have a pattern related to forage treatment or block to explain the high levels, except that they were all in the top 20 cm of soil. Therefore, it is most likely that these soil samples included some cattle feces or fertilizer residues that were on the soil surface, elevating the phosphate levels. Regardless, the majority of the phosphate levels measured at the research site were considered deficient (<15 mg/kg) according to Keyes et al. (2002). Generally, the phosphate levels decreased with soil depth, with a couple of exceptions. This trend was also observed by Baron et al. (1999), in a similar study conducted adjacent to the research site.

3.4.2.4 Other Anions and Cations

Sulfate (SO_4^{2-}) concentrations at the research site were quite variable between depth and treatments, although not tested statistically, ranging from 4.56 to 183.28 mg/kg (Table 7.2), with an average of 32.75 mg/kg. The highest levels occurred in the middle of the soil profile in two meadow bromegrass treatments, and at the surface (20 cm) in an annual treatment. According to Marx et al. (1999) and Keyes et al. (2002), 10-20 mg/kg of sulfate is optimum, but because sulfate is mobile in the soil, very high levels may indicate a potential leaching hazard.

Chloride (Cl^-) had very high variability between depths and treatments, although not tested statistically, ranging from 2.02 to 122.24 mg/kg (Table 7.2), averaging 18.33 mg/kg. Generally, in terms of plant growth, chlorine is considered deficient at levels of <8 mg/kg (Evans and Solberg 1998). However, most of the "deficient" soil samples were found well below the root zone, where "deficient" might not be the most accurate description. Similarly, the very high chlorine levels were found near the bottom of the root zone in Rep 1 of Block 1, at approximately 60 to 100 cm, so the high levels may not be a concern for surface water contamination, but could be a concern for groundwater contamination.

Calcium (Ca) and magnesium (Mg) levels were both relatively low, averaging 27.00 and 7.73 mg/kg, respectively (Table 7.2). On average, Ca and Mg levels at the surface (0-20 cm) were highest in the old grass and annual treatments (Table 3.2), although these differences were not tested statistically. According to Havlin et al. (1999), Ca levels range between 30 and 300 mg/kg and Mg levels less than 5 to 50 mg/kg in temperate region soils. Since the rate of weathering in these regions is not high, and the observed levels of these cations were at the low end of the expected ranges, there is little concern of either nutrient leaching into groundwater resources.

Potassium (K) was very low across the research site, ranging from 0.40 to 31.13 mg/kg (Table 7.2), and averaging 3.44 mg/kg. The meadow bromegrass treatments had the highest potassium levels in the surface 20 cm, averaging 21.25 mg/kg (Table 3.2), which was likely due to higher stocking rates for this forage type. However, it should be noted that these differences were not tested statistically. Potassium was depth dependent, as the highest levels were found in the surface 20 cm, and then the levels were considerably lower throughout the remainder of the soil profile. This trend was also measured by Baron et al. (1999) in a similar study conducted adjacent to this research site. The K levels were extremely low when compared to Keyes et al. (2002) guidelines, which state that the deficient to marginal level is <100 mg/kg.

3.5 Conclusions

Generally, the soil physical properties varied by forage treatment, so the null hypothesis must be rejected. Average bulk density varied by treatment in the rooting zone, with old grass having the highest and meadow bromegrass the lowest. However, below the rooting zone, there was no pattern related to forage treatment. At the surface (0-2.5 cm), bulk density was highest in the alfalfa treatments and lowest in the old grass treatments, likely due to surface litter. However, near-surface (2.5-7.5 cm) bulk density was highest in the old grass treatments. Penetration resistance was closely related to surface soil moisture, increasing with decreasing soil moisture. Regardless of moisture content, penetration resistance was highest in the old grass treatments and lowest in the annual treatments.

Soil organic matter varied by forage treatment, so the null hypothesis must be rejected. Soil organic matter decreased with depth in all treatments, and was highest in the meadow bromegrass treatments and lowest in the old grass treatments, although not tested statistically.

Overall, soil chemistry did not vary by forage treatment, so the null hypothesis cannot be rejected. It is suspected that the chemistry results at depth are more closely related to benchmark soil chemistry from soil texture and spatial variability within pastures than from forage treatments or grazing. In contrast, the surface soil chemistry is quite likely due to management factors, specifically fertilization or grazing. Soil pH, SAR, EC, and phosphate did not vary by forage treatment. On average, ammonium, nitrate, sulfate, calcium, and magnesium were slightly elevated in the surface soil of the annual treatments, whereas potassium was slightly elevated in the surface soil of the meadow bromegrass treatments. Soil pH, phosphate, and potassium were depth related, having the greatest acidity (lowest pH) and highest levels of P and K in the surface soil. Ammonium and nitrate often had the highest levels near the surface, generally decreasing with depth. Sulfate was found in quantities exceeding the optimum range in the middle of the soil profile in two meadow bromegrass treatments. Since it is a mobile nutrient in the soil, it had the greatest potential for leaching, which could contaminate groundwater.

Table 3.1 Average soil physical properties

Forage Trt.	Depth (cm)	% Sand	% Silt	% Clay	Texture	%OM
Annual	0-20	52	23	25	Sandy loam	6.7
	20-40	64	20	16	Sandy loam	5.8
	40-60	66	20	14	Sandy loam	3.4
	60-80	47	28	24	Loam	
	80-100	44	30	26	Loam	
	100-120	46	28	26	Loam	
	120-140	42	29	29	Clay loam	
	140-160	40	33	27	Clay loam	
	160-180	32	33	35	Clay loam	
	180-200	24	35	41	Clay	
Meadow Bromegrass	0-20	63	15	22	Sandy clay loam	10.8
	20-40	48	28	25	Sandy clay loam/ Loam	7.6
	40-60	59	21	20	Sandy clay loam/ Sandy loam	3.0
	60-80	47	21	32	Sandy clay loam	
	80-100	31	28	41	Clay	
	100-120	19	33	49	Clay	
	120-140	15	37	48	Clay	
	140-160	13	38	49	Clay	
	160-180	14	43	43	Clay	
	180-200	11	48	41	Silty clay	
Alfalfa	0-20	73	9	18	Sandy loam	8.8
	20-40	61	24	15	Sandy loam	6.1
	40-60	64	20	16	Sandy loam	3.6
	60-80	70	14	16	Sandy loam	
	80-100	65	15	20	Sandy loam/ Sandy clay loam	
	100-120	33	26	41	Clay	
	120-140	19	34	47	Clay	
	140-160	24	34	42	Clay	
	160-180	15	40	44	Clay	
	180-200	19	42	39	Silt clay loam	
Old Grass	0-20	67	20	14	Sandy loam	4.7
	20-40	67	21	12	Sandy loam	3.3
	40-60	71	18	11	Sandy loam	1.9
	60-80	75	17	9	Sandy loam	
	80-100	76	17	8	Sandy loam	
	100-120	79	12	10	Sandy loam	
	120-140	74	14	13	Sandy loam	
	140-160	58	27	16	Sandy loam	
	160-180	49	32	19	Loam	
	180-200	44	33	24	Loam	

Table 3.2 Average soil chemistry by forage treatment

Forage Trt.	Depth	pH	SAR	EC (dS/m)	Total Kjeldahl Nitrogen (%)	mg/kg								
						Available Ammonium - N	Available Nitrate - N	Available Phosphate - P	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
Annual	0-20	6.0	0.6	0.90	0.32	11.5	39.9	69	28.64	80.79	60.35	14.29	12.28	13.52
	20-40	7.2	0.8	0.50	0.25	2.1	13.3	9	15.05	20.56	28.24	6.15	0.72	14.10
	40-60	7.0	0.3	0.39	0.17	1.7	5.5	7	12.51	19.11	27.05	7.06	1.03	4.92
	60-80	6.9	0.5	0.66		2.4	2.9	4	46.32	31.23	31.68	10.09	1.62	7.75
	80-100	6.4	0.6	0.47		3.2	9.9	11	9.42	35.94	21.49	6.49	2.74	8.70
	100-120	6.4	0.6	0.42		2.8	8.9	7	9.85	32.21	17.76	5.33	2.80	7.24
	120-140	6.5	0.5	0.46		2.7	6.1	4	13.86	32.48	21.45	5.76	2.88	6.25
	140-160	6.8	0.5	0.48		3.9	7.7	4	12.99	34.76	24.08	6.00	3.00	6.66
	160-180	7.4	0.4	0.46		4.2	5.5	3	8.44	27.15	30.36	8.72	4.15	7.85
	180-200	7.3	0.4	0.38		5.1	5.9	2	6.31	21.73	24.69	7.13	4.19	7.22
Meadow Bromegrass	0-20	5.7	0.7	0.64	0.50	5.5	29.3	120	42.68	46.47	44.73	10.44	21.25	16.81
	20-40	6.6	1.1	0.37	0.35	2.4	7.0	11	14.84	26.43	22.00	5.66	0.85	16.70
	40-60	6.8	1.0	0.33	0.13	4.7	2.7	5	11.36	19.70	14.92	4.47	0.72	10.41
	60-80	6.7	0.6	0.52		3.4	2.4	2	19.21	45.24	27.65	8.08	2.11	10.28
	80-100	6.6	0.5	1.00		5.6	15.8	16	48.34	87.82	68.76	19.17	6.52	12.71
	100-120	6.9	0.5	0.61		5.5	3.1	5	24.76	110.25	48.01	13.94	3.58	10.69
	120-140	7.2	0.5	0.42		6.5	3.8	2	11.60	51.26	33.75	9.90	3.08	10.54
	140-160	7.3	0.5	0.33		5.3	2.5	2	7.82	37.22	25.80	7.72	2.75	9.76
	160-180	7.7	0.5	0.33		4.5	2.5	2	5.28	21.81	25.21	7.22	2.22	8.60
	180-200	7.7	0.5	0.36		5.0	2.5	1	5.82	39.36	29.03	8.24	2.65	9.28

Table 3.2 (continued) Average soil chemistry by forage treatment

						mg/kg								
Forage Trt.	Depth	pH	SAR	EC (dS/m)	Total Kjeldahl Nitrogen (%)	Available Ammonium - N	Available Nitrate - N	Available Phosphate - P	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
Alfalfa	0-20	5.6	0.2	0.46	0.29	5.1	20.7	67	32.61	27.50	28.17	6.39	9.46	4.41
	20-40	6.6	0.5	0.38	0.28	2.1	6.5	14	20.82	23.25	22.45	5.58	2.40	7.13
	40-60	6.8	0.7	0.37	0.17	1.6	3.8	9	19.13	23.86	17.07	4.71	1.26	7.85
	60-80	6.9	0.7	0.35		1.5	2.1	5	12.93	17.94	12.43	4.56	1.33	6.55
	80-100	6.7	0.5	0.39		2.6	3.5	10	10.38	26.12	15.36	6.58	2.22	5.29
	100-120	6.8	1.4	0.51		3.4	2.9	4	22.42	51.36	22.47	10.04	1.41	17.26
	120-140	7.0	1.4	0.51		4.0	2.3	4	27.76	45.58	27.96	11.40	1.83	18.77
	140-160	7.0	0.3	0.43		2.9	1.9	2	31.90	21.11	23.99	9.56	3.49	6.20
	160-180	7.4	0.4	0.48		2.8	1.8	3	34.30	30.80	30.82	12.02	3.44	7.08
	180-200	7.5	0.3	0.44		2.9	2.0	4	27.03	25.68	25.68	10.23	2.79	6.12
Old Grass	0-20	5.8	0.3	0.83	0.24	4.0	31.5	86	30.51	26.32	51.60	11.74	6.77	5.31
	20-40	6.7	0.4	0.79	0.18	2.1	25.8	27	32.23	22.25	47.88	9.94	1.25	5.63
	40-60	6.7	0.6	0.65	0.09	1.5	19.4	9	27.51	10.74	30.33	7.59	1.36	6.43
	60-80	6.9	0.9	0.26		0.8	4.7	8	6.05	12.21	8.80	2.23	1.30	5.79
	80-100	6.7	0.7	0.20		1.1	2.8	10	2.91	10.82	6.93	1.61	1.60	4.10
	100-120	7.0	0.7	0.23		1.5	2.5	8	2.63	8.19	9.76	1.90	1.93	4.02
	120-140	7.0	0.4	0.21		1.4	2.3	7	2.19	7.03	9.93	1.93	1.67	2.37
	140-160	7.1	0.4	0.26		1.6	2.2	8	3.30	9.09	12.27	2.38	2.24	2.54
	160-180	7.1	0.3	0.27		1.9	2.0	5	4.34	10.21	13.75	2.98	2.33	2.77
	180-200	7.3	0.3	0.26		2.4	2.1	8	4.73	12.61	13.84	3.32	2.72	3.01

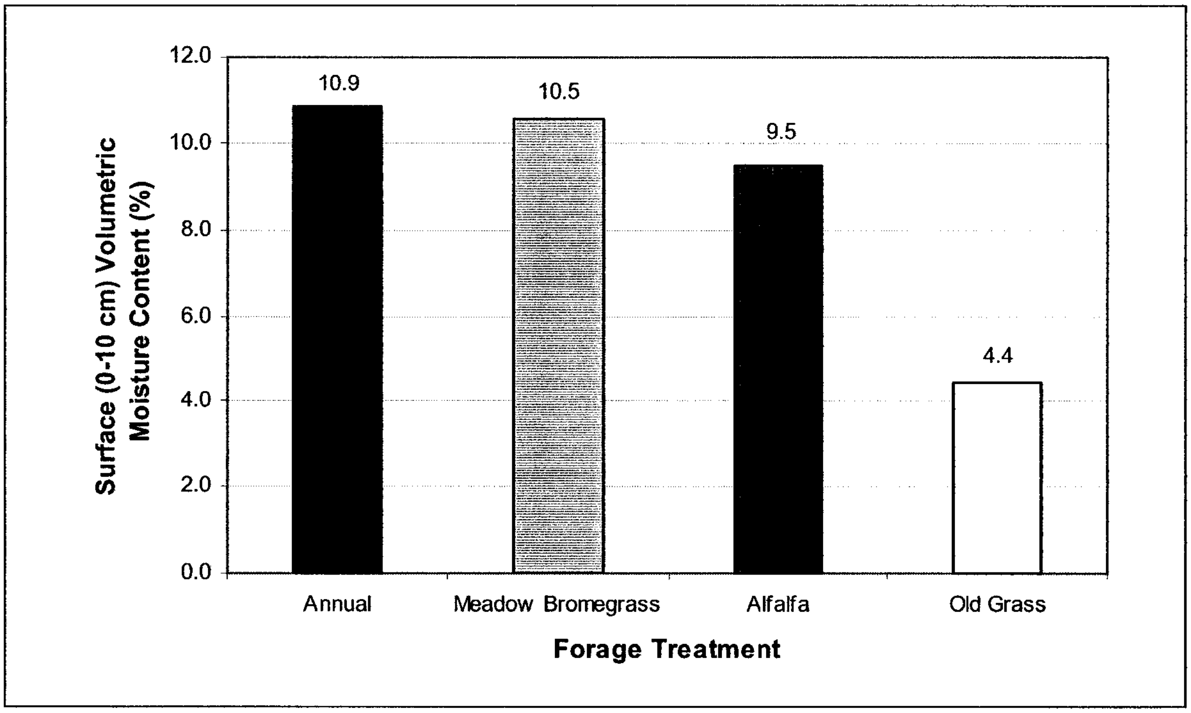

Figure 3.1 Average surface (0-10 cm) volumetric moisture content, as measured by MC-3 Portaprobe® on July 10, 2003

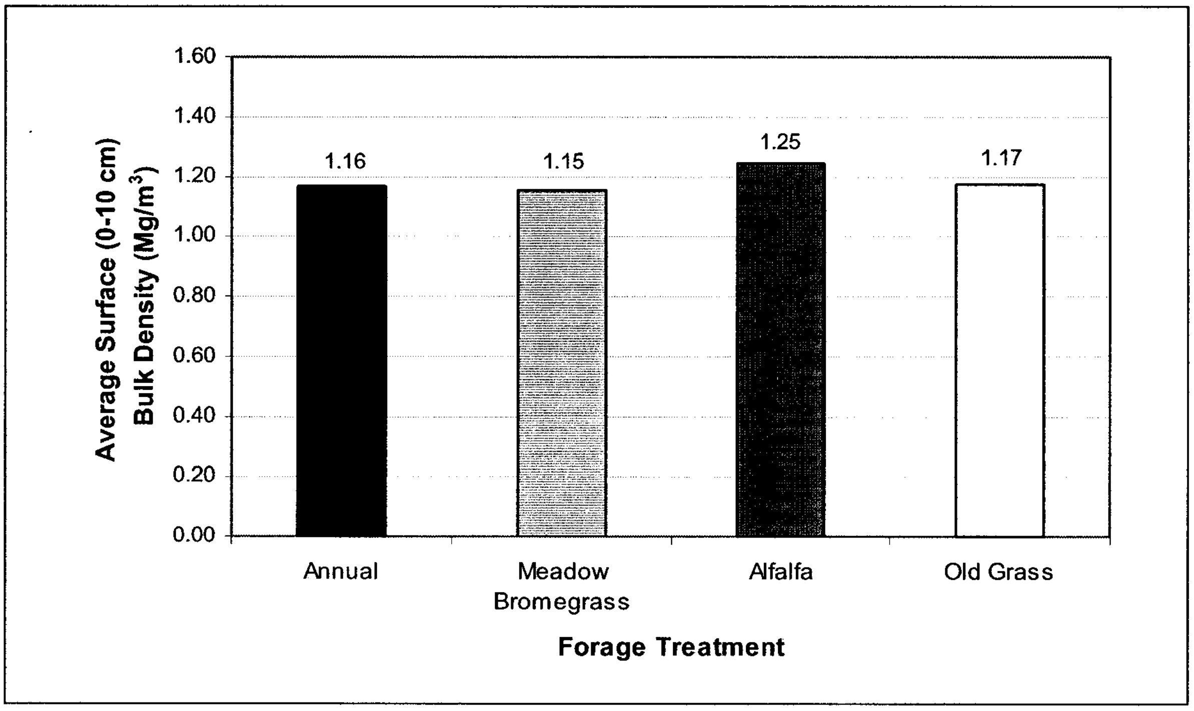

Figure 3.2 Average surface (0-10 cm) bulk density, as measured by MC-3 Portaprobe® on July 10, 2003

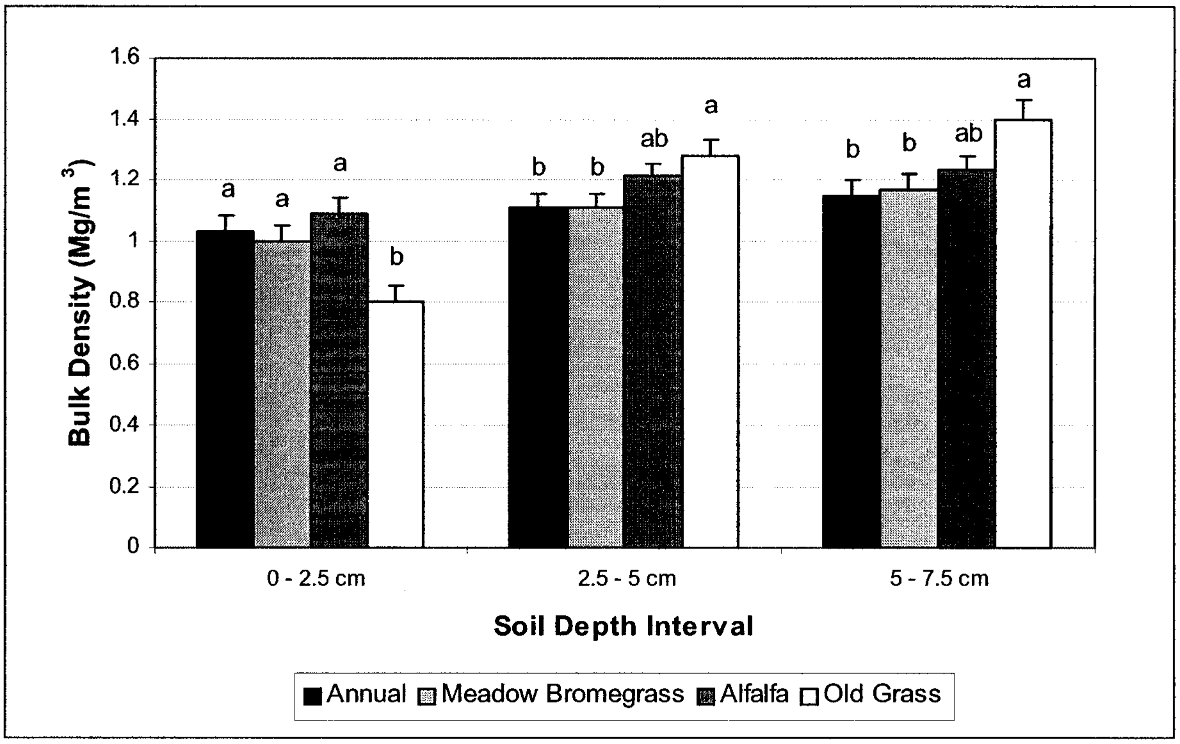

Figure 3.3 Average surface bulk density as measured by the Uhland core method
For a given depth increment, treatments with the same letter are not significantly different ($p \leq 0.05$).

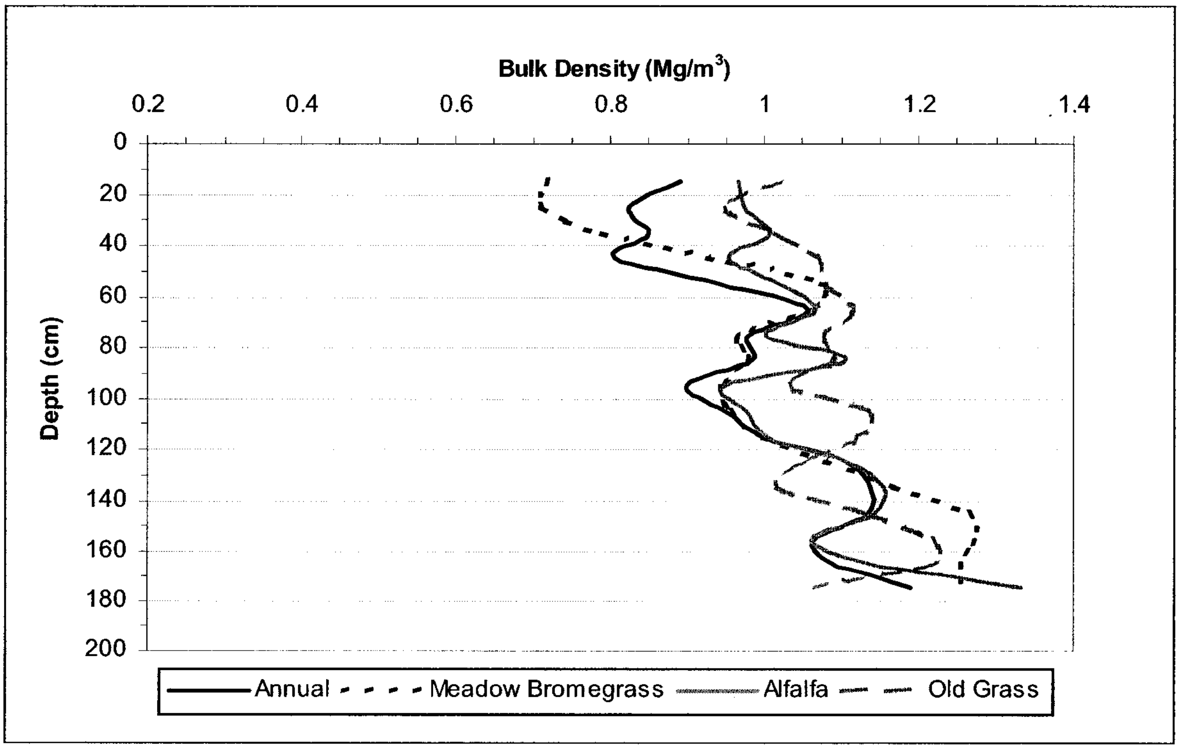

Figure 3.4 Average bulk density with depth

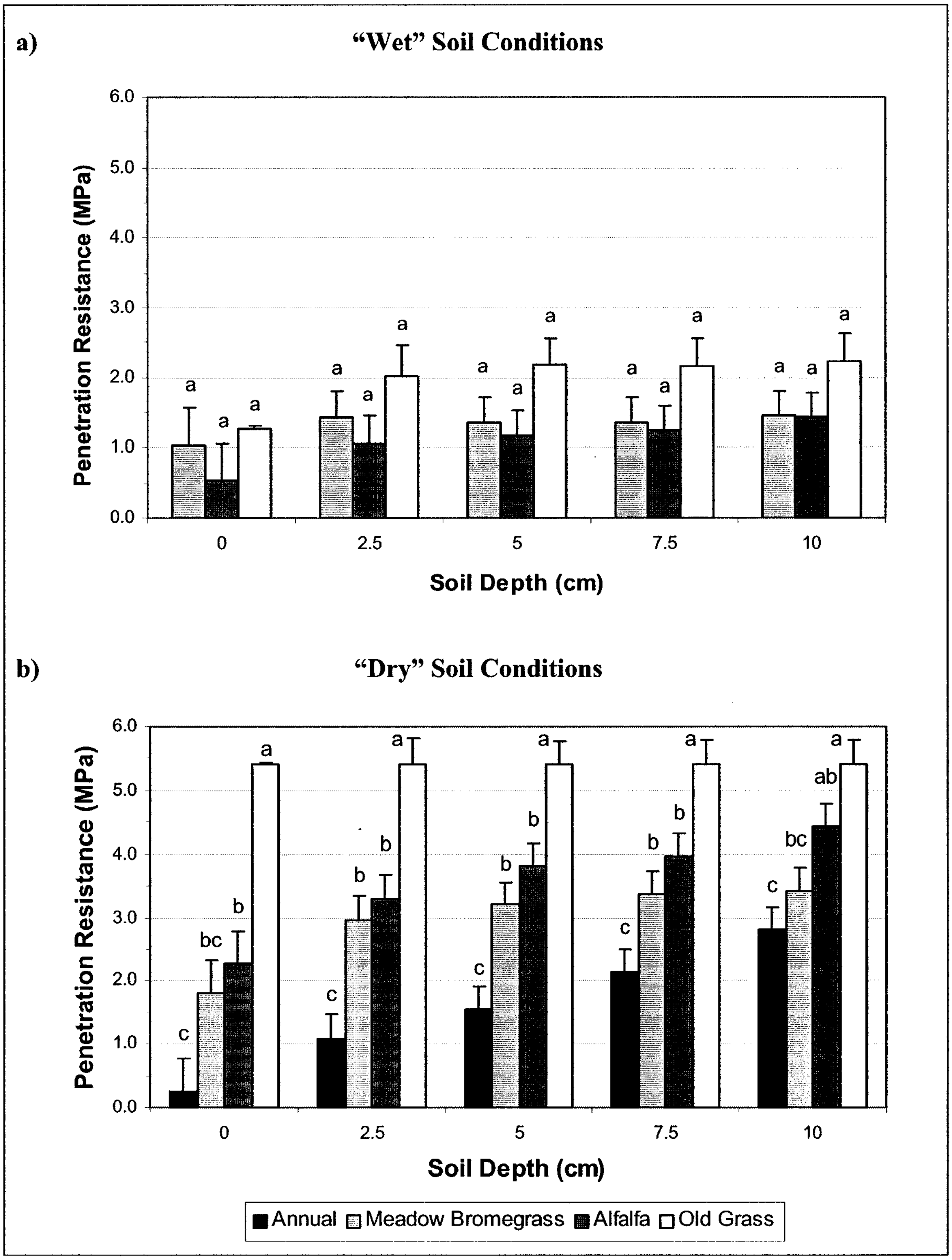

Figure 3.5 Average penetration resistance measured in a) relatively "wet" soil conditions (May 14, 2003), and b) relatively "dry" soil conditions (July 24, 2003). For a given depth increment, treatments with the same letter are not significantly different ($p \leq 0.05$).

3.6 References

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4 RESPONSES OF THE SOIL WATER REGIME TO MANAGED INTENSIVE GRAZING IN THE ASPEN PARKLAND ECOREGION OF ALBERTA

4.1 Introduction

Soil water is the primary limiting factor of rangeland plant productivity in most parts of the world (e.g., Holechek et al. 1998). The amount of soil water available during the growing season is the main factor affecting crop yield (Havlin et al. 1999) and plant growth. Available soil water depends heavily upon over-winter recharge, summer precipitation, and the efficiency of soil water storage in the profile (De Jong and Bootsma 1988; Twerdoff et al. 1999).

During the summer months on native rangelands west of 98° longitude, the major recharge of soil water occurs through infiltration of precipitation and spring snowmelt (Naeth and Chanasyk 1996), while evapotranspiration is the major source of soil water loss (Branson et al. 1981; Naeth et al. 1991). These parameters are represented in the hydrologic equation, which is a simplified method to describe the hydrologic cycle:

$$P = ET + D + R \pm \Delta S_m$$

where P is precipitation (including both rainfall and snowfall), ET is evapotranspiration, D is deep drainage (percolation), R is surface runoff, and ΔS_m is the change in soil moisture over the time period in question. If D and R are assumed to be negligible (equal to 0), or if they are known, ΔS_m can be used to determine ET.

The balance between infiltration, groundwater recharge, surface runoff, evapotranspiration, and leaching is soil water storage. The efficiency of storage is a function of soil texture and structure (Naeth and Chanasyk 1995), soil bulk density, antecedent soil water, vegetative species, vegetation growth stage (Naeth and Chanasyk

1993), and hydraulic conductivity (Singh et al. 1996). Consequently, soil water is impacted by the types of forage species grown on pasturelands, and by the management regime used.

Grazing of both perennial and annual forages is becoming increasingly popular in the aspen parkland ecoregion of Alberta. In general, perennial forages begin using soil water much earlier in the growing season than annuals simply because they are already established and transpiring as soon as they green-up. Annuals are seeded every spring (with the exception of fall seeded winter cereals), have shallower root systems, and tend to use less water than perennial forages (Baron et al. 1999; Twerdoff et al. 1999). Perennial forages have larger root system biomass compared to annuals (Baron et al. 1999; Mapfumo et al. 2002). Differences amongst perennial forage species also exist. Thurow et al. (1986) concluded that infiltration rates were higher under bunchgrasses than sodgrasses. Bunchgrasses (e.g., meadow bromegrass, timothy) are generally not rhizomatous resulting in bare ground space between plants (AAFRD 1998). In contrast, rhizomatous species such as smooth bromegrass and Kentucky bluegrass form dense sods with little bare ground between plants (AAFRD 1998). Therefore, soil water will be lower under rhizomatous species than bunchgrasses. Also, soil water under all perennial forages will be depleted earlier in the season and to a greater extent than by annual forages (Twerdoff 1996).

Perennial and annual forages are broadly grouped into two types of plants: cool-season (C_3) plants and warm-season (C_4) plants. Most pasturelands in central and northern Alberta are composed of cool-season grasses, whereas some native warm-season grasses are found in southern Alberta. Typically, the active season of growth for cool season plants in Alberta is from April to November, whereas the season is shortened to May to September for warm season plants (Conrad and Youngman 1965; Naeth et al. 1991). Cool-season grasses begin growing in the spring as soon as the soil thaws; they slow their growth during hot weather in summer; if moisture is available, they begin their growth again in late summer or fall; and they continue to grow until the soil freezes in late fall (Conrad and Youngman 1965). In contrast, warm-season grasses do not begin to grow in spring until the air and soil temperature is warm; if moisture is available, they grow rapidly during the late spring and summer; they become semi-dormant in the fall in central Alberta; and the first killing frost stops their growth (Conrad and Youngman 1965).

Grazing affects a number of hydrologic processes including infiltration, surface runoff, water retention, evapotranspiration, and percolation, thus impacting soil water (Gifford and Hawkins 1978; Mapfumo et al. 2002). The hoof action of grazing animals (treading) contributes to surface soil compaction, reducing infiltration and thus reducing soil water. In a southern Alberta study, Johnston (1962) found that the rate of water intake (infiltration) increased with increasing amounts of standing vegetation and litter, and that June soil moisture at all depths (to approximately 45 cm) decreased with increasing grazing intensity. Naeth et al. (1990) found in southern and central Alberta that heavy intensity and/or early season grazing resulted in a greater reduction of infiltration than light intensity and/or late season grazing. They also found that infiltration rates were higher in the ungrazed controls compared to grazed treatments. Similarly, in a study in north central Alberta, soil water was reduced by both continuous and short duration grazing to a 7.5-cm depth in the spring and to a 15-cm depth in the fall, when compared to an ungrazed control (Donkor et al. 2002). Although heavy grazing is most often related to changes in pastureland infiltration, these changes do not increase linearly with grazing intensity (Naeth and Chanasyk 1993; Naeth and Chanasyk 1995). In contrast, Twerdoff et al. (1999) found that pastures grazed under heavy-intensity had significantly higher accumulated soil water for all soil depths than pastures grazed under light- or medium-intensity.

Trampling and direct defoliation during grazing (Naeth and Chanasyk 1993) reduces plant biomass, decreasing losses of soil water due to reduced evapotranspiration. Consequently, defoliation can actually mitigate soil water depletion, increasing soil water later in the growing season compared to ungrazed pastures (Naeth et al. 1991). However, defoliation of forages also results in less litter to cover the soil, which can impact soil water through increased evaporation, increased runoff, which reduces infiltration, decreasing soil water (Branson et al. 1981; Naeth et al. 1991). In summary, forage grazing can help conserve soil water by decreasing evapotranspiration losses, although decreased infiltration can offset this benefit, resulting in unchanged or decreased soil water (Bremer et al. 2001).

As previously mentioned, the soil water regime is also affected by the type of grazing management. Specific management decisions for pastureland grazing include stocking rate, duration of grazing, and season of grazing. Short-duration, high intensity grazing has less of a negative impact on soil water than continuous grazing (Donkor et al. 2002). However, field studies have found that short-duration, high intensity grazing (when compared to ungrazed controls) increased bulk density and reduced hydraulic conductivity, which increased the potential for runoff and erosion when combined with accompanying loss of vegetation (Warren et al. 1986; Dormaar et al. 1989). Therefore, short-duration, high intensity grazing can be expected to result in decreased soil water when compared to ungrazed pasturelands.

The season in which grazing occurs also impacts soil water. Naeth et al. (1991) found that soil water increased in the fall under light to moderate grazing, due to decreased plant growth and thus decreased evapotranspiration. Therefore, soil water is typically higher during fall grazing than during spring and summer grazing.

4.2 Research Hypotheses

Soil water at the research site was measured to help quantify the soil moisture regime and to assess the likelihood of groundwater contamination from the movement of nutrients through the soil profile. The null hypotheses for the soil water component of the study are:

i. Soil moisture does not vary by forage treatment.
ii. Leaching potential does not vary by forage treatment.

4.3 Materials and Methods

4.3.1 Instrumentation

Refer to Chapter 2 for detailed description.

4.3.2 Data Collection

Soil moisture was monitored across the study site, at 3 locations within each of the 11 paddocks (Figure 2.1), every two weeks, starting on June 10 in 2002 and May 2 in

2003, and then every three weeks from September to mid-October. These measurements were taken in aluminum soil access tubes with a Campbell Scientific 503DR neutron probe, set for 16-sec counts, starting at a depth of 15 cm and continuing in 10-cm intervals to maximum depth allowable in each tube. Each count was entered into a locally derived calibration equation, specific to each probe, to calculate volumetric moisture content.

Soil samples were collected for water retention determinations on July 24, 2003, next to tubes with "representative" soil profiles. These locations were chosen to provide a cross-section of the soil textures at the study site. Representative soil profiles were identified using soil physical property data collected in 2002 in addition to field observations taken during access tube installation. Soil profiles in paddocks 3, 14, 15, and 24 were deemed to be "representative". The soil sampling methods used in 2002 were employed again, and samples were taken at depth intervals of 20 cm to a total depth of 200 cm. All samples were collected approximately 1 m to the east of each tube. The soil samples were air dried, crushed, and then ground by hand so that the majority of the sample could pass through a 2-mm sieve. Pressure plate analyses (Topp et al. 1993) were conducted to determine water retention characteristics at pressures of 0.01, 0.033, 0.1, 0.3, and 1.5 MPa, where 0.01 MPa represents field capacity for coarse-textured soils, 0.033 MPa represents field capacity for fine-textured soils, and 1.5 MPa represents wilting point, regardless of soil texture.

4.3.3 Data Analyses

Long-term normal (LTN) meteorological data for the Lacombe CDA weather station was obtained from Environment Canada, for the most recent 30-year period, from 1971 to 2000. The Lacombe CDA weather station is located approximately 1 km south of the study site, and its data were used to compare temperature and precipitation over the study period. Meteorological data were recorded year round during the study period with a portable automated weather station, located in the northwest corner of Paddock 24 (Figure 2.1), as described in Chapter 2. Typically, April to October is considered the growing season, and November to March the winter/dormant season. Meteorological data at the research site were not collected during April and May of 2002, therefore June to October, inclusive, was used as the growing season for making comparisons between the 2 study years and the LTN.

Soil water was converted from volumetric moisture content, as recorded from field counts, to soil water expressed as a total depth, hereinafter referred to as total soil water (TSW). The amount of water in a given depth interval (TSW) was calculated by multiplying the volumetric water content by the thickness of the depth increment, and then summing appropriately to the given depth (Burk et al. 2000). TSW40, for example, was the amount of water found in the soil profile to a depth of 40 cm, in mm. This was calculated from volumetric moisture content (expressed as a percent) in the following manner:

$$\text{TSW40} = \left(\frac{VMC_{15}}{100} \times 200mm \right) + VMC_{25} + VMC_{35}$$

where VMC_{15} was the volumetric moisture content at a depth of 15 cm (assumed to represent the top 20 cm of soil), and VMC_{25} and VMC_{35} were the volumetric moisture contents at depths of 25 and 35 cm, respectively, all expressed as a percent. TSW80, TSW120, TSW160, and TSW120-160 were all calculated in a similar fashion, considering the appropriate depth increments.

For this study, 160 cm was the maximum depth that the soil water was summed to, which represented the greatest depth achieved at all tube locations. Therefore, the five total soil water parameters used to quantify the soil moisture regime were TSW40, TSW80, TSW120, TSW160, and TSW120-160. Each TSW parameter represented a different section of the soil profile; for instance, TSW40 represented the topsoil, while TSW120-160 represented the soil profile below the rooting zone.

To present representative volumetric moisture contents (VMCs) with respect to depth, total soil water to 160 cm was examined for two select dates with extreme moisture conditions. For the study period, May 13, 2003 was chosen to represent the wettest soil conditions, hereinafter referred to as the "wet day"; likewise August 6, 2003 was chosen to represent the driest soil conditions, hereinafter referred to as the "dry day".

Wilting point (WP), expressed as mm of soil water to a given depth, was calculated by multiplying the laboratory-determined gravimetric moisture content at 1.5 MPa by the thickness of the depth increment, then multiplying by the average field measured bulk density for that depth increment, and summing appropriately to the given depth. WP_{40}, for example, was the amount of water at wilting point, found in the soil profile to a depth of 40 cm, in mm. This was calculated from gravimetric moisture content (expressed as a percent) in the following manner:

$$\mathrm{WP}_{40} = \left(\frac{GMC_{20}}{100} \times \frac{DB_{20} Mg/m^3}{1 Mg/m^3} \times 200mm \right) + \left(\frac{GMC_{40}}{100} \times \frac{DB_{40} Mg/m^3}{1 Mg/m^3} \times 200mm \right)$$

where GMC_{20} was the volumetric moisture content between 0 and 20 cm, and GMC_{40} was the gravimetric moisture content between 20 and 40 cm, all expressed as a percent.

Field capacity (FC), also expressed as mm of soil water to a given depth, was calculated in a similar fashion with the following exception. Gravimetric moisture content at 0.01 MPa was used for coarse textured soils (sands, loamy sands, and sandy loams), whereas gravimetric moisture content at 0.033 MP was used for fine textured soils (all remaining soil textures, including clays and loams). It is important to note that these WP and FC values might not truly reflect field values of WP and FC, as they were calculated from laboratory measurement on crushed soil samples in combination with field measured bulk densities (Mapfumo et al. 2003). Additionally, regression-based empirical equations, which related texture (% clay) to gravimetric moisture content, and data from the site were used to derive water retention parameters for soil depth intervals that were not measured in the lab.

4.3.4 Statistical Analyses

Refer to Chapter 2 for detailed description.

4.4 Results and Discussion

4.4.1 Meteorological Trends

The full meteorological data set, collected from the weather station at the study site (located in Paddock 24), is included in the Appendix (Tables 7.3 and 7.4.). Overall, the field seasons of 2002 and 2003 were very dry; during the June to October period, there was 117 mm of rainfall in 2002 and 89 mm of rainfall in 2003 at the research site, compared to the LTN for Lacombe of 294 mm of rainfall (Table 4.1). For this time period only 40% of the LTN rainfall was received in 2002, and 30% in 2003. About half as much precipitation fell in June 2002 as in June 2003 (8.1 mm compared with 19.9 mm), both of which were considerably less than the June LTN of 76 mm (Tables 4.1 and 7.5). However, there was more precipitation in July, August, and September 2002 than in 2003, although both were still considerably less than the LTNs for the same time period (Table 4.1).

In 2002, it rained 42 days (a rainy day is defined herein as at least 0.254 mm of precipitation) during the growing season (June to October, inclusive), whereas in 2003, it rained 37 days (Tables 7.3 and 7.4). However, in 2003, the rainless periods were slightly longer and more frequent than in 2002. In 2002, there were only 2 rainless periods that exceeded 10 days, whereas in 2003, there were 4 of these periods. In 2002, these periods occurred near the end of summer (late August and September), whereas in 2003, they occurred throughout the growing season (July, August, September, and October). In 2002, there were 8 days in which the daily precipitation totaled between 5 and 10 mm, whereas in 2003 there were 2 days, and 1 day where the precipitation was between 10 and 15 mm.

The maximum air temperatures for the summer months of 2003 were slightly higher than those for 2002, with the exception of June, which had a higher maximum summer temperature in 2002 than 2003 (Table 7.5). When compared to the average temperature LTNs, June and July in both 2002 and 2003 were warmer than average, and August, September, and October were cooler than average in 2002 but warmer than average in 2003 (Table 4.1).

4.4.2 Soil Water Trends

4.4.2.1 Soil Water Retention

Field capacity (FC) and wilting point (WP) data for each paddock are included in the Appendix (Table 7.6). The average FC_{40} for meadow bromegrass was the lowest relative to the other treatments due to near-surface coarse soil texture and/or low near-surface bulk density in this treatment (Table 4.2 a). Field capacity to the bottom of the rooting zone (80 cm) was lowest for the annual treatments and highest for the alfalfa treatments, with a relatively narrow range from 239 mm to 256 mm, respectively (Table 4.2 a). Field capacities were very similar among forage treatments from 20 to 120 cm in depth, likely due to soil textural and bulk density similarities, regardless of forage treatment. Between 120 and 180 cm, alfalfa and meadow bromegrass treatments had slightly higher FC values than annual and old grass treatments (Table 4.2 a).

Wilting point (WP) to the bottom of the rooting zone (80 cm) was lowest for the old grass treatments and highest for meadow bromegrass, ranging from 59 mm to 95 mm, respectively (Table 4.2 b). However, wilting point varied among treatments with depth more than field capacity did. Between 60 and 180 cm, meadow bromegrass and alfalfa treatments generally had the highest WP, and the annual and old grass treatments generally had the lowest (Table 4.2 b). Since the management implication of wilting point is influenced by plants, rather than by soil properties, WP for meadow bromegrass treatments was influenced by the physiological and morphological properties of the plants in addition to the coarse soil texture.

Overall, the meadow bromegrass and alfalfa treatments have the highest field capacities and wilting points, whereas annual and old grass treatments have the lowest.

4.4.2.2 Cumulative Soil Water

Generally, the annual and meadow bromegrass treatments had the highest TSW40 across both 2002 and 2003 (Tables 4.3 and 7.7; Figure 4.1). In 2002, the annual treatments were initially the wettest on average, followed by the meadow bromegrass, alfalfa, and old grass treatments, respectively (Figure 4.1). This trend continued for the remainder of the sampling dates in 2002. However, in 2003, the old grass treatments were the wettest on the first monitoring date, followed by meadow bromegrass, annual, and alfalfa, respectively (Figure 4.1). This was similar to Burk et al.'s (2000) findings of higher spring TSW30 in treatments with standing dead vegetation and litter compared to fallow treatments. Since annual and alfalfa treatments had less vegetation (surface litter) remaining in the fall, it is fair to assume that less snow was trapped, resulting in lower spring soil water contents.

By the second monitoring date in 2003, the annual treatments were once again the wettest, and continued to be the wettest throughout the remainder of the year. In general, for both years, the annual and meadow bromegrass treatments had similar trends for TSW40, and the alfalfa and old grass treatments had similar trends. Individual treatment TSW40s returned to similar levels in fall of each study year (i.e., 55 mm in October 2002 to 57 mm in October 2003 for the annual treatment), although the total soil water varied among forage treatments (Tables 4.3 and 7.7). This suggests that vegetation was using all the available soil water possible, as evidenced by Naeth and Chanasyk (1995) who found that profile soil water (TSW50) was similar across all grazing treatments in fall, generally regardless of year on rangelands dominated by rough fescue (*Festuca campestris* Rydb.) and Parry's oat grass (*Danthonia parryi* Scribn.).

It is important to note that the TSW40 for 2003 was not significantly different between forage treatments. For TSW40 in 2002 and 2003, the interactions between sampling dates and forage treatments were significant, indicating that the two effects are dependent on each other to produce significant variation in TSW40, as phenology is an important factor in crop water use (Table 7.9). Statistically significant differences between forage treatments for each sampling date are shown in Table 4.3. Given that the interaction was significant, neither sampling date nor forage treatment were as important on their own.

All TSW40s were greater than WP_{40} for both annual and meadow bromegrass treatments for all sampling dates in 2002, and the TSW40 for the annual treatments was even greater than FC_{40} for the first sampling date (Table 4.2). In 2003, soil water was greater than WP_{40} for most of the monitoring dates in these treatments, and was even greater than FC_{40} for both treatments on May 13, and for annual on June 12. However, soil water was lower than WP_{40} for alfalfa and old grass treatments for the majority of the monitoring dates in 2002 and 2003, only rising above WP_{40} following a summer rainstorm in 2002, and following snowmelt in 2003.

Trends observed for TSW80 were very similar to those for TSW40, with the following exceptions. For the first sampling date in 2003, meadow bromegrass was the wettest, followed by old grass, alfalfa, and annual, respectively (Figure 4.2). Annual, meadow bromegrass, and alfalfa had virtually the same TSW80 for the second sampling date, whereas old grass was considerably lower. Beginning at the third sampling date (May 28, 2003), the annual treatment was the wettest, followed by meadow bromegrass, alfalfa, and old grass. The interaction between sampling date and forage treatment was significant, increasing the importance of timing versus crop water use (Table 7.9). Differences between forage treatments for each sampling date are shown in Table 4.5. For most of 2002, and the later sampling dates in 2003, the ranking of TSW80 by treatment was annual < meadow bromegrass < alfalfa < old grass.

TSW80s and TSW160s in the annual treatment were greater than WP_{80} and WP_{160}, respectively, during all sampling dates in 2002 and 2003 (Table 4.2). In the meadow bromegrass treatment they were greater than WP_{80} and WP_{160} following snowmelt in both 2002 and 2003, and following considerable accumulation from summer rainstorms (in this study, accumulations ≥ 34 mm) (Table 4.4). However, TSW80s and TSW160s under both alfalfa and old grass treatments only rose above WP_{80} and WP_{160}, respectively, following a relatively large summer rainstorm (August 2, 2002) in combination with 7 other rainy days for that time period in 2002, and following snowmelt in 2003. In general, soil water under perennial forages was often below wilting point by mid-summer, where it remained through to fall in both study years. These results agree with those from other rangeland and pastureland studies in Alberta, where soil water in both mid-summer and fall was generally at or near wilting point (Naeth and Chanasyk 1995; Twerdoff 1996; Mapfumo et al. 2003). This indicates that perennial forage species tend to use all of the soil water available to them by the end of the growing season.

Trends for TSW120 (data not shown) were very similar to those for TSW80, except the interactions between sampling date and forage treatment were not significant in 2002 (Table 7.9). The interactions were not significant for either year for TSW160 (Tables 4.5 and 7.8). However, there were significant differences in TSW120 and TSW160 between sampling dates in both years, as expected. There was a significant difference in TSW120 between forage treatment in 2002; the old grass treatment was significantly lower than the annual and meadow bromegrass treatments. Alfalfa and old grass continued to show similar trends in soil water, maintaining the lowest TSW120 and TSW160 values across both 2002 and 2003. In contrast, annual and meadow bromegrass also maintained the highest TSW120 and TSW160 values across both years. The exception to this, was the first sampling date in 2003, where alfalfa and annual were the driest treatments, and old grass and meadow bromegrass were the wettest, for TSW40, TSW80, TSW120, and TSW160. This might be due to lower infiltration in the alfalfa and annual treatments, resulting from lower amounts of standing dead vegetation and litter. There were no statistically significant treatment differences in TSW120 for 2003 nor TSW160 for 2002 and 2003 (Table 7.9).

The trends for TSW120-160 were similar to the other TSW values, in that annual and meadow bromegrass treatments were the wettest, and alfalfa and old grass treatments the driest, although these differences were not significant (Table 7.9). Similarly, there were no significant differences in TSW120-160 between dates. In 2002, TSW120-160s remained relatively constant at approximately 100 mm for the annual treatments (Figure 4.3). However, it is interesting to note that TSW120-160 decreased over winter for the annual treatment, whereas it remained virtually the same for the meadow bromegrass and alfalfa treatments, and increased for the old grass treatments (Figure 4.3). Meadow bromegrass treatment TSW120-160s started at approximately 100 mm in 2002, but dropped in mid-July to approximately 80 mm, whereas the alfalfa treatment started lower (approximately 70 mm) and increased slightly in mid-July to 80 mm (Figure 4.3). The TSW120-160s for the alfalfa treatment were low during the first part of 2002, which might be an effect of averaging, since Paddock 7, which was typically wetter than the other paddocks in Reps 1 and 3 of Block 1, was not being monitored at that time.

Throughout both years, the old grass treatment was the driest during all sampling dates. In 2002, its TSW120-160s remained relatively steady, with the exceptions of the initial drawdown of soil water at the start of the growing season, and on the mid-August sampling date that followed a considerable precipitation event (Table 7.3). In 2003, the old grass treatment's TSW120-160s started around 70 mm following springmelt, and decreased throughout the year to 50 mm, again with the exception of considerable precipitation events (Table 7.4).

In general, soil water was higher for the annual treatment compared to the perennial treatments. These results were likely due to the higher amount of bare ground in the annual treatment, as evidenced by Gill et al.'s (1998) study at Lacombe, which found that bare ground was significantly greater under annuals than perennials. The high incidence of bare ground likely resulted in increased infiltration due to low actual evapotranspiration compared to perennials in addition to the lack of plant material to intercept rainfall. However, Le Maitre et al. (1999) found that litter on the ground surface tends to retain more water than bare soil, thus increasing infiltration. Therefore, annuals may experience decreased infiltration, but water that enters the soil is more likely to remain there because actual evapotranspiration is greatly reduced from these forages (Twerdoff 1996).

Increased soil water under annual forages was similar to the results of two other studies conducted on cropland pastures in Alberta. In Lacombe, Mapfumo et al. (2003) found that soil water was greatest in the annual forage treatment and lowest in the old grass treatment, which was the same as the old grass treatment used in this study. They concluded that the general dryness of old grass was due to greater root biomass compared to alfalfa, meadow bromegrass/alfalfa, and annual forages. Although Twerdoff (1996) also found that TSW was higher under annual than perennial forages in Lacombe, by late August TSW was lowest under the annual forages compared to meadow bromegrass and smooth bromegrass. However, above normal precipitation was received in Lacombe in 1994 and 1995, during Twerdoff's study, unlike during this study.

4.4.2.3 Soil Water with Depth

For the "wet" day, the average volumetric moisture content (VMC) for the four treatments ranged from 25 to 34% at the top of the soil profile (15 cm), to 12 to 18% at the bottom of the rooting zone (approximately 80 cm), to 22 to 28% at the bottom of the profile (approximately 180 cm) (Figures 4.4 and 4.5). For the "dry" day, the average volumetric moisture content for the four forage treatments ranged from 1 to 9% at the top of the soil profile (uppermost 15 cm), to 3 to 11% at the bottom of the rooting zone (depth of approximately 80 cm), to 21 to 31% at the bottom of the profile (depth of approximately 180 cm) (Figures 4.4 and 4.5). For the "wet" day, the VMC generally decreased with depth until the bottom of the rooting zone (between 70 and 100 cm), at which point the VMC began to steadily increase to the bottom of the soil profile (approximately 180 cm) (Figures 4.4 and 4.5). For the "dry" day, the VMC was the lowest at the top of the soil profile (15 cm), from which it fluctuated slightly, until the bottom of the rooting zone (approximately 100 cm) where it steadily increased to a maximum at the bottom of the soil profile (approximately 180 cm) (Figures 4.4 and 4.5).

At first glance, this contrasts with Twerdoff et al.'s (1999) results where soil water was generally higher in the uppermost 0 to 30 cm than deeper in the profile for both the dry and wet days selected in his study. However, their study only examined soil profiles to 90 cm, so the results of this study and their study are actually very similar down to 90 cm. Consequently, the results of this study highlight the importance of monitoring soil moisture below the root zone.

Soil water varied by rep the most during a relatively "wet" day (May 13, 2003) (data not shown). The greatest differences were between Rep 2 and the other reps in Block 1, and at the mid to bottom depths of Rep 1 and the other reps. However, it should be noted that during the springmelt of 2003, two tubes in Paddock 7 (an alfalfa plot in Rep 2, Block 1) were flooded with water approximately 155 cm from the ground surface. As a result, the upper layer of soil in these tubes likely became saturated, increasing the average VMC at all depths for Rep 2. Since these tubes in Paddock 7 were located close to a pond, one can speculate that perhaps the water table rose during the springmelt, forcing water into the bottom of the aluminum access tubes. Differences observed between blocks for both the "wet" day and "dry" day can likely be attributed to differences in soil texture; Rep 3 of Block 1 had coarse textured soil, Block 2 had medium textured soil, and Reps 1 and 2 of Block 1 had fine textured soil (Table 3.1).

4.4.2.4 Soil Water with Time

In general, soil water in the root zone (0-80 cm) fluctuated more over time than soil water below the root zone (Figure 4.6), as one might expect. At a depth of 55 cm, old grass and meadow bromegrass appeared to be the most sensitive to precipitation events, increasing in volumetric moisture content (VMC) in response to them. At 55 cm, 105 cm, and 155 cm, old grass and meadow bromegrass treatments had very similar trends in VMC, although the magnitude of each differed, with the meadow bromegrass having consistently higher VMCs over time than the old grass. When considering individual VMC values for a given date, annual and meadow bromegrass were alike, as were alfalfa and old grass.

The meadow bromegrass and annual paddocks had the highest average VMC55 in both 2002 and 2003 (Figure 4.6). In 2002, VMC55 for these two forage treatments ranged from 20% in June to 10% in October, compared with 5% in June and 2% in October for alfalfa and old grass (Figure 4.6). In 2003, VMC55 ranged from 22% in May to 8% in October for meadow bromegrass and annual, compared with 22% in May to 2% in October for alfalfa and old grass (Figure 4.6 a and d).

The overall trend for VMC105 was very similar to that for VMC55, although VMC105 values were slightly higher in 2002 and slightly lower in 2003 (Figure 4.6 b and e). Meadow bromegrass and annual continued to act like a pair, maintaining the highest VMC values for both study years, whereas alfalfa and old grass maintained the lowest VMC values, but acted similarly to one another.

In general, volumetric moisture content increased with decreasing depth over time. For a given date, VMC155 was greater than VMC105, which was greater than VMC55. The annual treatments were an exception to this during spring (May to June), when they had higher soil water at VMC55 than at VMC105. Since the annuals had just been seeded, the young seedlings were likely not able to consume the available soil water in the typical rooting zone (VMC55). Therefore, the extra soil water likely percolated, raising VMC105 in mid July.

4.4.2.5 Recharge

The TSW40, TSW80, TSW120, and TSW160 for the old grass and alfalfa treatments increased considerably from Fall 2002 to Spring 2003, indicating a large over-winter recharge in the observed profile (160 cm) of 172 mm for old grass and 222 mm for alfalfa (Figures 4.1 and 4.2; Tables 4.3 and 7.7). The actual precipitation (includes rainfall and snowfall) for the Lacombe CDA weather station in April and May 2003 was approximately 100 mm (data not shown). Therefore, soil water replenishment throughout the soil profile of the old grass treatments relies heavily upon spring snowmelt. The TSW40, TSW80, and TSW120 for the meadow bromegrass treatment also increased over the winter of 2002/2003 (increases of 73 mm, 117 mm, and 138 mm, respectively), and the water content for the whole profile (TSW160) increased by 140 mm. When considering the same TSW data sets, the annual treatment experienced over-winter recharge of 118 mm for the whole profile (TSW160). Between May 2 and May 13, 2003, the annual and alfalfa treatments both experienced a large recharge to 80 cm of approximately 75 mm (Figure 4.2), although there was only 13 mm of precipitation (Table 4.4). This physical inconsistency is difficult to explain. Over-winter and spring recharge, followed by summer soil water depletion due to evapotranspiration, are normal patterns for Albertan pasturelands, and do not tend to be altered by grazing (Naeth et al. 1991).

In both study years, TSW40, TSW80, TSW120, and TSW160 increased following summer precipitation events in all treatments (Figures 4.1 and 4.2). Although soil water was never recharged to field capacity, the response to precipitation was greater during 2002 than 2003 (Table 4.4). Naeth and Chanasyk (1995) found that only rainstorms greater than 75 mm recharged soil water to field capacity in southern Alberta. This may explain the low soil water status observed in this study, since rainstorms close to this size did not occur during 2002 and 2003. Furthermore, increases in soil water during the growing season in 2002 were short lived, as plants quickly used the additional water, as observed in other studies (Naeth and Chanasyk 1995). Burk et al. (2000) also found a large TSW30 decrease in all treatments (hayed, mowed, and fallow) following recharge from summer precipitation, which was likely due to a period of high soil water uptake and high actual evapotranspiration by vegetation.

4.4.3 Leaching Potential

4.4.3.1 TSW40 vs. TSW40-80

Overall, there was little net downward movement of water in the uppermost 80 cm, as evidenced by TSW40 in comparison to TSW40-80 over time (Figure 4.7). The annual (Figure 4.7 a and c) and meadow bromegrass (data not shown) treatments had similar trends, in that increases of soil water to 40 cm were not observed between 40 and 80 cm, not even at a delayed date. In contrast, the old grass (Figure 4.7 b and d) and alfalfa (data not shown) treatments had similar trends, increasing slightly between 40 and 80 cm when soil water to 40 cm increased. In mid-May, following over-winter recharge, actively growing plants in the perennial treatments began to utilize the water between 40 and 80 cm, which likely indicated this region had a concentration of roots. However, the annual plants did not begin to actively utilize the stored water between 40 and 80 cm until late June, which was when these grasses developed a full canopy resulting in increased actual evapotranspiration. Therefore, it seems that any soil water within the uppermost 80 cm was consumed by actively growing forage plants, preventing any percolation out of the root zone (0-80 cm).

4.4.3.2 Moisture Content at Depth

Since moisture contents were similar for 130 and 180 cm depths in the annual treatments, there was little difference in matric potential, no hydraulic gradient, and likely a very low leaching potential (Figure 4.5 a). Furthermore, this was true for both the "wet" and the "dry" days, and increases in soil water at the top of the profile appeared to have little effect on the soil water at the bottom of the profile. However, in years with more summer precipitation resulting in higher soil water, the leaching potential may be slightly higher.

The moisture contents in the meadow bromegrass treatments increased with depth between 140 to 180 cm, indicating an upward hydraulic gradient, and no leaching potential (Figure 4.5 b). Interestingly, there was no difference in the moisture contents in this depth interval between the "wet" and "dry" days, suggesting that soil water increases in the top of the profile have little effect on those at the bottom of the profile. This suggests that any additional water that enters into the top of the soil profile is readily consumed by growing vegetation.

The moisture contents in the alfalfa treatments also increased with depth between 120 and 180 cm (Figure 4.5 c). This indicates a difference in matric potentials, resulting in an upward hydraulic gradient and no leaching potential. The increase with depth is evident for both the "wet" day and the "dry" day, although the "dry" day moisture contents were slightly and consistently lower. However, caution is advised, as the "wet day" moisture increase with depth may be a result of averaging due to the probable water table rise in Paddock 7, and hence much higher water contents following snowmelt in 2003.

Soil water in the old grass treatments also increased with depth between 130 and 180 cm (Figure 4.5 d). This indicates a higher matric potential at 180 cm than at 130 cm, creating an upward hydraulic gradient and no leaching potential. This trend was consistent for both the "wet" and "dry" days, although the "dry" day values in this depth interval were lower. Although the old grass treatments had coarse textured soil (sandy loam) throughout the profile, increases in soil water in the top of the profile during the growing season would likely be lost to actual evapotranspiration rather than leaching since water use under old grass is very high.

4.4.3.3 Overall Leaching Potential

In the deep portions of the profile, the meadow bromegrass, alfalfa, and old grass treatments had an upward hydraulic gradient, and thus likely had no leaching potential. The annual treatments also likely had little leaching, as they had only a small downward hydraulic gradient deep in the profile. Hence, in general there was likely little potential of nutrient leaching from any of the forage treatments during the study period.

4.5 Conclusions

It is important to identify that 2002 and 2003 were very dry years compared to the long-term normals for the Lacombe area. Thus, the study period had a large influence on the results and conclusions presented here, and interpretation should be placed in this context.

Overall, soil water was highest in the spring and declined throughout summer and fall, with the exception of considerable precipitation events, reaching the lowest levels in late fall. Annual and meadow bromegrass treatments had similar soil water trends over time, whereas alfalfa and old grass were similar. Annual and meadow bromegrass treatments had the highest soil water levels, in terms of cumulative and volumetric water contents, and old grass consistently had the lowest. This was likely due to a combination of a large root mass and high plant density in the old grass treatments, resulting in restricted infiltration and increased soil water uptake, both of which decrease soil water levels. Therefore, the null hypothesis must be rejected, as soil moisture clearly did vary by forage treatment.

Once plant growth was initiated, both annual and perennial forages tended to use all available soil water for growth. However, the delayed growth of annual forages in the spring and shallower root systems in the summer resulted in greater storage of soil moisture in these pastures. Hence, annual forages can effectively be used in pasture rotations if they have an economical carrying capacity.

Since all forage treatments had either an upward hydraulic gradient or none at all, the leaching potential for all forage treatments was likely quite low during the study period. These results are representative for a very dry period. Since there were no differences in the leaching potential of the forage treatments, the null hypothesis cannot be rejected.

Table 4.1 Long-term climate normals (LTN) for Lacombe CDA site

	Total Rainfall (mm)			Average Mean Temperature (°C)		
Date	LTN*	2002	2003	LTN*	2002	2003
April	11	5.5^	28	4.3	-0.9^	3.6
May	52	8.7^	30	10.1	7.6^	8.9
June	76	8	20	13.9	16.0	14.2
July	89	29	9	15.4	18.3	17.9
August	71	34	24	14.7	14.1	17.5
September	46	35	29	9.8	9.3	10.1
October	12	11	8	4.5	0.9	6.3
April - October	357	-	148			
June - October	294	117	89			
November - March	4	42	-			

* Long-term normal (1971-2000)

^ Data from Lacombe CDA site

All other listed data for 2002 and 2003 was collected from the automated weather station at the research site in Paddock 24.

Table 4.2a Average cumulative field capacities (FC)

Depth (cm)	Field Capacity (mm) Annual	Meadow Bromegrass	Alfalfa	Old Grass
20	66	54	68	68
40	124	105	132	130
60	179	169	198	191
80	239	245	256	241
100	306	315	323	289
120	370	391	397	341
140	436	478	484	389
160	506	575	581	444
180	579	673	713	519
120-160	136	183	183	103

Table 4.2b Average cumulative wilting points (WP)

Depth (cm)	Wilting Point (mm) Annual	Meadow Bromegrass	Alfalfa	Old Grass
20	26	19	24	19
40	42	39	43	34
60	57	59	62	48
80	82	95	79	59
100	111	132	103	70
120	139	175	144	84
140	168	224	192	99
160	197	278	242	114
180	231	332	309	139
120-160	58	102	99	30

Table 4.3 Cumulative soil water to 40 cm (TSW40)

	TSW40 (mm)			
Date	Annual	Meadow Bromegrass	Alfalfa	Old Grass
10-Jun-02	125[1] (10)[2] a	89 (10) c	51 (10) c	26 (4) b
24-Jun-02	84 (10) a	58 (10) b	25 (10) bc	11 (4) c
10-Jul-02	46 (10) a	49 (11) a	19 (10) ab	7 (4) b
22-Jul-02	43 (9) a	42 (9) a	26 (9) ab	11 (4) b
07-Aug-02	104 (9) a	101 (9) a	85 (9) ab	68 (4) b
19-Aug-02	81 (9) a	73 (9) ac	52 (9) bc	39 (4) b
03-Sep-02	63 (9) a	51 (9) ac	31 (9) bc	21 (4) b
28-Sep-02	48 (9) a	42 (9) a	25 (10) ab	12 (4) b
21-Oct-02	55 (9) a	50 (9) a	37 (9) ab	24 (4) b
02-May-03	92 (11) a	105 (11) a	82 (11) a	106 (8) a
13-May-03	129 (11) a	123 (11) a	119 (11) a	93 (8) a
28-May-03	122 (11) a	88 (11) c	96 (11) ac	52 (8) b
12-Jun-03	126 (11) a	83 (12) b	73 (11) b	59 (8) b
26-Jun-03	100 (11) a	50 (11) b	55 (11) b	24 (8) b
09-Jul-03	65 (11) a	40 (11) ab	39 (11) ab	11 (8) b
23-Jul-03	46 (11) a	33 (11) a	19 (11) a	5 (8) a
06-Aug-03	40 (11) a	33 (11) a	20 (11) a	5 (8) a
20-Aug-03	48 (11) a	39 (11) a	26 (11) a	13 (8) a
02-Sep-03	51 (11) a	43 (11) a	26 (11) a	22 (8) a
27-Sep-03	58 (11) a	46 (11) a	31 (11) a	25 (8) a
15-Oct-03	57 (11) a	39 (11) a	26 (11) a	13 (8) a
FC$_{40}$ (mm)	124	105	132	130
WP$_{40}$ (mm)	42	39	43	34

[1] Means

[2] Standard Error

For a given date (row), treatments with the same letter are not significantly different ($p \leq 0.05$).

Table 4.4 Cumulative soil water to 80 cm (TSW80)

		TSW80 (mm)			
Date	Ppt.* (mm)	Annual	Meadow Bromegrass	Alfalfa	Old Grass
10-Jun-02	-	202[1] (24)[2] a	159 (24) ac	75 (24) bc	45 (6) b
24-Jun-02	4	152 (24) a	119 (24) ac	40 (24) bc	24 (6) b
10-Jul-02	7	91 (24) a	99 (25) a	30 (24) ab	17 (6) b
22-Jul-02	11	85 (22) a	83 (22) a	46 (22) ab	22 (6) b
07-Aug-02	34	149 (22) a	151 (22) a	110 (22) ab	93 (6) b
19-Aug-02	10	123 (22) a	121 (22) a	76 (22) ab	60 (6) b
03-Sep-02	15	105 (22) a	94 (22) a	51 (22) ab	35 (6) b
28-Sep-02	12	87 (22) a	82 (22) a	49 (23) ab	23 (6) b
21-Oct-02	21	96 (22) a	92 (22) a	55 (22) ab	34 (6) b
02-May-03	-	129 (26) a	174 (26) a	135 (26) a	157 (12) a
13-May-03	13	205 (26) ab	209 (26) a	209 (26) a	146 (12) b
28-May-03	17	205 (26) a	161 (26) a	172 (26) a	94 (12) b
12-Jun-03	13	204 (26) a	151 (28) ab	129 (26) ab	86 (12) b
26-Jun-03	6	175 (26) a	98 (26) ab	101 (26) ab	42 (12) b
09-Jul-03	5	126 (26) a	82 (26) ab	75 (26) ab	23 (12) b
23-Jul-03	3	86 (26) a	69 (26) a	43 (26) a	11 (12) a
06-Aug-03	3	76 (26) a	68 (26) a	40 (26) a	11 (12) a
20-Aug-03	17	87 (26) a	78 (26) a	46 (26) a	25 (12) a
02-Sep-03	6	89 (26) a	81 (26) a	44 (26) a	33 (12) a
27-Sep-03	29	96 (26) a	83 (26) a	48 (26) a	32 (12) a
15-Oct-03	1	96 (26) a	77 (26) a	43 (26) a	20 (12) a
	FC_{80} (mm)	239	245	256	241
	WP_{80} (mm)	82	95	79	59

* Cumulative since previous measurement date

[1] Means

[2] Standard Error

For a given date (row), treatments with the same letter are not significantly different ($p \leq 0.05$).

Table 4.5 Cumulative soil water to 160 cm (TSW160)

	TSW160 (mm)			
Date	**Annual**	**Meadow Bromegrass**	**Alfalfa**	**Old Grass**
10-Jun-02	364 [1](53)[2]	336(53)	182(53)	132(59)
24-Jun-02	312(53)	284(53)	131(53)	116(59)
10-Jul-02	249(53)	266(54)	112(53)	88(59)
22-Jul-02	250(50)	226(50)	156(50)	95(59)
07-Aug-02	313(50)	294(50)	222(50)	174(59)
19-Aug-02	283(50)	266(50)	188(50)	148(59)
03-Sep-02	267(50)	234(50)	160(50)	111(59)
28-Sep-02	248(50)	219(50)	173(52)	93(59)
21-Oct-02	260(50)	233(50)	153(50)	105(59)
02-May-03	254(67)	323(67)	258(67)	277(24)
13-May-03	378(67)	373(67)	375(67)	265(24)
28-May-03	368(67)	329(67)	335(67)	211(24)
12-Jun-03	370(67)	340(67)	283(67)	187(24)
26-Jun-03	345(67)	263(67)	249(67)	151(24)
09-Jul-03	292(67)	234(67)	213(67)	115(24)
23-Jul-03	241(67)	207(67)	160(67)	88(24)
06-Aug-03	231(67)	208(67)	160(67)	82(24)
20-Aug-03	238(67)	221(67)	148(67)	90(24)
02-Sep-03	240(67)	221(67)	155(67)	103(24)
27-Sep-03	261(67)	226(67)	173(67)	97(24)
15-Oct-03	257(67)	220(67)	146(67)	90(24)
FC_{160} (mm)	506	575	581	444
WP_{160} (mm)	197	278	242	114

[1] Means

[2] Standard Error

There were no significant treatment differences ($p<0.05$)

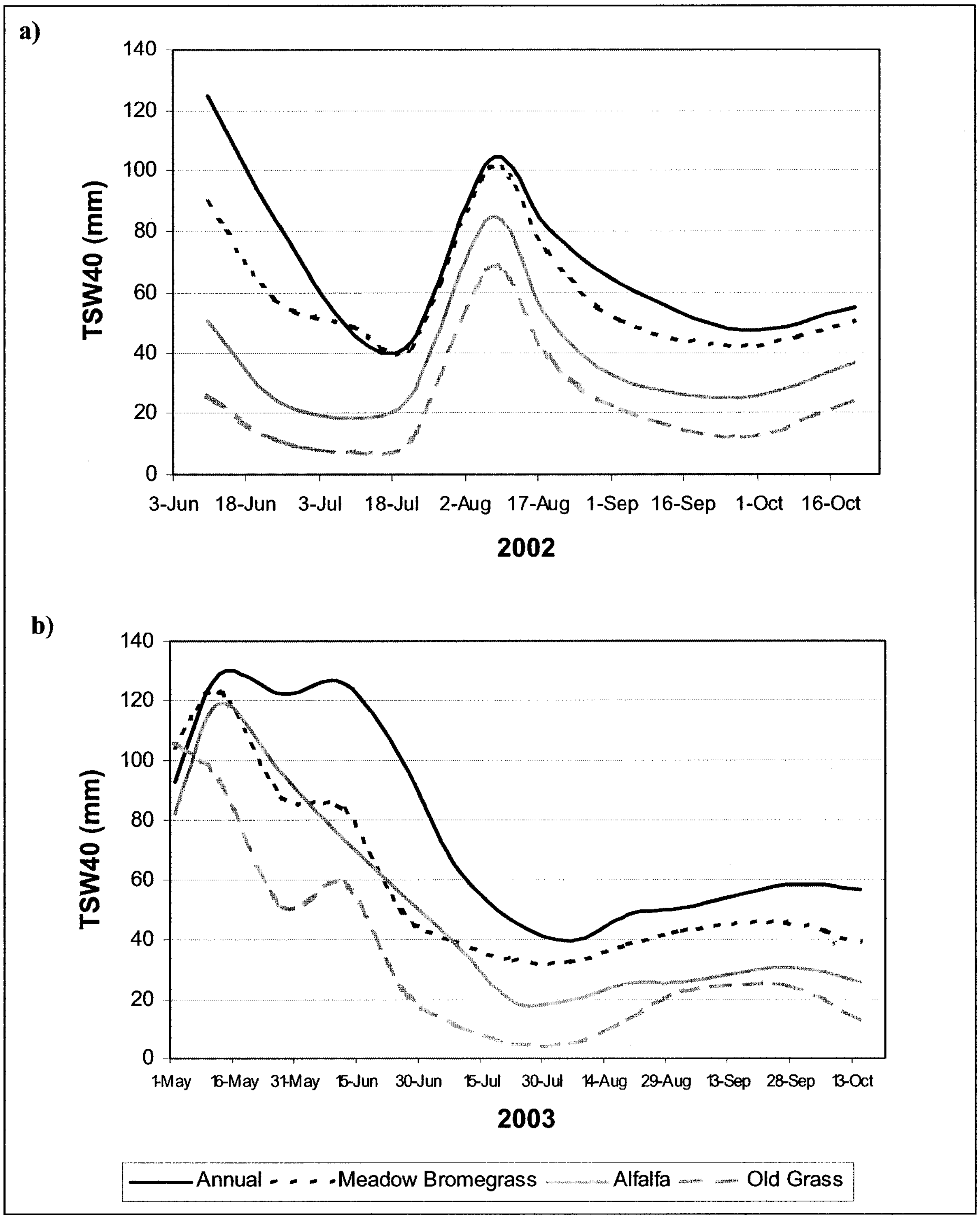


Figure 4.1 **Cumulative soil water to 40 cm (TSW40) by forage treatment in a) 2002, and b) 2003**

FC$_{40}$: annual = 124 mm, meadow bromegrass = 105 mm, alfalfa = 132 mm, old grass = 130 mm. WP$_{40}$: annual = 42 mm, meadow bromegrass = 39 mm, alfalfa = 43 mm, old grass = 34 mm.

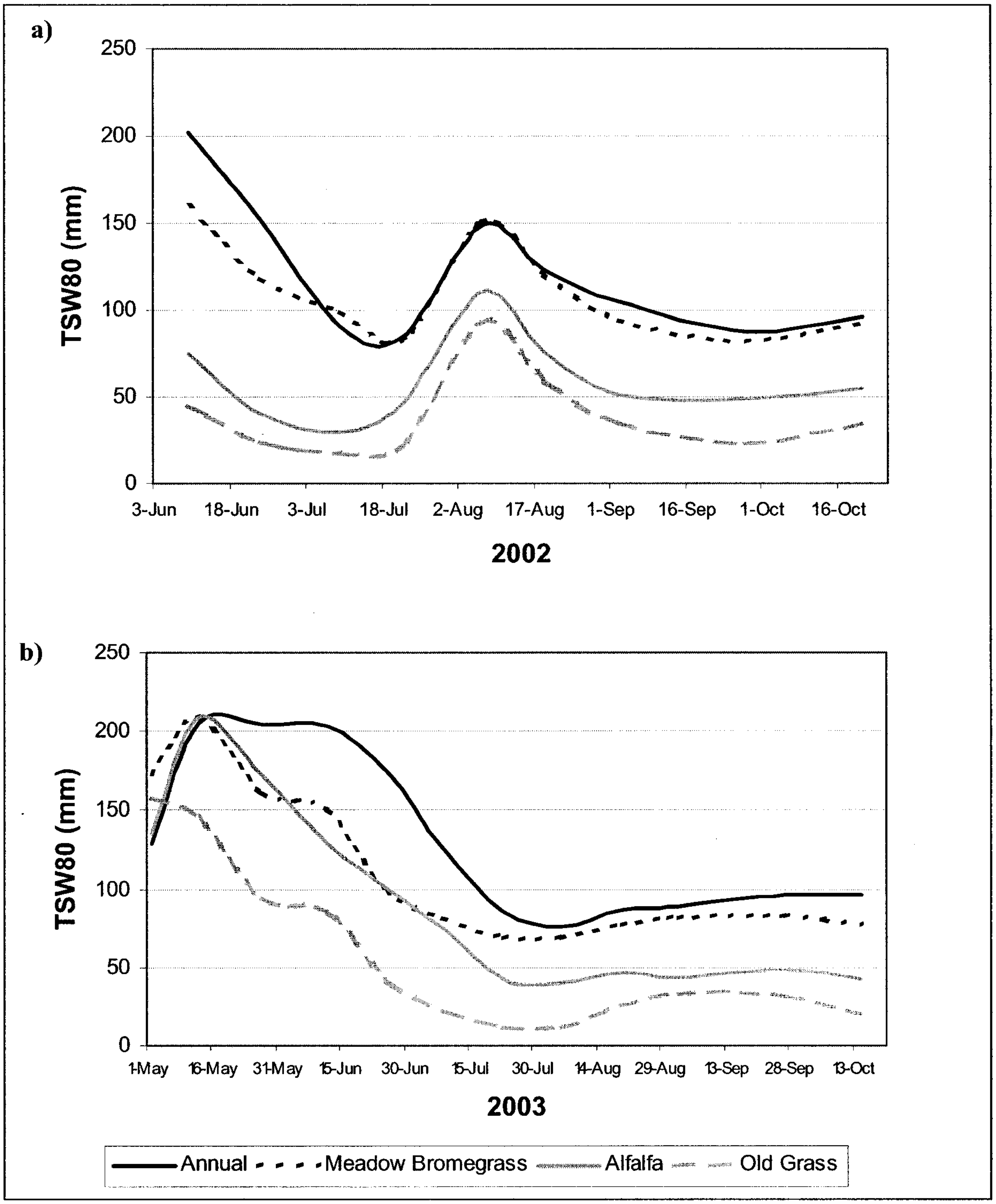


Figure 4.2 Cumulative soil water to 80 cm (TSW80) by forage treatment in a) 2002, and b) 2003

FC_{80}: annual = 239 mm, meadow bromegrass = 245 mm, alfalfa = 256 mm, old grass = 241 mm. WP_{80}: annual = 82 mm, meadow bromegrass = 95 mm, alfalfa = 79 mm, old grass = 59 mm.

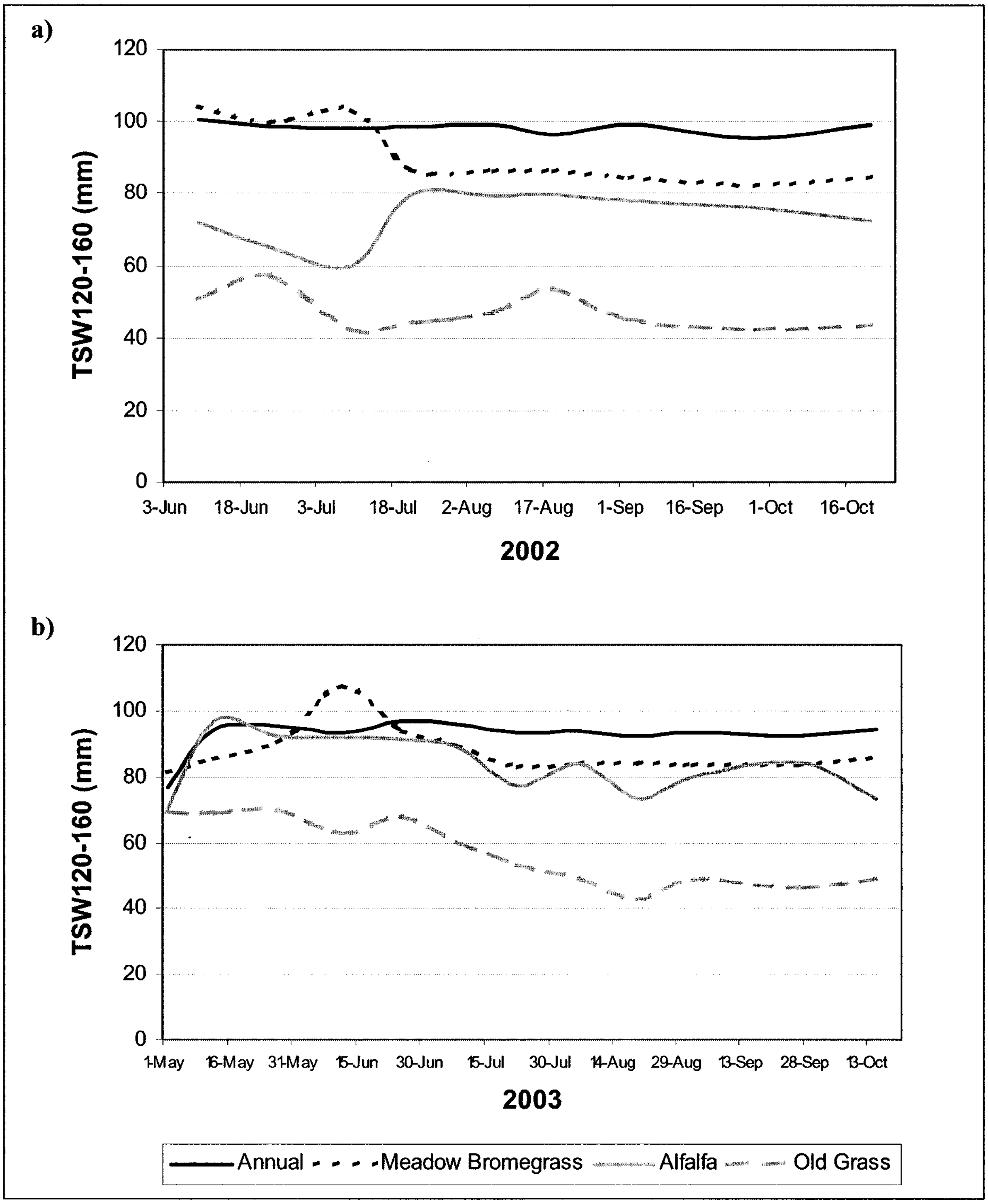
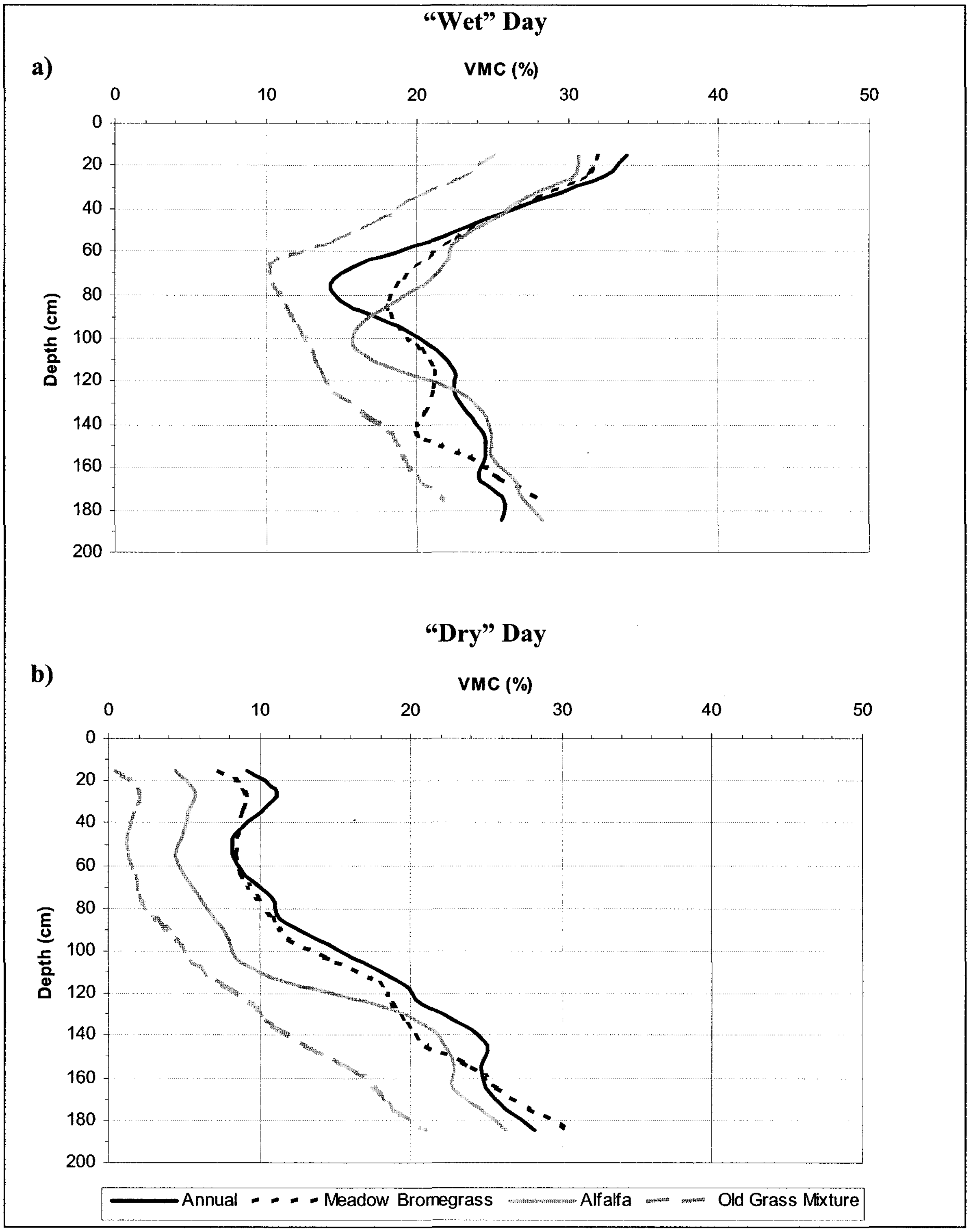


Figure 4.3 Cumulative soil water between 120 and 160 cm (TSW120-160) by forage treatment for a) 2002, and b) 2003

$FC_{120\text{-}160}$: annual = 136 mm, meadow bromegrass = 183 mm, alfalfa = 183 mm, old grass = 103 mm. $WP_{120\text{-}160}$: annual = 58 mm, meadow bromegrass = 102 mm, alfalfa = 99 mm, old grass =30 mm.


a) “Wet” Day

b) “Dry” Day

Figure 4.4 Average volumetric moisture content (VMC) by forage treatment for a) a relatively wet day (May 13, 2003) and b) a relatively dry day (August 6, 2003)

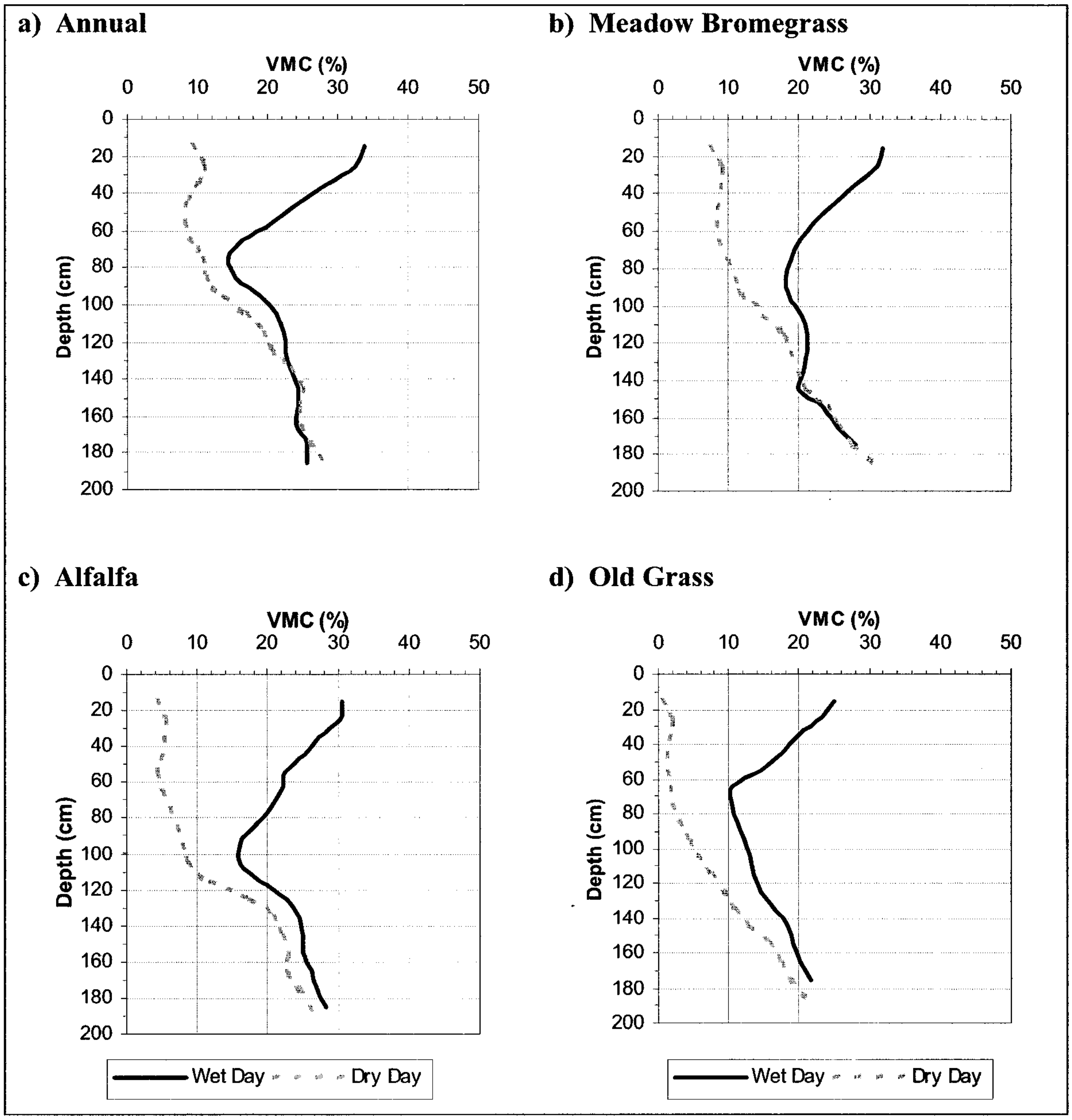


Figure 4.5 Average volumetric moisture content (VMC) by forage treatment for a wet day (May 13, 2003) and dry day (August 6, 2003)

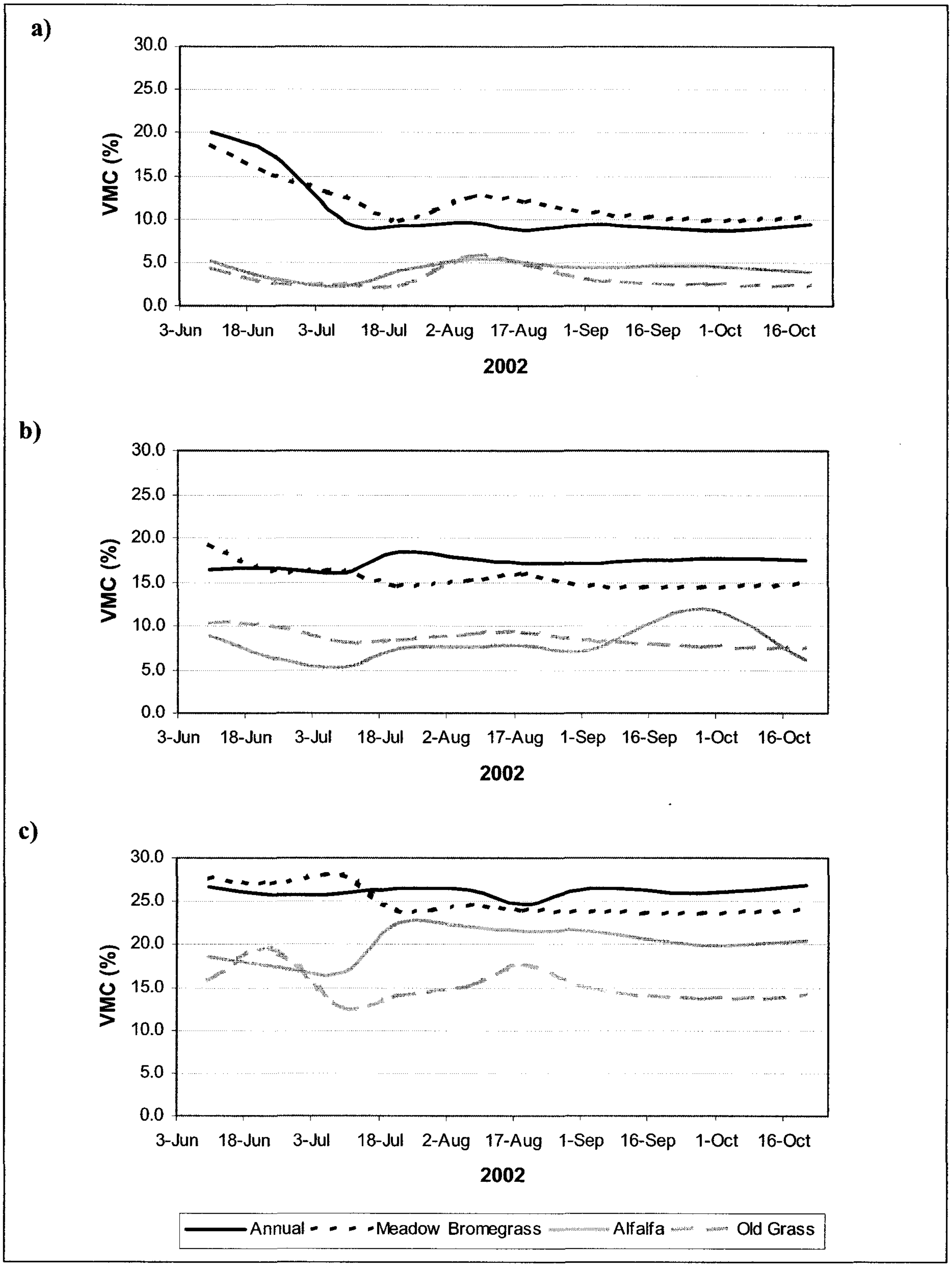


Figure 4.6 **Average volumetric moisture content (VMC) in 2002 at a) 55 cm, b) 105 cm, and c) 155 cm**

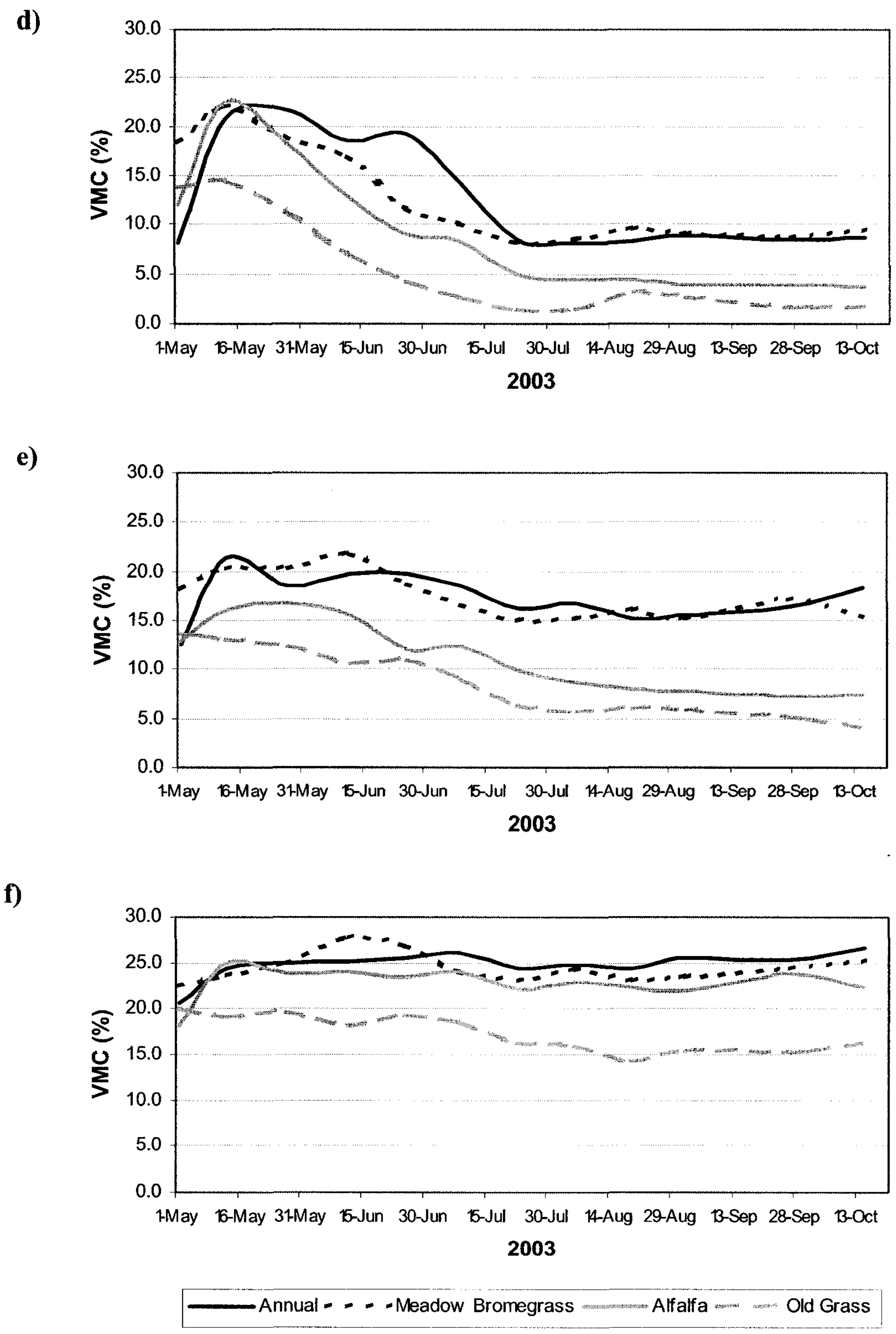
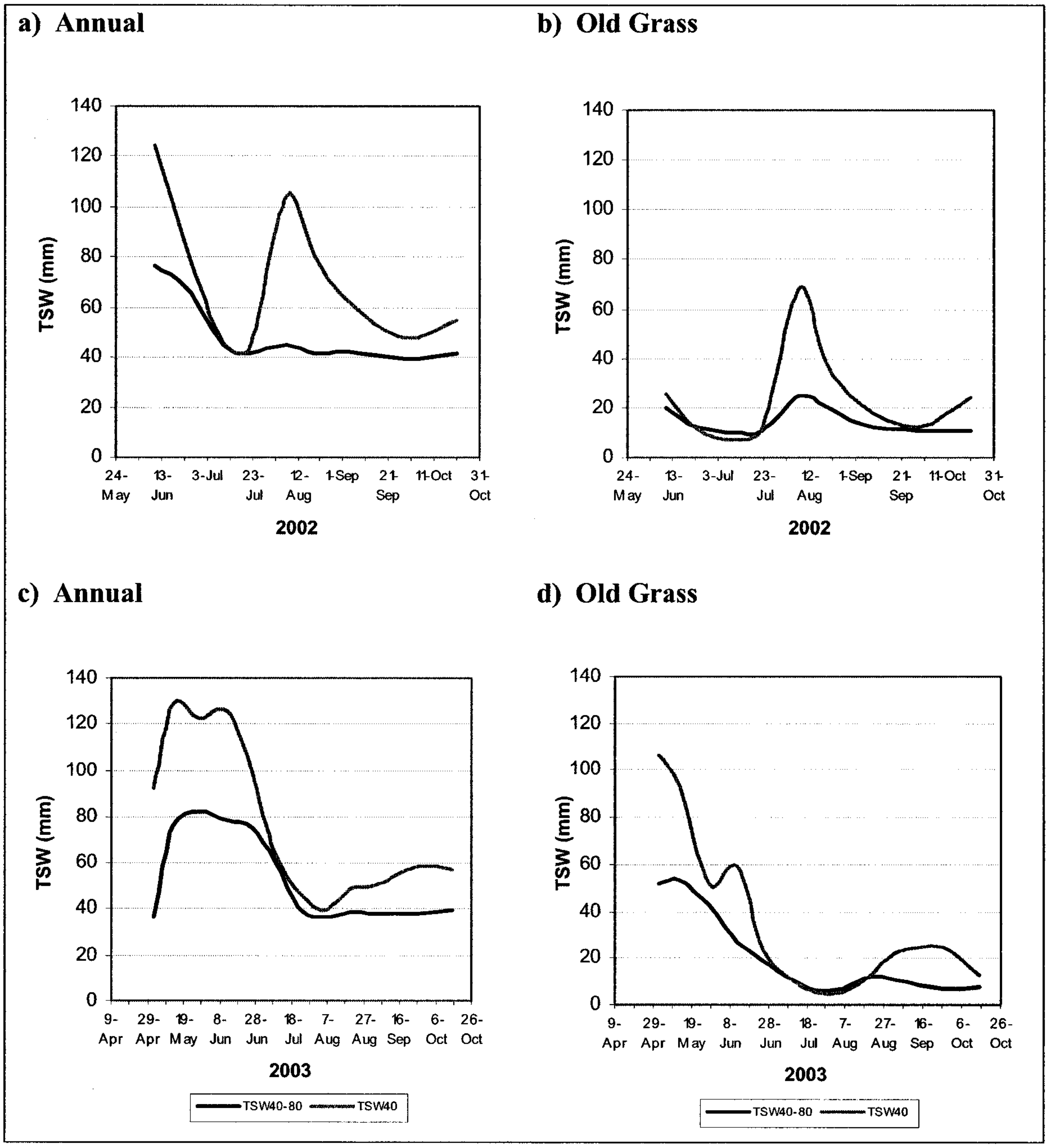


Figure 4.6 (continued) **Average volumetric moisture content (VMC) in 2003 at d) 55 cm, e) 105 cm, and f) 155 cm**


a) Annual

b) Old Grass

c) Annual

d) Old Grass

Figure 4.7 Comparison of cumulative soil water to 40 cm (TSW40) and between 40 and 80 cm (TSW40-80) for annual treatments and old grass treatments in 2002 and 2003

4.6 References

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5 IMPACTS OF MANAGED INTENSIVE GRAZING ON SURFACE RUNOFF IN THE ASPEN PARKLAND ECOREGION OF ALBERTA

5.1 Introduction

Surface runoff, or overland flow, is an output of the hydrologic cycle, and occurs whenever the rate of water supply to the soil surface exceeds the rate of infiltration or storage capacity of the soil (Hillel 1998; Holechek et al. 1998). Conditions that are most conducive to infiltration rates being exceeded by precipitation are high intensity rainfall (e.g., Alderfer and Robinson 1947), long duration rainfall (e.g., Branson et al. 1981), high antecedent moisture conditions (e.g., Rauzi and Hanson 1966), or rapid snowmelt. Additionally, rainfall or snowmelt that occurs on frozen soil will likely not infiltrate, and will likely runoff (Kalff 2002).

Runoff is affected by a number of hydrologic and topographic parameters. Infiltration capacity greatly impacts runoff, and in general, if the infiltration capacity decreases, runoff increases (Naeth and Chanasyk 1996). The amount of time that water is in contact with the soil surface before flowing away, also determines the amount of runoff. Increased slope and smooth surfaces decrease the amount of time that water has to infiltrate the soil. This is simply attributable to the fact that more water will flow off a surface with a steeper slope, and smooth surfaces do not impede water movement with areas of high friction (Burk et al. 1999). In pasturelands, vegetation (standing dead or living) and litter cause the ground surface to be rougher, reducing the runoff potential (Holechek et al. 1998).

Grazing, and therefore grazing management, can indirectly affect runoff due to its impacts on infiltration. Hoof-action (treading) compacts the ground surface and increases bulk density (e.g., Alderfer and Robinson 1947; Lodge 1954), which decreases infiltration and increases the potential for surface runoff. Numerous researchers have found that increased grazing intensity reduces water intake (infiltration) and thus increases runoff (Rauzi 1963).

Forage species grown on pasturelands also impact runoff. Bare ground increases runoff, as water movement is not impeded by vegetation or litter. Higher amounts of bare ground are generally found in annual rather than perennial forages, as documented by Gill et al. (1998) and Burk et al. (1999). This is especially true during early spring, when annual pastures have been cultivated and newly seeded. Unfortunately, Alberta receives the most rainfall during this time of year, and often these storms are more intense and longer lasting than summer storms (Alberta Agriculture 1991). The loose soil and bare ground are more susceptible to raindrop impact and thus runoff and erosion. However, the problem continues once the annual plants begin to grow, as the row pattern tends to channel water, intensifying rill erosion (Gill 1996).

Erosion is the main potential hazard of surface runoff. Erosion causes the degradation and loss of topsoil, and can cause water quality concerns through the movement of particulates, nutrients, and contaminants off-site into surface water bodies (Kalff 2002). High nutrient loads from pasturelands can lead to contamination of drinking water supplies for humans and livestock. Therefore, pasture lands with heavy grazing regimes can be expected to be at greater risk of surface runoff and its associated hazards.

In addition to erosion, runoff can have detrimental effects on crop and pasture production. Since it is the result of decreased infiltration, it reduces the amount of water available for plant growth (Chanasyk and Woytowich 1986). In prairie regions where the major source of soil water recharge is from over-winter precipitation (Naeth and Chanasyk 1996), it becomes especially important for land managers to capture as much snowmelt as possible, to improve soil moisture reserves for plant growth. Therefore, any management regime that reduces infiltration and increases runoff, also potentially decreases crop and pasture production.

5.2 Research Hypotheses

Surface runoff at the research site was measured to help assess the likelihood of surface water contamination from the movement of nutrients over the ground surface. The null hypotheses for the surface runoff component of the study are:

i. Surface runoff does not vary by forage treatment.
ii. Rainfall runoff does not exceed snowmelt runoff.

5.3 Materials and Methods

5.3.1 Instrumentation

In August 2002, sixteen 1-m^2 runoff frames and collection containers were installed within Paddocks 1, 3, 4, 13, 14, 15, 21, and 24, comprising two reps of Block 1 (Reps 1 and 3), and the old grass area (Block 2). The two runoff frames in each paddock were located halfway between soil access tubes 1 and 2, and 2 and 3 (Figure 2.1). The metal frames were pounded a few centimeters into the soil surface and situated so that the outlet emptied downslope, discharging runoff into a series of collection containers. The outlet drained directly into an 4-L container, which was inside a 20-L container, which was inside a 64-L container that was buried in the ground. Once runoff exceeded 4 L, water overflowed into the 20-L container until it was full, at which point it overflowed into the largest container. Each 1-L of runoff collected in the containers corresponded to a water depth of 1 mm from the frames (Naeth and Chanasyk 1996). A tight fitting lid was placed on this container, and both the hole and the container were covered with plywood (19-mm thick) to protect the collection system.

5.3.2 Data Collection

Snow depth in the runoff frames was measured with a meter stick, to the nearest whole centimeter, prior to (April 7) and at the time of snowmelt runoff sampling (April 8, 11, and 14, 2003). A vegetation assessment within each of the runoff frames was conducted on July 21, 2003. Ground cover, aerial canopy cover, and species composition were assessed from two 0.1-m^2 quadrats (0.5 m x 0.2 m) in each frame. The frames were divided into 4 equal quadrants, two of which were randomly selected for placement of the quadrats. Litter was defined as all dead organic material not incorporated with mineral soil and occurring above soil mineral horizons (Naeth et al. 1991). Litter was further divided into standing and fallen litter. Ground cover consisted of bare ground, manure, litter (standing and fallen), and live vegetation (including dried tips of live plants). Aerial canopy cover included both live vegetation and standing litter.

Snowmelt runoff volumes were measured at least twice daily from the collection containers on April 8, 11, and 14, 2003, and the quantities were summed for each day. Water samples, for runoff water quality analysis, were obtained by removing the smallest collection container to collect a water sample in a 1-L plastic bottle. The entire sample of runoff was used if the total amount of runoff was less than 1.0 L. These water samples were immediately shipped in a cooler to a commercial water-testing laboratory (Enviro-Test Labs) in Edmonton, Alberta. The samples from April 8th were analyzed on April 11, 2003 and the samples from April 11th and 14th were analyzed on April 16, 2003. Total volume of runoff was the only rainfall runoff parameter measured during fall 2002 and summer 2003.

5.3.3 Data Analyses

Since snowmelt runoff occurred over a short period of time and it was only measured a few times per day, accurate volume measurements were not achieved. Hence, caution should be used in the interpretation of the snowmelt runoff volumes.

The spring runoff water samples were analyzed by Enviro-Test for various chemical parameters. The laboratory methods used followed procedures generally based on nationally or internationally accepted methodologies. The following analyses were conducted on every runoff water sample from both sampling dates. The summer runoff water samples were not chemically analyzed since the samples were not immediately collected after the runoff events.

Total dissolved solids (TDS) were determined by drying the total water volume at 103-105 °C. Electrical conductivity (EC) was calculated from a conductivity cell at 25 °C; pH was determined using the electrometric method; and alkalinity was determined through titration to measure the concentration of carbonate, bicarbonate, and hydroxide. Hardness, calcium, potassium, magnesium, sodium, and sulfate were analyzed with emission spectroscopy using the inductively coupled plasma (ICP) method. Chloride was determined with the low-level amperometric titration method. Nitrate was analyzed using the automated hydrazine reduction method, and nitrite was determined through the colorimetric method. (APHA 2003)

5.3.4 Statistical Analyses

Refer to Chapter 2 for detailed description.

5.4 Results and Discussion

5.4.1 Meteorological Trends

The full meteorological data set, collected from the weather station at the research site (located in Paddock 24), is included in the Appendix (Tables 7.3 and 7.4.). General meteorological results and discussion were included in Chapter 4. In the first half of March 2003, the maximum air temperatures were generally below 0 °C, and the minimum air temperatures fell as low as –34.8 °C (Table 7.4). In the last half of March 2003 (March 15-31), the maximum daily air temperature fluctuated between 2.5 and 15.1 °C, whereas the minimum daily air temperature fluctuated between 1.9 and –9.9 °C (Table 7.4). In the first 15 days of April 2003, the daily temperatures fell to the lowest maximum of –7.8 °C and a lowest minimum of –16.3 °C (Table 7.4). Both the maximum and minimum temperature began to steadily increase again on April 5, 2003. From this date onwards, the maximum temperature did not fall below 0 °C, with the exception of May 6, 2003, when it was –0.2 °C. Daily maximum temperatures increased markedly on April 7, from 1.6 to 8.6 °C, and then again on April 8 to 13.6 °C (Figure 5.1).

In the 2003 growing season (June 1 to October 31), there were 37 rainy days (days with at least 0.254 mm of precipitation were considered "rainy") (Table 7.4). However, the daily precipitation only totaled between 0.254 and 5 mm for 34 of those 37 days. There were 2 days when there was between 5 and 10 mm of precipitation, and 1 day (August 9, 2003) when there was between 10 and 15 mm of precipitation (11.94 mm).

5.4.2 Snow Depth

Snow depths measured in the runoff frames on April 8, when the snow was first starting to melt, ranged from 1 to 13 cm, excluding frames 24-A and 24-B, which did not have any snow (Table 5.1). There were no definite trends in snow depth related to forage treatment. In Rep 1 of Block 1, the alfalfa treatment had the lowest average snow depth (2 cm), whereas in Rep 3 of Block 1, the annual treatment had the lowest average snow depth (10 cm). This was similar to Naeth and Chanasyk's (1996) study, where the greatest snow depths were in treatments with the greatest amount of standing dead vegetation or litter. Therefore, the treatments with the greatest amount of vegetation should have the greatest snow depths, and thus potentially the highest amount of runoff. However, a deeper snowpack would require more energy to heat it to the point of melting, resulting in delayed runoff compared to a shallower snowpack. Snowmelt occurred only over a few days (April 7-11, 2003), and the snow disappeared within all runoff frames by April 11, 2003.

5.4.3 Vegetation Assessment

On July 21, 2003, all quadrats in the annual treatments had ≥79% bare ground, ≤15% litter, ≤35% canopy cover, and ≤6% live vegetation (Table 5.2). The higher bare ground and lower canopy cover means that the annual treatments would not trap as much snow, and likely would have smaller amounts of snowmelt runoff. A large population of Richardson's ground squirrels (*Spermophilus richardsonii*) were observed in the annual treatments, likely due to the less compacted soil conditions, which may have contributed to the high bare ground and low litter and live vegetation in those treatments. Numerous ground squirrel tunnels were observed under the plywood, around the runoff frame collection containers. It is likely that they consumed both the annual forage seeds and plants in and around the runoff frames, as this was where they were living.

The old grass treatments had no bare ground within the runoff frames on July 21, 2003, whereas two of four quadrats within the meadow bromegrass runoff frames had 10% bare ground, and four of four quadrats in the alfalfa runoff frames had between 5 and 30% bare ground (Table 5.2). The ranking of % bare ground for the forage treatments was: old grass < meadow bromegrass < alfalfa < annual, where the differences between annual and the other forage treatments, and between alfalfa and old grass were statistically significant. Gill et al. (1998) also found that annual forages had more bare ground than did perennial forages, due to their yearly cultivation and planting. The ranking of % canopy cover for the forage treatments was: annual < old grass < meadow bromegrass < alfalfa (Table 5.2), where the differences between alfalfa and annual, and between alfalfa and meadow bromegrass were statistically significant.

The old grass canopy was dominated by smooth bromegrass (*Bromus inermis* Leyss.) (Moss 1994) and quack grass (*Elytrigia repens* L.) (Moss 1994), with small percentages of Kentucky bluegrass (*Poa pratensis* L.) (Moss 1994). The meadow bromegrass canopy was dominated by meadow bromegrass (*Bromus riparius* Rehm.) (Knowles et al. 1993), with small percentages of alfalfa (*Medicago sativa* L.) (Moss 1994) in one frame. Some runoff frames in the alfalfa treatment (1-A and 1-B) were dominated by alfalfa and Kentucky bluegrass, whereas runoff frames 14-A and 14-B were dominated by alfalfa and various weed species. Similarly, the annual treatments were dominated by triticale (*X Triticosecale* Wittmack) and various weed species.

The runoff frames in the annual treatments had the least ground cover and therefore the highest potential for runoff. However, the low ground cover would result in less snow being trapped, thus decreasing the potential runoff. In contrast, the old grass treatments had the most ground cover, although the majority of it was composed of litter rather than live vegetation. Accordingly, runoff would not likely occur on this thick mat of vegetation due to enhanced infiltration, but the greater amount of trapped snow increases the amount of potential runoff.

5.4.4 Snowmelt Runoff

Snowmelt occurred very quickly in 2003, between April 7-14, and resulted in high volumes of runoff. The snow within the frames completely melted within 4 relatively warm days (April 7-11) that immediately followed a brief cold period (April 2-5), where the daily maximum air temperature dropped as low as –7.8 °C (Table 5.1; Figure 5.1). Within this 4-day warm period, the maximum air temperatures were 8.6, 13.6, 11.3, and 11.7 °C, respectively (Figure 5.1). The snowpack most likely ripened prior to this warm period, as daily maximum air temperatures of 15.1, 11.4, and 12.4 °C were reached on March 21, 30, and 31, respectively (Table 7.2). The relatively quick snowmelt during early April likely contributed to the high runoff volumes, as there was not much time for the snowmelt to infiltrate.

During the monitoring of snowmelt runoff, a few unique conditions occurred, that may or may not have affected the results. The plywood at runoff frame 24-A (old grass treatment) was lifted and the collection containers were opened to determine the runoff start date. Therefore, the lower albedo of the exposed soil surface around the edges of the plywood may have caused the snow to melt around the frame earlier and more rapidly than around the non-disturbed frames. At runoff frame 15-B (annual treatment), a large rodent hole acted as a sump, draining away water that had overflowed from the largest collection container and/or water that had flowed into the hole from outside the runoff frame. Additionally, between April 8 and April 11, the plastic tubing that directed water from the drain spout into the containers broke off on two runoff frames (3-B in a meadow bromegrass treatment; 15-A in an annual treatment), presumably lowering measured runoff volumes. Runoff frame 24-B in the old grass treatment was completely submerged under a pool of snowmelt runoff for the first two spring sampling dates, so an accurate volume measurement was not possible. Thus, this frame was not included in the treatment averages for those sampling dates.

Total snowmelt runoff in 2003 was highest in the alfalfa treatments (approximately 98 L) and lowest in the old grass treatments (approximately 63 L) (Table 5.3), although this difference was not significant. The larger amount of runoff from the alfalfa treatments was possibly due to the smaller stalk size of the alfalfa plants, resulting in less canopy cover and greater runoff potential. However, one would expect that as % canopy cover decreases, the snow depth would also decrease, thus reducing the potential amount of runoff. For some runoff frames, this relationship held true, but for others it did not, perhaps because of mid-winter snowmelts or greater snow depths due to topographical features rather than vegetative cover. For example, the runoff frames in Paddock 14 had a low % canopy cover in the summer of 2003, but were situated on gently rolling topography, possibly contributing to the increased amounts of runoff from this paddock (Table 5.2).

The annual treatments had a greater volume of snowmelt runoff than meadow bromegrass and old grass, as expected, which was likely due to a lower amount of canopy cover that is common for annual crops (Gill et al. 1998). Therefore, the overall ranking of snowmelt runoff for the treatments was: old grass < meadow bromegrass < annual < alfalfa, but as previously mentioned these differences were minor and not significant. Burk et al. (1999) found similar results comparing summer runoff volumes of annual and perennial pastures in north-central Alberta. Additionally, annual treatments will not catch as much snow, and will not require as much energy to heat up for melting, so their snowpacks will start to melt earlier, and should finish melting first. However, the smaller amount of snow caught in these treatments will result in smaller amounts of snowmelt runoff (Naeth and Chanasyk 1996). On the other hand, runoff occurs easily from bare ground. Earlier snowmelt means that the ground was more likely to be frozen, so runoff would likely occur, although the final volumes would be less than perennial treatments.

The majority of the runoff occurred on the first two sampling dates: April 8 and 11. Only the old grass treatment had accumulated runoff on the last monitoring date, April 14, which was likely residual water from the pooled runoff that had submerged frame 24-B during the two previous sampling dates.

Snowmelt runoff in 2003 was considerably higher in Rep 3 than in Rep 1 of Block 1or Block 2 (125 L compared with 55 and 78 L, respectively) (data not shown), likely due to the slightly steeper slope in Rep 3 of Block 1. Similarly, Naeth and Chanasyk (1996) found that runoff was greater from sampling positions with steeper slope, as expected.

5.4.4.1 Snowmelt Runoff Water Quality

In general, the water quality of the 2003 snowmelt runoff was very good, in relation to the agriculture, community, and aesthetic water quality guidelines (Alberta Environment 1999; CCME 2002). The runoff water pH values, ranging from 6.4 to 7.6 (Table 5.4), were within or very close the CCME guideline range of 6.5 to 8.5 for the Aesthetic Objective of the community water guidelines (CCME 2002). The total dissolved solids (TDS) were well below both the community (500 mg/L) and agriculture (3,500 mg/L) water quality guidelines (Table 5.4). Sodium ranged from <1 to 4 mg/L, and sulfate ranged from 1.8 to 16.4 mg/L (Table 5.4), both of which were well below the water quality guidelines of 200 and 500 mg/L, respectively for community water (CCME 2002). Similarly, chloride ranged from 2 to 46 mg/L, whereas the water quality guidelines range from 250 to 860 mg/L, for community and agricultural water (Alberta Environment 1999; CCME 2002). The measured nitrate and nitrate + nitrite levels were well below the community water guidelines of 45 mg/L (nitrate), and the agricultural water quality guidelines of 100 mg/L (nitrate +nitrite) (CCME 2002). The only water quality guideline that could be found for calcium was an agricultural water guideline of 1,000 mg/L for irrigation; the calcium levels measured in the snowmelt runoff ranged from 1.4 to 22 mg/L, well below this guideline. Canadian water quality guidelines were not found for conductivity, hardness, bicarbonate, carbonate, hydroxide, ion balance, potassium, or magnesium.

Alkalinity and nitrite were the only measured parameters that exceeded one of the water quality guidelines for some treatments. Alkalinity, expressed as $CaCO_3$, ranged between 21 and 105 mg/L, whereas the current water quality guideline from the United States Environmental Protection Agency (USEPA) is 20 mg/L as a continuous concentration (Alberta Environment 1999). Since these concentrations would be diluted and evened out over time, one can assume that alkalinity is likely not of major concern. The nitrite (NO_2^-) levels of the runoff water ranged from below detection limit of 0.05 to 0.91 mg/L, with the highest levels being measured on the first sampling date (Table 5.4). The water quality guideline for freshwater aquatic life had a limit of 0.06 mg/L, compared with 3.2 mg/L for community water, and 10 mg/L for agricultural water (CCME 2002). Thus, the nitrite levels found in the snowmelt runoff were not dangerously high, but may be high enough to promote aquatic weed or algae growth, decreasing water quality.

The highest TDS, potassium, nitrate, nitrate + nitrite, sulfate and chloride levels were found in the second water samples (April 11) from runoff frame 24-B in the old grass treatment (Table 5.4 b). This frame was located in a depressional area, and was submerged during snowmelt. Since runoff in the containers was collected from a greater area (rather than just the 1-m^2 runoff frame), the runoff water would likely have flowed over more manure, soil, and vegetative litter (as evidenced by the relatively higher TDS levels), thus elevating some of the measured nutrient levels.

Overall, there did not appear to be any treatment differences in snowmelt runoff water quality at this research site, nor generally were there any major water quality concerns with the measured parameters. There were no significant differences between forage treatments for EC, TDS, alkalinity, potassium, chloride, nitrate, and nitrite (Table 7.9). However, there was a significant difference in the pH between the following treatment pairs: alfalfa vs. meadow bromegrass, annual, and old grass, and annual vs. old grass. There was also a significant difference in pH, TDS, and alkalinity between the two sampling dates (Table 7.9).

Although the nitrite levels for the first sampling date and alkalinity for both sampling dates were slightly elevated, they are not of major concern for water quality degradation. The water quality indicators of manure contamination are nitrate, nitrite, potassium, and chloride (Havlin et al. 1999; Maulé and Fonstad 2000). Since these parameters either did not exceed the guidelines, or were only slightly elevated, runoff water quality during snowmelt should not be a concern at this site.

5.4.5 Summer Rainfall Runoff

Runoff from rainfall did not occur at all during fall 2002 and for the majority of 2003. One major runoff event occurred on August 9, 2003 following a rainstorm that had a short period of "high" intensity, in which approximately 12 mm of rain fell within 25 minutes (data not shown). The 5-min intensity of this rainstorm ranged from 3 mm/h to 67 mm/h, with an average of 29 mm/h. To put this into perspective, Rauzi (1963) found that during a 30-minute storm with an intensity of 50 mm/h, no runoff occurred from a moderately grazed area, but almost half of the rainfall would run off on a heavily grazed area. He also stated that a 5-minute storm with an intensity of 152 mm/h would result in some runoff on most pasturelands.

Runoff from the rainstorm on August 9, 2003 was greater from the alfalfa treatments than from the other treatments (Table 5.3), and this difference was statistically significant. This may be explained by alfalfa's narrower crown and smaller stalk size, which results in less canopy cover in older alfalfa stands. During previous small summer storms, the exposed bare ground would have been susceptible to raindrop impact, which can lead to surface sealing and consequent crusting upon drying, thus decreasing infiltration and increasing runoff (Hillel 1998; Ruan et al. 2001). This is the most likely explanation, as antecedent soil moisture conditions were very low at the time of runoff.

Unexpectedly, the annual treatments produced very low amounts of runoff, only 0.5 L. Hoof-action on this looser soil surface likely created small depressions, resulting in irregular micro-relief (Warren et al. 1986) that may not have been prone to surface sealing. Furthermore, the high organic matter (6.7%) in the soil surface likely acted as a sponge, drawing water into the soil pores and reducing its susceptibility to raindrop impact.

The runoff from the meadow bromegrass and old grass treatments were very similar, at approximately 2 L. The overall ranking of summer rainfall runoff from the treatments was: annual < meadow bromegrass = old grass < alfalfa, although only the alfalfa treatments were significantly different from the others. This concurs with the vegetation assessment results that alfalfa treatments had significantly more bare ground than old grass treatments. Similar to snowmelt runoff volumes, Rep 3 of Block 1 produced the most runoff from the August 9th rainstorm, with little difference between the amount of runoff produced on Block 2 and Rep 1 of Block 1 (data not shown).

On September 25, 2003, small amounts of runoff water (50 mL and 295 mL) were found in the collection containers of two frames (13-B, meadow bromegrass, and 24-A, old grass, respectively). It is unknown whether this water was a result of runoff from one rainfall event, or from a number of very small runoff events. However, two rainfall events with 5-min intensities of 15 and 18 mm/h occurred during September 2003, prior to the presence of the runoff. The second of these storms, which occurred on September 22, and had a 5-min period with a 15 mm/h intensity, followed immediately by another 5-min period with a 18 mm/h intensity. Therefore, it is possible that one or both of these storms resulted in the small amount of runoff that was measured on September 25, 2003.

5.4.6 Total Annual Runoff

Average annual runoff was dominated (>85%) by snowmelt runoff that occurred in spring 2003 (Table 5.3), and this dominance did not vary by forage treatment or by block. Similarly, the annual runoff volume was not significantly different between forage treatments. Other researchers have also found that snowmelt was the dominant (averaging between 70 and 89%) source of runoff on Albertan rangelands and pastures (Chanasyk and Woytowich 1986; Naeth and Chanasyk 1996; Gill et al. 1998). This large quantity of water is very important for creating ephemeral surface water supplies and replenishing existing ones. It can also be utilized for crop production by reducing or slowing runoff to increase infiltration. Grazing managers hoping to maximize soil moisture recharge should decrease grazing pressure in the late fall, increasing the amount of vegetation and reducing the amount of manure left on the ground surface in the spring, thus trapping more snow and improving snowmelt runoff water quality. Pasture management strategies should be based on whether producers want to augment surface water supplies with this runoff, or maximize soil moisture by reducing the amount and velocity of runoff.

5.5 Conclusions

Old grass treatments generally had the lowest snow depths at the beginning of snowmelt, relatively low amounts of canopy cover, and the lowest runoff volumes, as expected. Therefore, the null hypothesis must be rejected, as snowmelt surface runoff did vary by forage treatment. However, the relationship between canopy cover and snow depth, and thus runoff volume, was not always consistent. Snowmelt runoff volumes were highest in the alfalfa treatments, even though they had low amounts of canopy cover and relatively low snow depths. The greater snow depths in relation to topographical features, mid-winter snowmelts, and hence earlier ripening of the snowpack, or snowmelt on frozen ground are hypothesized to have influenced the relationship between snow depth and runoff volume.

There were generally no major concerns regarding water quality of snowmelt runoff. However, alkalinity was elevated, but since it was likely temporary and related to high runoff volumes in a short amount of time, it is not an important water quality concern. Similarly, nitrite levels were high enough to promote unwanted aquatic weed and algae growth, but were not high enough to degrade the overall water quality.

Rainfall runoff volumes were highest in the alfalfa treatments, likely due to higher amounts of bare ground and surface sealing from previous rainfall events. Unexpectedly, summer runoff volumes were lowest in the annual treatments, even though they had the highest percentage of bare ground. Therefore, the null hypothesis must be rejected, as summer surface runoff does vary by forage treatment. Summer rainfall runoff only resulted from high intensity, short-duration storms, as found in other Albertan pasture studies.

Total annual runoff was dominated by snowmelt runoff compared to summer rainfall runoff, as found by numerous prairie researchers. Therefore, the null hypothesis cannot be rejected, as rainfall runoff does not exceed snowmelt runoff.

Table 5.1 Snow depths in runoff frames, spring 2003

	Snow Depth (cm)							
	Alfalfa		Meadow Bromegrass		Annual		Meadow Bromegrass	
Date	**1-A**[+]	**1-B**	**3-A**	**3-B**	**4-A**	**4-B**	**13-A**	**13-B**
7-Apr				not sampled				
8-Apr	2	2	8	7	11	9	10	12
11-Apr	0	0	0	0	0	0	0	0
14-Apr	0	0	0	0	0	0	0	0

	Snow Depth (cm)							
	Alfalfa		Annual		Old Grass			
Date	**14-A**	**14-B**	**15-A**	**15-B**	**21-A**	**21-B**	**24-A***	**24-B**
7-Apr			not sampled				5	0^
8-Apr	10	11	12	8	13	0 to 5	0	0^
11-Apr	0	0	0	0	0	0	0	0^
14-Apr	0	0	0	0	0	0	0	0

[+] Runoff frames are numbered Paddock-Frame; Frame A was located between Tubes #1 and 2, closest to the exclosure in each paddock, and Frame B was located between Tubes #2 and 3, furthest away from each exclosure.

* Runoff frame disturbed prior to runoff

^ Runoff frame submerged under springmelt water

Table 5.2 Vegetation assessment within runoff frames, July 21, 2003

Forage Treatment	**Alfalfa**				**Alfalfa**				**Meadow Bromegrass**			
Frame #	**1A**		**1B**		**14A**		**14B**		**3A**		**3B**	
Recently Grazed?	not grazed		not grazed		not grazed		not grazed		grazed		grazed	
Quadrat #	1	2	1	2	1	2	1	2	1	2	1	2
Ground Cover												
% Bare	5	2	0	0	10	0	30	20	0	0	10	0
% Manure	0	0	5	5	0	0	0	0	T	0	0	0
% Litter (Standing + Fallen)	85	86	85	80	87	96	67	74	94	96	87	94
% Live Vegetation	10	12	10	15	3	4	3	6	6	4	3	6
% Fallen Litter	20	10	5	3	10	2	0	1	15	30	10	15
% Canopy Cover (Aerial)	40	60	80	85	25	30	25	60	35	25	20	40
Species Composition												
Bromus riparius (meadow bromegrass)									35	25	20	40
Elytrigia repens (quack grass)												
Poa pratensis (bluegrass)	1	T	40	25								
Medicago sativa (alfalfa)	40	60	40	60	5	10	25	2				
X Triticosecale (triticale)												
Poaceae spp. (oat)												
Plantago spp. (plantain)											T	
Chenopodium album (lamb's quarters)							T	60				
Polygonum convolvulus (wild buckwheat)												
Descurainia sophia (flixweed)					3	1						
Amaranthus retroflexus (redroot pigweed)					20	20						

Notes: % Canopy Cover (Aerial) included live vegetation and standing litter.

Sum of Species Composition = % Canopy Cover

Litter included all dead organic material not incorporated with mineral soil and occurring above soil mineral horizons.

Live vegetation included dried tips of live plants.

*Runoff Frame A was located between Tubes #1 and 2, closest to the exclosure in each paddock, and Frame B was located between Tubes #2 and 3, furthest away from each exclosure.

Table 5.2 (continued) Vegetation assessment within runoff frames, July 21, 2003

Forage Treatment	**Meadow Bromegrass**				**Annual**				**Annual**			
Frame #	**13A**		**13B**		**4A**		**4B**		**15A**		**15B**	
Recently Grazed?	grazed		grazed		grazed		grazed		grazed		grazed	
Quadrat #	1	2	1	2	1	2	1	2	1	2	1	2
Ground Cover												
% Bare	1	0	10	0	87	92	98	90	81	81	79	100
% Manure	20	0	5	0	3	0	0	0	3	0	20	0
% Litter (Standing + Fallen)	69	75	82	94	5	3	1	5	10	15	1	T
% Live Vegetation	10	25	3	6	5	5	1	5	6	4	0	0
% Fallen Litter	15	10	25	15	0	0	0	0	0	10	0	0
% Canopy Cover (Aerial)	30	35	12	15	25	30	1	35	10	12	0	0
Species Composition												
Bromus riparius (meadow bromegrass)	30	35	6	14								
Elytrigia repens (quack grass)												
Poa pratensis (bluegrass)												
Medicago sativa (alfalfa)			6	1								
X Triticosecale (triticale)					3	4	1	10	10	12		
Poaceae spp. (oat)												
Plantago spp. (plantain)												
Chenopodium album (lamb's quarters)					2	10		30	T	T		
Polygonum convolvulus (wild buckwheat)					20	16						
Descurainia sophia (flixweed)												
Amaranthus retroflexus (redroot pigweed)												

Notes: % Canopy Cover (Aerial) included live vegetation and standing litter. Sum of Species Composition = % Canopy Cover

Litter included all dead organic material not incorporated with mineral soil and occurring above soil mineral horizons.

Live vegetation included dried tips of live plants.

*Runoff Frame A was located between Tubes #1 and 2, closest to the exclosure in each paddock, and Frame B was located between Tubes #2 and 3, furthest away from each exclosure.

Table 5.2 (continued) Vegetation assessment within runoff frames, July 21, 2003

Forage Treatment	**Old Grass**				**Old Grass**			
Frame #	**21A**		**21B**		**24A**		**24B**	
Recently Grazed?	grazed		grazed		not grazed		not grazed	
Quadrat #	1	2	1	2	1	2	1	2
Ground Cover								
% Bare	0	0	0	0	0	0	0	0
% Manure	T	0	0	0	10	10	0	0
% Litter (Standing + Fallen)	98	99	98	99	88	86	93	90
% Live Vegetation	2	1	2	1	2	4	T	10
% Fallen Litter	30	70	15	20	5	10	25	30
% Canopy Cover (Aerial)	20	12	5	3	7	10	60	60
Species Composition								
Bromus inermis (smooth bromegrass)	16	9	1		1	0	4	50
Elytrigia repens (quack grass)	3	1	5	3	6	10	53	10
Poa pratensis (bluegrass)	1				T		3	T
Medicago sativa (alfalfa)								
X Triticosecale (triticale)								
Poaceae spp. (oat)								
Plantago spp. (plantain)								
Chenopodium album (lamb's quarters)								
Polygonum convolvulus (wild buckwheat)								
Descurainia sophia (flixweed)								
Amaranthus retroflexus (redroot pigweed)								

Notes: % Canopy Cover (Aerial) included live vegetation and standing litter. Sum of Species Composition = % Canopy Cover

Litter included all dead organic material not incorporated with mineral soil and occurring above soil mineral horizons.

Live vegetation included dried tips of live plants.

*Runoff Frame A was located between Tubes #1 and 2, closest to the exclosure in each paddock, and Frame B was located between Tubes #2 and 3, furthest away from each exclosure.

Table 5.3 Snowmelt and rainfall runoff in 2003

Type	Date	Runoff (mm) Annual			Meadow Bromegrass			Alfalfa			Old Grass		
Snow	08-Apr	39.75			25.25			59.50			44.33 ^		
Snow	11-Apr	52.50			54.25			38.50			17.67 ^		
Snow	14-Apr	0.00			0.00			0.00			16.25		
Total Snow Runoff		92.25[1]	(28.40)[2]	a	79.50	(28.40)	a	98.00	(28.40)	a	62.75	(28.40)	a
Rain	26-Aug+	0.05			2.31			11.70			2.54		
Rain	25-Sep	0.00			0.01			0.00			0.07		
Total Rain Runoff		0.05	(1.99)	b	2.33	(1.99)	b	11.70	(1.99)	a	2.61	(1.99)	b
Total Annual Runoff		92.30	(28.63)	a	81.83	(28.63)	a	109.70	(28.63)	a	65.36	(28.63)	a
% of annual that is snowmelt		99.9			97.2			89.3			96.0		

[1] Means

[2] Standard Error

^ Container submerged; could not sample one frame

+ Runoff from Aug. 9 rainstorm

For a given runoff summary (row), treatments with the same letter are not significantly different ($p \leq 0.05$).

Table 5.4a Snowmelt runoff water quality analysis, April 8, 2003

	Alfalfa				Meadow Bromegrass				Annual				Old Grass			
	1-A*	1-B	14-A	14-B	3-A	3-B	13-A	13-B	4-A	4-B	15-A	15-B	21-A	21-B	24-A	24-B
pH	7.6	7.4	7.2	7.3	7.1	6.5	7.3	7.2	7.1	6.5	6.4	7	7.1	7.2	7.2	7
Conductivity (dS/m)	0.165	0.241	0.0657	0.116	0.0846	0.118	0.163	0.206	0.0858	0.118	0.15	0.125	0.119	0.163	0.163	0.0882
TDS measured (mg/L)	80	170	60	120	40	60	120	120	70	70	70	90	70	100	100	70
Hardness (as CaCO3-mg/L)	53	61	18	29	11	10	27	24	8	11	15	9	11	16	12	6
Alkalinity (as CaCO3-mg/L)	72	91	26	46	25	36	48	45	30	42	52	29	29	45	38	21
Bicarbonate (HCO3-mg/L)	88	111	32	56	30	44	59	55	36	51	63	35	36	55	46	26
Carbonate (CO3- mg/L)	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Hydroxide (OH- mg/L)	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Ion Balance (%)	94.5	92.2	Low EC	91.4	Low EC	63.6	90.4	79.8	Low EC	59.2	53.8	73	80.4	68	79.3	Low EC
Calcium (Ca- mg/L)	15.7	16.9	5.1	8	2.6	2.2	6.8	5.5	1.7	2.4	3.5	2.3	2.5	3.8	2.8	1.4
Potassium (K- mg/L)	15.7	28.4	5.5	21.3	12.4	15.8	22.6	32.3	11.9	14.6	14.3	16.7	16.5	20.4	25	14.4
Magnesium (Mg- mg/L)	3.4	4.5	1.4	2.3	1.2	1	2.4	2.4	0.9	1.2	1.5	0.7	1.2	1.7	1.3	0.6
Sodium (Na- mg/L)	< 1	2	< 1	4	1	< 1	3	1	< 1	< 1	< 1	3	3	1	2	1
Sulfate (SO4- mg/L)	2.5	6	1.8	7.6	1.9	2.4	4.9	6.2	2.3	3.8	3.9	5.8	4.4	7.7	5.4	2.7
Chloride (Cl- mg/L)	2	9	2	8	5	5	9	19	3	3	3	7	8	9	11	5
Nitrate N (mg/L)	< 0.1	< 0.1	0.2	1.6	0.5	0.3	0.6	1.3	< 0.1	< 0.1	0.3	0.6	0.7	< 0.1	0.6	0.9
Nitrite N (mg/L)	< 0.05	< 0.05	< 0.05	0.17	<0.05	0.06	0.16	0.28	<0.05	<0.05	0.16	0.91	0.11	<0.05	0.11	0.08
Nitrate+Nitrite-N (mg/L)	< 0.1	< 0.1	0.2	1.8	0.5	0.3	0.7	1.6	< 0.1	< 0.1	0.5	1.5	0.8	< 0.1	0.7	1

*Runoff Frame A was located between Tubes #1 and 2, closest to the exclosure in each paddock, and Frame B was located between Tubes #2 and 3, furthest away from each exclosure.

Table 5.4b Snowmelt runoff water quality analysis, April 11, 2003

	Alfalfa				Meadow Bromegrass				Annual				Old Grass			
	1-A*	1-B	14-A	14-B	3-A	3-B	13-A	13-B	4-A	4-B	15-A	15-B	21-A	21-B	24-A	24-B
pH	7.3	7.5	7.6	7.4	6.9	7	7.3	7.2	7.1	7.2	7.2	7.2	7.1			7.3
Conductivity (dS/m)	0.172	0.254	0.207	0.152	0.146	0.127	0.199	0.087	0.175	0.092	0.099	0.0934	0.112			0.433
TDS measured (mg/L)	150	210	150	110	140	130	170	110	190	110	120	80	120			340
Hardness (as CaCO3-mg/L)	48	78	65	41	21	17	35	20	12	10	12	6	9			24
Alkalinity (as CaCO3-mg/L)	73	105	88	62	46	39	66	38	52	39	44	30	30			78
Bicarbonate (HCO3-mg/L)	89	128	108	75	56	47	81	47	63	48	54	37	37			95
Carbonate (CO3- mg/L)	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5			< 5
Hydroxide (OH- mg/L)	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5			<5
Ion Balance (%)	93.7	98.9	99	90.4	92.7	96.7	98.8	Low EC	89.3	Low EC	Low EC	Low EC	78.1			90.2
Calcium (Ca- mg/L)	14	22	18.8	11.7	4.6	4.1	8.5	4.7	2.6	2.2	3.2	1.6	2.2			5.5
Potassium (K- mg/L)	21.2	30.9	22.4	16.8	24.7	23.1	31.5	17.6	35.1	23.9	20.5	14.8	19			92.7
Magnesium (Mg- mg/L)	3.2	5.6	4.4	2.8	2.2	1.7	3.4	2	1.3	1	1	0.6	0.9			2.4
Sodium (Na- mg/L)	1	1	1	< 1	1	< 1	2	< 1	2	1	1	< 1	< 1			4
Sulfate (SO4- mg/L)	3.2	6	3.9	3	2.7	2.7	4.4	2.9	5.3	3.5	3.4	2.8	3.6			16.4
Chloride (Cl- mg/L)	4	7	3	3	7	5	7	5	8	4	4	3	6			46
Nitrate N (mg/L)	0.2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1			1.8
Nitrite N (mg/L)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.07			0.3
Nitrate+Nitrite-N (mg/L)	0.2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.2	< 0.1	< 0.1	< 0.1	<0.1	0.1			2.1

*Runoff Frame A was located between Tubes #1 and 2, closest to the exclosure in each paddock, and Frame B was located between Tubes #2 and 3, furthest away from each exclosure.

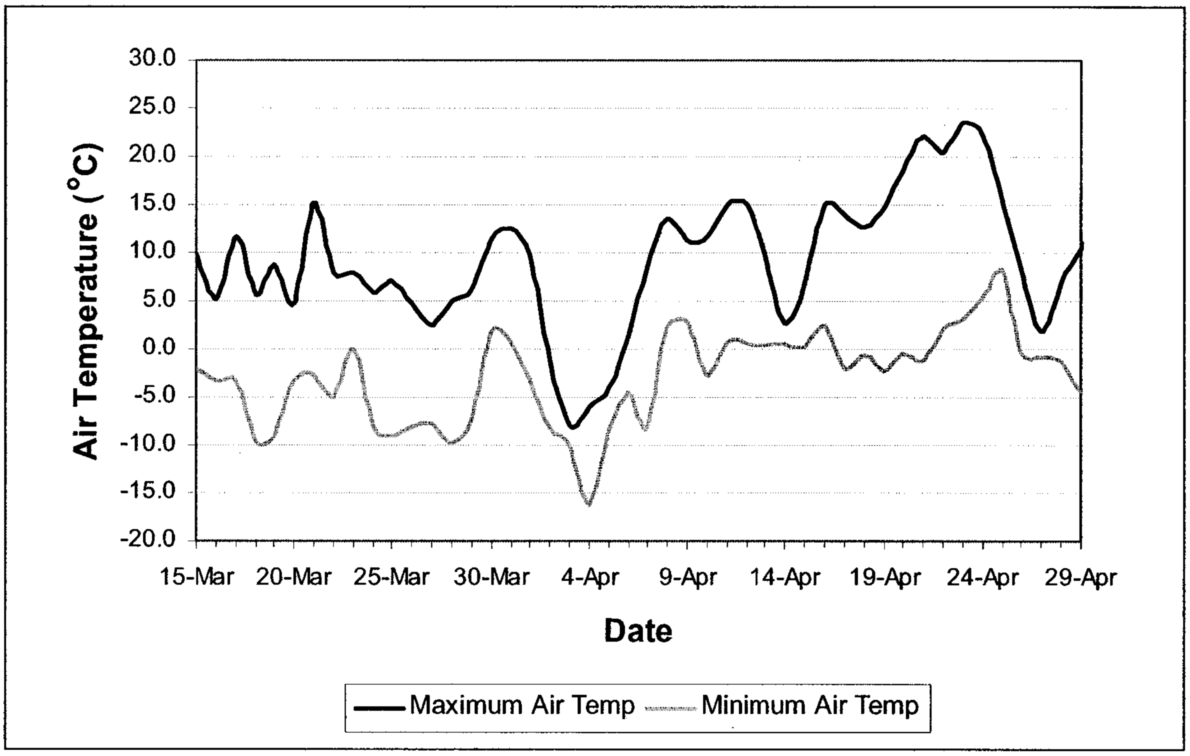

Figure 5.1 **Maximum and minimum air temperatures in spring 2003**
(Snowmelt runoff measurement dates: April 8, 11, and 14, 2003)

5.6 References

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6 SYNTHESIS

The overall global objectives of this study were to evaluate the hydrologic regime of different forages under managed intensive grazing. By increasing the efficiency of pasture utilization through management practices such as managed intensive grazing, pasture resources in central Alberta can be both environmentally and economically sustainable.

6.1 The Hydrologic Regime and Leaching Potential

Snowmelt runoff was the dominant source of pastureland runoff at the study site compared to summer storm runoff. Water quality of this runoff was generally not an environmental concern, regardless of forage treatment. Since the ground was frozen and the old manure and urine spots had somewhat decomposed or been subjected to volatilization and leaching losses during the previous summer and fall, fewer nutrients could be moved off-site in the runoff water than if the soil surface and manure had thawed.

Soil water was usually at its highest immediately following snowmelt in the spring. Overwinter recharge of soil moisture was the greatest source of annual recharge, and thus was very important for crop and pasture production. Even though summer storms did occur, those that produced enough water to help recharge soil moisture or cause runoff were quite infrequent. Although water quality of summer rainfall runoff was not assessed, it may be a concern since runoff would potentially flow over fresh urine and manure spots on the ground surface, moving nutrients off-site. However, as noted above, measured water quality of this runoff was not an environmental concern based on Canadian government standards.

Throughout the growing season, vegetation draws down soil water reserves, bringing soil water to its lowest point just prior to freeze-up. The closer a pasture is to field capacity in the fall, the lower the amount of infiltration of snowmelt water in the spring. In other words, high antecedent moisture conditions decrease infiltration.

Generally, annual and meadow bromegrass had similar trends in soil water, as did old grass and alfalfa. In terms of snowmelt runoff, annual and alfalfa had similar trends, as did old grass and meadow bromegrass. Leaching potentials were very low for all four forage treatments.

6.1.1 Annual Forages

Annual forage pastures were characterized by their low surface bulk density, high percentage of bare ground, low amount of canopy cover, and thus low evapotranspiration and water use. Annual cultivation and seeding of these pastures led to less compacted soil conditions compared to the perennials, contributing to the lower penetration resistances observed under annuals. Generally, gentle rains of low quantities would likely infiltrate these pastures, as the micro-relief and surface depressions in the soft soil likely enhance infiltration. All factors considered, annuals should have higher soil water levels than perennials, as observed. Additionally, their soil water status was higher in the spring since their growth was delayed compared to perennials.

Due to their generally high soil water levels, one would assume that annual forages had the greatest amount of water available for percolation. However, moisture contents were similar, with depth, deep in the soil profile, indicating that there was a low hydraulic gradient and thus likely a very low leaching potential. In years with higher amounts of precipitation and thus greater soil water than the study years, the leaching potential may be slightly increased.

Since annual forages had the highest soil water contents in the fall, they gained the least amount of water in the spring, as expected. The high antecedent moisture conditions combined with low canopy cover may have contributed to the higher amounts of snowmelt runoff observed compared to the meadow bromegrass and old grass pastures.

6.1.2 Perennial Forages

Perennial forages were characterized by their higher surface bulk densities, increased litter layer and canopy cover, established forage stand and greater root mass, and thus increased evapotranspiration and water use compared to annuals. The compacted soil surface and thick fallen litter layer in some of the pastures may have decreased infiltration slightly, but the roughness created by the vegetation and litter likely slowed water movement on the surface, thus increasing infiltration. However, perennials use more soil water than annuals, so soil water levels under perennials were likely to be lower, as observed. Drier soil conditions compared to annuals contributed to the higher penetration resistances observed.

The old grass pastures had the lowest soil water levels of all the forages examined, likely because they used the most water and/or the thick fallen litter layer did not allow as much water to infiltrate. Regardless, soil water deep in the soil profile increased with depth, indicating an upward hydraulic gradient and thus no leaching potential. Similarly, the soil water deep in the profiles of alfalfa and meadow bromegrass pastures also increased with depth, indicating an upward hydraulic gradient and little chance of leaching.

Since old grass pastures had the lowest soil water contents in the fall, they gained the most soil water in the spring, as expected. The very low antecedent moisture conditions prior to snowmelt and high canopy cover in the previous year may have contributed to the lower amount of spring runoff measured. Similarly, meadow bromegrass pastures had a high amount of canopy cover, which may have contributed to the low amount of runoff measured. In contrast, alfalfa pastures unexpectedly produced the most runoff both from snowmelt and summer storms, likely due to the lower amount of canopy cover.

Runoff notwithstanding, alfalfa pastures generally performed like the old grass pastures, having the second lowest soil water status throughout the year, whereas meadow bromegrass pastures generally shadowed the trends of annuals, having the second highest soil water status throughout the year.

6.2 Future Research Considerations

This study indicated the importance of monitoring the soil profile below 1 m, as it allows greater understanding of the hydrologic regime. Therefore, future studies should continue monitoring soil moisture to 2 m.

Although the old grass area was used as a benchmark site for comparison purposes, the addition of an ungrazed control for each forage treatment would be beneficial in the future. Exclosures already exist within each paddock, but their small size presents other challenges. A full-sized, ungrazed paddock for each forage treatment would enable runoff measurement and more thorough soil sampling. However, it is recognized that these additional paddocks would require a considerable amount of space, which may not be feasible.

This study was conducted over a rather dry, 2-year period, resulting in only one summer storm that produced runoff. Conclusions drawn about leaching potential were tempered by this dry study period, so a longer monitoring period is recommended for future research. Additionally, rainfall simulation experiments may give a more complete picture of summer runoff potential and/or patterns from each forage treatment.

Alfalfa treatments produced more runoff than the annual treatments in this study, which was difficult to explain. It was hypothesized that there was a hard surface layer in these treatments, which may have acted like a surface crust. However, other research indicates that Chernozems do not crust due to their high organic matter contents. Hence, further investigation is warranted of the soil conditions in the alfalfa treatments.

7 APPENDIX

Table 7.1 Soil physical properties by paddock, Lacombe, Alberta

Paddock –Tube* Forage Trt.	Depth (cm)	% Sand	% Silt	% Clay	Texture	%OM
1-2 Alfalfa	0-20	85	1	14	Loamy sand	8.2
	20-40	71	17	12	Sandy loam	5.7
	40-60	69	18	13	Sandy loam	2.9
	60-80	79	13	8	Sandy loam	
	80-100	70	14	16	Sandy loam	
	100-120	40	24	36	Clay loam	
	120-140	26	31	43	Clay	
	140-160	20	34	46	Clay	
	160-180	18	34	48	Clay	
	180-200	27	34	39	Clay	
3-2 Meadow Bromegrass	0-20	39	31	30	Clay loam	13
	20-40	35	35	30	Clay loam	10
	40-60	41	29	30	Clay loam	4.6
	60-80	61	21	18	Sandy loam	
	80-100	25	33	42	Clay	
	100-120	18	32	50	Clay	
	120-140	15	31	54	Clay	
	140-160	12	32	56	Clay	
	160-180	20	32	48	Clay	
	180-200	14	39	47	Clay	
4-2 Annual	0-20	58	22	20	Sandy clay loam	8.4
	20-40	66	18	16	Sandy loam	3.8
	40-60	78	11	11	Sandy loam	1.1
	60-80	28	36	36	Clay loam	
	80-100	24	31	45	Clay	
	100-120	20	28	52	Clay	
	120-140	10	33	57	Clay	
	140-160	18	32	50	Clay	
	160-180	12	34	54	Clay	
	180-200	14	32	54	Clay	
7-2 Alfalfa	0-20	73	3	24	Sandy clay loam	8.4
	20-40	65	17	18	Sandy loam	5.9
	40-60	66	14	20	Sandy clay loam	3.4
	60-80	74	10	16	Sandy loam	1.2
	80-100	78	10	12	Sandy loam	
	100-120	26	22	52	Clay	
	120-140	12	33	55	Clay	
	140-160	16	34	50	Clay	
	160-180	12	38	50	Clay	
	180-200	15	34	51	Clay	

*Tube # refers to position of soil access tube in each paddock; tube #2 is located approximately 50 m from the exclosure in each paddock (see Figure 2.1).

Table 7.1 (continued) Soil physical properties by paddock, Lacombe, Alberta

Paddock –Tube* Forage Trt.	Depth (cm)	% Sand	% Silt	% Clay	Texture	%OM
9-2 Annual	0-20	32	28	40	Clay	3.1
	20-40	63	19	18	Sandy loam	8.4
	40-60	50	28	22	Sandy clay loam	7.9
	60-80	62	17	21	Sandy clay loam	
	80-100	66	16	18	Sandy loam	
	100-120	72	12	16	Sandy loam	
	120-140	72	13	15	Sandy loam	
	140-160	70	17	13	Sandy loam	
	160-180	36	24	40	Clay	
	180-200	12	30	58	Clay	
12-2 Meadow Bromegrass	0-20	81	2	17	Sandy loam	9.5
	20-40	66	16	18	Sandy loam	4.3
	40-60	78	10	12	Sandy loam	1.6
	60-80	44	20	36	Clay loam	
	80-100	46	26	28	Sandy clay loam	
	100-120	16	36	48	Clay	
	120-140	10	40	50	Silty Clay/ Clay	
	140-160	12	34	54	Clay	
	160-180	14	34	52	Clay	
	180-200	10	36	54	Clay	
13-2 Meadow Bromegrass	0-20	68	12	20	Sandy clay loam/ Sandy loam	10
	20-40	42	32	26	Loam	8.5
	40-60	58	24	18	Sandy loam	2.9
	60-80	36	21	43	Clay	
	80-100	23	25	52	Clay	
	100-120	22	30	48	Clay	
	120-140	21	39	40	Clay	
	140-160	14	49	37	Silt Clay Loam	
	160-180	8	63	29	Silt Clay Loam	
	180-200	9	68	23	Silt Loam	
14-2 Alfalfa	0-20	62	23	15	Sandy loam	9.8
	20-40	47	37	16	Loam	6.6
	40-60	58	27	15	Sandy loam	4.5
	60-80	58	18	24	Sandy clay loam	
	80-100	46	22	32	Sandy clay loam/ Clay loam	
	100-120	33	31	36	Clay loam	
	120-140	18	38	44	Clay	
	140-160	37	33	30	Clay loam	
	160-180	16	49	35	Silt clay loam	
	180-200	16	58	26	Silt clay loam/ Silt loam	

*Tube # refers to position of soil access tube in each paddock; tube #2 is located approximately 50 m from the exclosure in each paddock (see Figure 2.1).

Table 7.1 (continued) Soil physical properties by paddock, Lacombe, Alberta

Paddock -Tube* Forage Trt.	Depth (cm)	% Sand	% Silt	% Clay	Texture	%OM
15-2	0-20	67	19	14	Sandy loam	8.7
	20-40	62	24	14	Sandy loam	5.2
	40-60	70	20	10	Sandy loam	1.3
	60-80	52	32	16	Sandy loam/ Loam	
	80-100	42	43	15	Loam	
Annual	100-120	45	44	11	Loam	
	120-140	44	42	14	Loam	
	140-160	32	50	18	Loam/ Silt loam	
	160-180	49	41	10	Loam	
	180-200	46	44	10	Loam	
21-2	0-20	62	23	15	Sandy loam	3.7
	20-40	64	22	14	Sandy loam	3.3
	40-60	72	16	12	Sandy loam	1.3
	60-80	73	19	8	Sandy loam	
	80-100	69	20	11	Sandy loam	
Old Grass	100-120	72	12	16	Sandy loam	
	120-140	67	14	19	Sandy loam	
	140-160	64	19	17	Sandy loam	
	160-180	52	32	16	Sandy loam/ Loam	
	180-200	60	27	13	Sandy loam	
24-2	0-20	71	17	12	Sandy loam	5.7
	20-40	70	20	10	Sandy loam	3.3
	40-60	70	20	10	Sandy loam	2.4
	60-80	76	15	9	Sandy loam	
	80-100	82	13	5	Loamy sand	
Old Grass	100-120	85	11	4	Loamy sand	
	120-140	80	14	6	Loamy sand	
	140-160	52	34	14	Loamy sand	
	160-180	46	32	22	Loam	
	180-200	28	38	34	Clay loam	

*Tube # refers to position of soil access tube in each paddock; tube #2 is located approximately 50 m from the exclosure in each paddock (see Figure 2.1).

Table 7.2 Soil chemistry by paddock, Lacombe, Alberta

					Total Kjeldahl Nitrogen (%)	mg/kg								
Paddock-Tube	Depth	pH	SAR	EC (dS/m)		Available Ammonium - N	Available Nitrate - N	Available Phosphate - P	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
1-2 Alfalfa	0-20	5.3	0.3	0.59	0.39	6.9	12.2	61	57.13	27.12	28.38	6.67	12.52	5.18
	20-40	6.4	0.5	0.46	0.24	1.7	3.6	17	38.05	23.53	20.98	5.17	3.64	7.37
	40-60	6.7	0.7	0.39	0.14	1.1	2.8	7	25.43	19.66	15.29	3.94	0.86	7.72
	60-80	7.1	1.1	0.38		0.8	1.8	4	13.82	18.67	10.86	2.82	0.66	9.11
	80-100	6.0	0.7	0.51		2.6	4.2	16	22.13	28.65	15.54	4.38	2.16	6.48
	100-120	6.3	0.5	0.71		2.8	1.8	2	46.23	84.33	35.65	10.62	1.51	10.09
	120-140	6.9	0.5	0.83		4.8	1.6	2	58.19	75.41	56.57	16.32	2.39	12.27
	140-160	6.6	0.4	0.62		2.9	1.4	3	73.94	30.35	34.92	10.18	1.10	8.00
	160-180	7.5	0.4	0.71		2.7	1.6	1	77.01	28.25	44.32	12.29	1.61	8.50
	180-200	7.7	0.3	0.60		2.5	1.4	<1	54.43	24.42	32.86	8.97	1.01	6.32
3-2 Meadow Bromegrass	0-20	6.2	1.5	0.55	0.54	3.4	10.8	128	45.80	43.37	29.96	7.75	25.47	31.21
	20-40	6.8	1.8	0.33	0.45	2.7	3.8	11	8.43	26.72	17.24	4.70	0.85	26.52
	40-60	7.0	0.8	0.41	0.21	2.0	1.6	4	20.58	19.15	21.28	6.90	0.53	12.09
	60-80	7.3	0.5	0.51		1.8	2.0	3	4.21	14.57	19.96	6.48	1.45	5.94
	80-100	7.1	0.4	1.24		3.4	2.4	5	107.44	89.76	75.34	23.93	2.52	12.19
	100-120	7.5	0.5	0.87		5.5	3.6	9	51.24	115.97	63.68	19.53	4.45	14.41
	120-140	7.9	0.6	0.56		5.9	3.0	2	15.75	69.76	44.54	13.18	3.54	14.18
	140-160	7.8	0.6	0.43		5.1	2.6	1	8.01	43.82	32.88	10.02	3.36	13.48
	160-180	7.9	0.7	0.40		6.0	2.8	2	5.94	23.86	29.92	9.02	2.93	13.78
	180-200	7.9	0.7	0.37		5.1	2.8	1	4.06	22.68	24.30	7.26	2.13	12.43
4-2 Annual	0-20	5.8	0.6	0.48	0.41	8.2	26.4	91	20.46	23.45	25.30	6.55	8.03	9.46
	20-40	6.9	0.3	0.23	0.20	1.4	3.6	7	7.71	9.06	10.86	3.00	0.40	3.20
	40-60	7.1	0.3	0.18	0.05	1.1	2.0	6	3.94	7.27	6.97	2.13	0.54	1.70
	60-80	6.8	0.5	1.17		4.1	1.2	2	122.24	48.01	58.17	19.71	2.70	12.84
	80-100	6.5	0.7	0.47		3.8	4.8	2	6.46	59.31	25.17	8.24	3.25	12.19
	100-120	6.2	0.7	0.40		5.0	7.0	4	7.89	50.21	21.29	6.91	3.61	12.01
	120-140	6.2	0.8	0.34		5.4	4.6	3	8.46	34.39	16.48	5.37	2.90	11.21
	140-160	6.3	0.8	0.33		7.0	5.8	4	10.14	22.87	15.39	4.90	3.44	11.60
	160-180	7.1	0.8	0.37		7.7	4.0	1	9.81	29.48	26.02	8.67	3.71	15.38
	180-200	7.1	0.8	0.31		7.2	4.6	1	7.54	21.28	19.21	6.36	3.26	13.37

Table 7.2 (continued) Soil chemistry by paddock, Lacombe, Alberta

					Total Kjeldahl Nitrogen (%)	mg/kg								
Paddock-Tube	Depth	pH	SAR	EC (dS/m)		Available Ammonium - N	Available Nitrate - N	Available Phosphate - P	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
7-2 Alfalfa	0-20	6.2	0.2	0.29	0.37	4.5	15.0	72	23.05	18.79	16.18	3.67	12.26	3.10
	20-40	6.5	0.7	0.26	0.26	2.3	4.8	15	12.31	19.79	11.07	2.80	1.63	7.11
	40-60	6.6	0.8	0.23	0.18	2.0	3.4	14	4.57	15.03	9.46	2.65	1.90	6.84
	60-80	6.4	0.5	0.22		1.3	2.0	9	3.69	8.50	8.14	2.21	2.08	3.36
	80-100	6.3	0.4	0.16		1.1	2.0	13	2.08	7.39	5.40	1.47	2.53	2.44
	100-120	6.3	3.3	0.39		2.8	4.0	8	15.44	36.94	8.79	2.66	0.62	33.59
	120-140	6.1	3.4	0.37		3.0	2.6	6	22.30	45.18	9.41	2.87	0.75	37.24
	140-160	6.4	0.3	0.30		3.1	2.0	3	19.13	16.16	20.55	5.53	6.27	5.53
	160-180	6.6	0.3	0.34		3.0	2.0	5	22.94	18.86	28.31	7.17	6.74	6.00
	180-200	6.7	0.2	0.33		3.1	2.6	4	23.86	18.68	27.08	6.50	6.23	4.68
9-2 Annual	0-20	6.7	0.4	1.23	0.16	5.0	24.8	16	37.34	183.28	95.62	23.71	6.47	14.33
	20-40	7.5	0.8	0.58	0.28	2.6	16.4	7	12.89	21.54	34.85	7.22	1.16	12.61
	40-60	6.8	0.3	0.53	0.38	3.0	8.2	7	15.44	37.97	54.00	14.07	1.91	8.22
	60-80	6.9	0.5	0.43		1.6	4.6	5	9.42	30.36	19.91	5.78	0.90	5.97
	80-100	6.4	0.5	0.50		1.8	14.4	11	11.02	32.36	22.49	6.36	2.63	6.51
	100-120	6.1	0.4	0.49		1.6	15.4	11	8.38	31.00	18.36	5.14	3.70	4.40
	120-140	6.1	0.4	0.35		1.1	7.2	6	6.63	20.18	9.68	2.63	3.36	2.64
	140-160	6.5	0.3	0.33		1.1	4.2	6	5.05	14.47	10.97	3.18	3.70	2.29
	160-180	7.1	0.2	0.57		2.6	6.6	4	8.70	24.66	44.43	12.82	7.87	4.53
	180-200	6.9	0.2	0.39		3.5	5.8	2	5.57	23.29	33.80	10.44	7.62	4.67
12-2 Meadow Bromegrass	0-20	5.7	0.3	0.36	0.45	2.6	18.3	111	32.24	29.35	19.29	3.92	31.13	5.08
	20-40	6.8	0.9	0.37	0.21	1.5	5.2	7	14.07	17.36	18.79	4.17	1.01	11.54
	40-60	7.2	1.5	0.30	0.07	9.9	3.8	4	5.46	13.14	12.06	3.06	1.12	14.12
	60-80	6.9	0.7	0.71		3.3	3.0	1	47.58	65.49	42.76	11.70	2.44	14.38
	80-100	6.7	0.5	1.47		6.7	42.8	42	33.72	117.34	112.33	27.93	13.94	17.19
	100-120	7.5	0.4	0.71		5.3	3.4	3	20.38	162.25	65.57	17.68	4.33	11.87
	120-140	7.7	0.5	0.42		6.4	3.8	1	11.82	52.19	37.80	10.73	3.30	10.31
	140-160	7.8	0.5	0.38		4.8	2.4	1	10.51	46.22	32.86	9.58	3.44	10.71
	160-180	7.8	0.4	0.28		3.1	2.0	<1	6.57	25.12	21.29	5.95	1.88	6.92
	180-200	7.5	0.4	0.45		5.7	2.2	<1	10.24	83.32	42.61	12.11	4.01	11.06

Table 7.2 (continued) Soil chemistry by paddock, Lacombe, Alberta

Paddock-Tube	Depth	pH	SAR	EC (dS/m)	Total Kjeldahl Nitrogen (%)	mg/kg								
						Available Ammonium - N	Available Nitrate - N	Available Phosphate - P	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
13-2 Meadow Bromegrass	0-20	5.3	0.4	1.00	0.52	10.6	58.8	122	50.01	66.70	84.93	19.64	7.14	14.15
	20-40	6.1	0.6	0.40	0.38	3.0	12.0	16	22.02	35.21	29.98	8.10	0.68	12.05
	40-60	6.2	0.6	0.28	0.12	2.1	2.8	7	8.05	26.81	11.42	3.46	0.51	5.03
	60-80	6.0	0.7	0.35		5.1	2.2	3	5.83	55.65	20.22	6.06	2.44	10.53
	80-100	5.9	0.6	0.30		6.8	2.2	2	3.86	56.35	18.61	5.64	3.09	8.74
	100-120	5.8	0.5	0.26		5.6	2.2	2	2.67	52.52	14.77	4.60	1.97	5.78
	120-140	6.1	0.5	0.29		7.2	4.6	4	7.23	31.84	18.91	5.79	2.41	7.14
	140-160	6.3	0.4	0.19		6.0	2.4	3	4.94	21.63	11.65	3.56	1.44	5.08
	160-180	7.3	0.3	0.30		4.4	2.6	1	3.32	16.45	24.42	6.69	1.84	5.10
	180-200	7.6	0.3	0.26		4.3	2.4	<1	3.16	12.08	20.18	5.35	1.80	4.35
14-2 Alfalfa	0-20	5.3	0.2	0.49	0.12	4.0	35.0	67	17.66	36.58	39.95	8.82	3.60	4.96
	20-40	7.0	0.4	0.41	0.35	2.2	11.0	11	12.10	26.42	35.31	8.77	1.93	6.90
	40-60	7.2	0.6	0.50	0.19	1.6	5.2	5	27.40	36.88	26.47	7.54	1.02	8.98
	60-80	7.1	0.6	0.45		2.5	2.6	2	21.28	26.64	18.29	8.65	1.24	7.17
	80-100	7.7	0.4	0.49		4.2	4.4	1	6.92	42.32	25.13	13.88	1.98	6.94
	100-120	7.9	0.4	0.43		4.7	3.0	1	5.60	32.80	22.96	16.85	2.10	8.10
	120-140	8.0	0.4	0.33		4.1	2.6	<1	2.78	16.15	17.91	15.00	2.34	6.79
	140-160	7.9	0.3	0.37		2.8	2.2	1	2.64	16.82	16.51	12.98	3.10	5.06
	160-180	8.0	0.4	0.40		2.6	1.8	<1	2.95	45.29	19.82	16.61	1.97	6.74
	180-200	8.0	0.4	0.38		3.1	2.0	<1	2.80	33.94	17.10	15.23	1.13	7.37
15-2 Annual	0-20	5.4	0.7	1.00	0.39	21.2	68.4	101	28.13	35.64	60.12	12.60	22.35	16.76
	20-40	7.1	1.4	0.70	0.28	2.2	19.8	13	24.55	31.07	39.00	8.22	0.59	26.48
	40-60	7.1	0.4	0.47	0.07	1.0	6.2	9	18.16	12.09	20.18	4.99	0.65	4.83
	60-80	7.1	0.4	0.38		1.6	3.0	5	7.29	15.31	16.97	4.77	1.27	4.45
	80-100	6.3	0.7	0.43		4.0	10.6	19	10.78	16.15	16.80	4.88	2.35	7.41
	100-120	6.8	0.6	0.36		1.7	4.4	6	13.28	15.42	13.62	3.93	1.10	5.31
	120-140	7.3	0.3	0.68		1.7	6.6	2	26.49	42.87	38.18	9.28	2.37	4.91
	140-160	7.6	0.3	0.78		3.7	13.2	2	23.77	66.94	45.87	9.92	1.85	6.09
	160-180	7.9	0.3	0.45		2.4	6.0	<1	6.82	27.31	20.64	4.67	0.88	3.64
	180-200	7.8	0.3	0.44		4.6	7.2	2	5.81	20.63	21.07	4.59	1.68	3.63

Table 7.2 (continued) Soil chemistry by paddock, Lacombe, Alberta

						mg/kg								
Paddock-Tube	Depth	pH	SAR	EC (dS/m)	Total Kjeldahl Nitrogen (%)	Available Ammonium - N	Available Nitrate - N	Available Phosphate - P	Cl$^-$	SO$_4^{2-}$	Ca^{2+}	Mg^{2+}	K$^+$	Na$^+$
21-2	0-20	6.0	0.2	1.22	0.20	5.3	46.8	32	45.08	27.19	79.76	13.75	8.20	4.09
	20-40	6.9	0.2	1.19	0.18	2.5	40.8	9	52.05	26.67	74.64	14.28	1.33	4.67
	40-60	6.8	0.2	0.98	0.07	1.6	32.4	4	46.37	8.26	48.36	11.03	1.81	4.09
	60-80	7.2	0.4	0.21		1.1	6.4	2	6.10	4.86	9.12	2.32	0.62	2.61
Old Grass	80-100	7.1	0.4	0.19		1.4	2.6	5	3.19	4.56	8.02	1.63	0.53	2.94
	100-120	7.8	0.4	0.29		2.1	2.6	1	2.84	6.47	15.68	2.77	1.87	3.88
	120-140	7.7	0.3	0.31		1.8	2.0	1	2.36	9.02	17.76	3.16	1.68	3.17
	140-160	7.9	0.2	0.31		2.0	2.2	1	2.13	7.92	18.89	3.08	1.77	2.47
	160-180	8.0	0.2	0.33		2.5	2.4	1	2.81	9.42	21.32	3.82	1.95	2.85
	180-200	8.1	0.2	0.28		1.6	1.8	<1	3.34	8.39	15.83	3.08	1.58	2.30
24-2	0-20	5.6	0.4	0.44	0.27	2.6	16.2	140	15.94	25.45	23.43	9.72	5.34	6.53
	20-40	6.4	0.5	0.38	0.17	1.6	10.8	44	12.40	17.82	21.11	5.60	1.17	6.59
	40-60	6.6	0.9	0.32	0.10	1.3	6.4	14	8.65	13.21	12.29	4.15	0.90	8.76
	60-80	6.5	1.3	0.30		0.5	3.0	14	5.99	19.56	8.47	2.14	1.98	8.96
Old Grass	80-100	6.3	0.9	0.21		0.8	3.0	14	2.63	17.08	5.84	1.58	2.67	5.25
	100-120	6.2	0.9	0.16		0.9	2.4	14	2.42	9.90	3.84	1.03	1.98	4.15
	120-140	6.3	0.4	0.10		1.0	2.6	13	2.02	5.03	2.10	0.69	1.65	1.56
	140-160	6.2	0.5	0.20		1.2	2.2	14	4.47	10.25	5.65	1.68	2.70	2.61
	160-180	6.1	0.4	0.20		1.3	1.6	8	5.86	10.99	6.17	2.14	2.71	2.69
	180-200	6.5	0.3	0.24		3.2	2.4	8	6.12	16.82	11.84	3.56	3.85	3.72

Table 7.3 Daily meteorological data from Paddock 24, Lacombe Research Station, 2002

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
22-May-02	3.6	62.0	0.00	8.8	0.6	5.7		
23-May-02	5.7	52.4	0.00	12.4	-2.0	5.4		
24-May-02	7.1	66.3	0.00	11.4	3.7	6.1		
25-May-02	9.3	53.9	0.00	16.6	0.3	6.3		
26-May-02	13.0	42.1	0.00	21.8	0.9	7.2		
27-May-02	15.9	42.8	0.00	23.8	4.5	8.5		
28-May-02	16.5	51.3	0.00	24.6	5.7	9.2		
29-May-02	18.4	36.9	0.00	24.1	10.6	10.3		
30-May-02	16.5	39.0	0.00	23.2	9.6	10.5		
31-May-02	12.6	29.9	0.00	18.1	M	10.4		
1-Jun-02	12.3	0.0	0.00	18.6	2.2	9.8		
2-Jun-02	12.5	0.0	0.00	15.4	9.2	10.1		
3-Jun-02	M	M	0.00	18.8	M	8.8		
4-Jun-02	15.9	56.5	0.00	24.3	5.8	11.1		
5-Jun-02	17.0	46.3	0.00	24.5	7.3	11.6		
6-Jun-02	12.6	43.2	0.00	18.6	8.2	11.3		
7-Jun-02	9.4	47.6	0.00	15.8	-1.0	10.1		
8-Jun-02	10.7	54.5	0.00	16.0	3.3	9.9		
9-Jun-02	12.5	65.4	0.00	18.8	7.5	10.2		
10-Jun-02	13.0	60.1	0.00	18.7	7.0	10.4		
11-Jun-02	13.8	46.8	0.00	19.4	7.7	10.7		
12-Jun-02	14.9	45.9	0.00	24.7	1.7	10.7		
13-Jun-02	18.0	44.7	0.00	28.3	5.9	11.7	0.87	99
14-Jun-02	18.8	47.1	0.00	24.8	12.8	13.2	2.10	137
15-Jun-02	19.0	56.8	0.00	28.3	8.2	13.5	2.28	246
16-Jun-02	20.0	51.6	0.00	26.9	10.3	14.6	2.21	244
17-Jun-02	15.2	70.8	2.29	22.6	8.1	14.6	3.55	272
18-Jun-02	8.6	86.4	1.52	11.0	6.6	12.7	1.80	159
19-Jun-02	11.8	71.9	0.25	20.3	0.9	12.7	2.66	263
20-Jun-02	15.5	59.9	0.00	22.4	7.0	13.6	1.66	202
21-Jun-02	17.9	49.5	0.00	26.3	7.0	13.9	1.49	228
22-Jun-02	19.5	52.1	0.00	28.9	6.8	14.1	2.71	198
23-Jun-02	20.0	55.3	0.00	28.6	10.3	14.7	2.50	193
24-Jun-02	19.6	60.2	0.25	26.6	14.5	15.9	2.48	197
25-Jun-02	20.5	53.0	0.00	28.7	9.7	16.2	1.45	226
26-Jun-02	23.3	49.8	0.00	33.3	10.0	16.8	1.81	179
27-Jun-02	22.6	57.6	0.00	34.6	13.7	17.3	1.60	184
28-Jun-02	18.6	71.1	0.00	23.4	13.8	17.2	2.48	246
29-Jun-02	16.9	74.7	3.81	25.4	10.8	16.4	2.09	251
30-Jun-02	13.8	62.4	0.00	21.5	7.2	16.0	2.53	284

Table 7.3 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2002

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
1-Jul-02	13.1	48.8	0.00	20.1	2.3	14.7	2.72	257
2-Jul-02	14.4	40.6	0.00	22.0	2.9	14.7	2.12	215
3-Jul-02	15.8	48.4	0.00	23.0	8.0	14.1	3.32	117
4-Jul-02	15.5	57.7	0.00	20.9	10.3	14.7	2.79	269
5-Jul-02	14.2	45.6	0.00	20.8	4.1	14.7	2.53	252
6-Jul-02	15.2	50.5	0.00	24.5	3.1	14.8	1.53	221
7-Jul-02	19.9	43.7	0.00	29.8	6.5	15.8	2.21	184
8-Jul-02	18.6	68.1	3.30	23.6	14.5	16.3	3.92	133
9-Jul-02	18.5	72.2	0.00	24.7	13.8	17.2	2.60	277
10-Jul-02	20.4	67.7	0.00	28.8	10.5	17.3	3.46	175
11-Jul-02	24.8	57.6	0.00	34.3	13.1	18.7	1.85	211
12-Jul-02	24.6	54.1	0.00	34.3	13.3	19.4	1.56	221
13-Jul-02	23.8	57.7	0.00	33.7	14.6	19.6	1.73	275
14-Jul-02	21.3	64.1	0.00	26.4	13.7	19.7	3.38	304
15-Jul-02	20.0	56.2	0.00	28.8	8.8	18.9	2.12	195
16-Jul-02	21.0	54.8	2.29	29.6	11.4	19.5	2.49	107
17-Jul-02	24.2	47.7	0.00	33.4	12.9	19.8	1.83	132
18-Jul-02	21.5	64.7	0.00	29.6	15.1	20.0	2.57	217
19-Jul-02	20.0	73.3	8.38	28.4	15.3	20.2	3.17	131
20-Jul-02	16.6	58.5	0.25	21.4	11.3	18.9	5.60	320
21-Jul-02	16.6	58.7	0.00	22.2	12.4	18.4	4.60	330
22-Jul-02	17.5	58.1	0.00	26.7	6.3	17.6	1.74	185
23-Jul-02	21.0	47.9	0.00	29.9	10.4	18.1	2.23	211
24-Jul-02	22.1	54.2	0.00	29.4	15.3	19.5	2.59	268
25-Jul-02	24.2	51.9	0.00	32.4	15.1	20.4	1.67	245
26-Jul-02	17.2	73.2	8.89	24.4	12.5	19.3	3.12	306
27-Jul-02	17.7	61.3	0.00	23.5	12.3	18.5	3.10	268
28-Jul-02	14.3	78.2	0.76	18.8	8.8	17.7	1.99	258
29-Jul-02	13.7	69.2	1.02	19.0	7.6	17.2	1.88	132
30-Jul-02	12.8	64.4	0.00	19.3	8.5	16.6	2.49	220
31-Jul-02	6.9	81.6	4.32	9.9	5.2	14.3	5.52	312
1-Aug-02	8.2	73.0	0.00	11.2	3.9	13.1	2.44	229
2-Aug-02	5.6	88.5	9.62	8.8	3.4	11.5	3.06	154
3-Aug-02	6.9	83.2	2.54	10.6	3.5	10.4	1.42	228
4-Aug-02	7.7	85.1	0.00	9.3	6.5	10.6	3.57	133
5-Aug-02	11.7	84.5	6.10	18.7	6.7	11.5	2.73	135
6-Aug-02	11.5	93.2	1.02	15.7	6.0	12.6	1.67	223
7-Aug-02	12.9	71.5	0.00	21.7	2.7	13.5	1.28	221
8-Aug-02	15.2	67.8	0.00	24.2	4.8	14.3	1.31	244
9-Aug-02	17.4	66.5	0.00	27.0	7.4	15.2	1.59	189
10-Aug-02	12.4	87.4	7.62	17.0	9.3	14.9	2.00	206

Table 7.3 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2002

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
11-Aug-02	13.0	73.0	0.00	18.9	9.1	14.6	3.63	297
12-Aug-02	14.6	68.7	0.00	21.6	7.0	15.1	2.11	259
13-Aug-02	18.0	62.4	0.00	25.1	9.8	16.0	2.22	238
14-Aug-02	13.4	74.0	2.29	16.5	9.9	15.4	5.69	309
15-Aug-02	10.4	80.6	0.00	15.3	4.2	14.2	3.14	283
16-Aug-02	8.9	73.0	0.00	14.4	5.0	13.5	3.08	298
17-Aug-02	11.5	68.8	0.00	20.9	2.9	13.2	2.39	230
18-Aug-02	13.0	68.5	0.00	21.6	2.1	13.6	1.85	227
19-Aug-02	14.3	70.3	2.79	21.3	6.0	13.9	2.19	198
20-Aug-02	14.6	81.6	2.29	21.1	9.6	14.6	1.84	203
21-Aug-02	15.1	73.4	0.00	24.2	4.4	14.4	1.86	193
22-Aug-02	17.4	65.0	0.00	26.2	8.1	14.6	1.00	202
23-Aug-02	19.1	67.9	0.00	27.9	9.5	15.3	0.97	225
24-Aug-02	20.2	65.9	0.00	29.7	10.0	15.8	1.53	197
25-Aug-02	19.6	65.1	0.00	29.4	9.9	16.1	1.69	207
26-Aug-02	18.1	74.1	0.00	23.5	11.8	16.5	2.42	312
27-Aug-02	17.4	68.4	0.00	26.6	8.0	15.9	1.17	248
28-Aug-02	18.7	61.5	0.00	29.0	8.5	15.6	2.80	188
29-Aug-02	19.8	64.0	0.00	27.8	11.6	16.2	2.64	203
30-Aug-02	16.4	75.8	0.00	19.9	12.8	16.4	3.83	320
31-Aug-02	15.5	69.5	0.00	23.7	6.0	15.8	1.45	192
1-Sep-02	12.1	84.2	9.65	15.7	7.9	14.9	2.39	297
2-Sep-02	11.3	71.9	0.00	18.6	2.3	13.2	2.09	170
3-Sep-02	10.7	85.2	0.25	16.1	6.4	12.9	2.30	301
4-Sep-02	9.9	76.8	0.00	14.3	5.3	13.3	2.69	305
5-Sep-02	6.3	90.5	1.52	8.0	5.0	12.0	1.85	111
6-Sep-02	7.5	87.3	3.05	12.0	4.5	11.4	1.11	166
7-Sep-02	7.9	91.7	0.25	13.0	3.3	10.6	1.57	176
8-Sep-02	10.4	68.9	0.25	19.7	0.9	10.7	1.68	203
9-Sep-02	12.0	61.5	0.00	21.4	2.3	10.9	1.61	196
10-Sep-02	15.4	59.0	0.00	26.4	4.9	11.9	2.21	205
11-Sep-02	13.4	64.1	0.00	19.5	6.8	12.4	1.68	233
12-Sep-02	13.6	72.8	0.00	23.3	4.1	12.1	1.36	214
13-Sep-02	11.9	66.1	0.00	17.0	5.6	12.2	3.36	296
14-Sep-02	13.0	68.6	0.00	24.0	4.1	11.5	2.10	178
15-Sep-02	15.7	62.1	0.00	25.6	5.6	12.2	2.00	160
16-Sep-02	12.9	72.7	0.00	22.9	4.8	11.9	1.73	206
17-Sep-02	9.9	69.7	0.00	16.6	3.9	11.4	1.44	268
18-Sep-02	9.2	64.7	0.00	17.5	-0.9	10.7	1.64	205
19-Sep-02	11.0	59.2	0.00	23.2	4.8	10.7	4.96	241
20-Sep-02	7.5	62.8	1.78	12.0	4.4	9.7	6.26	313

Table 7.3 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2002

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
21-Sep-02	6.8	68.0	0.00	12.2	3.4	9.2	4.47	304
22-Sep-02	5.2	78.4	0.76	9.0	-1.4	8.7	3.46	305
23-Sep-02	3.2	88.8	1.27	11.7	-5.2	7.0	1.97	245
24-Sep-02	5.6	77.0	0.00	11.6	-0.1	8.0	2.11	293
25-Sep-02	4.5	76.1	0.00	12.8	-3.1	7.3	1.39	188
26-Sep-02	6.8	84.4	3.30	9.1	2.1	8.1	1.45	212
27-Sep-02	3.9	82.4	0.00	10.0	-1.5	7.4	1.91	212
28-Sep-02	10.9	66.6	0.00	22.9	2.3	8.3	2.35	199
29-Sep-02	7.9	77.8	3.81	14.8	4.3	8.7	2.78	288
30-Sep-02	3.5	93.5	8.89	4.6	2.3	7.3	3.68	258
1-Oct-02	3.0	82.2	0.00	10.3	-4.3	6.4	1.94	237
2-Oct-02	4.4	72.4	0.00	16.1	-2.6	5.8	1.93	183
3-Oct-02	7.3	66.2	0.00	13.8	3.5	6.8	3.60	304
4-Oct-02	2.1	80.6	0.25	6.7	-1.0	6.2	1.79	293
5-Oct-02	2.9	78.9	0.25	5.4	0.0	5.8	3.77	262
6-Oct-02	4.1	82.1	0.00	13.2	-2.2	5.4	1.64	230
7-Oct-02	10.0	69.1	0.25	13.2	7.2	7.1	3.47	276
8-Oct-02	5.2	76.9	0.00	15.8	-2.2	6.3	1.58	215
9-Oct-02	5.2	71.2	0.25	13.6	-3.3	5.8	1.73	191
10-Oct-02	2.5	87.9	5.33	11.1	0.1	5.3	2.77	244
11-Oct-02	-1.2	78.3	0.00	3.9	-4.2	4.4	4.44	331
12-Oct-02	-1.6	66.5	0.00	8.1	-8.6	2.8	2.02	230
13-Oct-02	2.5	68.9	0.00	13.8	-2.8	2.7	2.11	211
14-Oct-02	6.1	56.2	0.00	11.2	0.0	3.8	3.64	306
15-Oct-02	3.8	70.6	0.00	11.9	-2.2	4.0	2.57	252
16-Oct-02	6.4	67.1	0.00	14.7	0.7	4.5	1.70	246
17-Oct-02	9.2	57.4	0.00	13.2	3.3	5.4	2.57	260
18-Oct-02	5.5	92.0	1.52	11.2	2.3	6.0	2.39	196
19-Oct-02	2.5	100.0	0.00	5.5	-1.2	5.5	1.77	141
20-Oct-02	3.5	95.8	0.00	8.2	1.7	5.4	1.71	153
21-Oct-02	0.2	95.7	0.76	4.4	-3.0	5.0	1.82	74
22-Oct-02	-5.8	88.5	0.00	-0.2	-10.1	2.6	2.61	159
23-Oct-02	-4.5	85.2	1.27	2.4	-10.2	1.1	2.75	180
24-Oct-02	-2.6	90.6	0.00	5.9	-8.5	0.5	1.47	225
25-Oct-02	-0.8	96.4	0.00	3.5	-5.8	0.6	0.71	194
26-Oct-02	-2.9	92.9	0.00	-1.0	-4.1	0.7	1.66	183
27-Oct-02	-2.3	90.3	0.00	-0.6	-4.6	0.6	2.84	157
28-Oct-02	-4.3	90.4	0.00	-0.7	-7.8	0.6	2.54	86
29-Oct-02	-10.5	83.8	0.00	-5.3	-18.6	0.1	0.70	208
30-Oct-02	-13.5	83.1	0.00	-5.2	-19.4	-0.9	1.24	182
31-Oct-02	-9.5	78.2	0.76	1.1	-15.6	-1.9	1.79	180

Table 7.3 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2002

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
1-Nov-02	-5.1	74.2	0.00	6.6	-12.7	-2.2	1.52	197
2-Nov-02	-2.0	72.7	0.00	7.3	-10.2	-2.0	1.39	229
3-Nov-02	-1.6	81.8	0.00	5.2	-7.8	-1.8	1.43	190
4-Nov-02	-1.4	78.2	0.00	6.6	-8.8	-1.6	1.30	243
5-Nov-02	3.2	59.7	0.00	12.6	-3.1	-1.1	1.28	212
6-Nov-02	2.0	77.2	0.00	8.6	-2.7	-0.4	1.20	257
7-Nov-02	4.3	71.8	0.00	10.5	-0.4	-0.2	1.05	161
8-Nov-02	-0.3	95.3	0.00	5.6	-4.3	-0.1	2.57	76
9-Nov-02	-6.8	96.5	0.00	-4.3	-7.7	0.0	1.77	74
10-Nov-02	-8.3	92.9	0.00	-6.7	-10.3	-0.2	1.38	77
11-Nov-02	-6.8	92.1	0.25	-0.2	-12.1	-0.5	1.57	184
12-Nov-02	-3.7	96.0	0.00	-1.0	-6.1	-0.5	2.29	100
13-Nov-02	-2.6	96.2	0.00	2.0	-6.3	-0.5	1.12	239
14-Nov-02	-2.4	91.9	1.27	4.3	-8.4	-0.6	0.94	179
15-Nov-02	-0.5	82.3	2.54	7.8	-7.2	-0.7	1.00	187
16-Nov-02	-0.8	81.4	0.00	7.1	-6.7	-0.8	1.35	196
17-Nov-02	3.7	57.1	0.00	8.1	-1.0	-0.4	2.45	237
18-Nov-02	1.3	64.2	0.00	5.1	-2.0	-0.3	1.34	176
19-Nov-02	3.3	68.1	0.00	11.0	-1.4	-0.4	1.62	183
20-Nov-02	5.9	71.5	0.00	13.8	1.3	-0.2	1.39	178
21-Nov-02	2.8	84.5	0.00	7.6	-1.0	0.0	1.47	195
22-Nov-02	5.4	62.2	0.00	10.5	1.6	0.0	4.79	296
23-Nov-02	-4.3	80.8	0.00	1.7	-9.0	-0.1	1.17	252
24-Nov-02	-7.7	87.5	0.00	-0.2	-12.1	-2.0	1.81	185
25-Nov-02	1.1	43.5	0.00	6.3	-7.3	-1.9	4.22	277
26-Nov-02	1.7	58.6	0.00	6.5	-1.8	-1.9	1.65	264
27-Nov-02	5.7	77.6	0.00	13.5	0.6	-0.8	1.96	251
28-Nov-02	5.8	63.3	0.00	10.1	1.2	-0.4	2.88	236
29-Nov-02	2.0	54.3	0.00	5.8	-4.2	-0.3	2.84	287
30-Nov-02	2.7	64.0	0.00	13.1	-3.1	-0.6	1.53	204
1-Dec-02	3.2	72.7	0.00	9.9	-3.0	-0.6	1.98	234
2-Dec-02	0.2	77.2	0.00	6.8	-9.0	-0.3	3.83	230
3-Dec-02	-10.9	87.3	0.00	-6.7	-14.6	-1.8	1.75	130
4-Dec-02	-12.4	87.4	0.00	-3.6	-17.2	-4.8	1.28	194
5-Dec-02	-9.1	82.0	0.00	0.7	-14.2	-6.2	1.46	172
6-Dec-02	-1.6	70.6	0.00	2.2	-6.7	-5.0	2.04	262
7-Dec-02	-6.7	80.9	0.00	2.1	-12.5	-5.9	1.25	235
8-Dec-02	-2.2	81.8	0.00	4.3	-6.5	-4.9	1.55	171
9-Dec-02	-1.7	82.6	0.00	4.5	-5.3	-4.3	1.23	181
10-Dec-02	-1.7	79.5	0.00	8.3	-6.8	-4.3	1.20	180
11-Dec-02	1.7	63.0	0.00	6.7	-4.2	-3.3	1.57	235

Table 7.3 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2002

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
12-Dec-02	-1.3	65.8	0.00	6.6	-5.4	-3.8	1.50	183
13-Dec-02	4.3	58.5	0.00	9.2	-1.7	-2.6	2.13	204
14-Dec-02	0.4	74.1	0.00	4.9	-4.3	-2.8	2.34	170
15-Dec-02	4.9	68.7	0.00	7.4	1.6	-1.7	2.15	206
16-Dec-02	-0.5	81.7	0.00	5.2	-5.1	-2.0	2.24	174
17-Dec-02	0.1	82.6	0.00	5.4	-6.0	-2.0	1.48	249
18-Dec-02	-6.3	88.9	0.00	1.1	-13.0	-3.7	1.16	200
19-Dec-02	-9.2	84.9	0.00	-0.9	-14.3	-5.8	1.02	175
20-Dec-02	-11.7	87.5	0.00	-2.9	-17.5	-7.5	0.74	220
21-Dec-02	-11.7	84.7	0.00	-4.8	-18.8	-8.7	1.16	192
22-Dec-02	-15.9	86.8	0.00	-7.7	-21.8	-10.4	0.53	210
23-Dec-02	-12.5	84.6	0.00	-3.2	-17.1	-10.9	1.09	189
24-Dec-02	-11.6	79.4	0.00	-3.6	-19.0	-10.9	1.41	201
25-Dec-02	-11.4	73.5	0.00	1.6	-18.0	-11.4	1.72	183
26-Dec-02	0.6	53.0	0.00	4.6	-3.9	-8.1	2.92	212
27-Dec-02	-7.5	65.1	0.00	0.5	-14.2	-8.3	1.35	183
28-Dec-02	-7.5	83.8	0.00	-4.3	-12.3	-8.0	1.03	252
29-Dec-02	-8.3	94.8	0.00	-7.0	-10.2	-7.4	2.06	239
30-Dec-02	-13.4	91.2	0.00	-8.1	-18.4	-7.1	1.59	205
31-Dec-02	-14.8	90.0	0.00	-7.2	-18.2	-7.4	0.93	181

Table 7.4 Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
1-Jan-03	-11.2	81.9	0.00	-2.0	-17.4	-7.6	1.88	179
2-Jan-03	-5.9	81.1	2.54	5.3	-12.2	-7.3	1.43	198
3-Jan-03	0.8	68.1	2.29	6.8	-6.8	-6.4	2.35	244
4-Jan-03	-4.0	68.3	0.00	5.5	-11.2	-5.6	1.69	198
5-Jan-03	-2.6	83.0	0.00	3.9	-6.4	-5.6	0.88	185
6-Jan-03	0.0	77.5	0.00	5.1	-3.7	-5.0	2.09	185
7-Jan-03	2.4	60.5	0.00	12.9	-3.0	-4.6	2.07	189
8-Jan-03	2.8	47.4	0.25	12.5	-2.4	-3.9	4.66	305
9-Jan-03	-9.1	57.3	0.00	-2.0	-17.7	-4.8	3.43	268
10-Jan-03	-16.6	76.4	0.00	-9.6	-24.4	-7.3	0.52	212
11-Jan-03	-15.2	80.0	0.00	-6.8	-19.8	-9.0	2.19	238
12-Jan-03	-18.6	80.3	0.00	-14.6	-21.7	-9.6	3.08	190
13-Jan-03	-17.1	85.9	0.00	-11.5	-20.7	-10.0	0.96	147
14-Jan-03	-19.7	85.0	0.00	-14.9	-25.3	-10.5	2.29	203
15-Jan-03	-13.7	88.7	0.00	-5.6	-17.1	-10.1	0.98	203
16-Jan-03	-13.6	90.0	0.00	-9.2	-18.9	-9.6	1.21	178
17-Jan-03	-6.5	80.9	1.78	3.5	-14.3	-9.2	1.98	239
18-Jan-03	-0.9	93.2	4.32	1.8	-7.6	-7.7	2.35	248
19-Jan-03	-5.4	97.5	0.00	2.0	-9.7	-6.4	1.24	143
20-Jan-03	-14.8	90.4	0.00	-9.7	-17.6	-6.4	2.01	90
21-Jan-03	-20.7	84.7	0.00	-17.4	-25.2	-6.8	2.32	312
22-Jan-03	-31.4	74.2	0.00	-22.5	-38.1	-7.7	0.47	188
23-Jan-03	-22.4	81.2	0.00	-18.9	-23.6	-8.6	3.69	127
24-Jan-03	-21.4	77.5	0.00	-20.1	-24.3	-8.6	1.98	234
25-Jan-03	-22.8	78.2	0.00	-21.2	-23.9	-8.5	3.04	144
26-Jan-03	-15.3	80.2	0.00	-3.3	-21.6	-8.6	5.15	169
27-Jan-03	-3.5	90.7	2.03	3.2	-10.6	-8.0	2.67	169
28-Jan-03	-15.5	84.7	0.00	-10.7	-17.4	-7.4	2.02	72
29-Jan-03	-14.8	83.4	0.00	-4.9	-19.3	-7.6	2.15	183
30-Jan-03	-1.0	87.0	2.54	3.9	-7.7	-7.5	2.09	265
31-Jan-03	-2.3	76.6	0.00	6.2	-7.5	-6.5	1.30	177
1-Feb-03	-4.5	84.1	0.00	1.3	-9.0	-6.3	1.38	211
2-Feb-03	-8.8	91.2	0.00	-0.4	-15.8	-6.2	0.73	189
3-Feb-03	-6.6	89.1	0.00	-0.3	-10.2	-6.4	1.06	200
4-Feb-03	-2.0	74.8	0.00	1.3	-4.6	-5.9	3.93	312
5-Feb-03	-2.1	81.8	0.00	1.2	-4.3	-5.3	4.15	311
6-Feb-03	-10.5	86.3	0.00	-0.2	-16.2	-5.3	1.10	192
7-Feb-03	1.4	59.7	0.00	4.3	-7.1	-5.6	5.21	305
8-Feb-03	-5.1	88.6	0.00	-0.4	-9.8	-4.9	2.45	211
9-Feb-03	-2.9	91.0	0.25	-1.3	-4.9	-4.7	3.20	291

Table 7.4 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
10-Feb-03	-2.6	89.9	0.00	0.8	-5.6	-4.5	3.22	281
11-Feb-03	-3.6	82.4	0.25	0.8	-7.7	-4.2	3.08	208
12-Feb-03	-3.0	86.8	2.29	2.3	-8.0	-4.1	0.97	169
13-Feb-03	-10.0	89.7	0.00	1.7	-18.6	-4.1	0.79	222
14-Feb-03	-10.5	93.8	0.00	-8.8	-12.5	-4.4	2.49	181
15-Feb-03	-12.3	89.5	0.00	-7.9	-15.9	-4.5	3.02	147
16-Feb-03	-11.0	92.8	0.00	-9.7	-12.4	-4.6	2.47	273
17-Feb-03	-11.4	90.9	0.00	-8.9	-14.2	-4.6	1.83	261
18-Feb-03	-9.0	77.5	2.29	1.4	-14.1	-4.6	2.01	181
19-Feb-03	-7.3	70.3	0.25	1.8	-12.5	-4.6	2.38	159
20-Feb-03	-17.3	82.2	0.00	-10.9	-20.2	-4.6	3.13	109
21-Feb-03	-21.0	81.4	0.00	-18.7	-23.2	-4.9	2.94	130
22-Feb-03	-20.1	81.0	0.00	-18.4	-21.3	-5.3	2.43	291
23-Feb-03	-25.7	75.0	0.00	-16.2	-33.5	-5.6	0.85	223
24-Feb-03	-22.0	72.8	0.51	-6.3	-30.4	-6.1	1.57	183
25-Feb-03	-9.4	69.3	2.29	3.5	-18.0	-6.5	1.33	187
26-Feb-03	-3.3	87.1	0.76	0.7	-5.7	-6.4	1.28	149
27-Feb-03	-10.0	90.9	0.00	-5.5	-19.0	-5.9	1.08	144
28-Feb-03	-9.7	87.8	0.25	-0.3	-15.7	-5.6	2.52	200
1-Mar-03	-13.8	82.6	0.00	-7.1	-17.7	-5.5	3.65	108
2-Mar-03	-7.2	83.3	1.52	3.1	-14.1	-5.6	3.91	228
3-Mar-03	-12.5	82.7	0.25	0.5	-17.2	-5.4	4.31	159
4-Mar-03	-18.8	82.1	0.00	-15.3	-24.7	-5.4	1.46	208
5-Mar-03	-14.8	81.3	0.00	-8.6	-17.4	-5.8	5.33	255
6-Mar-03	-20.7	69.1	0.00	-16.5	-26.0	-6.0	3.29	236
7-Mar-03	-27.6	67.7	0.00	-21.4	-34.4	-6.5	1.13	211
8-Mar-03	-29.2	64.1	0.00	-23.7	-34.8	-7.4	1.21	264
9-Mar-03	-28.2	65.1	0.00	-19.6	-34.8	-8.2	1.93	176
10-Mar-03	-19.9	75.3	0.00	-15.9	-22.3	-8.8	3.91	204
11-Mar-03	-16.6	84.5	0.00	-14.9	-18.0	-8.7	2.82	257
12-Mar-03	-15.9	86.3	0.00	-12.7	-17.6	-8.4	3.68	153
13-Mar-03	-12.2	85.2	2.03	-4.7	-16.0	-8.1	2.43	194
14-Mar-03	0.3	71.0	0.25	12.2	-11.8	-7.7	2.25	212
15-Mar-03	4.2	67.3	0.00	9.9	-2.0	-6.7	1.75	206
16-Mar-03	0.5	89.2	0.51	5.2	-3.3	-4.2	2.42	231
17-Mar-03	1.4	83.9	4.83	11.6	-3.3	-3.3	1.89	239
18-Mar-03	-1.5	72.9	0.00	5.7	-9.5	-2.9	1.59	173
19-Mar-03	-1.1	77.2	0.00	8.7	-9.2	-3.1	1.69	196
20-Mar-03	0.4	69.4	0.00	4.8	-3.3	-3.3	2.49	165
21-Mar-03	3.4	66.3	0.00	15.1	-2.6	-2.1	1.22	201
22-Mar-03	1.8	64.3	0.00	7.9	-5.1	-1.7	2.15	188

Table 7.4 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
23-Mar-03	4.0	55.6	0.00	7.8	0.0	-1.0	3.69	287
24-Mar-03	-0.9	54.2	0.00	5.9	-8.2	-0.7	3.25	294
25-Mar-03	-2.8	78.3	0.00	7.0	-8.9	-0.5	1.19	197
26-Mar-03	-2.1	68.0	0.00	4.8	-8.1	-0.5	1.04	203
27-Mar-03	-2.3	73.2	0.00	2.5	-7.7	-0.4	1.82	214
28-Mar-03	-3.1	78.4	0.00	5.0	-9.9	-0.3	1.40	175
29-Mar-03	-0.4	76.3	0.00	6.2	-7.2	-0.3	1.37	178
30-Mar-03	4.9	74.8	0.00	11.4	1.9	-0.3	1.28	174
31-Mar-03	4.2	82.0	3.30	12.4	0.6	-0.2	2.41	288
1-Apr-03	0.3	95.6	4.83	9.8	-3.1	-0.2	2.39	153
2-Apr-03	-5.9	91.0	0.00	-1.0	-8.1	-0.1	5.26	118
3-Apr-03	-8.9	87.5	0.00	-7.8	-10.0	-0.1	4.54	115
4-Apr-03	-11.2	86.6	0.00	-6.0	-16.3	-0.1	1.93	132
5-Apr-03	-6.6	90.6	0.00	-3.9	-8.3	-0.2	3.08	120
6-Apr-03	-2.9	87.9	0.25	1.6	-4.6	-0.3	1.83	126
7-Apr-03	-0.7	77.6	0.00	8.6	-8.1	-0.2	2.68	162
8-Apr-03	7.1	59.0	0.00	13.6	2.3	-0.1	3.29	197
9-Apr-03	6.8	61.0	0.00	11.3	2.9	-0.1	4.08	220
10-Apr-03	3.8	64.6	0.00	11.7	-2.7	-0.1	1.57	209
11-Apr-03	6.8	68.0	0.00	15.1	0.7	-0.1	1.20	206
12-Apr-03	7.5	75.7	1.52	14.9	0.5	1.3	2.46	277
13-Apr-03	3.5	95.7	1.78	9.8	0.4	2.5	2.07	77
14-Apr-03	1.4	96.0	3.56	2.7	0.6	1.1	2.29	122
15-Apr-03	1.9	95.7	5.84	6.8	0.2	1.2	1.66	205
16-Apr-03	6.3	77.1	0.00	15.1	2.5	3.7	2.31	159
17-Apr-03	7.2	53.1	0.00	14.1	-2.0	4.4	1.73	227
18-Apr-03	4.1	76.5	0.25	12.7	-0.7	4.1	2.69	237
19-Apr-03	5.3	70.0	0.00	14.7	-2.4	3.9	1.40	177
20-Apr-03	9.1	51.5	0.00	18.5	-0.5	5.1	1.86	229
21-Apr-03	11.0	52.5	0.00	22.2	-1.2	5.9	2.05	201
22-Apr-03	12.3	49.3	0.00	20.5	2.0	6.3	2.50	166
23-Apr-03	12.4	58.6	0.00	23.4	3.1	6.7	2.26	236
24-Apr-03	13.9	65.1	0.76	22.1	5.4	7.5	2.35	136
25-Apr-03	11.5	85.7	2.03	15.0	8.2	8.3	4.13	34
26-Apr-03	2.6	94.0	1.18	8.4	-0.5	6.1	7.91	220
27-Apr-03	0.4	96.5	4.32	1.8	-0.9	3.5	6.64	331
28-Apr-03	1.0	87.2	2.03	6.9	-1.2	3.5	2.46	247
29-Apr-03	3.0	72.5	0.00	10.4	-4.3	4.3	1.95	175
30-Apr-03	4.8	79.3	0.00	14.0	-2.3	4.9	1.28	205
1-May-03	9.0	61.3	0.00	18.3	-0.2	6.1	1.51	180
2-May-03	7.6	62.2	0.00	17.5	0.4	6.4	3.46	238

Table 7.4 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
3-May-03	-0.8	82.3	0.00	4.3	-3.9	5.0	4.44	298
4-May-03	-1.4	88.8	1.27	0.7	-3.1	3.5	2.41	76
5-May-03	-1.1	95.0	2.54	0.7	-2.4	3.0	3.41	244
6-May-03	-1.0	97.9	2.03	-0.2	-1.6	2.2	5.67	335
7-May-03	0.2	98.8	5.84	1.8	-0.8	1.9	5.45	337
8-May-03	1.8	94.8	1.27	3.3	1.0	1.6	5.02	332
9-May-03	2.5	92.1	0.25	7.7	0.9	1.3	3.02	327
10-May-03	4.5	76.0	0.00	12.4	-3.0	1.5	2.17	190
11-May-03	8.5	64.1	0.00	17.4	0.7	3.7	2.75	170
12-May-03	11.5	52.7	0.00	19.9	1.5	5.9	1.92	193
13-May-03	11.9	54.2	0.00	19.7	2.0	7.2	1.92	232
14-May-03	13.1	48.2	0.00	22.3	3.2	7.5	3.21	187
15-May-03	10.3	50.5	0.00	21.7	3.7	7.7	3.25	294
16-May-03	4.5	74.5	9.65	9.9	0.9	6.5	4.79	298
17-May-03	4.4	61.3	0.00	9.1	-1.0	6.1	3.73	286
18-May-03	4.1	51.2	0.00	10.6	-0.5	5.7	6.08	322
19-May-03	6.2	46.1	0.00	15.1	-4.1	5.5	2.70	233
20-May-03	9.3	38.1	0.00	16.7	-0.4	6.6	1.82	225
21-May-03	11.2	47.2	0.00	17.7	4.3	7.9	1.49	309
22-May-03	11.9	51.4	0.00	20.1	3.3	8.2	2.16	195
23-May-03	16.1	47.6	0.00	23.5	8.5	9.4	1.53	184
24-May-03	18.2	48.0	0.00	28.8	8.1	10.4	2.90	173
25-May-03	21.9	45.0	0.00	28.6	15.1	12.1	3.37	193
26-May-03	15.0	78.0	7.62	25.7	10.8	12.5	3.75	286
27-May-03	14.4	67.4	0.00	22.0	7.0	12.0	1.70	260
28-May-03	15.4	60.6	0.00	23.6	6.5	12.0	1.93	221
29-May-03	16.7	47.8	0.00	21.9	11.4	12.2	4.04	290
30-May-03	14.4	54.3	0.00	23.3	3.3	11.7	2.57	245
31-May-03	17.1	48.3	0.00	23.2	10.1	12.2	4.63	151
1-Jun-03	14.9	73.5	0.00	20.4	11.7	12.3	2.46	295
2-Jun-03	13.2	67.7	0.51	20.0	10.5	12.0	4.15	311
3-Jun-03	9.9	53.9	0.25	14.4	6.6	10.6	5.70	306
4-Jun-03	14.4	47.3	0.00	20.2	9.1	10.6	6.43	330
5-Jun-03	15.6	42.2	0.00	19.7	9.9	12.0	4.56	280
6-Jun-03	9.4	70.8	0.00	17.2	6.6	11.7	4.57	246
7-Jun-03	11.0	68.7	0.00	23.8	1.2	10.7	1.85	151
8-Jun-03	14.9	67.2	0.51	23.5	10.0	11.9	2.84	234
9-Jun-03	12.1	73.7	0.00	16.3	8.0	12.0	2.19	118
10-Jun-03	10.5	84.0	9.56	15.4	8.8	11.6	2.40	106
11-Jun-03	11.3	87.5	1.78	17.4	9.1	11.4	1.42	221
12-Jun-03	13.3	72.4	0.00	23.3	4.8	12.1	1.61	213

Table 7.4 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
13-Jun-03	18.0	59.7	0.00	25.0	9.2	13.6	2.11	169
14-Jun-03	16.2	68.8	0.00	24.0	9.8	14.1	2.02	253
15-Jun-03	15.3	65.2	0.00	21.9	8.7	14.0	1.94	182
16-Jun-03	16.3	55.8	0.00	23.9	6.4	13.9	1.31	227
17-Jun-03	17.6	55.5	0.00	25.9	8.3	14.1	2.47	219
18-Jun-03	21.3	49.2	0.00	30.9	14.9	14.9	4.29	161
19-Jun-03	17.2	65.3	0.00	25.2	12.2	15.3	3.25	200
20-Jun-03	12.1	86.4	1.68	18.1	9.8	13.8	2.04	104
21-Jun-03	9.7	86.5	0.25	11.5	8.3	12.5	4.76	313
22-Jun-03	7.7	84.6	1.52	11.3	5.4	11.3	5.05	309
23-Jun-03	8.5	83.2	2.79	12.7	5.4	11.0	4.40	319
24-Jun-03	10.7	74.7	0.00	18.9	2.3	11.4	1.40	201
25-Jun-03	13.9	65.3	0.00	22.7	5.0	12.9	1.93	202
26-Jun-03	17.0	58.2	0.25	22.5	9.3	14.0	1.77	280
27-Jun-03	15.9	61.4	0.76	21.5	10.2	14.3	2.99	267
28-Jun-03	15.5	58.9	0.00	23.8	5.8	14.3	1.50	234
29-Jun-03	19.5	57.1	0.00	29.8	9.3	14.8	2.36	178
30-Jun-03	22.2	49.8	0.00	31.3	13.1	15.9	3.73	161
1-Jul-03	16.6	59.5	0.00	25.9	6.5	15.5	2.57	197
2-Jul-03	15.0	64.3	0.00	25.0	8.2	15.3	2.25	288
3-Jul-03	13.8	63.9	0.76	22.3	5.6	14.7	1.64	239
4-Jul-03	16.2	61.5	0.00	23.0	9.0	14.9	1.51	202
5-Jul-03	14.2	72.7	3.05	21.4	8.8	14.9	2.81	246
6-Jul-03	11.9	76.4	0.00	16.5	8.5	14.0	4.05	301
7-Jul-03	12.4	81.5	0.00	20.4	6.0	13.4	2.64	151
8-Jul-03	15.8	72.2	0.00	21.8	10.7	14.1	2.95	148
9-Jul-03	15.3	69.7	0.00	22.8	6.2	14.7	2.21	273
10-Jul-03	16.2	63.5	0.00	24.1	9.0	15.0	2.59	294
11-Jul-03	18.8	63.1	0.00	29.4	9.9	15.7	2.22	164
12-Jul-03	21.5	59.8	0.00	30.0	13.0	16.6	1.85	183
13-Jul-03	19.0	65.0	0.00	29.6	11.9	17.1	2.40	226
14-Jul-03	16.6	66.2	0.00	25.7	8.2	16.2	1.79	235
15-Jul-03	18.5	48.4	0.00	26.7	7.5	16.7	1.64	155
16-Jul-03	20.1	53.6	0.00	30.2	11.3	17.0	3.12	121
17-Jul-03	17.6	66.5	2.54	29.8	9.6	17.4	3.03	221
18-Jul-03	18.1	58.3	0.00	27.0	8.3	17.3	1.85	228
19-Jul-03	19.4	56.5	0.00	26.5	12.1	17.9	1.28	191
20-Jul-03	20.7	58.4	0.00	27.0	14.7	18.0	2.67	140
21-Jul-03	19.8	67.7	0.00	29.0	9.0	17.8	1.87	146
22-Jul-03	22.7	50.7	0.00	33.6	12.2	18.5	1.81	175
23-Jul-03	22.4	59.4	0.00	32.4	13.1	19.4	2.08	177

Table 7.4 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
24-Jul-03	18.9	66.6	0.00	30.1	12.2	19.5	3.34	117
25-Jul-03	14.4	74.7	2.54	20.7	10.9	18.3	2.62	255
26-Jul-03	16.3	70.2	0.00	27.3	6.3	17.3	2.05	212
27-Jul-03	19.4	63.0	0.00	32.1	7.6	17.4	1.74	190
28-Jul-03	21.3	49.9	0.00	30.6	11.0	18.4	2.28	269
29-Jul-03	18.6	58.4	0.00	28.0	8.3	18.4	1.32	214
30-Jul-03	21.1	49.4	0.00	30.0	11.1	18.5	2.06	131
31-Jul-03	22.8	49.6	0.00	30.4	12.3	19.1	2.02	173
1-Aug-03	22.1	51.9	0.00	32.6	13.2	18.8	3.75	165
2-Aug-03	21.6	48.4	0.00	31.9	14.8	19.0	3.24	229
3-Aug-03	18.5	61.5	0.00	26.7	9.1	18.5	1.87	189
4-Aug-03	18.5	66.3	0.00	26.5	12.6	18.9	2.59	249
5-Aug-03	19.5	57.5	0.00	27.6	12.5	18.7	3.70	104
6-Aug-03	19.9	60.1	0.00	27.2	11.6	18.8	2.03	214
7-Aug-03	19.3	71.2	0.00	26.5	11.2	19.3	2.09	229
8-Aug-03	17.7	72.7	0.00	24.9	10.3	18.8	1.85	217
9-Aug-03	19.6	69.9	11.94	29.1	10.1	18.6	2.54	152
10-Aug-03	17.8	76.9	0.00	25.4	10.6	18.6	2.50	226
11-Aug-03	16.5	83.7	0.00	21.2	12.4	18.3	2.60	163
12-Aug-03	18.1	79.5	3.05	26.3	13.6	18.9	2.51	150
13-Aug-03	17.5	71.5	0.00	28.2	6.9	19.0	2.19	238
14-Aug-03	19.1	45.4	0.00	29.4	7.4	18.0	1.91	217
15-Aug-03	19.1	56.9	0.00	32.9	7.6	17.7	2.38	191
16-Aug-03	20.2	57.7	2.29	30.5	14.5	17.7	1.34	231
17-Aug-03	18.3	70.5	0.00	27.8	9.5	18.1	1.84	213
18-Aug-03	20.3	59.8	0.00	32.2	9.4	18.5	1.53	192
19-Aug-03	17.5	56.7	0.00	31.8	8.1	18.1	2.40	195
20-Aug-03	16.4	65.8	1.52	22.4	11.1	18.7	2.25	159
21-Aug-03	17.5	60.8	0.00	29.5	8.3	17.7	2.64	144
22-Aug-03	17.1	70.7	0.00	26.3	10.2	17.4	2.04	255
23-Aug-03	15.4	72.0	1.27	24.2	10.5	17.2	3.07	308
24-Aug-03	12.6	61.6	0.00	22.8	2.7	15.8	2.23	219
25-Aug-03	13.6	54.1	0.00	20.2	7.8	15.4	1.51	199
26-Aug-03	15.0	52.9	0.00	24.6	8.3	15.0	2.94	184
27-Aug-03	14.4	59.8	0.51	23.3	10.5	14.7	3.26	226
28-Aug-03	12.4	84.7	2.95	18.5	9.5	15.7	3.49	325
29-Aug-03	13.2	73.3	0.00	23.8	4.1	17.0	1.35	199
30-Aug-03	15.9	61.9	0.00	25.9	6.0	16.5	1.67	228
31-Aug-03	16.6	54.2	0.00	25.7	7.4	16.2	1.54	186
1-Sep-03	15.4	62.2	0.00	22.5	10.5	17.4	3.48	308
2-Sep-03	12.3	59.9	0.00	23.8	2.1	15.2	1.52	196

Table 7.4 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
3-Sep-03	17.3	48.6	0.00	29.8	9.1	15.2	1.65	176
4-Sep-03	17.3	56.9	0.00	26.9	8.0	15.0	2.34	185
5-Sep-03	17.4	66.2	0.00	27.6	7.8	15.2	1.82	231
6-Sep-03	17.2	70.1	0.00	29.5	6.6	15.5	1.07	190
7-Sep-03	18.4	54.6	0.00	31.9	6.2	15.6	2.16	209
8-Sep-03	14.1	73.5	1.02	23.5	11.2	15.6	3.76	318
9-Sep-03	10.7	76.6	3.05	12.7	8.8	14.0	3.51	301
10-Sep-03	13.5	57.5	0.00	21.4	7.9	13.8	2.62	277
11-Sep-03	10.0	74.8	2.03	18.0	6.0	14.0	1.63	200
12-Sep-03	8.1	81.4	4.83	11.9	4.6	12.6	4.83	293
13-Sep-03	10.5	71.3	0.00	17.6	4.6	12.5	3.13	286
14-Sep-03	10.1	75.4	1.02	17.8	6.5	13.3	2.62	221
15-Sep-03	5.8	79.9	0.00	10.0	4.1	11.4	3.25	287
16-Sep-03	1.1	88.0	2.79	5.2	-1.1	9.7	2.72	45
17-Sep-03	-1.1	92.8	1.27	0.4	-2.9	7.8	1.75	265
18-Sep-03	2.9	81.7	0.25	13.8	-2.4	7.2	2.82	151
19-Sep-03	9.1	72.5	0.00	18.4	1.7	8.8	1.00	169
20-Sep-03	9.6	71.6	1.52	15.3	2.6	10.3	1.83	286
21-Sep-03	8.5	69.6	1.52	14.4	3.2	10.5	2.09	272
22-Sep-03	9.5	70.7	0.00	18.2	4.1	10.3	2.12	194
23-Sep-03	7.3	69.0	9.65	14.2	2.9	10.9	5.01	302
24-Sep-03	4.1	64.1	0.00	12.1	-3.9	8.9	3.14	205
25-Sep-03	10.1	63.9	0.00	15.7	3.0	9.5	2.04	235
26-Sep-03	13.5	45.5	0.00	17.0	10.2	10.8	4.94	322
27-Sep-03	10.4	62.6	0.00	15.1	6.2	10.5	2.01	279
28-Sep-03	8.4	67.2	0.00	12.3	4.3	10.5	1.20	220
29-Sep-03	5.7	73.1	0.00	13.1	-1.9	9.3	1.19	248
30-Sep-03	6.4	70.7	0.00	18.2	-2.2	8.4	1.28	197
1-Oct-03	9.2	61.8	0.00	22.3	-1.0	8.4	1.20	216
2-Oct-03	11.9	58.9	0.00	20.1	2.2	9.3	1.26	218
3-Oct-03	10.3	72.6	0.00	23.9	0.4	9.2	1.23	202
4-Oct-03	12.9	60.1	0.00	26.3	1.1	9.5	1.14	221
5-Oct-03	12.3	62.7	0.00	26.7	1.4	9.6	1.04	215
6-Oct-03	13.1	59.2	0.00	26.3	2.8	9.6	1.28	195
7-Oct-03	11.4	68.0	0.00	19.7	3.3	9.6	1.91	230
8-Oct-03	8.6	76.0	0.00	17.6	-0.7	9.1	2.92	206
9-Oct-03	10.6	40.7	0.00	15.2	1.2	8.9	3.15	250
10-Oct-03	6.0	50.6	0.00	13.2	-1.9	8.0	1.96	237
11-Oct-03	4.7	56.0	0.00	12.7	-4.4	6.9	1.76	208
12-Oct-03	5.1	59.2	0.00	13.0	-3.3	6.2	2.04	247
13-Oct-03	6.7	70.1	0.25	10.7	4.1	7.4	2.05	262

Table 7.4 (continued) Daily meteorological data from Paddock 24, Lacombe Research Station, 2003

Date	Ave. Air Temp (°C)	Ave. Air Relative Humidity (%)	Total Rain (mm)	Max. Air Temp (°C)	Min. Air Temp (°C)	Ave. Soil Temp (°C)	Ave. Wind Speed (m/s)	Ave. Wind Direction (deg)
14-Oct-03	4.1	83.1	0.25	9.2	1.0	7.2	1.41	206
15-Oct-03	1.2	82.6	0.00	5.6	-2.4	6.3	1.42	241
16-Oct-03	2.1	76.9	0.00	11.7	-3.3	5.3	3.27	150
17-Oct-03	8.3	63.4	0.00	14.6	0.5	6.1	1.78	203
18-Oct-03	10.7	61.4	0.00	22.8	1.4	7.1	1.53	167
19-Oct-03	9.9	46.1	0.00	20.2	2.0	7.0	2.13	239
20-Oct-03	5.4	83.3	0.00	10.7	-1.6	6.5	2.19	212
21-Oct-03	11.9	62.5	0.00	24.4	4.6	6.9	2.33	167
22-Oct-03	7.5	61.5	0.00	13.9	0.9	7.0	2.82	202
23-Oct-03	7.6	62.9	2.29	10.5	3.6	6.9	4.41	251
24-Oct-03	5.4	43.5	0.00	7.5	1.9	5.9	7.08	292
25-Oct-03	0.2	86.5	0.00	9.4	-4.9	4.1	1.70	174
26-Oct-03	10.9	71.0	0.00	19.7	5.5	6.0	1.54	195
27-Oct-03	11.5	44.3	0.00	18.0	5.4	7.2	5.66	307
28-Oct-03	2.7	84.3	4.83	6.6	0.4	6.0	1.95	169
29-Oct-03	-3.9	93.0	0.00	0.5	-5.6	5.3	5.86	151
30-Oct-03	-8.8	79.0	0.00	-4.7	-11.8	4.5	5.44	303
31-Oct-03	-13.7	77.3	0.00	-7.3	-20.2	1.2	2.47	237

Table 7.5 Meteorological data summarized by month, Paddock 24, Lacombe Research Station

		MIG research site (Paddock 24), Lacombe Research Station							Long-term Normal[2] Lacombe CDA			
Year	Month	Average Air Temp (°C)	Average Air R.H. (%)	Total Rain (mm)	Average Maximum Air Temp (°C)	Average Minimum Air Temp (°C)	Average Soil Temp[1] (°C)	Average Wind Speed (m/s)	Average Air Temp (°C)	Precipitation (mm)	Average Maximum Air Temp (°C)	Average Minimum Air Temp (°C)
2002	6*	16.0	53.1	8	23.3	7.7	13.1	1.32	13.9	76	20.4	7.2
2002	7	18.3	59.1	29	25.6	10.3	17.6	2.72	15.4	89	22.0	8.8
2002	8	14.1	72.8	34	20.9	7.1	14.3	2.28	14.7	71	21.6	7.8
2002	9	9.3	74.4	35	16.2	3.0	10.6	2.39	9.8	47	16.6	3.0
2002	10	0.9	80.5	11	7.3	-4.0	3.7	2.23	4.5	17	11.4	-2.5
2002	11	0.3	78.2	4	6.7	-4.5	1.4	2.03	-4.9	14	0.5	-10.3
2002	12	-5.6	78.9	0	1.0	-10.9	-5.5	1.60	-11.0	15	-5.5	-16.4
2003	1	-11.0	79.7	16	-4.3	-16.0	-7.5	2.14	-12.3	18	-6.7	-17.9
2003	2	-9.3	83.5	9	-3.3	-13.9	-5.2	2.24	-10.2	11	-4.3	-16.0
2003	3	-7.3	74.6	13	-0.4	-12.7	-4.2	2.39	-3.8	13	2.1	-9.6
2003	4	3.6	76.1	28	10.2	-1.6	2.8	2.79	4.3	21	10.9	-2.3
2003	5	8.9	64.1	30	15.7	2.6	7.0	3.19	10.1	56	17.1	3.1
2003	6	14.2	65.1	20	21.1	8.3	12.8	2.98	13.9	76	20.4	7.2
2003	7	17.9	62.6	9	26.7	9.6	16.7	2.27	15.4	89	22.0	8.8
2003	8	17.5	63.5	24	26.6	9.7	17.7	2.35	14.7	71	21.6	7.8
2003	9	10.1	69.1	29	17.6	4.3	12.0	2.48	9.8	47	16.6	3.0
2003	10	6.3	66.4	8	14.2	-0.6	7.0	2.51	4.5	17	11.4	-2.5

* Missing data for 1 day within this month.

[1] Soil temperature was measured 12 cm below the ground surface.

[2] Long-term Normal data is for 1971-2000

Table 7.6a Average cumulative field capacities (FC), summarized by paddock

	Total Field Capacity (mm)										
Depth	**1**	**3**	**4**	**7**	**9**	**12**	**13**	**14**	**15**	**21**	**24**
20	57	58	60	73	86	53	50	74	53	69	68
40	119	102	115	143	146	106	107	132	110	135	126
60	196	158	188	208	192	157	192	189	158	204	178
80	242	227	278	276	242	231	276	250	196	267	214
100	310	285	374	341	305	295	364	318	241	335	243
120	384	363	479	430	358	371	439	379	273	413	268
140	478	458	584	533	414	463	511	442	308	489	290
160	583	557	687	642	476	561	606	516	354	567	320
180	687	654	787	739	541		692		409	642	396

Table 7.6b Average cumulative wilting points (WP), summarized by paddock

	Total Wilting Point (mm)										
Depth	**1**	**3**	**4**	**7**	**9**	**12**	**13**	**14**	**15**	**21**	**24**
20	15	27	19	32	46	15	16	24	13	19	19
40	30	46	34	52	64	31	41	47	28	36	33
60	49	67	51	73	83	43	67	64	37	52	45
80	58	93	97	92	103	81	112	88	46	65	53
100	77	122	150	108	122	111	163	124	61	80	60
120	115	168	210	158	137	154	205	158	71	102	66
140	166	223	271	218	152	206	243	191	79	125	72
160	224	279	330	280	167	262	292	223	93	148	80
180	283	331	387	335	202		332		104	169	110

Table 7.7 Cumulative soil water to 40 cm (TSW40) summarized by paddock (mm)

		2002										
Paddock	**Forage Type**	**10-Jun**	**24-Jun**	**10-Jul**	**22-Jul**	**07-Aug**	**19-Aug**	**03-Sep**	**28-Sep**	**21-Oct**	**FC_{40}**	**WP_{40}**
4	Annual	129	93	53	43	97	69	50	43	53		
15	Annual	121	75	38	33	105	87	60	43	45		
9	Annual	tubes not installed			55	109	88	78	56	66		
Average Annual		125	84	46	43	104	81	63	48	55	124	42
3	M. Bromegrass	105	71	63	59	114	89	69	58	66		
13	M. Bromegrass	73	45	35	38	103	75	51	42	48		
12	M. Bromegrass	tubes not installed			27	86	54	33	27	37		
Average M. Bromegrass		89	58	49	42	101	73	51	42	50	105	39
1	Alfalfa	49	25	18	20	75	43	24	21	31		
14	Alfalfa	52	25	19	17	78	48	24	18	22		
7	Alfalfa	tubes not installed			42	101	65	46	36	56		
Average Alfalfa		51	25	19	26	85	52	31	25	37	132	43
21	Old Grass	25	10	6	10	69	37	18	9	20		
24	Old Grass	26	13	8	12	68	41	25	15	28		
Average Old Grass		26	11	7	11	68	39	21	12	24	130	34

		2003													
Paddock	**Forage Type**	**02-May**	**13-May**	**28-May**	**12-Jun**	**26-Jun**	**09-Jul**	**23-Jul**	**06-Aug**	**20-Aug**	**02-Sep**	**27-Sep**	**15-Oct**	**FC_{40}**	**WP_{40}**
4	Annual	126	141	125	130	85	58	53	37	49	46	53	56		
15	Annual	77	125	129	126	102	61	35	34	39	45	53	46		
9	Annual	75	120	113	120	112	76	52	48	57	61	69	68		
Average Annual		92	129	122	126	100	65	46	40	48	51	58	57	124	42
3	M. Bromegrass	89	136	106	86	65	55	46	45	53	51	55	52		
13	M. Bromegrass	117	119	82	81	49	39	33	32	38	53	54	41		
12	M. Bromegrass	108	114	75	M	35	25	21	21	25	25	29	24		
Average M. Bromegrass		105	123	88	83	50	40	33	33	39	43	46	39	105	39
1	Alfalfa	55	105	73	57	41	25	12	12	17	17	20	16		
14	Alfalfa	64	103	84	52	29	20	13	12	15	18	23	18		
7	Alfalfa	127	148	130	110	96	72	33	35	44	43	48	43		
Average Alfalfa		82	119	96	73	55	39	19	20	26	26	31	26	132	43
21	Old Grass	113	88	46	51	20	8	3	3	8	18	17	6		
24	Old Grass	99	98	57	66	27	15	7	7	17	27	33	19		
Average Old Grass		106	93	52	59	24	11	5	5	13	22	25	13	130	34

M= missing data

Table 7.8 Cumulative soil water to 160 cm (TSW160) summarized by paddock (mm)

		2002										
Paddock	**Forage Type**	**10-Jun**	**24-Jun**	**10-Jul**	**22-Jul**	**07-Aug**	**19-Aug**	**03-Sep**	**28-Sep**	**21-Oct**	**FC_{160}**	**WP_{160}**
4	Annual	472	419	354	339	383	343	329	317	344		
15	Annual	256	205	144	134	214	192	166	147	139		
9	Annual	tubes not installed			278	343	315	307	280	295		
Average Annual		364	312	249	250	313	283	267	248	260	506	197
3	M. Bromegrass	398	346	322	321	378	348	329	308	339		
13	M. Bromegrass	274	223	210	208	292	257	227	211	207		
12	M. Bromegrass	tubes not installed			148	213	192	147	136	153		
Average M. Bromegrass		336	284	266	226	294	266	234	219	233	575	278
1	Alfalfa	199	139	111	123	183	151	129	125	123		
14	Alfalfa	166	124	112	109	190	149	119	109	108		
7	Alfalfa	tubes not installed			236	294	262	231	284	228		
Average Alfalfa		182	131	112	156	222	188	160	173	153	581	242
21	Old Grass	148	116	97	102	166	133	106	88	94		
24	Old Grass	116	115	80	88	181	164	116	98	115		
Average Old Grass		132	116	88	95	174	148	111	93	105	444	114

		2003													
Paddock	**Forage Type**	**02-May**	**13-May**	**28-May**	**12-Jun**	**26-Jun**	**09-Jul**	**23-Jul**	**06-Aug**	**20-Aug**	**02-Sep**	**27-Sep**	**15-Oct**	**FC_{160}**	**WP_{160}**
4	Annual	416	486	460	469	415	362	324	302	292	298	343	330		
15	Annual	127	246	278	268	246	190	125	125	139	147	153	146		
9	Annual	218	401	367	373	375	325	274	268	282	276	287	296		
Average Annual		254	378	368	370	345	292	241	231	238	240	261	257	506	197
3	M. Bromegrass	312	434	410	386	351	325	293	294	310	301	302	315		
13	M. Bromegrass	356	343	306	294	243	231	203	204	213	237	227	214		
12	M. Bromegrass	302	340	270	M	196	147	126	127	141	127	149	131		
Average M. Bromegrass		323	373	329	340	263	234	207	208	221	221	226	220	575	278
1	Alfalfa	128	266	218	187	159	124	109	108	83	98	113	98		
14	Alfalfa	134	246	237	183	140	119	92	94	94	101	154	98		
7	Alfalfa	513	614	550	480	449	396	279	278	268	265	253	243		
Average Alfalfa		258	375	335	283	249	213	160	160	148	155	173	146	581	242
21	Old Grass	309	259	209	177	136	104	73	73	89	94	80	66		
24	Old Grass	246	271	214	197	165	125	102	90	91	112	115	115		
Average Old Grass		277	265	211	187	151	115	88	82	90	103	97	90	444	114

M= missing data

Table 7.9 Analysis of variance summary of select parameters

Variable / Level	Model parameterization		Effect		
	Group	Structure	Trt	Date	Date*Trt
Bulk density				*P values*	
0 - 2.5 cm	exp	none	0.005		
2.5 - 5 cm	none	none	0.035		
5 - 7.5 cm	none	none	0.034		
15 cm	exp	none	0.079		
Penetration Resistance					
0 cm	exp	cs	< 0.001	< 0.001	< 0.001
2.5 cm	exp	none	0.002	< 0.001	< 0.001
5 cm	exp	none	0.002	< 0.001	< 0.001
7.5 cm	exp	none	0.007	< 0.001	< 0.001
10 cm	exp	none	0.021	< 0.001	< 0.001
TSW40					
2002	exp	cs	0.002	0.000	0.000
2003	none	none	0.061	0.000	0.000
TSW80					
2002	exp	cs	0.006	0.000	0.018
2003	exp	cs	0.026	0.000	0.001
TSW120					
2002	exp	cs	0.018	0.000	0.796
2003	exp	none	0.326	0.000	0.037
TSW160					
2002	exp	none	0.189	0.000	0.992
2003	exp	cs	0.099	0.000	0.212
TSW120-160					
2002	none	none	0.463	0.781	1.000
2003	exp	none	0.853	0.254	0.995
Vegetation in Runoff Frames					
Bare ground	none	none	< 0.001		
Canopy cover	none	none	0.024		
Runoff Volume					
Annual	none	none	0.193		
Rainfall	none	none	0.007		
Snowmelt	none	none	0.465		
Runoff Water Quality					
pH	exp	none	0.008	0.044	0.336
EC	exp	none	0.453	0.164	0.412
TDS	exp	none	0.518	0.008	0.630
Alkalinity	none	none	0.172	0.024	0.528
Potassium	exp	none	0.574	0.073	0.522
Chloride	exp	none	0.267	0.333	0.353
Nitrate	none	cs	0.295	0.159	0.222
Nitrite	none	none	0.576	0.201	0.238

Group - variance components kept constant (none) or allowed to vary between experiments (exp)
Structure - variation within experimental units was modeled (cs) or was not (none)

Table 7.10 Contrasts testing the treatment effect for each consecutive date

Variable / Level	Date 1	Date 2	Date 3	Date 4	Date 5	Date 6	Date 7	Date 8	Date 9	Date 10	Date 11	Date 12
						P values						
Penetration Resistance												
0 cm	0.399	< 0.001										
2.5 cm	0.310	0.001										
5 cm	0.188	0.001										
7.5 cm	0.248	0.003										
10 cm	0.313	0.008										
TSW40												
2002	< 0.001	< 0.001	< 0.001	0.008	0.004	0.002	0.003	0.005	0.015			
2003	0.380	0.186	0.004	0.002	0.001	0.034	0.093	0.197	0.174	0.250	0.172	0.070
TSW80												
2002	< 0.001	< 0.001	0.005	0.016	0.031	0.018	0.014	0.017	0.023			
2003	0.491	0.042	0.004	0.005	0.002	0.011	0.056	0.089	0.117	0.165	0.117	0.057
TSW120												
2002	0.001	0.003	0.023	0.044	0.079	0.062	0.045	0.042	0.047			
2003	0.614	0.476	0.253	0.167	0.128	0.216	0.330	0.365	0.346	0.375	0.257	0.256
TSW160												
2002	0.058	0.099	0.182	0.259	0.311	0.313	0.242	0.283	0.238			
2003	0.821	0.185	0.087	0.075	0.065	0.080	0.130	0.125	0.133	0.181	0.110	0.101
TSW120_160												
2002	0.579	0.675	0.487	0.491	0.518	0.658	0.495	0.280	0.437			
2003	0.997	0.918	0.926	0.829	0.899	0.839	0.854	0.788	0.656	0.732	0.813	0.700
Runoff Water Quality												
pH	0.011	0.216										
EC	0.921	0.233										
TDS	0.773	0.426										
Alkalinity	0.360	0.082										
Potassium	0.772	0.485										
Chloride	0.276	0.303										
Nitrate	0.339	0.479										
Nitrite	0.300	0.658										