5-1986

Effect of Short Duration Grazing on Soil Moisture Depletion and Plant Water Status in a Crested Wheatgrass Pasture

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Recommended Citation

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EFFECT OF SHORT DURATION GRAZING ON SOIL MOISTURE DEPLETION AND PLANT WATER STATUS IN A CRESTED WHEATGRASS PASTURE

by

Jon M. Wraith

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Range Science

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

1986

ACKNOWLEDGEMENTS

This research was supported through funds from Utah Agricultural Experiment Station Project 780.

I would like to thank my advisor, Dr. Douglas A. Johnson, for his assistance during all phases of this project. My introduction to research has been greatly enhanced through his thoughtful guidance and generous gift of time.

Dr. R.J. Hanks provided valuable input on many occasions throughout the course of the project, and I look forward to our future collaboration. Drs. D.V. Sisson and F.D. Provenza were extremely helpful and patient during numerous statistical consultations.

Royce Larsen helped with the installation of field plots, and he and Chuck Warner both assisted in data collection. Their contributions to the success of this project are appreciated.

Finally and most importantly I would like to thank my wife Caroline for her constant love and support. She has demonstrated great patience and has endured many personal sacrifices while indulging my desire for an education. This work is dedicated to her with respect and gratitude.

Jon M. Wraith

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Effect of Short Duration Grazing on Soil Moisture Depletion and Plant Water Status in a Crested Wheatgrass Pasture

by

Jon M. Wraith, Master of Science

Utah State University, 1986

Major Professor: Dr. Douglas A. Johnson
Department: Range Science

A short duration grazing system was utilized to determine the effects of intensive periodic defoliation during spring on soil moisture depletion patterns and plant water status in a crested wheatgrass (Agropyron cristatum and A. desertorum) pasture in central Utah. Exclosures were constructed to compare grazed and ungrazed responses. Soil moisture was monitored to a depth of 193 cm at one to two week intervals from mid-April to late-September using a neutron moisture gauge. Predawn and midday leaf water potentials were estimated using a pressure chamber technique. The two paddocks included in the study were grazed three times between mid-April and mid-June in 1985. A difference in time of grazing between the two paddocks was also examined for its effect on soil moisture depletion patterns and plant water status.

Soil moisture was depleted at a higher rate within ungrazed plots than grazed plots during 13 April to 1 July in both paddocks. Soil moisture was depleted at a higher rate after 1 July in grazed compared to ungrazed plots in the early-grazed paddock; however, no difference in soil moisture depletion rate was noted after 1 July within the late-grazed paddock. Total cumulative depletion was greater within ungrazed plots than grazed plots in the early-grazed paddock from 6 June until 13 August, and from 23 May until 30 July in the late-grazed paddock. During the pre-July period, soil moisture was depleted more rapidly in the upper- and mid-portions of the soil profile in ungrazed plots. By 25 September there was no difference in total soil water depletion through 53 cm between grazed and ungrazed treatments, but ungrazed plots extracted relatively more water in the mid- and lower-portions of the soil profile.

Grazing had no effect on predawn leaf water potentials prior to 1 July, but predawn leaf water potentials were lower for ungrazed plants than for grazed plants after 1 July. Midday leaf water potentials were lower for grazed plants than for ungrazed plants before 1 July, but did not differ between grazed and ungrazed plants after 1 July. Time of grazing had no effect on either predawn or midday leaf water potentials.

(68 pages)

INTRODUCTION

Soil moisture is one of the limiting resources for primary production in much of the Great Basin area (West 1983). The seasonal dynamics of moisture availability, evaporative demand, and vegetative utilization significantly affect the growth and competitive interactions of the various plant communities present in this region.

Two of the most successful species used to reseed Intermountain rangelands have been the crested wheatgrasses (*Agropyron cristatum* (L.) Gaertn. and *A. desertorum* (Fisch. ex Link) Schult). Their early spring growth and tolerance to grazing and drought make the crested wheatgrasses an extremely valuable forage resource (Frank 1981, Mohammad et al. 1982). It has been estimated that approximately 4 million hectares in the Intermountain Region have been seeded to these grasses (Provenza and Richards 1984).

Short duration grazing systems are another recent development on Intermountain ranges. These systems concentrate large numbers of livestock on relatively small paddocks for a short period of time (usually a few days). The paddocks are then allowed to "rest" for several weeks. There has been considerable interest in these systems recently because of purported increases in animal and forage production in some instances (Savory and Parsons 1980, Heitschmidt et al. 1982a, 1982b, Jung et al. 1985). Malechek and Dwyer (1983) suggested that short duration grazing might provide an efficient means of utilizing crested wheatgrass ranges during spring in Utah.

Reviews by Gifford and Springer (1980) and Blackburn et al. (1982)

on the impacts of grazing on rangeland watersheds showed that little research has been done regarding the effects of livestock grazing on soil moisture use patterns. Because atmospheric conditions such as temperature and humidity greatly influence the water status of a plant, measurements of soil moisture content alone are not sufficient to determine the effects of water supply on plant water status. As the availability of soil water and its atmospheric demand at any given time are reflected in the water status of a plant, estimates of plant water potential are essentially indications of the effective soil moisture potential that the plant is actually experiencing, regardless of soil water content.

Optimal management of rangelands is dependent on an understanding of the physical and biological processes at work in these natural systems. A knowledge of plant-soil-water interactions and how these are influenced by management practices is especially critical in semiarid regions such as the Great Basin. The primary objective of this study was to investigate the effect of short duration grazing on seasonal soil moisture depletion patterns and plant water relations in a crested wheatgrass pasture in an Intermountain foothill rangeland area in central Utah.

LITERATURE REVIEW

Related Studies

Buckhouse and Coltharp (1976) reported that extreme clipping treatments (complete denudation) of a crested wheatgrass and alfalfa (*Medicago sativa* L.) mixture at a mid-elevation site in Utah resulted in significantly less soil moisture depletion than a control treatment. Other clipping intensities also showed reductions in soil moisture depletion as compared to control plots, although in some cases the differences were not statistically significant. Galbraith (1971) found that continuous grazing treatments significantly reduced evapotranspiration on a shortgrass prairie site in northeastern Colorado. Heitschmidt et al. (1982a) observed an increase in fall aboveground live biomass under a short duration grazing system in Texas. They hypothesized that this enhanced growth may have resulted from accelerated regrowth after grazing caused by shading differences of individual leaves and/or differences in evapotranspiration. Berg and Sims (1985) found no statistical difference in depletion or recharge of soil moisture between short duration and continuous grazing systems over a 10 to 12 month grazing season in Oklahoma.

Caldwell et al. (1981) and Richards (1984) in studies involving resource allocation among crested and bluebunch (<u>Pseudoroegneria spicata</u> (Pursh) A. Love subsp. <u>spicata</u>) wheatgrasses noted that crested wheatgrass curtails root production by as much as 50 percent in response to defoliation, thus allowing a more rapid return to the preclipping root-shoot balance than bluebunch wheatgrass. Thorgeirsson (1984), working with crested wheatgrass, and other researchers studying various plant species (Taylor and Klepper 1975, Nnyamah and Black 1977, Rambal 1984) demonstrated that rate of water uptake and rooting density were highly correlated. These studies suggest that defoliation of crested wheatgrass plants by livestock might be expected to influence soil moisture depletion patterns by their effect on root production as well as by reducing the photosynthetic area of defoliated plants.

Measurement of Soil Moisture Depletion

There are several methods of monitoring the apportionment of water in the environment, many of which involve the principle of a water balance. Water balance refers to the balance between the income of water from precipitation and snowmelt and the outflow of water by evapotranspiration, streamflow, and groundwater recharge (Dunne and Leopold 1978, Branson et al. 1981). This method has commonly been applied to studies involving the annual cycle of soil moisture depletion and recharge, using some modification of the basic equation:

$$P = Et + Ro + Dr \pm \Delta S$$

where P is precipitation, Et is evapotranspiration, Ro is surface runoff, Dr is drainage beyond the soil zone under consideration, and ΔS is change in soil moisture storage. Because evapotranspiration constitutes by far the largest loss of water in most cases, studies concerned with soil moisture depletion consider the equation as:

$$Et = P - Ro - Dr \pm \Delta S$$

Precipitation, runoff, and changes in soil moisture are readily measurable, but drainage is difficult to measure or calculate. Because drainage often constitutes a negligible portion of water loss in arid and semiarid environments (Rambal 1984, Galbraith 1971), it is often ignored (Thorgeirsson 1984, Lauenroth and Sims 1976). However, other investigators, particularly those utilizing irrigation treatments, have stressed the importance of incorporating drainage measurements into the equation to accurately estimate evapotranspiration in areas where some drainage may occur (Bowman and King 1965, Van Bavel and Stirk 1967, Van

Bavel et al. 1968a, 1968b).

Lysimetry is one method of monitoring changes in soil moisture, and several types of lysimeters have been employed (Hanks and Shawcroft 1965, Van Bavel and Reginato 1965, Harrold and Dreibelbis 1967). Lysimeters have the advantage of being quite precise, but they are relatively difficult and expensive to install. In addition, the relationship between results obtained with soil in a lysimeter to those obtained under external soil conditions is sometimes suspect (Hanks pers. comm.).

A more commonly used method for monitoring changes in soil moisture in the field is the neutron moisture gauge. Provided that runoff and deep percolation are known or negligible, evapotranspiration measurements obtained by lysimeters and neutron probes are generally quite comparable (Bowman and King 1965, Van Bavel and Stirk 1967, Wight 1971). Rouse and Wilson (1972) also found comparable values of evapotranspiration in a study using the neutron probe and energy-budget calculations. Advantages of the neutron moisture gauge are that repeated, non-destructive measures can be made through time, readings are integrated over a volume of soil, and the necessary equipment is relatively inexpensive in comparison to other methods.

Numerous studies within the past 30 years have explored the mechanics, appropriateness, and limitations of using neutron probes in evapotranspiration and soil moisture research (Merriam 1959, Hanks and Bowers 1960, McHenry 1962, Douglass 1966, Koshi 1966, Hajdukovic et al. 1967, Leubs et al. 1968, Cameron 1970, Richardson and Burroughs 1972, DeJong and McDonald 1975, Sinclair and Williams 1979, Haverkamp et al.

1984). Concensus opinion has been very favorable, provided basic procedures and precautions are heeded. Hewlett et al. (1964), Sinclair and Williams (1979), and Haverkamp et al. (1984) reported on the various sources of error associated with the method and stressed the importance of accurate instrument calibration and consideration of spatial variability. Rouse and Wilson (1972) showed that the accuracy of evapotranspiration estimates was greatly influenced by the length of the interval between soil moisture measurements and by the number of replications. They found that an interval of at least 8 days was necessary to maintain accuracy within 10% for their six sites. Lawless et al. (1963), Van Bavel and Stirk (1967), and Wight (1971) noted that greater precision and sensitivity resulted when depth increments were 15 cm or less.

Measurement of Plant Water Status

The pressure chamber technique has become the standard for measuring plant water status in the field (Ritchie and Hinckley 1975) because of its ease of use, speed, and reliability. In addition this technique does not require fine control of temperature, which is a requirement with psychrometric procedures (Turner 1981).

Plant water status is proportional to the difference between water gained from the soil and water lost to the atmosphere. During periods of high atmospheric demand, transpiration can exceed uptake, and the column of water within the vascular system is placed under tension. When a twig or leaf is severed, the water column is broken and water withdraws into the plant tissues. If pressure is applied to the leaves, the water column is forced back to the cut surface. The pressure at which water is observed at the cut surface is assumed to be the tension on the water column before it was severed (Waring and Cleary 1967). This method measures the combined gravitational and frictional plant water potentials, collectively termed xylem pressure potential. The combined solute and matric potentials are not measured, but their value in the xylem sap of most plants is considered either constant or negligible (Ritchie and Hinckley 1975). Pressure chamber determinations are thus estimates of the total water potential of the xylem sap.

Plants generally undergo a diurnal fluctuation in xylem pressure potential. During the day when atmospheric demand is high, transpiration exceeds water uptake and plants may experience water stress. During the night, transpiration is generally curtailed because of lower air temperatures and higher relative humidities. In the presence of high soil water potentials an equilibrium is established between the plant and soil at night. Consequently, predawn measurements of xylem pressure potential provide an estimate of the effective soil water potential to which the plant is exposed. As the soil dries, equilibrium time between the plant and the soil increases until predawn measurements of xylem pressure potential may no longer be directly indicative of soil moisture. Nevertheless, measurement of predawn xylem pressure potential is still informative because it indicates the minimum level of water stress experienced during the diurnal period.

METHODS

Study Area

The study was conducted at the Tintic Valley research site located approximately 10 km southwest of Eureka, Juab County, Utah (39 51'N, 112 08'W, 1750 m elevation) (Fig. 1). This site has been cooperatively maintained by the Utah State University Range Science Department and the U.S. Department of Interior/Bureau of Land Management since 1949.

The area receives 374 mm average annual precipitation, which is quite evenly distributed throughout the year (Fig. 2). Monthly precipitation is highly variable between years, as is common in semiarid environments. Precipitation during the study period was representative of the long-term average for the site (Fig. 3). Total precipitation for the year ending at the conclusion of the study was 370 mm. Measurable runoff totalling approximately 8 mm occurred during July.

Plots were established within a 28-ha pasture that was seeded to crested wheatgrass in the early 1950's. At the time of this study Pasture 8 was part of a 10-paddock short duration grazing cell (Fig. 4) that had been in operation for 2 years (Malechek and Dwyer 1983). The pastures adjacent to Pasture 8 were also incorporated within the grazing cell; however, they were not included in this study because of differences in forage composition. Pasture 7 was seeded to intermediate wheatgrass (_Thinopyrum_ _intermedium_ (Host) Barkw. & D.R. Dewey subsp. _intermedium_), while Pasture 9 contains a mixture of crested, intermediate, and tall (_T_. _ponticum_ (Podp.) Barkw. & D.R. Dewey) wheatgrasses.

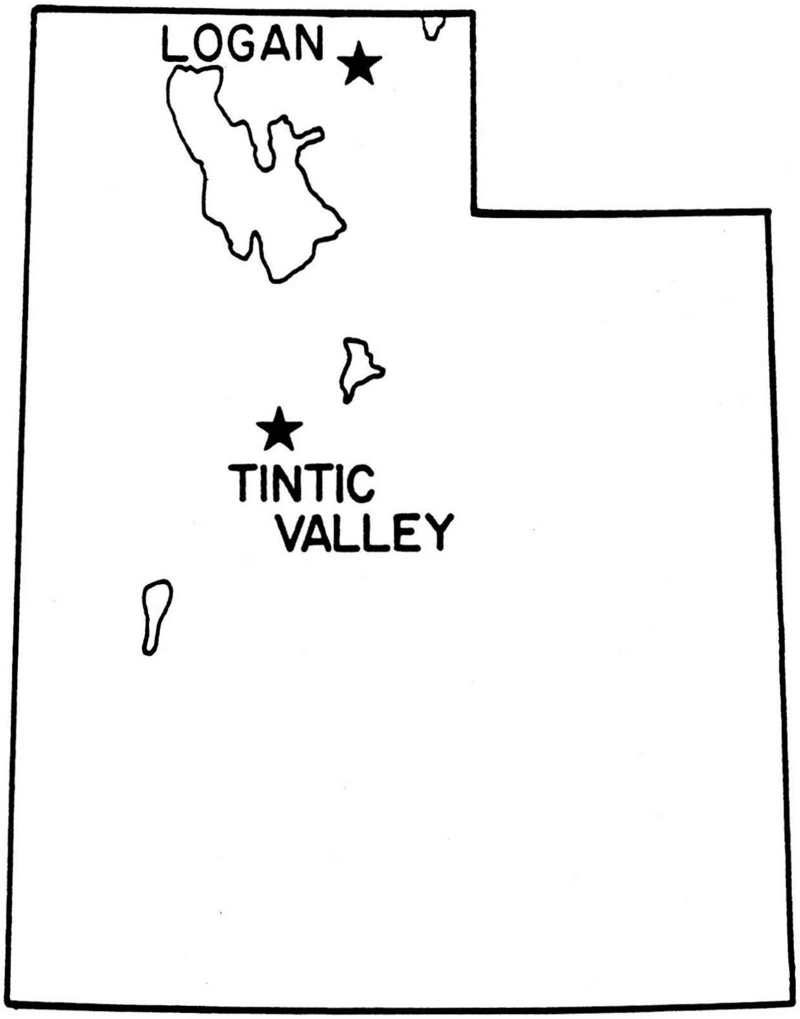

Fig. 1. Location of the Tintic Valley research site, Juab County, Utah.

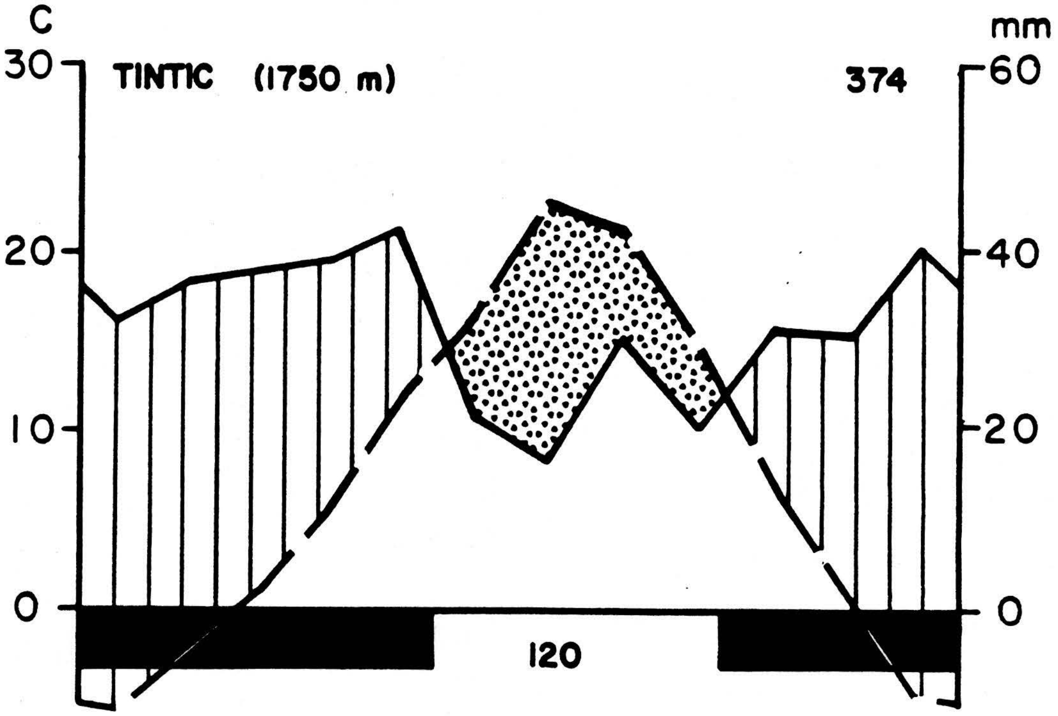

Fig. 2. Climate diagram for the Tintic study site following the general format of Walter and Leith (1960). Temperature averages (dashed line) were estimated by normalizing data from the Delta and Tooele stations (30-year normals, 1951 to 1980). Precipitation averages are based on 23 years of data collected at the research site between 1940 and 1984. The abscissa represents the 12 months of the year beginning in January. The horizontal bar along the abscissa represents the portion of the year between the mean first and last 0 C day; the number below the center of the abscissa represents the mean length of this freeze-free period in days. The site elevation and mean annual precipitation values are at the top of the diagram.

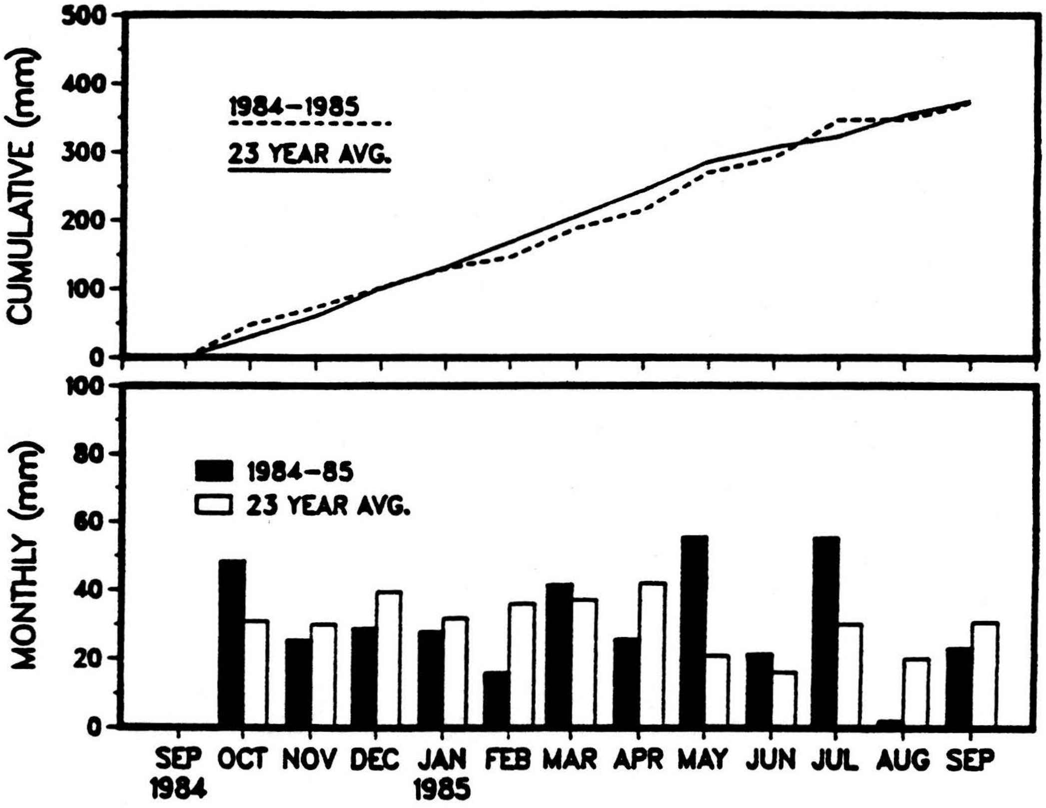

Fig. 3. Cumulative and monthly precipitation totals (mm) for the study site. Long-term average values are based on 23 years of data collected at the site from 1940 to 1984.

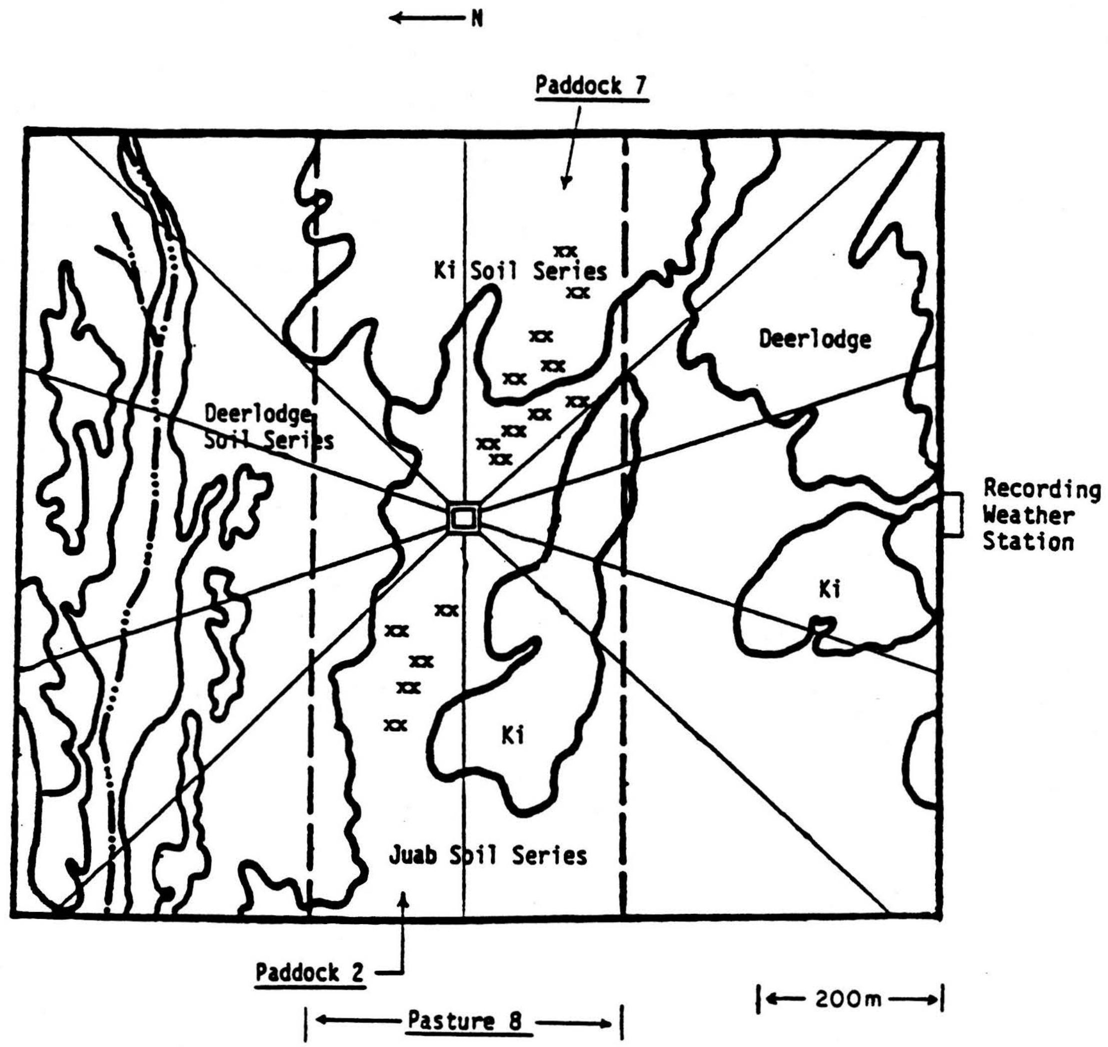

Fig. 4. Diagram of the short duration grazing cell at the Tintic Valley research site. Paired x's represent locations of field plots within Pasture 8. Vertical dashed lines indicate where fences between pastures were removed upon establishment of the grazing cell. Lines radiating from the center represent paddock borders. Mapped soil types (Jensen 1983) are outlined and labeled.

Design

Experiments were established within three soil type-time of grazing combinations. Soil types were delineated based on an intensive (order 1-2) survey of the soils within the research site (Jensen 1983, 1985) and were selected to compare responses between areas of dissimilar available soil moisture characteristics. Five replications were established in Paddock 2, with each replication consisting of a pair of grazed and ungrazed plots. The soil where the plots were placed is a mixed (calcareous), mesic, Torrifluventic Haploxeroll (Jensen 1983, 1985). Five replications were also established on the same soil type in Paddock 7. Five additional replications were established in Paddock 7 on a loamy skeletal, mixed, mesic, Xerollic Calciorthid (Jensen 1983, 1985). These two soils will hereafter be referred to as the Juab and Ki series, respectively.

Plots were 3 m by 4 m in size. Pairs of plots were randomly located within the appropriate study areas, and grazed and ungrazed treatments were then randomly assigned to the individual plots. Fencing was installed around each of the ungrazed plots to exclude livestock. A 2-m corridor was left between each of the paired plots to minimize undue disturbance to the grazed plots by livestock attracted to the exclosures (Fig. 5).

Paddocks were stocked with yearling Angus heifers at 0.7 ha per AUM. The spring grazing season lasted from mid-April to mid-June in 1985. Three grazing cycles were completed utilizing a 2-day rotation through each paddock during the first two cycles and a 1-day rotation during the final cycle. Paddock 7 was grazed during 24 and 25 April,

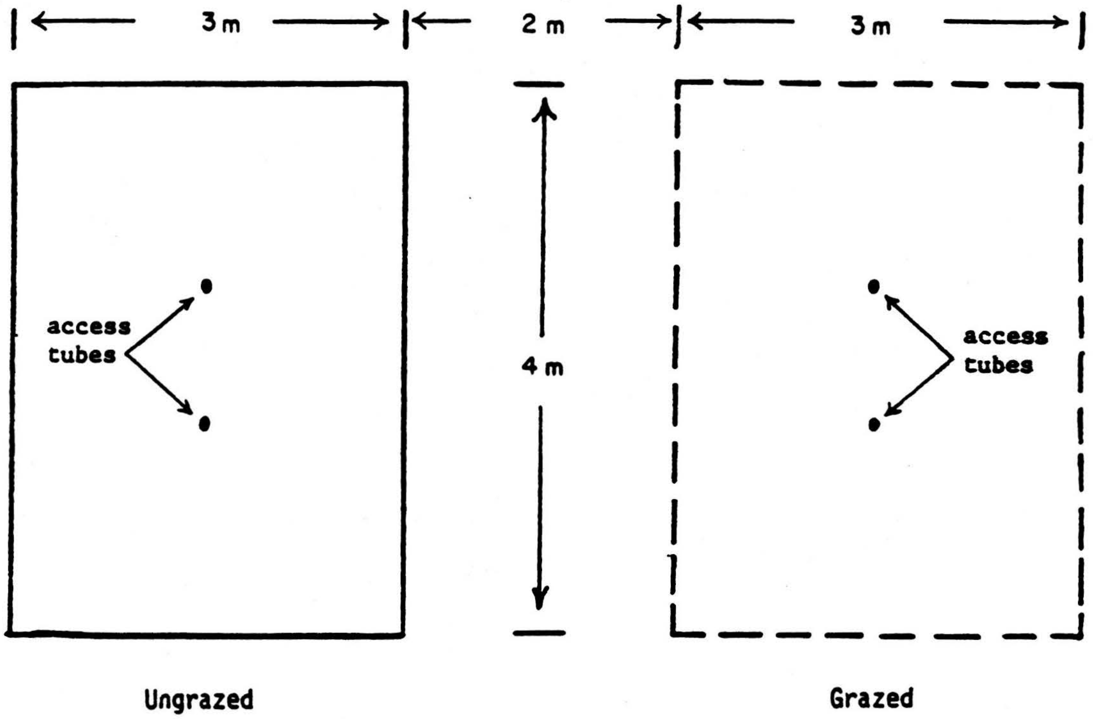

Fig. 5. Dimensions and spatial relationship of paired field plots. Solid border indicates a livestock exclosure around the ungrazed plot.

14 and 15 May, and 3 June. Paddock 2 was grazed during 2 and 3 May, 22 and 23 May, and 7 June.

Soil Moisture Depletion

Two thin-walled aluminum access tubes (Alcoa 6061-T6) were installed within each plot using a motor-driven hydraulic core sampler (Giddings Machine Co.). One tube was installed to a depth of approximately 2 m and one was installed to 2.5 m. The 0.5-cm space surrounding the access tubes was backfilled with a very fine sand, except that the top 5 to 7 cm of each hole was filled with topsoil to prevent free surface water from draining along the tubes. The tubes were spaced 1 m apart, resulting in a distance of slightly greater than 1.5 m from each tube to the nearest plot boundary (Fig. 5).

Soil moisture was monitored with a neutron moisture gauge (Campbell Pacific Nuclear, Inc.). Data were gathered at approximately weekly to biweekly intervals from mid-April to late-September during 1985. Readings were taken at 15-cm increments to a depth of 105 cm, then at 25-cm increments to a depth of 180 cm (thus monitoring soil moisture to 192.5 cm) in all tubes. Additional measurements were obtained at 25-cm increments to 230 cm in tubes that were installed to a 2.5 m depth. The gauge was field-calibrated for the study soils using a gravimetric sampling technique. Separate calibration curves were utilized for the readings at 15-cm depth and for the remainder of the soil profile (Fig. 6).

Soil moisture depletion and evapotranspiration were calculated both cumulatively and between successive sampling dates. Evapotranspiration was calculated using a water balance equation:

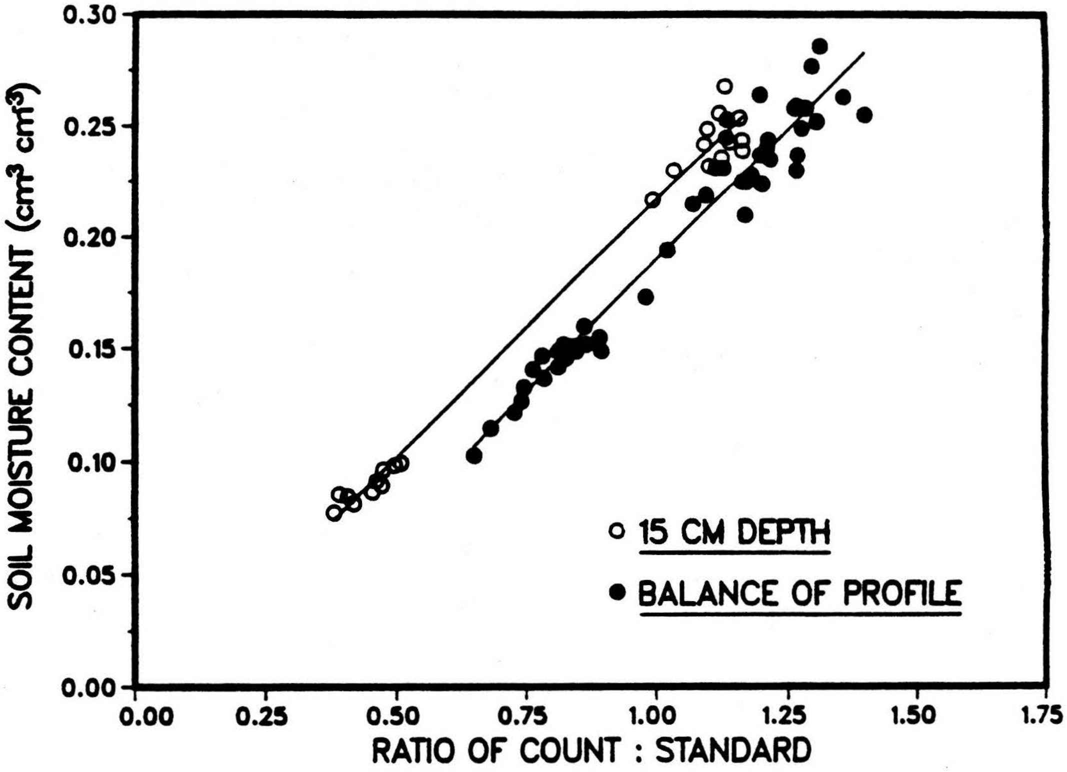

Fig. 6. Calibration relationships for the neutron soil moisture gauge. Regression equations for volumetric water content are: 0.228 R - 0.013 (r^2 = 0.99, n = 22) for 15-cm depth readings, and 0.230 R - 0.043 (r^2 = 0.93, n = 47) for the balance of the profile.

$$Et = P - Ro - Dr \pm \Delta S$$

where Et is evapotranspiration, P is precipitation, Ro is surface runoff, Dr is drainage beyond the soil zone under consideration (192.5 cm in this case), and ΔS is change in soil moisture storage. Surface runoff was estimated by installing metal frames around a pair of plots in each study area and collecting any water that ran to the downhill edge of the plots in a buried container. Estimates of drainage were made by using a physically-based computer simulation model (modified from Childs and Hanks 1975), utilizing the 192.5 cm to 242.5 cm soil moisture data from the 2.5 m tubes as a reference for comparing model output.

Precipitation was monitored with a standard rain gauge at each study area as well as by a recording weather station located along the border of Pastures 6 and 7 (Fig. 4). Incoming solar radiation and pan evaporation were measured at a similar station approximately 1.3 km north of the study site. Potential evapotranspiration was calculated by both the Class A Pan and Jensen-Haise (Jensen and Haise 1963) methods. A coefficient of 0.71 was used in the evaporation pan calculations.

Texture and bulk density were analyzed within each soil type. A soil moisture release curve was developed for each soil using tensiometers and a sample changer thermocouple psychrometer (Decagon Devices, Inc.).

Plant Water Status

Predawn and midday leaf xylem pressure potentials of crested wheatgrass plants were measured in the field using a pressure chamber technique (Waring and Cleary 1967). One leaf sample was taken from each of two plants sampled per plot. Sampled plants were selected at random from among those growing near the center of the plots. Attempts were made to select leaves of similar developmental stage and orientation for measurement; this was not always possible during late summer due to variability in leaf senescence. Leaves were enclosed in small plastic bags throughout the sampling process to minimize water loss after excision (Turner and Long 1980). Measurements were taken on the same schedule as soil moisture measurements, but were discontinued after the first week of September due to a lack of sufficient green leaf samples in the ungrazed plots.

Data Analysis

The individual study areas (soil type-time of grazing combinations) were considered a series of three experiments. This made it possible to analyze each experiment separately, then selectively combine them to evaluate the effects of soil type and time of grazing without mutual confounding. A randomized block design involving split plots was used for the analysis of variance. Plots were split through time for plant water status and by depth and through time for soil moisture depletion. Variances of the individual experiments were assumed to be homogeneous due to their close proximity and the negligible time differences between sampling. Violation of this assumption would probably result in only minimal changes in the analyses (Sisson 1962, Glass et al. 1972).

RESULTS

Analyses of soil water content-water potential relationships (Fig. 7) and soil texture and bulk density (Table 1) indicated that the two soils included in the study had very similar soil moisture characteristics. Analysis of soil moisture content on the first sample date (13 April), at which time the soils should have been very near field capacity, showed no difference between soils. The placement of the two experiments within Paddock 7 near the mapped soil boundary apparently did not result in the inclusion of typical pedons of the Ki soil. Evaluation of any effect due to a difference in available soil moisture was therefore not possible. Because of this, data from the two experiments in Paddock 7 were pooled, thus doubling the sample size within that paddock. To evaluate the effects of time of grazing, pooled data from Paddock 7 were compared to data from Paddock 2 using orthogonal contrasts.

The months of May and July received somewhat higher than average precipitation in 1985, while August was quite dry (Fig. 3). Plants which had been grazed responded to the July rainfall with a marked flush of new growth. Ungrazed plants, which were in an advanced phenological stage, exhibited less of a response. Because little foliage remained on grazed plants at the conclusion of the grazing season, nearly all foliage present on these plants after early July was young, mostly vegetative tillers. Consequently, the study period was divided into two sub-periods to examine responses before and after the differential growth occurred. Separate analyses were obtained for the

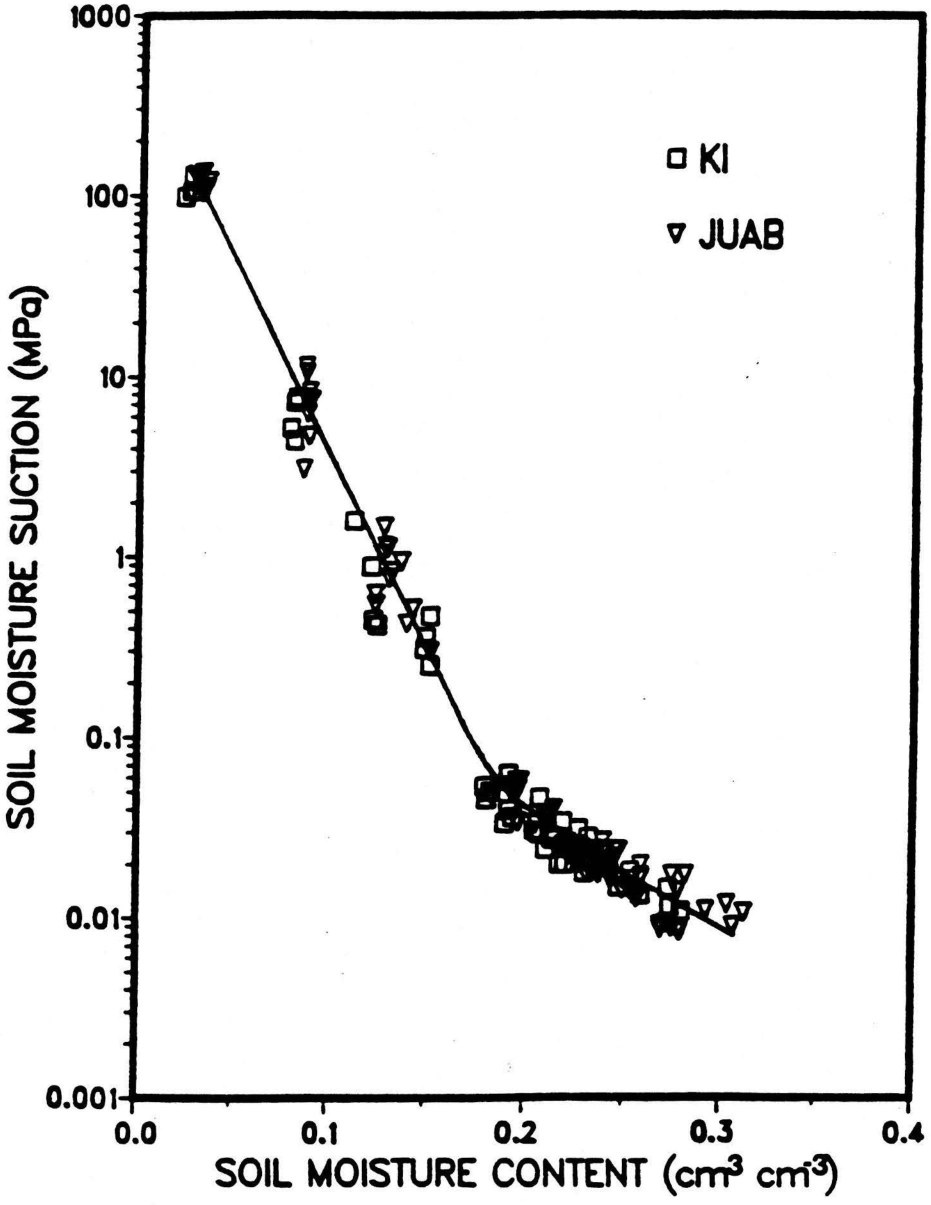

Fig. 7. Soil moisture release curve for soils within the study area. Data for the wet end of the relationship (bottom of figure) are field tensiometer values with the balance of data obtained with a sample-changer thermocouple psychrometer.

Table 1. Average texture (n = 2) and bulk density (n = 10) for core samples extracted from the three experimental areas within Pasture 8.

Paddock	Depth (cm)	Texture	% Sand	% Silt	% Clay	Bulk density
2(Juab)	0-30	Silt Loam	30.8	56.0	13.0	1.28
	30-60	Silt Loam	29.8	55.0	15.2	1.33
	60-90	Silt Loam	30.8	52.0	17.2	1.41
	90-120	Silt Loam	26.8	56.0	17.2	1.44
7(Juab)	0-30	Silt Loam	30.2	50.5	19.3	1.29
	30-60	Silt Loam	22.2	57.6	20.2	1.35
	60-90	Silt Loam	28.0	54.8	17.2	1.41
	90-120	Silt Loam	31.0	52.8	16.2	1.43
7(Ki)	0-30	Loam	36.2	49.6	14.2	1.33
	30-60	Silt Loam	31.2	51.6	17.2	1.35
	60-90	Loam	33.2	49.6	17.2	1.42

periods from 13 April through 1 July (which encompassed the grazing season), 2 July through 25 September, and for the entire study period (see Appendix).

Soil Moisture Depletion

There was no statistically significant difference ($p \leq 0.05$) in rate of soil moisture depletion between grazed and ungrazed treatments within either paddock when data were analyzed over the entire season. However, when data were analyzed separately for the time periods before 1 July and after 1 July, significant differences were detected. Soil moisture was depleted at a significantly ($p < 0.01$) higher rate within ungrazed plots than grazed plots during the April-June period in both Paddocks 2 and 7 (Fig. 8). After 1 July, depletion rate was significantly higher for grazed plots than ungrazed plots in Paddock 7. However, in Paddock 2 grazed and ungrazed plots were not statistically different in depletion rates after 1 July.

Total cumulative depletion was greater within ungrazed plots than grazed plots in Paddock 7 from 6 June through 13 August. Total cumulative soil moisture depletion was greater within ungrazed plots than grazed plots in Paddock 2 from 23 May through 16 July.

The time of grazing difference between Paddocks 2 and 7 resulted in different patterns of depletion rate through time in grazed plots within these paddocks during the pre-July period. Grazed plots in Paddock 7, which were grazed prior to those in Paddock 2 during each of the three grazing cycles, had a higher overall mean depletion rate by 1 July (0.11 mm d^{-1}) than grazed plots in Paddock 2 (0.08 mm d^{-1}).

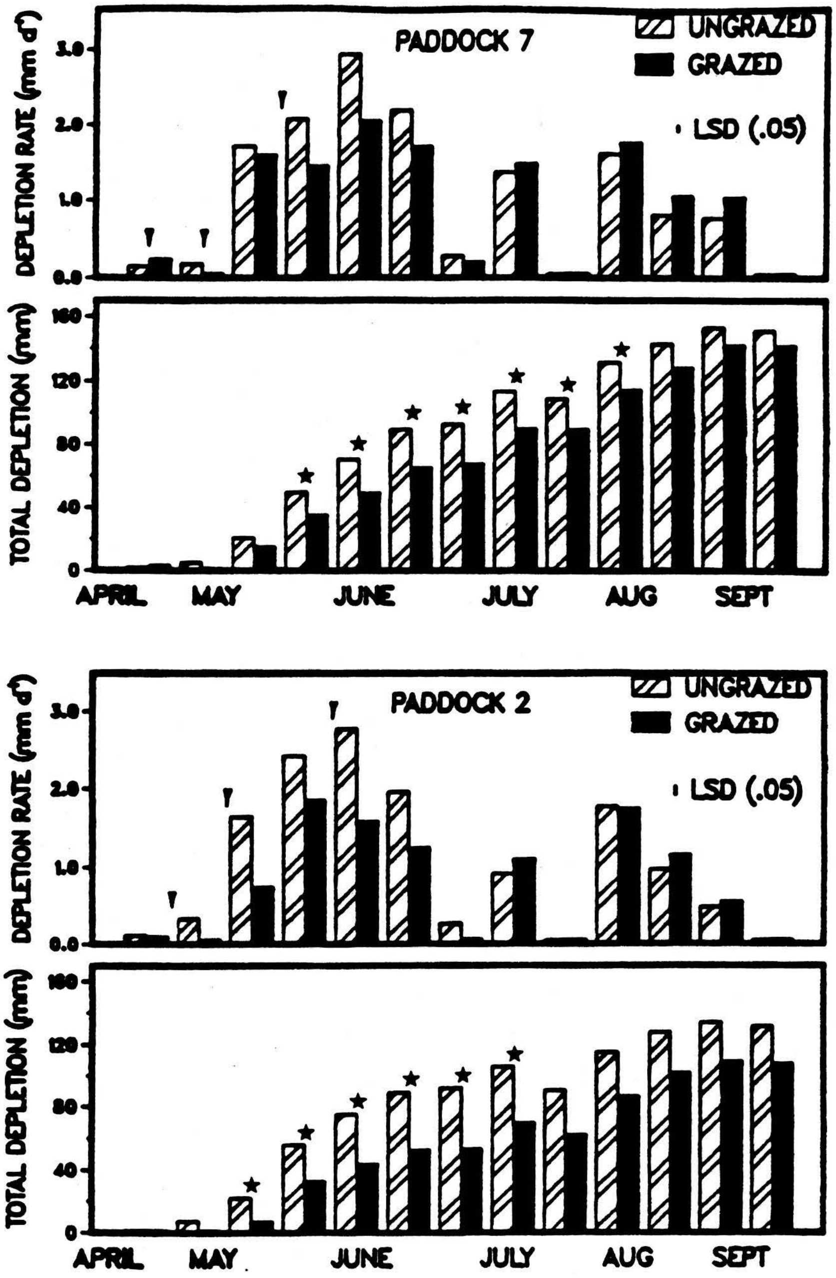

Fig. 8. Soil moisture depletion rates (mm d^{-1}) and total cumulative depletion (mm) within Paddock 2 ($n = 10$) and Paddock 7 ($n = 20$) during the study period. Stars in total depletion graphs indicate that grazed and ungrazed treatments are significantly different ($p < 0.05$) based on a one-way analysis of variance at each date. Points above bars in depletion rate graphs indicate approximate dates that the respective paddocks were grazed during each cycle.

Total cumulative depletion was greater in grazed plots for Paddock 7 than Paddock 2 beginning on 20 June (Fig. 9).

When data from ungrazed plots were analyzed over the entire season, soil moisture depletion rate was not statistically different between Paddocks 2 and 7. However, significantly more total cumulative soil moisture was depleted in ungrazed plots in Paddock 7 than in Paddock 2 from 30 July to 25 September (Fig. 9). Because of this difference in total cumulative soil moisture depletion, direct comparison of responses between Paddocks 2 and 7 after 16 July is not possible. This difference in cumulative depletion between ungrazed plots may be due to differential surface runoff that may have occurred between the paddocks during one or more of the high-intensity convective storms experienced at Tintic during July. Approximately 3 mm of surface runoff were measured between 1 July and 16 July in each paddock. Runoff during the 16 July to 30 July period was sufficient to exceed the 5 mm (depth equivalent) capacity of the storage containers used to measure runoff; thus a difference in total runoff between the paddocks would not have been detected. Between the 16 July and 30 July sample dates cumulative depletion totals for Paddock 2 declined somewhat more sharply than for Paddock 7 in both grazed and ungrazed plots (Fig. 10), suggesting that more soil moisture recharge may have occurred in Paddock 2 than in Paddock 7. If differential recharge did occur, this may be at least partially due to the slightly greater slopes present in Paddock 7 compared to Paddock 2.

Figures 11 and 12 illustrate the pattern of soil moisture depletion by depth for grazed and ungrazed plots during the study

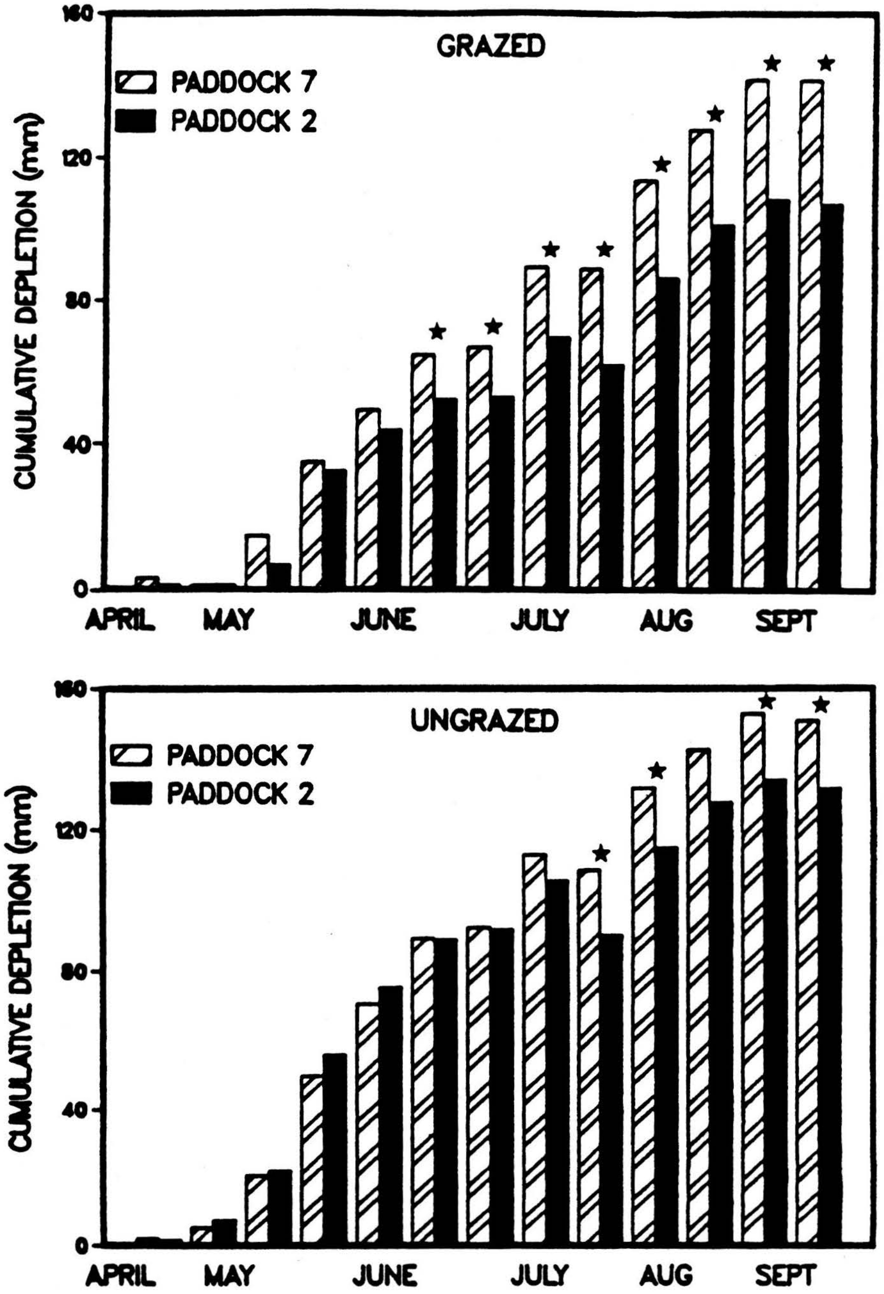

Fig. 9. Cumulative soil moisture depletion (mm) for grazed plots (top) and ungrazed plots (bottom) within Paddock 2 (n = 10) and Paddock 7 (n = 20) during the study period. Stars in each graph indicate treatment differences ($p < 0.05$) between paddocks based on a one-way analysis of variance at each sample date.

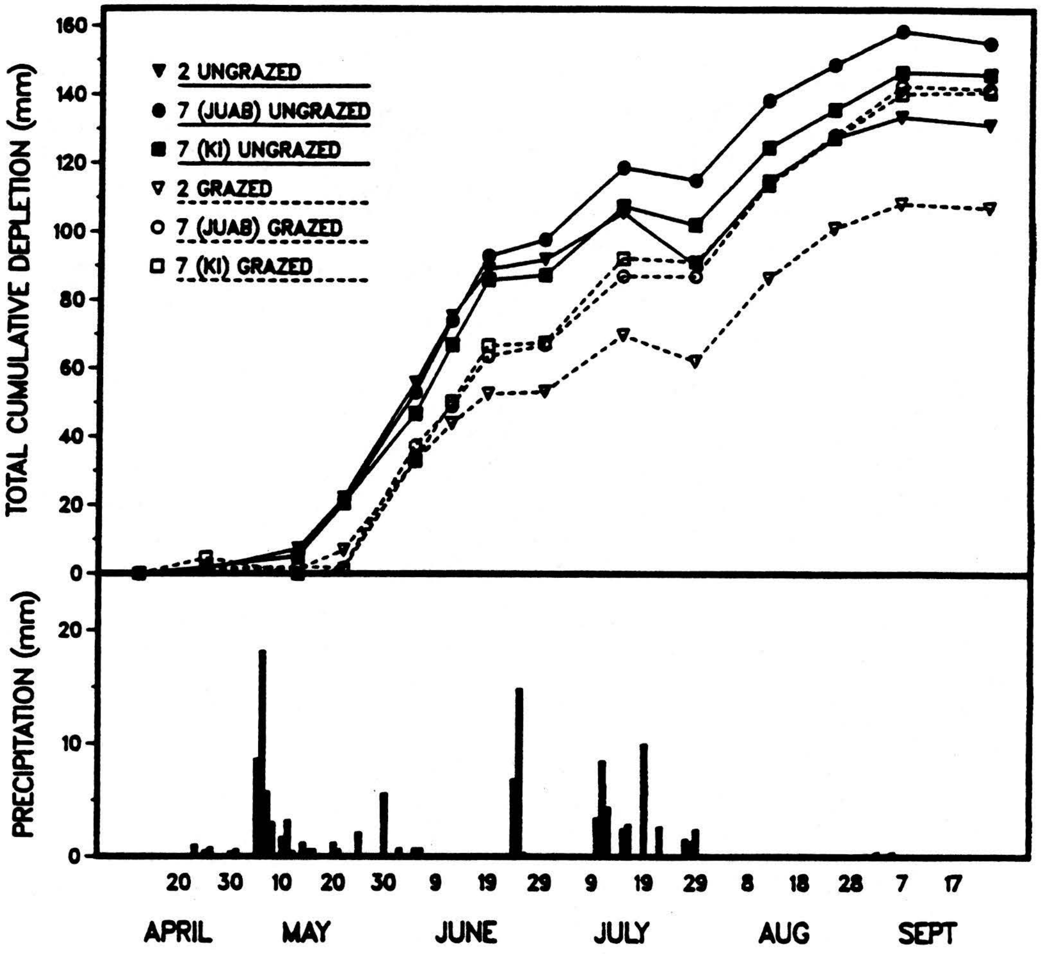

Fig. 10. Total cumulative soil moisture depletion (mm) for all treatments from 13 April to 25 September in 1985. Each point is the mean of 10 access tubes. Bars in the lower graph represent daily precipitation totals (mm).

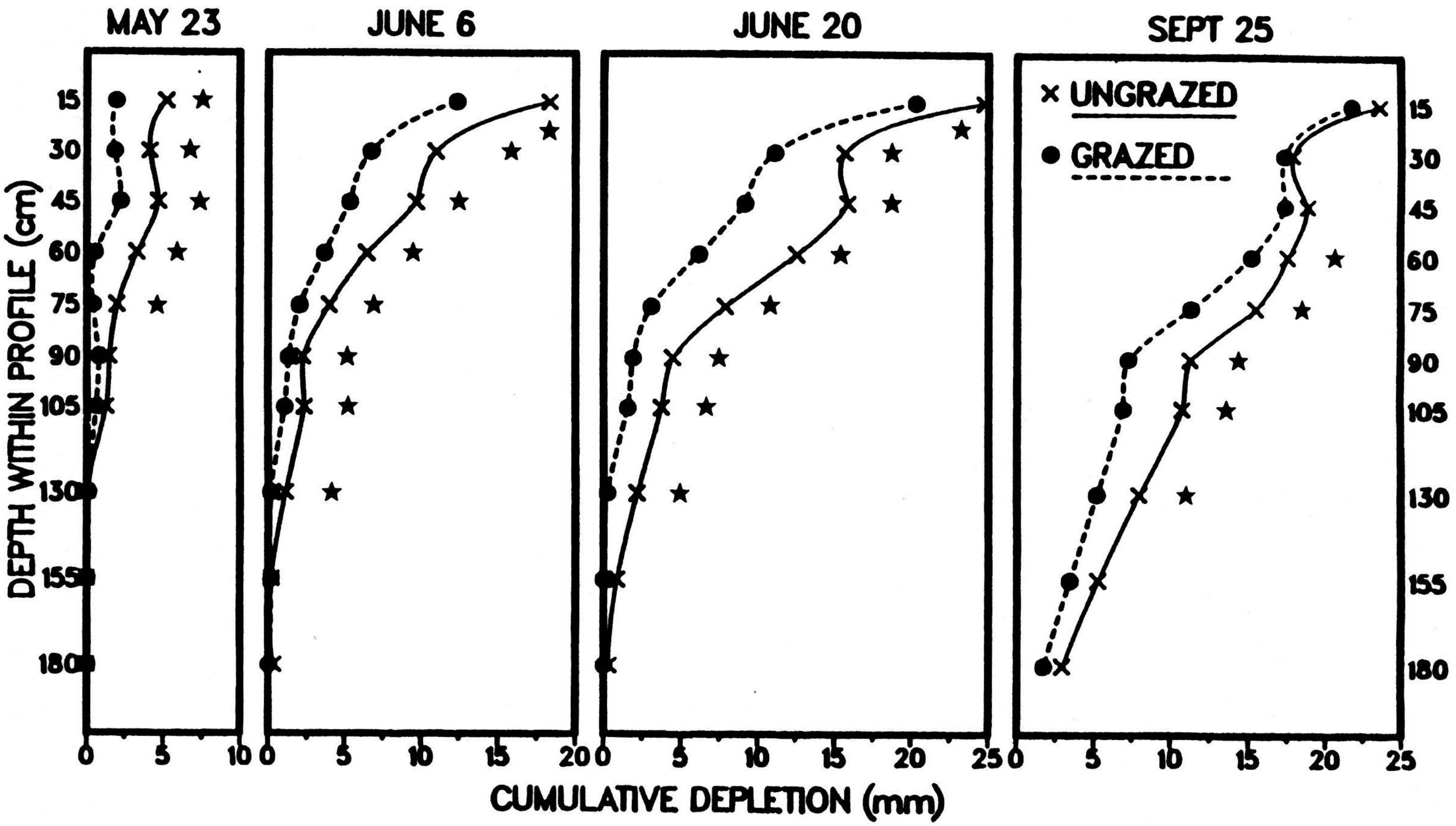

Fig. 11. Seasonal pattern of cumulative soil moisture depletion (mm) as a function of soil depth (cm) within Paddock 2 for grazed and ungrazed treatments on four measurement dates in 1985. The lines connecting the points were interpolated using a spline function. Each data point represents the mean of 10 observations. Stars indicate the depths at which treatment differences were statistically significant ($p < 0.05$) based on a one-way analysis of variance at each measurement date.

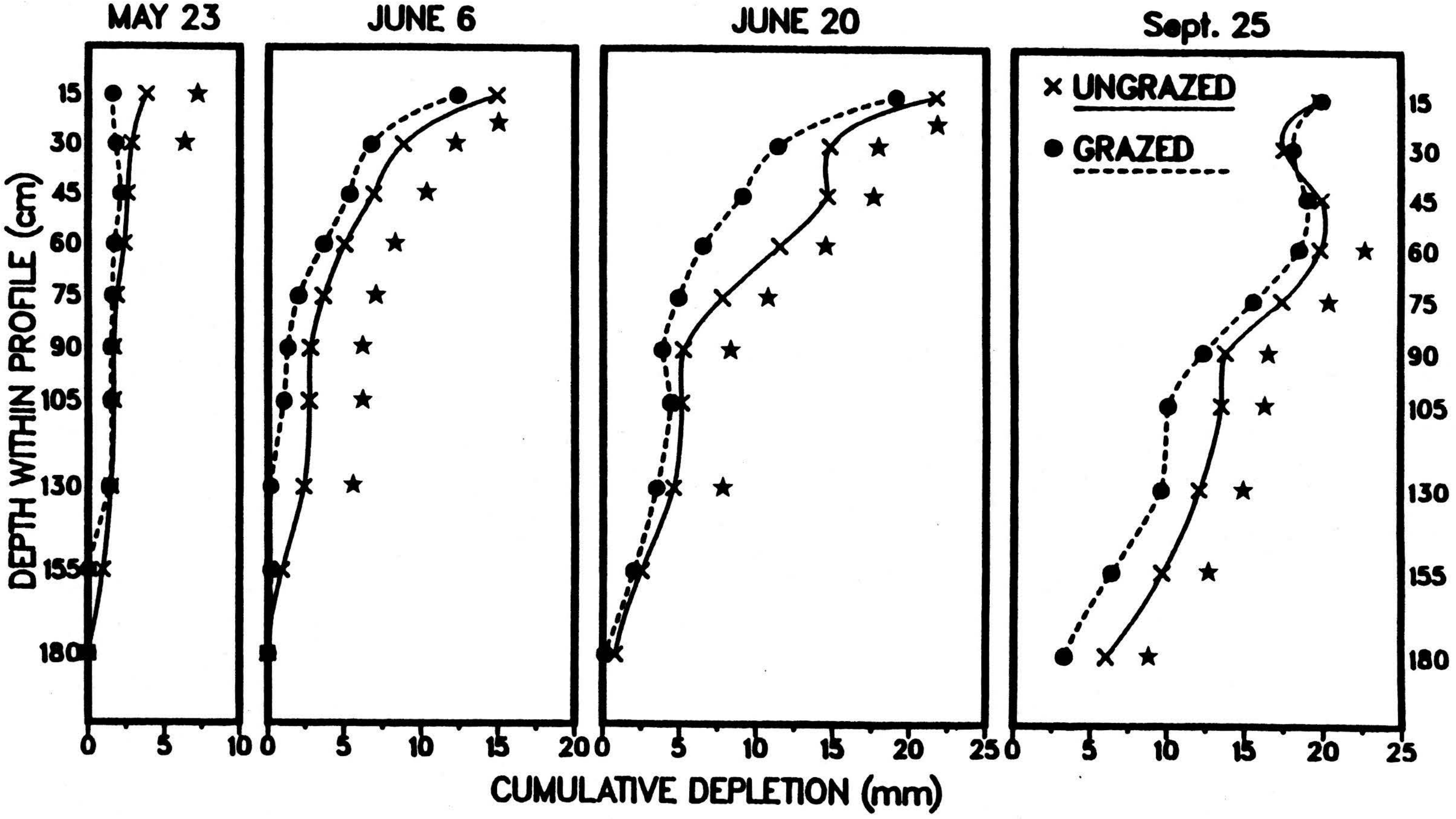

Fig. 12. Seasonal pattern of cumulative soil moisture depletion (mm) as a function of soil depth (cm) within Paddock 7 for grazed and ungrazed treatments on four measurement dates in 1985. The lines connecting the points were interpolated using a spline function. Each data point represents the mean of 10 observations. Stars indicate the depths at which treatment differences were statistically significant ($p < 0.05$) based on a one-way analysis of variance at each measurement date.

period for Paddocks 2 and 7, respectively. By 23 May, after each paddock had been grazed twice, ungrazed plots had extracted more total cumulative soil moisture than grazed plots to a depth of 83 cm in Paddock 2 and to 38 cm in Paddock 7. Ungrazed plots continued to extract more water to 143 cm than grazed plots by 6 June in both paddocks. Plant regrowth and subsequently higher rates of soil water depletion by defoliated plants during the latter part of the study reduced this difference in the upper soil profile by 25 September. On that date there was no difference between treatments in total cumulative depletion through 53 cm, but ungrazed plots had extracted relatively more water from the 53 to 143 cm depths in the soil profile than grazed plots within both paddocks. By 25 September plots within Paddock 7 had depleted somewhat more soil moisture from depths below 83 cm than plots in Paddock 2. This difference would be expected if soil moisture was recharged to a greater extent in Paddock 2 than compared to Paddock 7 during July (as discussed earlier).

Computer simulation of changes in soil water content agreed extremely well with actual field data (Table 2). Model inputs including initial water content at each depth, potential evapotranspiration, and relationships between soil moisture parameters were based on field-observed values. Because the model indicated only 0.016 mm of drainage during the early season when soil water content was highest, the assumption that soil moisture depletion during the study was due solely to evapotranspiration was supported.

Table 2. Comparison of field data with predicted values of volumetric soil water content and depth equivalent obtained from model SOWATET (modified from Childs and Hanks 1975) for the period of 13 April to 14 May in 1985. Field values are the means of 10 access tubes.

Soil depth (cm)	Vol. water content		Depth equivalent (mm)	
	Field	Model	Field	Model
0 - 22.5	0.252	0.246	56.66	55.46
22.5 - 37.5	0.225	0.226	33.70	33.93
37.5 - 52.5	0.235	0.235	35.28	35.22
52.5 - 67.5	0.239	0.236	35.90	35.43
67.5 - 82.5	0.256	0.257	38.36	38.59
82.5 - 97.5	0.269	0.272	40.37	40.87
97.5 - 117.5	0.264	0.270	52.73	54.05
117.5 - 142.5	0.253	0.255	63.19	63.75
142.5 - 167.5	0.247	0.246	61.80	61.62
167.5 - 192.5	0.269	0.265	67.21	66.19
192.5 - 217.5	0.252	0.255	62.98	63.75
217.5 - 242.5	0.240	0.239	59.98	59.87
			-------	-------
	Sum thru 192.5 cm		485.20	485.14
	Sum thru 242.5 cm		608.16	608.76

Model estimate of drainage beyond 192.5 cm: 0.016 mm

Plant Water Status

Predawn leaf xylem pressure potentials exhibited a general decline throughout the season with values remaining above -1.4 MPa (Fig. 13). Midday values declined to a greater extent during the season and ranged between -1.4 and -3.3 MPa. Grazing had no effect on predawn leaf water potential prior to 1 July, but predawn leaf water potentials were significantly lower for ungrazed than grazed plants after 1 July. Midday leaf water potentials were significantly lower for grazed than ungrazed plants before 1 July, but did not differ after 1 July.

When analyzed over the entire season, predawn leaf pressure potentials were lower for ungrazed plants; however, grazed and ungrazed plants did not exhibit differences in midday leaf pressure potentials. Time of grazing had no effect on either predawn or midday leaf xylem pressure potentials during the study period.

Both predawn and midday xylem pressure potentials were highly correlated with soil moisture content throughout most of the profile during the pre-July period and for the season as a whole (Table 3). During the July to September period, this correlation for ungrazed plants was similar to that before 1 July, but was shifted slightly deeper within the soil profile. Grazed plants showed no correlation between predawn pressure potentials and soil moisture content after 1 July, while midday values for grazed plants during this same time period were only significantly correlated with soil moisture for the 0 to 38 cm increment.

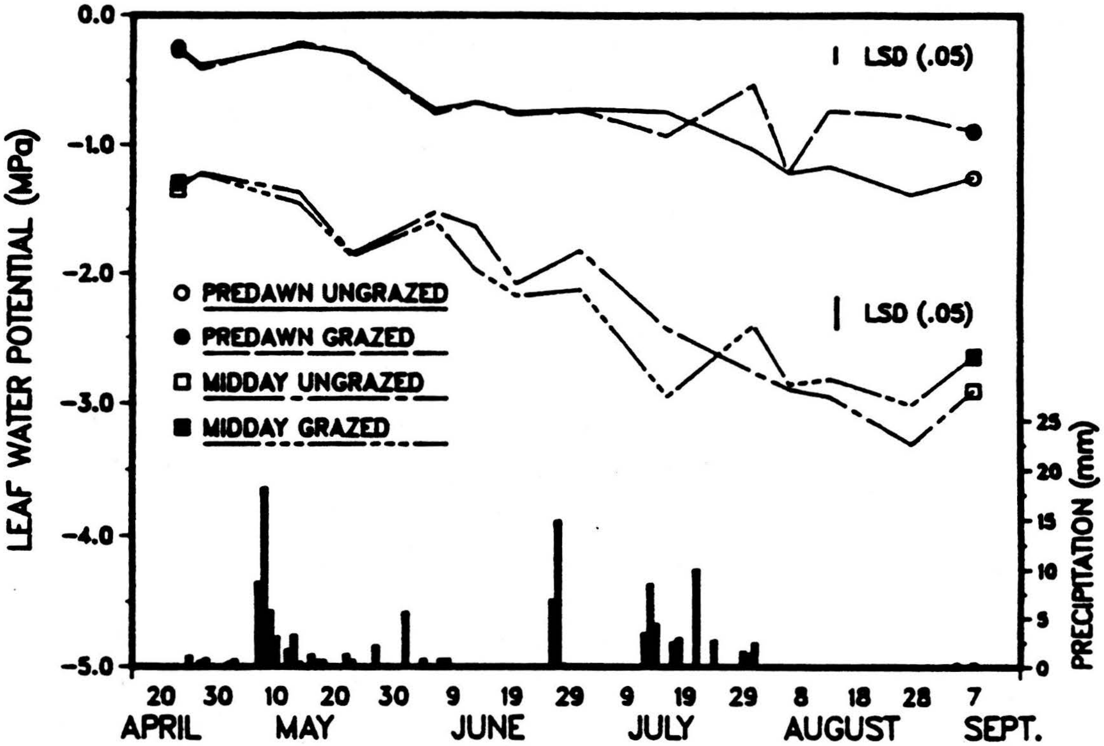

Fig. 13. Predawn and midday leaf water potentials (MPa) as estimated by a pressure chamber technique for grazed and ungrazed crested wheatgrass plants during the study period. Values are combined over both paddocks (n = 30). Bars at the bottom of the figure represent daily precipitation totals (mm).

Table 3. Correlations between mean leaf water potential and mean soil moisture content by depth within the soil profile. Significant ($p < 0.05$) correlation coefficients are followed by an asterisk. The soil profile was divided into increments of 0-38, 38-68, 68-98, 98-143, 143-193 cm, and the mean soil moisture content for the entire profile (0-193 cm).

Depth	Predawn leaf water potential		Midday leaf water potential	
(cm)	Ungrazed	Grazed	Ungrazed	Grazed
	--------------------Through	July 1	------------------------	
0-38	0.946*	0.951*	0.716*	0.805*
38-68	0.831*	0.869*	0.714*	0.805*
68-98	0.806*	0.884*	0.723*	0.788*
98-143	0.871*	0.691*	0.497	0.831*
143-193	0.307	0.347	0.627	0.435
0-193	0.897*	0.924*	0.728*	0.826*
	----------------------After	July 1	-----------------------	
0-38	0.584	0.312	0.603	0.755*
38-68	0.867*	-0.027	0.797*	0.261
68-98	0.827*	-0.006	0.791*	0.140
98-143	0.867*	0.205	0.797*	0.297
143-193	0.729*	-0.035	0.540	0.162
0-193	0.802*	0.103	0.730*	0.382
	----------------------Whole	Season	----------------------	
0-38	0.846*	0.829*	0.747*	0.905*
38-68	0.909*	0.693*	0.892*	0.913*
68-98	0.942*	0.636*	0.943*	0.866*
98-143	0.954*	0.658*	0.939*	0.892*
143-193	0.870*	0.508	0.909*	0.804*
0-193	0.941*	0.735*	0.906*	0.922*

DISCUSSION

Seasonal Water Balance

DeJong and MacDonald (1975) studied the soil moisture regime under a native grassland in Saskatchewan. They reported that soil moisture extraction started about mid-April and continued to mid-September or later with the most rapid water use occurring in May, June, and July. Water use exceeded precipitation during the growing season in their study and accounted for 90% of the annual precipitation received. Their findings were quite similar to the pattern observed in the present study at Tintic. Of the 312.5 mm average total evapotranspiration measured at Tintic during the study period, 56% (176 mm) came from precipitation and 44% (137 mm) was from soil moisture storage. This amounted to 84% of the year's precipitation at the site. Evapotranspiration during the fall and evaporation during winter and early spring, coupled with small amounts of runoff during the year probably account for the remaining yearly precipitation. There are no perennial streams on the Tintic study site, and percolation of water beyond the rooting zone is probably negligible (see discussion below).

Potential evapotranspiration (that which would occur under conditions of 100% vegetative cover and unlimited soil moisture) is a function of the energy available to change moisture from the liquid to the vapor state. Actual evapotranspiration refers to the rate of evapotranspiration (ET) measured under a given set of field conditions. Vegetative characteristics such as leaf area and leaf conductance in combination with soil factors including moisture content and the rate at which moisture can be transmitted to evaporative surfaces affect actual evapotranspiration rates. Actual evapotranspiration was relatively close to potential evapotranspiration during April (Fig. 14) when the soil was moist and temperature and solar irradiation were relatively low. However, actual and potential evapotranspiration differed markedly after this period. Potential ET rates rose to over 7 mm d^{-1} during June through August, then dropped back to 3 mm d^{-1} by September 25. The relatively cool and rainy weather during late July caused potential ET to decline during that period. Because moisture was periodically applied to the soil by precipitation, actual ET rates were fairly constant at approximately 2.0 to 2.4 mm d^{-1} through June, then declined rather gradually to near 1.4 mm d^{-1} by early fall.

Soil Moisture Depletion

The possibility of vertical soil moisture flux is a concern in water balance studies involving the rooting zone. The conclusion that no significant drainage occurred during this study is in agreement with Scholl (1976), Ng and Miller (1980), and Rambal (1984), who suggested that no measurable drainage loss occurred under annual precipitation totals below approximately 540 to 600 mm. Soil texture and structure in combination with precipitation patterns can affect the transmission of water through soil profiles. The silt loam soils investigated in this study should allow less potential drainage under similar conditions than the relatively more coarse soils involved in the studies of Scholl (1976) and Ng and Miller (1980). Additionally, during the periods of intense precipitation observed at Tintic during

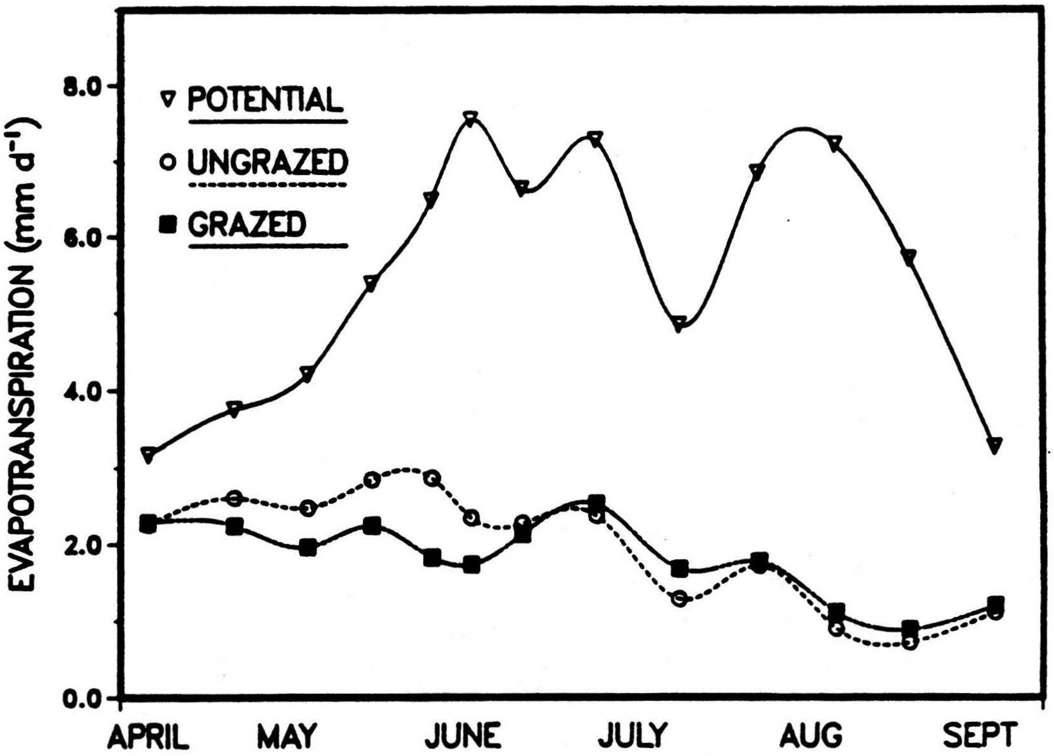

Fig. 14. Actual and potential evapotranspiration rates (mm d^{-1}) during the study period. Potential evapotranspiration is the mean of Class A Pan and Jensen-Haise calculations. Grazed and ungrazed values are means of 30 access tubes.

July, rainfall did not exceed the soil moisture deficit of the soil profile (Fig. 10). Little moisture was depleted from the deepest portion of the soil profile in the present study until late in the season. Consequently, hydraulic gradients across the lower boundary would have been minimal during most of the season, indicating that significant upward flux probably also did not occur.

More soil moisture was depleted in ungrazed plots than grazed plots during the spring and early-summer period in this study. The opposite pattern was noted during late-summer and early fall in Paddock 7, while no treatment difference occurred in Paddock 2 during that period. These responses for the early and late-season time periods tended to cancel each other when summed over the entire season. This emphasizes the importance of examining the patterns of water use through time rather than merely the net seasonal result.

Soil water use was highest in late-May through June, due to warm air temperatures in combination with relatively high residual soil moisture contents. Soil moisture depletion was lower in July than in May and June, largely due to the considerable precipitation received that month (Fig. 3). The 7 cm of precipitation that fell on the study site during July supplied additional moisture to the soil, resulting in fairly high depletion rates in early August. These depletion rates declined rather rapidly as this moisture was exhausted and plants became less physiologically active later in the month.

Several authors (Nnyamah and Black 1977, Sala et al. 1981, Rambal 1984) have noted that during the early growing season water is extracted from the upper soil layers where rooting density is highest.

As the soil dries, the deeper layers are increasingly utilized. This is especially pronounced in areas with dry growing seasons or where precipitation is prevented from reaching the soil. However, it was also evident in the present study at Tintic where 51% of the yearly precipitation was received during the 6-month study period. This precipitation pattern periodically added water to the upper soil profile, reducing the utilization of stored soil moisture. Approximately 65% of the soil moisture that had been depleted by 20 June in ungrazed plots and 85% of soil moisture depleted by that date in grazed plots was from the top 68 cm of the soil profile. By 25 September considerable quantities of moisture were depleted from sample depths greater than 1.0 m in the soil profile (Figs. 11 and 12).

Caldwell et al. (1981) and Richards (1984) noted that crested wheatgrass plants curtailed root production by up to 50% in response to defoliation, thus facilitating a return to the preclipping root-shoot balance. Rambal (1984) suggested that the late-spring profile of water uptake can be considered as an estimate of the rooting density profile of actively transpiring vegetation. The lower rate and amount of soil water depletion within grazed plots during the pre-July period in the present study was presumably due to a combination of reduced leaf surface area and decreased rooting densities for grazed plants during that time, although direct measurements of these parameters were not made.

Temperatures and daylength increased as the grazing season progressed, resulting in higher evaporative demands on plants within the grazing cell. Plants that were grazed earlier during the grazing season would have attained a higher degree of regrowth in relation to this increasing atmospheric evaporative demand when integrated over the grazing season. This may partially account for the greater extraction of soil moisture by 1 July for plots within Paddock 7 than those within Paddock 2, which were grazed on a later schedule during each cycle. Differences in the phenologic development of crested wheatgrass plants within Paddocks 2 and 7 at the time they were defoliated may have affected their regrowth and subsequent water use responses. Plant phenological development was not specifically monitored during this study, however.

Non-defoliated plants appeared to have considerably greater total leaf area during the July through September period, but tissue senescence on these plants was more advanced than on defoliated plants. Caldwell et al. (1981) found that leaf blades of crested wheatgrass that regrew following defoliation exhibited higher photosynthetic rates than foliage on control plants. Greater residual soil moisture content in grazed areas compared to ungrazed areas during part of this period (Fig. 8) probably also contributed to the higher extraction rates by grazed plants within Paddock 7. Paddock 2 did not exhibit differences between grazing treatments during this interval; however, this may have been due in part to a difference in recovery from defoliation related to the difference in time of grazing.

Although significant differences in soil moisture depletion within the mid and lower soil profiles were noted between grazed and ungrazed plots at the end of this study (Figs. 11 and 12), these were not sufficient to create a statistical difference in total cumulative depletion between defoliated and non-defoliated plots due to the relatively large proportion of soil moisture depleted within the upper portion of the profiles. The approximately 13.7 cm of stored soil moisture that was depleted during the 13 April to 25 September period in 1985 should be completely recharged by the 20.6 cm average precipitation total received during the balance of the year at Tintic (Fig. 3). This would be true even if some of this precipitation were lost to evaporation and surface runoff during the recharge period. The relatively small but statistically significant differences in soil moisture content between grazed and ungrazed plots deep in the profile on 25 September are therefore probably not important.

Plant Water Status

Grazed plants experienced lower midday leaf xylem pressure potentials than ungrazed plants during the grazing season, but recovered equally well by early morning (Fig. 13). Midday leaf pressure potential values were more variable between plots and from week to week than were predawn measurements because of the greater effect of fluctuating atmospheric conditions such as incident radiation, temperature, and humidity on midday plant water deficits. Because midday leaf water potentials were above -2.2 MPa during this pre-July period, crested wheatgrass plants were probably not under a high degree of water stress (Johnson 1978, Frank 1981).

The flush of new growth by grazed plants in response to July precipitation resulted in a dramatic increase in both predawn and midday leaf pressure potentials between the 16 and 30 July measurement dates (Fig. 13). A short period of cold weather in early August may have been the cause of the sharp decline in leaf pressure potentials of grazed plants to values similar to those of ungrazed plants for the 6 August measurements. However, this probable response to chilling was short-lived. Grazed plants had higher predawn leaf water potentials than ungrazed plants during the latter part of the study. These higher potentials were a result of a relatively more favorable soil moisture profile (Figs. 11 and 12) and more physiologically active leaves in the grazed plots.

Differences in rooting density in combination with gradients in soil moisture with depth and with atmospheric demands affect plant responses to water supply (Waring and Cleary 1967, Ritchie and Hinckley 1975, Sala et al. 1981). Leaf xylem pressure potential is a measure of the instantaneous water deficit experienced by a plant and does not necessarily indicate rate of water uptake. Plants that differ in leaf area, rooting density, or leaf physiological activity may have dissimilar transpiration rates yet experience essentially the same water deficit. Even though differences in total soil water content and soil moisture content with depth existed between treatment plots during much of the season (Figs. 9, 11 and 12), these soil differences were apparently buffered somewhat by the plant. Consequently, differences in soil moisture depletion during the season between grazed and ungrazed plots did not always produce significant differences in leaf pressure potential (Fig. 13). Differences in soil moisture depletion between plots that were grazed at different times did not result in any significant differences in predawn or midday leaf pressure potential. The ability of a plant to extract water from different portions of the soil profile may at least partially compensate for these soil differences. This is supported by the observation that both predawn and midday leaf water potentials of crested wheatgrass plants in the present study were highly correlated with soil water content throughout much of the soil profile (Table 3).

Implications

The present study demonstrated that the net seasonal water balance of a foothill crested wheatgrass pasture in central Utah was not affected by a spring short duration grazing treatment; however, differences were observed in water use patterns between grazed and ungrazed plots during the critical spring and early-summer period. These differences may be important in influencing growth and competitive relationships within crested wheatgrass communities.

In a near monoculture pasture, as was the case in the present study, plants tend to be utilized relatively uniformly under short duration grazing. Deferred soil water use due to defoliation might allow a lengthening of the grazing season under near-monoculture conditions. After the final grazing cycle in the present study, defoliated plants had been heavily utilized and appeared not able to tolerate additional use. However, under an intensively managed short duration grazing system using plant physiological development as a criterion for scheduling the rotation of livestock through individual paddocks, similar soil moisture responses might allow grazing to continue longer into the summer.

In a mixed-species pasture or where non-palatable shrubs are present, defoliated plants may be competing for soil resources with neighbors that are not palatable to grazing animals or that are utilized to a significantly lesser extent. Moisture that is not extracted by crested wheatgrass plants during the spring grazing season under these conditions may not be available for their use later in the growing season. The lower amount of soil moisture depleted within plots that were grazed 9 days later in the present study suggests that initial grazing should be rotated among paddocks from year to year in situations where this type of competition for soil moisture might be an important factor.

Managing for soil moisture may be an effective tool in achieving maximum on-site water use efficiency for forage production in semiarid rangelands. Further research should be conducted to investigate the feasibility of manipulating soil moisture depletion patterns to accomplish this goal. Studies involving different plant communities as well as research conducted at different locations should indicate whether the responses observed at Tintic are representative of those that would occur under other semiarid rangeland conditions. Additional research is also needed to examine competitive relationships between differentially defoliated co-occurring plant species in rangeland environments.

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APPENDIX

Summary Of Statistical Analyses

Paddock 2, Depletion Rate (See Fig. 8)

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.007	1	0.277	1	0.120
error a	4		4		4	
Depths	9	0.000	9	0.000	9	0.000
error b	36		36		36	
G x D	9	0.000	9	0.000	9	0.064
error c	36		36		36	
Weeks	6	0.000	5	0.000	12	0.000
error d	24		20		48	
G x W	6	0.000	5	0.210	12	0.000
D x W	54	0.000	45	0.000	108	0.000
G x D x W	54	0.046	45	0.038	108	0.000
error e	456		380		912	
Residual	700		600		1300	
Total	1399		1199		2599	

Paddock 7 (Juab), Depletion Rate

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.008	1	0.018	1	0.080
error a	4		4		4	
Depths	9	0.000	9	0.000	9	0.000
error b	36		36		36	
G x D	9	0.000	9	0.000	9	0.508
error c	36		36		36	
Weeks	6	0.000	5	0.000	12	0.000
error d	24		20		48	
G x W	6	0.000	5	0.040	12	0.000
D x W	54	0.000	45	0.000	108	0.000
G x D x W	54	0.000	45	0.000	108	0.000
error e	456		380		912	
Residual	700		600		1300	
Total	1399		1199		2599	

Paddock 7 (Ki), Depletion Rate

source	Through 7-1 df	Through 7-1 P	After 7-1 df	After 7-1 P	Whole Season df	Whole Season P
Reps	4		4		4	
Grazing	1	0.122	1	0.051	1	0.570
error a	4		4		4	
Depths	9	0.000	9	0.000	9	0.000
error b	36		36		36	
G x D	9	0.003	9	0.015	9	0.834
error c	36		36		36	
Weeks	6	0.000	5	0.000	12	0.000
error d	24		20		48	
G x W	6	0.006	5	0.265	12	0.000
D x W	54	0.000	45	0.000	108	0.000
G x D x W	54	0.000	45	0.002	108	0.000
error e	456		380		912	
Residual	700		600		1300	
Total	1399		1199		2599	

Paddock 7 Pooled, Depletion Rate (See Fig. 8)

source	Through 7-1 df	Through 7-1 P	After 7-1 df	After 7-1 P	Whole Season df	Whole Season P
Reps	9		9		9	
Grazing	1	0.000	1	0.002	1	0.087
error a	9		9		9	
Depths	9	0.000	9	0.599	9	0.000
error b	81		81		81	
G x D	9	0.000	9	0.000	9	0.012
error c	81		81		81	
Weeks	6	0.000	5	0.000	12	0.000
error d	54		45		108	
G x W	6	0.004	5	0.108	12	0.000
D x W	54	0.000	45	0.000	108	0.000
G x D x W	54	0.241	45	0.000	108	0.000
error e	1026		855		2052	
Residual	1400		1200		2600	
Total	2799		2399		5199	

Paddocks 2 and 7 Combined, Depletion Rate

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Time of Grazing	2	0.065	2	0.005	2	0.006
2 vs 7b + 7t	1	---	1	0.001	1	0.002
7b vs 7t	1	---	1	0.922	1	0.851
error a	12		12		12	
Grazing	1	0.000	1	0.005	1	0.018
TG x G	2	0.142	2	0.928	2	0.412
2 vs 7 (ungr.)	1	0.709	1	0.020	1	0.097
2 vs 7 (graz.)	1	0.008	1	0.012	1	0.005
error b	12		12		12	
Depths	9	0.000	9	0.000	9	0.000
error c	36		36		36	
TG x D	18	0.000	18	0.000	18	0.000
G x D	9	0.000	9	0.000	9	0.000
TG x G x D	18	0.774	18	0.693	18	0.892
error d	180		180		180	
Weeks	6	0.000	5	0.000	12	0.000
error e	24		20		48	
TG x W	12	0.000	10	0.000	24	0.000
G x W	6	0.000	5	0.144	12	0.000
D x W	54	0.000	45	0.000	108	0.000
TG x G x W	12	0.007	10	0.232	24	0.001
TG x D x W	108	0.000	90	0.001	216	0.000
G x D x W	54	0.000	45	0.000	108	0.000
TG x G x D x W	108	0.985	90	1.000	216	0.999
error f	1416		1180		2832	
Residual	2100		1800		3900	
Total	4199		3599		7799	

Paddock 2, Total Cumulative Depletion (See Fig. 8)

source	df	4-26 P	5-14 P	5-23 P	6-6 P	6-13 P	6-20 P	7-1 P
Reps	4							
Grazing	1	0.942	0.263	0.043	0.025	0.021	0.017	0.014
error a	4							
Depths	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000
error b	36							
G x D	9	0.945	0.228	0.316	0.000	0.000	0.000	0.000
error c	36							
Residual	100							
Total	199							

source	df	7-16 P	7-30 P	8-13 P	8-26 P	9-8 P	9-25 P
Reps	4						
Grazing	1	0.037	0.085	0.138	0.226	0.276	0.293
error a	4						
Depths	9	0.000	0.000	0.000	0.000	0.000	0.000
error b	36						
G x D	9	0.009	0.055	0.084	0.047	0.151	0.186
error c	36						
Residual	100						
Total	199						

Paddock 7 Pooled, Total Cumulative Depletion (See Fig. 8)

source	df	4-26 P	5-14 P	5-23 P	6-6 P	6-13 P	6-20 P	7-1 P
Reps	9							
Grazing	1	0.670	0.199	0.180	0.011	0.001	0.002	0.002
error a	9							
Depths	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000
error b	81							
G x D	9	0.927	0.621	0.088	0.000	0.000	0.001	0.000
error c	81							
Residual	200							
Total	399							

source	df	7-16 P	7-30 P	8-13 P	8-26 P	9-8 P	9-25 P
Reps	9						
Grazing	1	0.004	0.010	0.023	0.067	0.154	0.218
error a	9						
Depths	9	0.000	0.000	0.000	0.000	0.000	0.000
error b	81						
G x D	9	0.000	0.000	0.095	0.383	0.506	0.611
error c	81						
Residual	200						
Total	399						

Paddocks 2 and 7 Combined, Cumulative Depletion, Grazed Plots Only
(See Fig. 9)

source	df	4-26 P	5-14 P	5-23 P	6-6 P	6-13 P	6-20 P	7-1 P
Time of Grazing	2	0.429	0.810	0.283	0.584	0.479	0.048	0.039
Residual	27							
Total	29							

source	df	7-16 P	7-30 P	8-13 P	8-26 P	9-8 P	9-25 P
Time of Grazing	2	0.004	0.000	0.001	0.008	0.002	0.002
Residual	27						
Total	29						

Paddocks 2 and 7 Combined, Cumulative Depletion, Ungrazed Plots Only
(See Fig. 9)

source	df	4-26 P	5-14 P	5-23 P	6-6 P	6-13 P	6-20 P	7-1 P
Time of Grazing	2	0.832	0.545	0.745	0.264	0.363	0.950	0.925
Residual	27							
Total	29							

source	df	7-16 P	7-30 P	8-13 P	8-26 P	9-8 P	9-25 P
Time of Grazing	2	0.301	0.021	0.035	0.086	0.042	0.032
Residual	27						
Total	29						

Paddocks 2 and 7 Combined, Total Cumulative Depletion
(See Figs. 11 and 12)

		4-26	5-14	5-23	6-6	6-13	6-20	7-1
source	df	P	P	P	P	P	P	P
Time of Grazing	2	0.571	0.905	0.680	0.570	0.856	0.544	0.368
2 vs 7b + 7t	1	---	---	---	---	---	---	---
7b vs 7t	1	---	---	---	---	---	---	---
error a	12							
Grazing	1	0.751	0.090	0.019	0.001	0.000	0.000	0.000
TG x G	2	0.790	0.864	0.401	0.596	0.376	0.379	0.310
error b	12							
Depths	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000
error c	36							
TG x D	18	0.980	0.000	0.003	0.000	0.000	0.000	0.000
G x D	9	0.967	0.215	0.009	0.000	0.000	0.000	0.000
TG x G x D	18	0.996	0.958	0.897	0.951	0.996	0.979	0.873
error d	180							
Residual	300							
Total	599							

		7-16	7-30	8-13	8-26	9-8	9-25
source	df	P	P	P	P	P	P
Time of Grazing	2	0.111	0.005	0.011	0.034	0.017	0.018
2 vs 7b + 7t	1	---	0.001	0.000	0.003	0.001	0.002
7b vs 7t	1	---	0.392	0.138	0.258	0.281	0.467
error a	12						
Grazing	1	0.000	0.002	0.008	0.034	0.080	0.110
TG x G	2	0.298	0.377	0.543	0.636	0.653	0.619
error b	12						
Depths	9	0.000	0.000	0.000	0.000	0.000	0.000
error c	36						
TG x D	18	0.001	0.200	0.000	0.000	0.000	0.000
G x D	9	0.000	0.000	0.004	0.043	0.074	0.149
TG x G x D	18	0.947	0.971	0.976	0.953	0.982	0.948
error d	180						
Residual	300						
Total	599						

Paddock 2, Predawn Leaf Water Potential

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.942	1	0.005	1	0.013
error a	4		4		4	
Weeks	7	0.000	5	0.012	13	0.000
error b	28		20		52	
G x W	7	0.177	5	0.010	13	0.000
error c	28		20		52	
Residual	80		60		140	
Total	159		119		279	

Paddock 2, Midday Leaf Water Potential

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.034	1	0.061	1	0.465
error a	4		4		4	
Weeks	7	0.000	5	0.001	13	0.000
error b	28		20		52	
G x W	7	0.509	5	0.085	13	0.006
error c	28		20		52	
Residual	80		60		140	
Total	159		119		279	

Paddock 7 (Juab), Predawn Leaf Water Potential

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.496	1	0.005	1	0.007
error a	4		4		4	
Weeks	7	0.000	5	0.007	13	0.000
error b	28		20		52	
G x W	7	0.736	5	0.000	13	0.000
error c	28		20		52	
Residual	80		60		140	
Total	159		119		279	

Paddock 7 (Juab), Midday Leaf Water Potential

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.088	1	0.730	1	0.267
error a	4		4		4	
Weeks	7	0.000	5	0.020	13	0.000
error b	28		20		52	
G x W	7	0.157	5	0.006	13	0.002
error c	28		20		52	
Residual	80		60		140	
Total	159		119		279	

Paddock 7 (Ki), Predawn Leaf Water Potential

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.280	1	0.078	1	0.125
error a	4		4		4	
Weeks	7	0.000	5	0.001	13	0.000
error b	28		20		52	
G x W	7	0.160	5	0.014	13	0.000
error c	28		20		52	
Residual	80		60		140	
Total	159		119		279	

Paddock 7 (Ki), Midday Leaf Water Potential

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Reps	4		4		4	
Grazing	1	0.836	1	0.474	1	0.458
error a	4		4		4	
Weeks	7	0.000	5	0.031	13	0.000
error b	28		20		52	
G x W	7	0.971	5	0.674	13	0.903
error c	28		20		52	
Residual	80		60		140	
Total	159		119		279	

Paddock 7 Pooled, Predawn Leaf Water Potential

source	Through 7-1 df	Through 7-1 P	After 7-1 df	After 7-1 P	Whole Season df	Whole Season P
Reps	9		9		9	
Grazing	1	0.193	1	0.003	1	0.010
error a	9		9		9	
Weeks	7	0.000	5	0.000	13	0.000
error b	63		45		117	
G x W	7	0.666	5	0.054	13	0.000
error c	63		45		117	
Residual	160		120		280	
Total	319		239		559	

Paddock 7 Pooled, Midday Leaf Water Potential

source	Through 7-1 df	Through 7-1 P	After 7-1 df	After 7-1 P	Whole Season df	Whole Season P
Reps	9		9		9	
Grazing	1	0.252	1	0.795	1	0.712
error a	9		9		9	
Weeks	7	0.000	5	0.595	13	0.000
error b	63		45		117	
G x W	7	0.244	5	0.299	13	0.315
error c	63		45		117	
Residual	160		120		280	
Total	319		239		559	

Paddocks 2 and 7 Combined, Predawn Leaf Water Potential
(See Fig. 13)

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Paddock	2	0.102	2	0.140	2	0.843
2 vs 7b + 7t	1	---	1	---	1	---
7b vs 7t	1	---	1	---	1	---
error a	12		12		12	
Grazing	1	0.228	1	0.000	1	0.000
TG x G	2	0.697	2	0.326	2	0.304
error b	12		12		12	
Weeks	7	0.000	5	0.000	13	0.000
error c	28		20		52	
TG x W	14	0.002	10	0.278	26	0.000
G x W	7	0.963	5	0.000	13	0.000
TG x G x W	14	0.198	10	0.500	26	0.513
error d	140		100		260	
Residual	240		180		420	
Total	479		359		839	

Paddocks 2 and 7 Combined, Midday Leaf Water Potential
(See Fig. 13)

	Through 7-1		After 7-1		Whole Season	
source	df	P	df	P	df	P
Paddock	2	0.500	2	0.233	2	0.851
2 vs 7b + 7t	1	---	1	---	1	---
7b vs 7t	1	---	1	---	1	---
error a	12		12		12	
Grazing	1	0.007	1	0.178	1	0.532
TG x G	2	0.038	2	0.269	2	0.272
error b	12		12		12	
Weeks	7	0.000	5	0.007	13	0.000
error c	28		20		52	
TG x W	14	0.052	10	0.000	26	0.000
G x W	7	0.114	5	0.001	13	0.000
TG x G x W	14	0.977	10	0.180	26	0.259
error d	140		100		260	
Residual	240		180		420	
Total	479		359		839	