PART III

EXPERIMENTAL CHAPTERS

Chapter 7

Soil Water Relations under Grazed and Ungrazed Pasture

Abstract

High stocking rates may affect soil water content under grazed pastures by reducing infiltration, increasing evaporation and/or reducing transpiration. The net effect of these three mechanisms was measured in a 26-month study of soil water contents under pastures grazed at four stocking rates near Armidale, New South Wales, Australia. Soil water content was measured every 2–3 weeks using a neutron probe. Water content was occasionally higher under the ungrazed pasture near the soil surface. Differences between the grazed and ungrazed treatments were probably due to differences in evaporation rates.

The range of water contents measured in the field was compared with laboratory estimates of field capacity and permanent wilting point. During the drought conditions of 1993 and 1994, the pastures used most of the available soil water to at least 80 cm, and the surface soil was often drier than permanent wilting point.

Field-measured soil water deficits were compared with soil water deficits predicted from a simple water balance model. Good correlations between measured and predicted values were obtained for pastures grazed at low and medium stocking rates (r^2=0.86 and 0.84) but the measured soil water deficits under the ungrazed pasture was not predicted as well (r^2=0.64).

Introduction

Soil water content will vary with grazing regime if grazing has reduced the infiltration rate and runoff has occurred. The effect of defoliation and litter removal on the transpiration from pasture and the evaporation from soil will also influence soil water content. Litter and standing plant biomass can reduce evaporation by shading, insulating the soil from downward heat conduction and reducing wind speed at the soil surface (Russel 1939). Where grazing has altered the botanical composition of the pasture, there may be changes to the seasonal transpiration pattern which affect the soil water content.

Studies of the effects of grazing on soil water content have produced conflicting results. Langlands and Bennett (1973) found varying relationships between stocking rate and soil water content. At some times, the intermediate stocking rates were driest or there was no difference between treatments, while at other times, the stocking rate and soil water content were positively correlated. The higher soil water contents under the higher stocking rates were attributed to lower evapotranspiration from overgrazed pasture, which compensated for the lower infiltration rates. However, other studies (Johnston *et al.* 1971; Naeth *et al.* 1991b; Proffitt *et al.* 1993) have found less soil water under grazed treatments. The lack of a consistent effect of stocking rate on soil water is due to the opposing effects of stocking rate on the factors which affect soil water. Higher water contents at lower stocking rates are favoured by higher infiltration rates and lower evaporation due to greater plant cover. Conversely, lower transpiration rates may swing the balance in favour of higher water contents at higher stocking rates. The major water balance components and some factors which influence them are listed in Table 1.

Table 1. The main components of the soil water balance and some factors which influence them.

Water balance component	Influential factors
Evaporation	Near-surface soil water content
	Pan evaporation
	Plant cover
	Litter
Transpiration	Soil water content
	Pan evaporation
	Leaf area
	Root distribution
	Seasonal growth pattern
Runoff	Infiltration rates
	Rainfall intensity
	Soil water content
	Plant cover
	Microtopography
	Topography
Drainage	Soil water content
	Hydraulic gradient

In a study of root distribution and soil moisture, Pook and Costin (1971) pointed out the advantages of a deep root system to phalaris (*Phalaris aquatica*) in enabling it to survive during drought. At Armidale, New South Wales, Begg (1959) showed that phalaris pasture frequently dried the profile below permanent wilting point to depths of 1 m. Soil at 60 cm depth was usually wetter under native pastures.

The aim of the research described in this chapter was to determine how long-term grazing, at four stocking rates, affected soil moisture content. The ungrazed pasture was dominated by phalaris, while the grazed pastures included many annual species (Hutchinson *et al.* 1995). I expected that the soil profile would frequently be drier under the ungrazed pasture due to higher transpiration rates from the perennial phalaris. A simple soil water balance model (Scotter *et al.* 1979) was used to gain further insight into the differences between the stocking rate treatments.

Materials and Methods

Experiment location, history and design

The experimental area, known as Big Ridge 1 (lat. 30°38'S, long. 151°34'E, altitude 1065 m), is a long-term trial grazed at four stocking rates near Armidale, New South Wales. The region has a cool temperate climate with an average annual rainfall (1950–95) of 828 mm. The trial was established on CSIRO's Pastoral Research Laboratory.

In 1958, the experimental area was sown with phalaris (*Phalaris aquatica*) and white clover (*Trifolium repens*). The area was fenced into sixteen 0.40 ha plots in a 4x4 Latin square design to enable effects of slope and variation of soil type across the contour to be removed in statistical analyses. The average slope was 3%. Three soil types were identified in the experimental area by Schafer (1980): gleyed podzolic, prairie and wiesenboden (lateritic). Using the Australian soil classification (Isbell 1996), these soils correspond to brown chromosol, red ferrosol and brown ferrosol, respectively. A lateritic variant of the gleyed podzolic was also identified which had many ferromanganiferous nodules in some horizons below 15 cm.

Since 1963, the area has been set stocked at four rates by adult merino wethers (castrated male sheep), which were grazed year-long except during major droughts. When the trial commenced, the stocking rates were 10, 20, 30 and 40 sheep/ha. In 1969, all sheep from the 40 sheep/ha treatments were removed for animal welfare reasons and these plots have remained ungrazed. The stocking rates between 1983 and 1995 were 0, 10, 15 and 20 sheep/ha and will be referred to as the ungrazed, low, medium and high stocking rates. In January 1995, the stocking rates were reduced to 10 sheep/ha on all grazed plots.

After 30 years' grazing, the botanical composition of the pasture had been affected by stocking rate (Hutchinson *et al.* 1995). The ungrazed pasture was dominated by phalaris, a perennial grass. The botanical composition of the low and medium stocking rate plots included phalaris and other, mainly annual, grasses. At the high stocking rate, annual clovers and other dicot species were dominant. Further site details can be found in Hutchinson *et al.* (1995).

Sampling design

Four sites were selected in each plot using stratified random sampling. The plot was divided into four equal areas, along the longest axis, but not including areas within 10 m of each corner or within 1 m of fences, where sheep activity is concentrated. Triangular plots, resulting from a subdivision of some plots in 1978, were treated similarly. The soil physical measurements described in Chapter 6 were made at different locations to avoid sampling disturbance.

Rainfall and evaporation

Rainfall data were collected on working days at the experimental area (D.R. Wilkinson, unpubl. data). These rainfall data were supplemented by daily rainfall and evaporation (Australian standard tank) data recorded at the main weather station on CSIRO's Pastoral Research Laboratory, 3 km from the experimental area. Percentiles of monthly rainfall were calculated from data for 1950 to 1995 (George *et al.* 1977; C. Mulcahy, unpubl. data).

Soil profile water

Neutron probe access tubes were installed to enable measurements to a depth of at least 80 cm at each site. Installation of the access tubes followed the method described by Eeles (1969, cited in Prebble *et al.* 1981). A screw-type auger was used to auger ahead of a steel corer (Wilkinson and Burke 1995), which was bevelled on the inside. The corer was removed and the hole was reamed with a slightly larger diameter corer. The outside diameter of the reamer was slightly less than the outside diameter of the access tube, ensuring a snug fit between the access tube and the soil.

Measurements of soil water were taken with a CPN neutron probe (model number 503 DR) at 2–3 week intervals between 29 March 1993 and 9 June 1995. Measurements were made at 10 cm intervals to 80 cm using a count time of 16 seconds.

The neutron probe was calibrated at four locations adjacent to the experimental area. These locations were chosen to cover the range of soil types identified. At each location, three access tubes were installed and, after 32 second neutron probe counts were made, undisturbed cores were collected from a backhoe pit adjacent to one of the access tubes. Sampling was undertaken when the soil was dry, wet and intermediate. In two of the soil types, it was not possible to take core samples at lower depths due to a hard ironstone layer (ferricrete pan). In these cases, volumetric water content was calculated from the gravimetric water content and bulk density, determined using the Saran resin method (Brasher *et al.* 1966; Blake and Hartge 1986). The calibrations for each depth were calculated according to Greacen *et al.*

(1981) and are included in Appendix II. The calibration data for the lateritic wiesenboden at 60–80 cm depth, in the hard ironstone layer, were obviously in error as the slope was negative. The error was probably due to the small range of water contents of the calibration data. A new calibration was derived using a representative slope, from a horizon of high ironstone content in the lateritic podzolic soil, which was fitted through the average of the original data points to determine the intercept.

Data from individual access tubes were assigned calibrations for a given soil type based on profile descriptions of relatively undisturbed soil cores taken within each plot, observations made when installing the access tubes and behaviour of the raw data compared with nearby access tubes.

The experimental unit was considered to be the plot and hence, the data for the four access tubes within each plot have been averaged. (Data for two access tubes with much higher water contents than adjacent access tubes have not been included.) The effect of stocking rate on the soil water content, measured at 10, 20, 30 and averaged over 40–80 cm depths, was assessed using analysis of variance. The analysis was repeated for each date that water content was measured and used the Latin square experimental design.

The volumetric water contents of the soil profile are presented as colour contour plots over time (Greenwood 1996). In these images, time is represented along the x-axis and depth on the y-axis. The colours indicate the soil water content. These images were prepared using Spyglass Transform (Spyglass 1993) and annotated using Spyglass Format (Spyglass 1991) on a Macintosh computer.

Available soil water

Core samples (72 mm diameter x 38 mm) for the laboratory determination of field capacity were collected from pits for each soil type while undertaking the neutron probe calibration. Three to six replicate samples for each main soil horizon were equilibrated at 10 kPa tension using pressure chambers. The water content at 1500 kPa tension was determined using a psychrometer.

Soil-limited evapotranspiration

The relationship between evapotranspiration and soil water content was determined for a drying period between 25 January and 27 April 1995, when only 94 mm of rain fell over the 92 day period. Evapotranspiration was calculated from the water balance equation:

$$\Delta S = R - E_t - R_o$$

where ΔS is the change in water storage in the soil profile, R is the rainfall, E_t is the evapotranspiration and R_o is the runoff and/or drainage. All units are in mm. Evapotranspiration was estimated for each 2–3 weekly period between neutron probe measurements, assuming there was no runoff or drainage, and expressed as a daily evapotranspiration rate. This evapotranspiration rate was compared with the soil water deficit of the 0–85 cm profile at the start of each interval. The soil water deficit was calculated as the difference between the water content of the profile and the sum of the maximum water contents for each layer of the profile.

Linear regression was used to calculate the line of best fit between the five pairs of evapotranspiration/soil water deficit data. The coefficients of determination (r^2) averaged 0.97 (s.e. 0.006). The slopes of these lines were compared statistically using analysis of variance. The means of the individual treatment slopes were compared using Fisher's (protected) least significant difference (Steel and Torrie 1980, p. 176).

These calculations were repeated for another drying period between 5 March and 27 April 1994. The rainfall during this period was 50 mm and the lines of best fit were calculated for four pairs of evapotranspiration/soil water deficit data for each plot. The coefficients of determination averaged 0.86 (s.e. 0.014) for this data set.

Water balance model

The water balance model described by Scotter *et al.* (1979) was used to calculate the daily soil water deficit for an ungrazed and a low stocking rate plot on the gleyed podzolic and a medium stocking rate plot on the prairie soil type. These plots were chosen because the soil within the plots was spatially uniform.

The relationship between evapotranspiration and soil water deficit calculated for each plot for January–April 1995 was used to estimate soil-limited evapotranspiration. When daily rainfall data for the experimental area were not available, the rainfall which accumulated over a number of days was allocated to each day in proportion to the daily rainfall data from the main weather station. The daily pan evaporation data for the main meteorological station was multiplied by a pan factor of 0.87 to convert to potential evapotranspiration (Smith and Johns 1975). The model was run using a surface layer soil water storage (S') of 25 mm, as described by Scotter *et al.* (1979), and with the surface layer soil water storage reduced to 10 and 0 mm. The model output was compared with the measured soil water deficit.

Results

Monthly rainfall totals from January 1993 to June 1995 are shown in Figure 1, with the monthly percentiles. Rainfall was below average for most of the duration of the study and especially during winter and spring in 1994. The winter of 1993 had average rainfall and above average rainfall fell in December 1994–January 1995. The total rainfalls for 1993 and 1994 were 656 and 576 mm, respectively, compared with the long-term (1950–95) average rainfall of 828 mm. Figure 1 also shows the monthly pan evaporation.

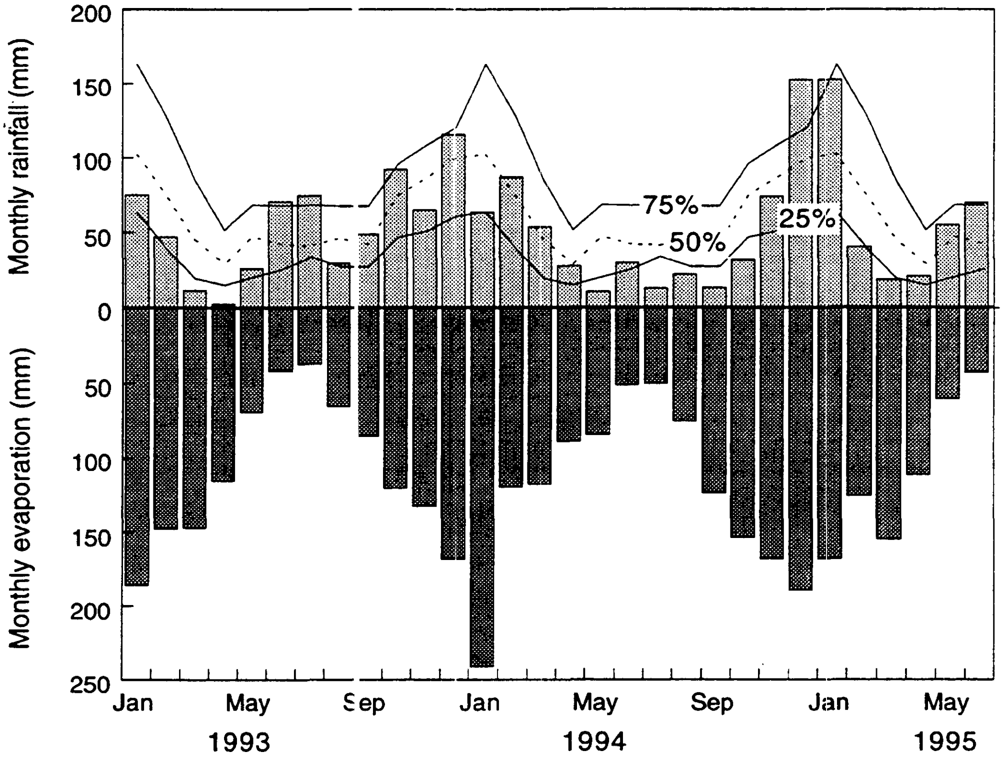

Figure 1. Monthly rainfall and evaporation from January 1993 to June 1995 recorded at the main weather station at CSIRO's Pastoral Research Laboratory near Armidale, New South Wales. The median, 25 and 75 percentile monthly rainfalls (1950–95) are also indicated.

The soil water contents for each plot are presented as colour contour plots in Figures 2–5. The plots show the soil water content between 5 and 85 cm depth over the 26-month study. The most noticeable feature of these colour contour plots is the large difference in soil water distribution between soil types, particularly at depths below 30 cm. For example, the high soil water contents in the gleyed podzolic subsoil (Figure 2) contrast markedly with the relatively uniform soil water distribution, with depth, of the prairie soil (Figure 4).

However, all plots show similar temporal changes in soil water content, with relatively moist periods throughout the latter half of 1993 and a short period of higher soil water

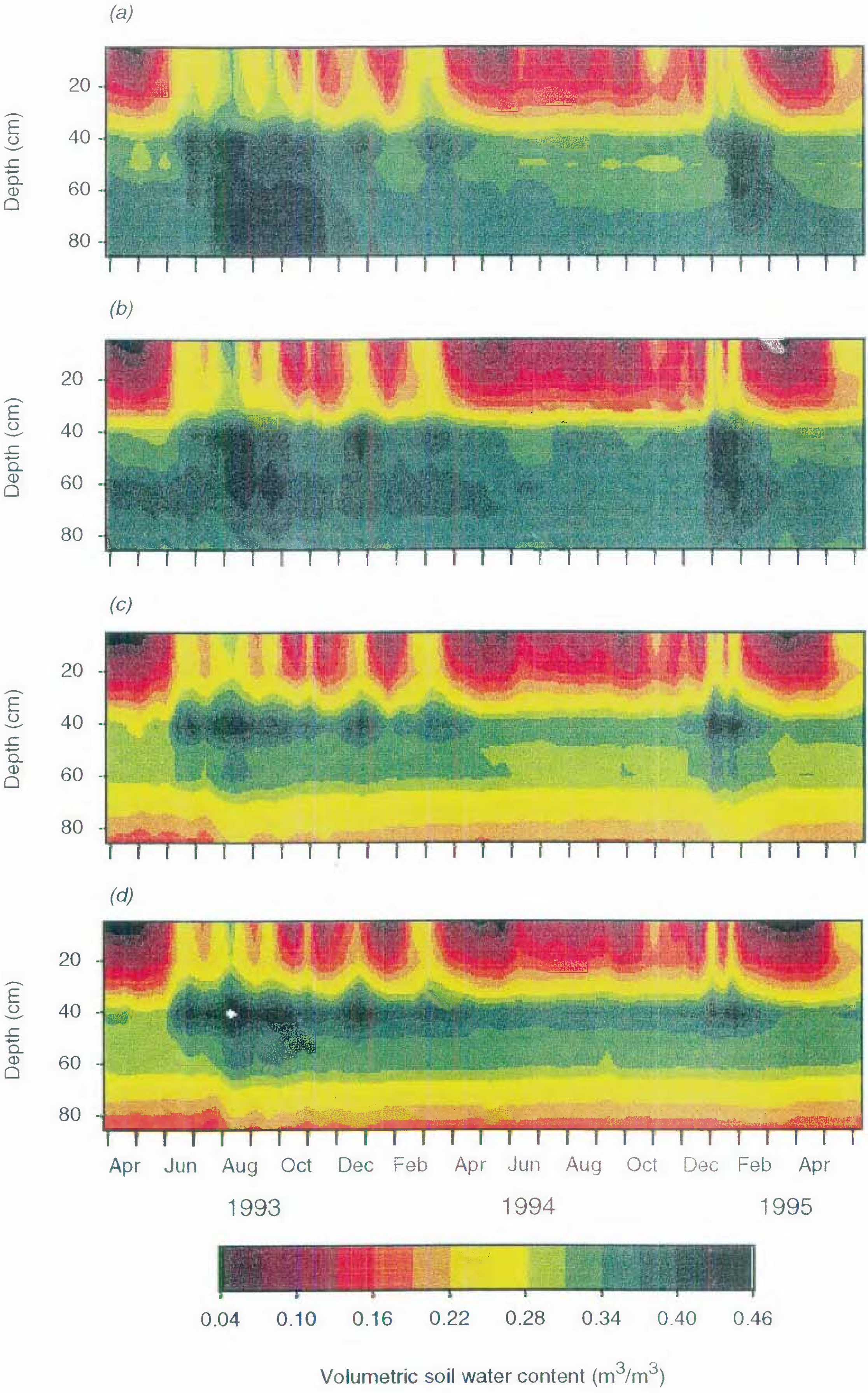

Figure 2. Colour contour images for four plots showing changes in volumetric soil water content over depth and time. These plots represent the first column of the Latin square experimental site. The main soil types represented are gleyed podzolic and lateritic podzolic. The stocking rates are (a) ungrazed, (b) low, (c) medium and (d) high.

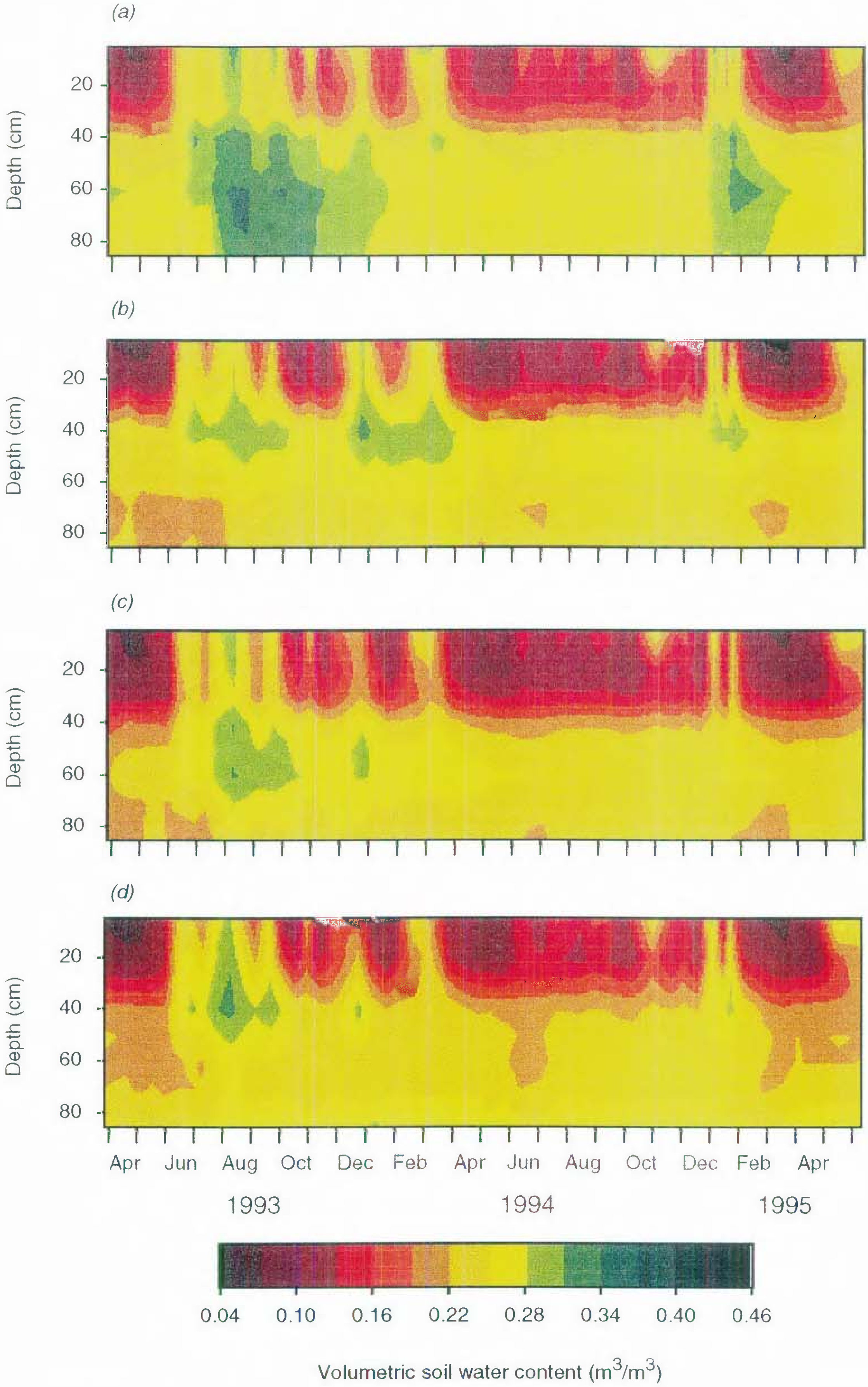

Figure 3. Colour contour images for four plots showing changes in volumetric soil water content over depth and time. These plots represent the second column of the Latin square experimental site. The main soil types represented are gleyed podzolic, lateritic podzolic and prairie. The stocking rates are (a) ungrazed, (b) low, (c) medium and (d) high.

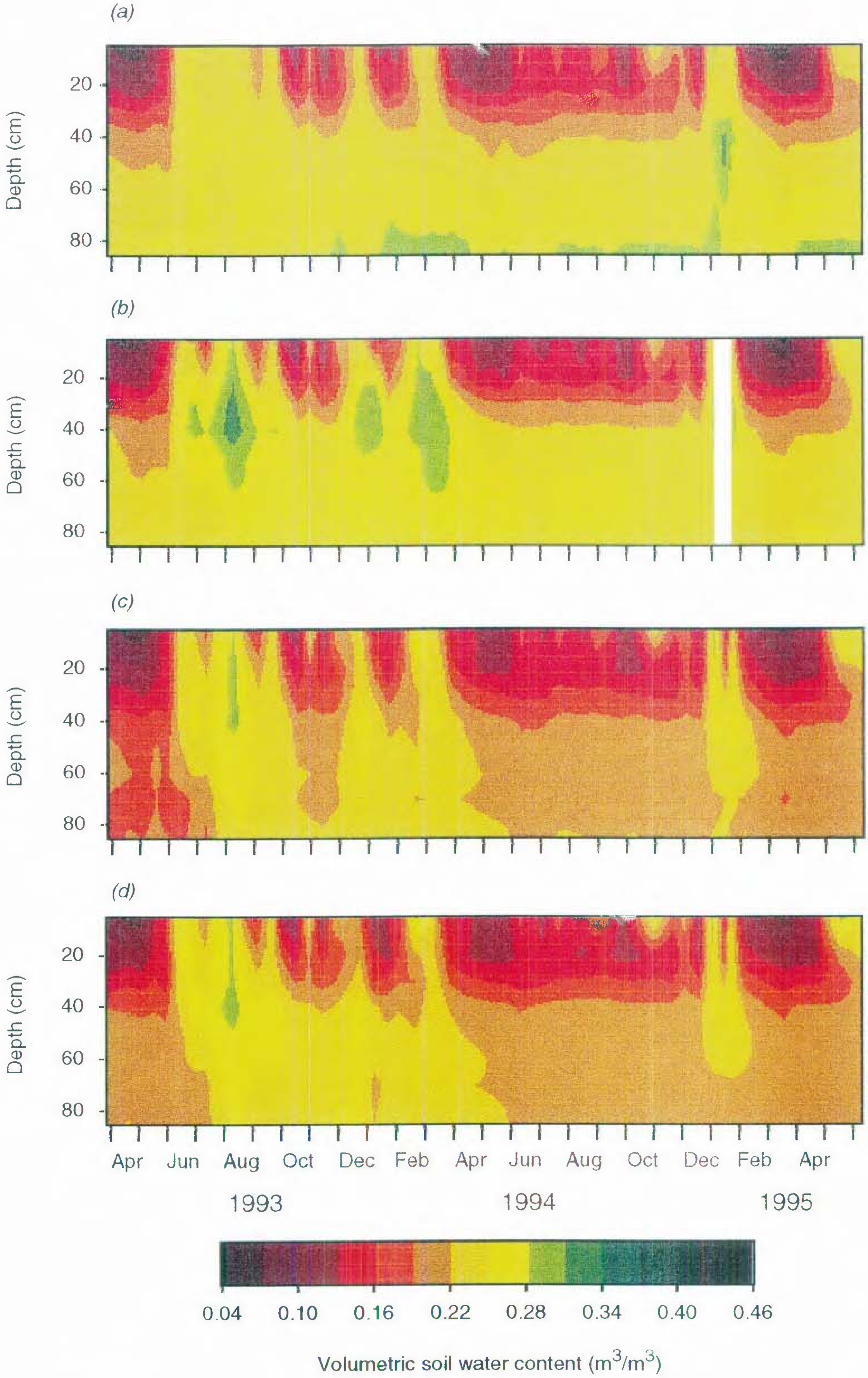

Figure 4. Colour contour images for four plots showing changes in volumetric soil water content over depth and time. These plots represent the third column of the Latin square experimental site. The main soil type represented is the prairie soil. The stocking rates are (a) ungrazed, (b) low, (c) medium and (d) high. The white band indicates missing data.

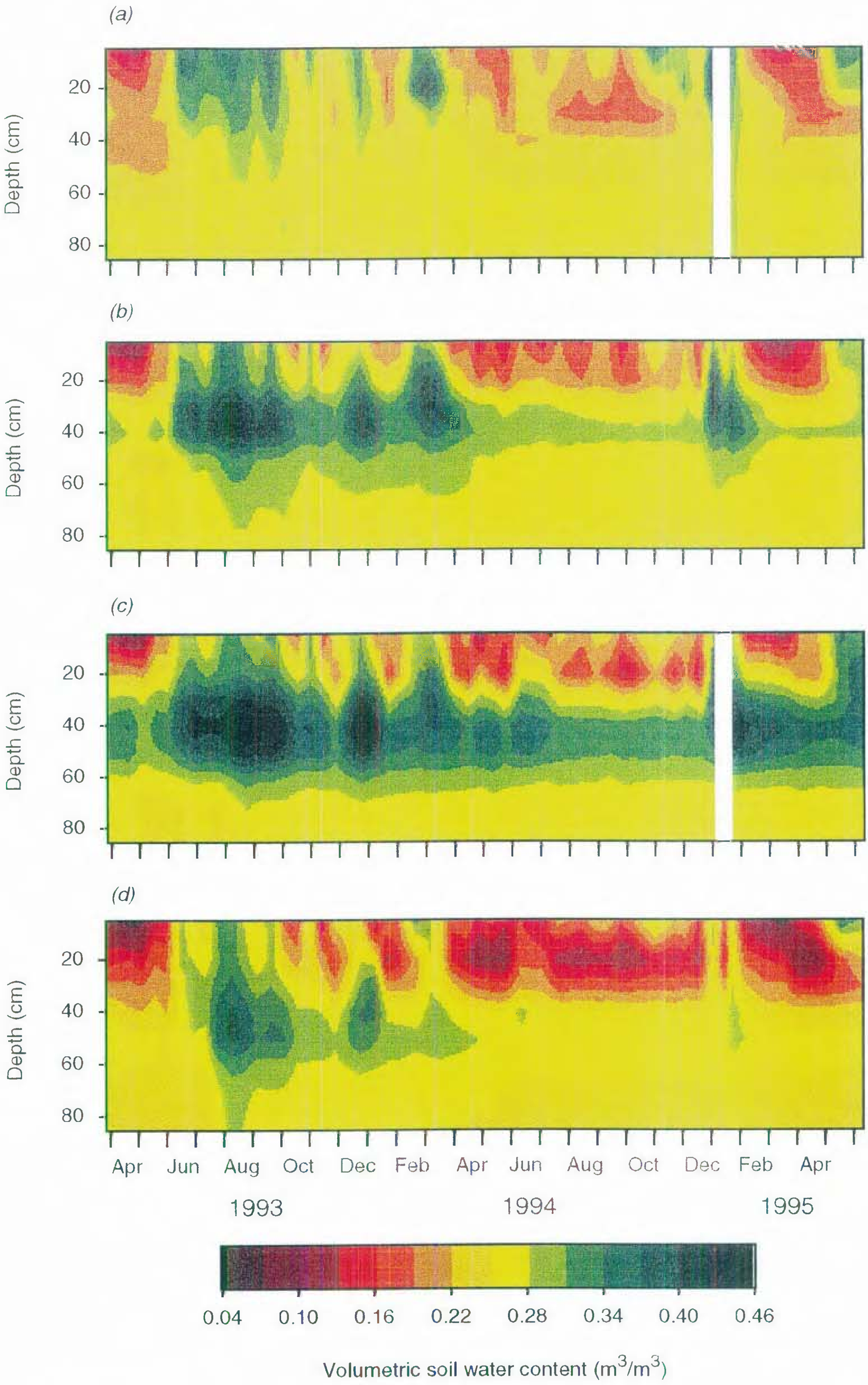

Figure 5. Colour contour images for four plots showing changes in volumetric soil water content over depth and time. These plots represent the fourth column of the Latin square experimental site. The main soil types represented are prairie and wiesenboden. The stocking rates are (a) ungrazed, (b) low, (c) medium and (d) high. The white band indicates missing data.

contents in January 1995. There were extended periods of dry soil conditions, particularly near the soil surface at the beginning of the study (April–May 1993) and from April–December 1994. In most of the plots, there was little variation in soil water content at 80 cm depth. Most changes in soil water content occurred in the top 50 cm of the profile.

The effects of stocking rate on the soil water content at 10, 20, 30 and 40–80 cm depths are shown in Figure 6. Significant differences between stocking rate treatments occurred in winter and spring 1993, mid-summer 1993–4 and late spring 1994. Differences in water content between treatments were more pronounced during wet periods. Usually, the ungrazed plots had the highest soil water contents and the high stocking rate plots had the lowest soil water contents. The water contents of the low and medium stocking rate treatments were usually intermediate.

Comparisons of the highest and lowest water contents measured using the neutron probe with the water contents at 10 kPa (field capacity) and 1500 kPa (permanent wilting point) tension are shown in Figure 7. For two of the four soils compared (gleyed podzolic and prairie), there was good agreement between the highest measured water content and field capacity above 30 cm depth. However, at depth, the maximum water content was below field capacity. The minimum soil water content was drier than permanent wilting point near the soil surface, but wetter below 40 cm in the gleyed podzolic.

The data for the A horizon of the lateritic podzolic are similar to the gleyed podzolic. However, the moisture characteristic data at depth are erroneous as the water content at 1500 kPa tension was greater than that at 10 kPa tension. These errors were probably due to the difficulty obtaining representative samples from the soil with a high content of ferromanganiferous nodules. The maximum water contents for the wiesenboden were much higher than field capacity and could have been due to the soil being waterlogged at some times. The small difference between the wettest and driest field-measured water content at depth is probably due to the hard ironstone layer having a high bulk density (~2.0 Mg/m^3, Appendix II) and therefore low porosity.

Evapotranspiration declined linearly with increasing soil water deficit for each plot for the period January–April 1995 (Figure 8). The slope of the line relating evapotranspiration to soil water deficit was significantly different between stocking rates ($P<0.05$), with the ungrazed treatment having a lower slope. The slopes were similar for all grazed treatments. However, for the March–April 1994 period, there were no significant differences between the slopes of the lines for any stocking rates.

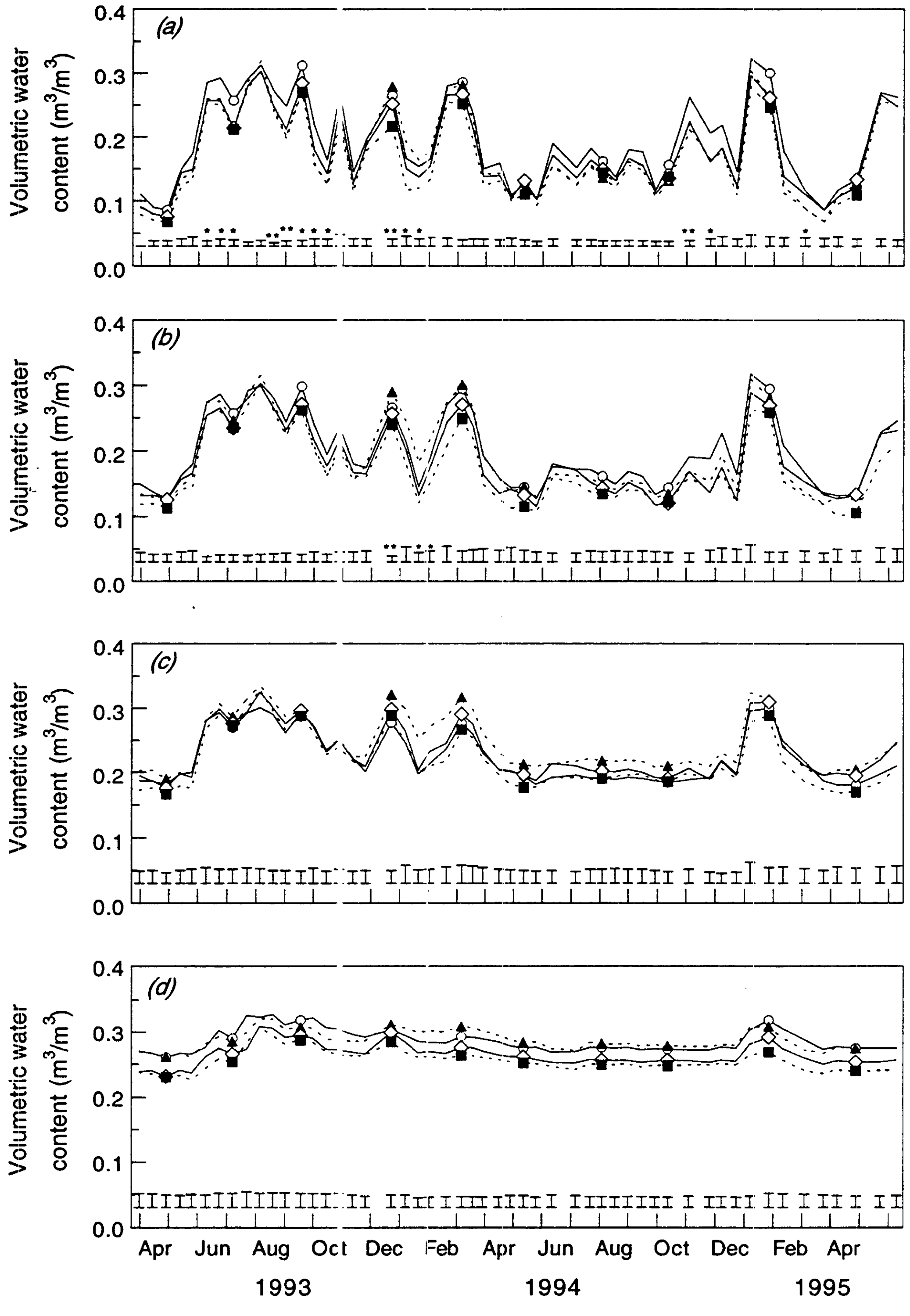

Figure 6. Changes in soil water content at (a) 10, (b) 20, (c) 30 and (d) 40–80 cm depths under ungrazed pastures (○) and pastures grazed at low (▲), medium (◇) and high (■) stocking rates. The vertical bars indicate one standard error of the difference between stocking rate means. Significant differences are indicated by * ($P<0.05$) and ** ($P<0.01$).

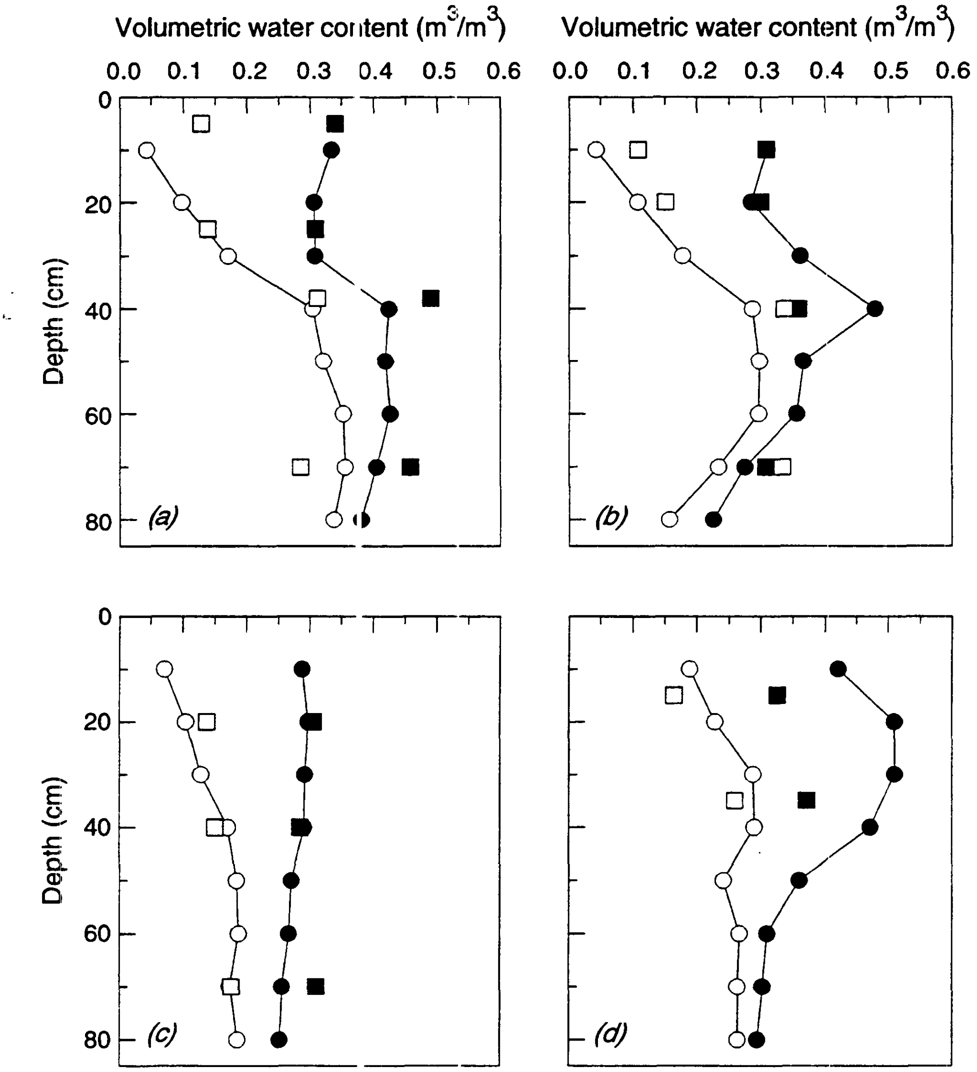

Figure 7. Comparison of the water content at 10 kPa (■) and 1500 kPa (□) tension measured in the laboratory with the wettest (●) and driest (○) field-measured water contents for (a) gleyed podzolic at a low stocking rate, (b) lateritic podzolic at a high stocking rate, (c) prairie soil at a medium stocking rate and (d) lateritic wiesenboden at a low stocking rate.

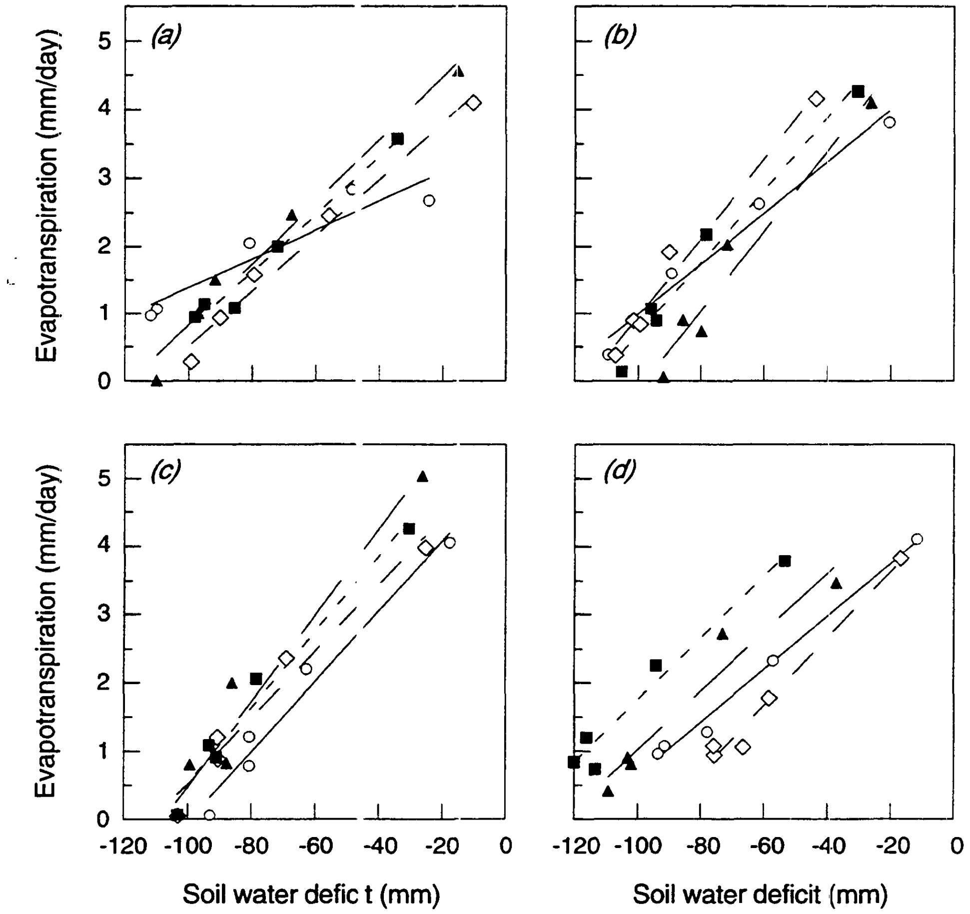

Figure 8. The relationship between evapotranspiration and soil water deficit for each plot at ungrazed (○), low (▲), medium (◇) and high (■) stocking rates, for the period from January to April 1995. Each graph presents data for one column of the Latin square design of the experimental area. The soil types represented by each column are (a) podzolic, (b) podzolic and prairie, (c) prairie and (d) prairie and wiesenboden.

The output from the water balance model for a low stocking rate plot on the gleyed podzolic soil is compared with measured data in Figure 9. When the upper limit of the surface layer soil water storage was 10 or 25 mm, the model over-estimated the soil water deficit by up to 54 or 88 mm, respectively. Omission of the surface layer soil water storage (i.e. $S' = 0$), produced a better fit between modelled and measured soil water deficit, with a maximum discrepancy of 36 mm. The model accounted for 86% of the variation in measured soil water deficit (Figure 10).

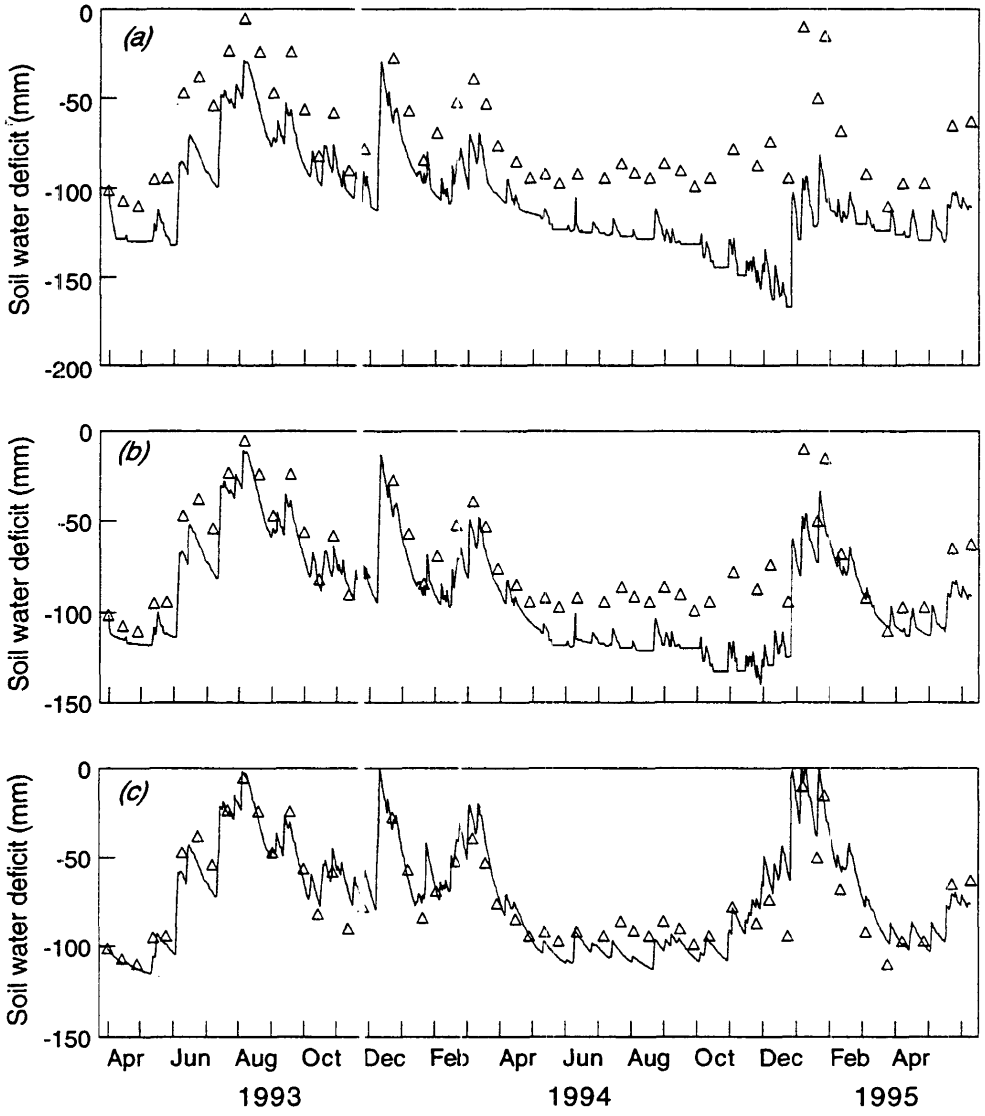

Figure 9. Daily output of soil water deficit from the water balance model (—) compared with the measured soil water deficit (△) for a low stocking rate plot on the gleyed podzolic soil. The surface layer soil water storage (S') was varied between (a) 25, (b) 10 and (c) 0 mm.

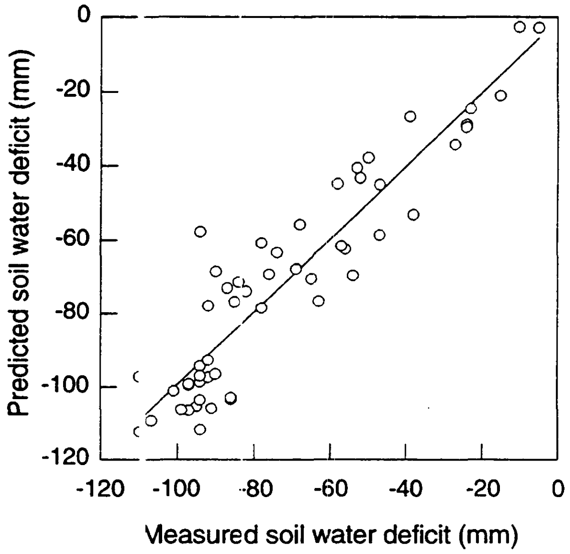

Figure 10. Relationship between measured and predicted soil water deficit for a low stocking rate plot on the gleyed podzolic soil, when the surface layer soil water storage was omitted. The regression equation is $y = -0.85 + 0.98x$ ($r^2 = 0.86$).

Figure 11 shows model predictions of soil water deficit on an ungrazed plot on the gleyed podzolic soil and a medium stocking rate plot on the prairie soil. The model's surface layer soil water storage was 0 mm. Model output for the prairie soil agreed well with the measured data (r^2=0.84). However, there was poor agreement between the predicted and measured soil water deficit for the ungrazed pasture (r^2=0.52). There was a better correlation between predicted and measured soil water deficit for the ungrazed plot when the soil-limited evapotranspiration for March–April 1994 was used rather than the function calculated for data from January–April 1995 (r^2=0.64), although the agreement was not as good as for other plots.

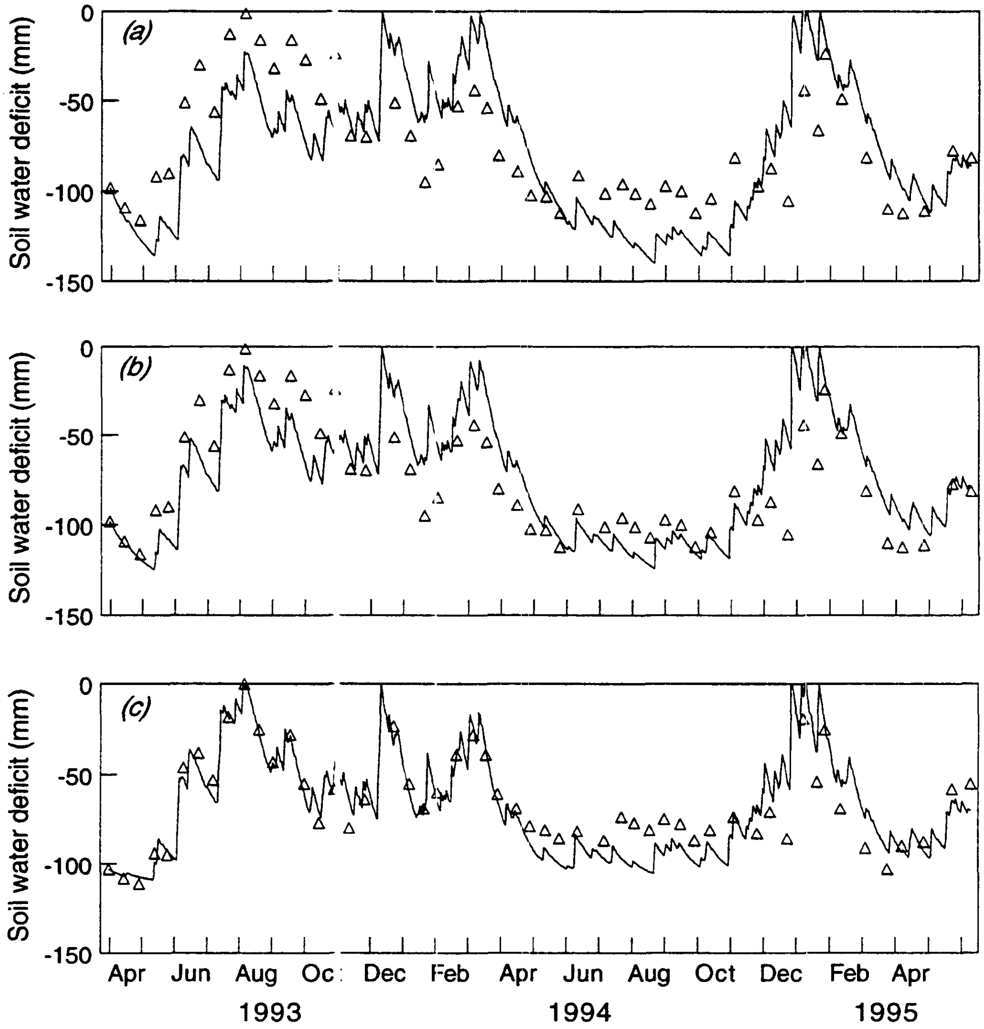

Figure 11. Daily soil water deficit from the water balance model (—) compared with the measured soil water deficit (△) for an ungrazed plot on the gleyed podzolic soil using the soil-limited evapotranspiration function derived from (a) January–April 1995 and (b) March–April 1994 data. The model for a medium stocking rate plot on the prairie soil (c) used the January–April 1995 data. The surface layer soil water storage (*S*') was 0 mm.

Discussion

Despite the large differences in stocking rate and botanical composition, more often than not, there were no significant differences in soil water content under the pastures at any depth. However, when significant differences in soil water content did occur, they were near the surface of the soil and the ungrazed stocking rate was usually wettest. The balance between three factors—infiltration, transpiration and evaporation—may account for these differences.

There were probably differences in the maximum potential infiltration rates between the stocking rate treatments, suggested by large and significant differences in near-saturated hydraulic conductivity (Chapter 6). However, these infiltration differences would only affect soil water content if rainfall intensities were high enough to cause runoff. Runoff was not measured in this study but evidence of runoff (litter dams) was noted on a few occasions following summer thunderstorms. There were more litter dams at the high stocking rate, and none on the ungrazed pasture. However, differences in runoff would probably not account for the lower soil water contents at higher stocking rates measured in winter and spring 1993 as rainfall intensities during these seasons were probably low.

Differences in transpiration rates between the different pastures may also contribute to differences in soil water content. Annuals and short-lived perennials dominated the pasture at the high stocking rate and many of these plants were spring- and summer-growing. In contrast, phalaris, which was dominant in the ungrazed and low stocking rate plots, can have reduced growth in summer (Hilder 1963). Transpiration rate can also be affected by leaf area under well-watered conditions (Johns and Lazenby 1973). In this study, the greatest leaf biomasses were obviously at the lower stocking rates and hence, given similar growth patterns, transpiration would be greatest under the lower stocking rates (although light may limit growth of the ungrazed pasture due to high amounts of standing dead plant material). As most of the differences in soil water content occurred during winter when transpiration would have been low, particularly for the species found on the higher stocking rate plots, I think it is very unlikely that differences in transpiration rates would have caused the lower water content at the higher stocking rates.

Evaporation could, therefore, be the main mechanism causing differences in soil water content between stocking rate treatments. This seems a reasonable explanation for differences observed during summer months, as there was more litter and standing dead plant material at the lower stocking rates to reduce evaporation from the soil surface. But this may not be a satisfactory explanation for differences observed during winter 1993 as evaporation rates are approximately four times lower in winter than in summer (Figure 1).

Other reasons for the differences in water content near the soil surface in winter 1993 are also possible. Although good calibrations were obtained for the neutron probe at 10 and 20 cm depth in a heavily grazed paddock adjacent to the experimental area (Appendix II), it is possible that these calibrations may not be accurate under an ungrazed pasture with a large amount of plant matter above the soil surface. In particular, when this plant matter is moist due to recent rain or dew, the neutron probe may overestimate the water content of the soil at 10 cm. Naeth *et al.* (1991a) measured gravimetric water contents of up to 200% in pasture litter.

An independent measurement of soil water content near the soil surface would be able to confirm these differences, but although tensiometers and filter paper were installed adjacent to the access tubes, data from these instruments were not reliable due to possible hysteresis effects and low air entry potentials (Chapter 4). The possible causes of the soil water content differences are discussed again later in this chapter.

The extended dry periods experienced by the pasture during this study offered an excellent opportunity to look at the effects of drought on plant water uptake. The data presented in Figure 7 for the gleyed podzolic and prairie soils (data for the other soil types are not reliable at depth) indicate that the pastures extracted water to at least 80 cm depth and, in the prairie soil, water was extracted to about 1500 kPa tension. Based on these data, however, water was still available at depths below 50 cm in the gleyed podzolic. Root length densities were greater than the 1–5 cm/cm^3 required to use the available soil water (van Noordwijk 1983) at all depths in this plot (Chapter 8). Clumping of roots within macropores, poor contact between the soil and the root (Passioura 1991) and low unsaturated hydraulic conductivities (Douglas 1995) may explain the failure of the pasture to utilise this water.

Water contents drier than the permanent wilting point above about 25 cm depth were probably due to direct evaporation from the soil surface. I estimated that approximately 13–17 mm of rain was required to wet the surface 25 cm of soil up to permanent wilting point when the soil was driest.

The different relationships between evapotranspiration and soil water deficit for the drying period from January to April 1995 (Figure 8) indicated that differences in the evapotranspiration rate are at least partly the cause of differences in soil water content measured in February 1995. At low soil water deficits, the ungrazed pastures had lower evapotranspiration rates than grazed pastures. If the linear functions for soil-limited evapotranspiration had been parallel with significantly different intercepts, this may have indicated that evaporation only was the cause of the treatment differences. Failure to find differences between treatments in this relationship for the March–April 1994 drying period is perplexing. The range of soil water deficits for this period may not have been large enough for differences to be apparent.

This method for calculating the soil-limited evapotranspiration rate has some limitations. The soil water deficit used here was the deficit at the beginning of the interval for which evapotranspiration was calculated. Other relationships would have been found if the soil water deficit at the end of the interval or the average soil water deficit over the interval was used. The distribution of water within the soil profile and the pattern of rainfall events during the drying period may also affect the calculated soil-limited evapotranspiration rate. The relationship may also vary depending on the growth rhythms of the pasture. More frequent soil water content measurements would provide better data for the calculation of soil-limited evapotranspiration rate, with the possibility of determining seasonal variations.

The simple soil water model of Scotter *et al.* (1979) proved to be satisfactory for predicting the soil water deficit in the low stocking rate plot on gleyed podzolic soil and the medium stocking rate plot on the prairie soil, when no allowance was made for surface layer soil water storage. This model used the relationships for soil-limited evapotranspiration shown in Figure 8. The poor relationship between measured and predicted soil water deficit for the ungrazed plot is probably because the soil-limited evapotranspiration function for January–April 1995 was not representative of the whole 26-month period. Also, the calculated function implies that evapotranspiration would continue down to a soil water deficit of 165 mm whereas evapotranspiration was negligible at a soil water deficit of 120 mm on other plots on this soil type (Figure 3). Use of the soil-limited evapotranspiration function calculated for 1994 gave a better relationship between measured soil water deficit and model output.

The inclusion of surface layer soil water storage in the model (Scotter *et al.* 1979) did not improve the model output. Surface layer soil water storage is "to account for the effect of rain when the soil profile is relatively dry" (Scotter *et al.* 1979) and allows evapotranspiration at the potential rate (up to the storage limit) regardless of the soil water deficit. Intuitively, the idea of a surface layer soil water storage makes sense, although the storage limit of 25 mm suggested by Scotter *et al.* (1979) may not be appropriate in all pastures. Again, I am perplexed why the model worked so well without surface layer soil water storage. Other factors which limit the performance of this simple water balance model include seasonal variation in transpiration rate and differences in the distribution of water within the profile. Nevertheless, a simple model is probably most appropriate for data sets such as this and can usefully indicate where the model assumptions are inappropriate or could be refined.

One useful application of a daily water balance model is to enable the soil water deficit to be "interpolated" between measurement dates. The model outputs shown in Figures 9 and 11 provide a more detailed "picture" of the wetting and drying cycles than the 2–3 weekly data presented in Figure 6. The model used also allows discrimination between soil- and weather-limited evapotranspiration. Model output for the low stocking rate plot on the gleyed podzolic soil indicated that evapotranspiration was limited by dry soil conditions on 72% of the days between March 1993 and June 1995. For the same period, actual evapotranspiration from the model was 1340 mm compared with potential evapotranspiration of 2556 mm.

This study highlights the ability of neutron probes to provide good data on changes in soil water content at a site over time but the accuracy of individual water content measurements will not be as high (Hewlett *et al.* 1964). For example, a significant difference in soil-limited evapotranspiration rate between grazed and ungrazed treatments was determined for the January–April 1995 drying period but only one significant difference in soil water content was found during the same time period. On 16 January 1995, significant differences were found in gravimetric soil water content down to 20 cm (Chapter 6) but no differences were found in volumetric water content at 10 and 20 cm depth using the neutron probe on 18 January. The neutron probe data would have greater errors associated with water content measurement than gravimetric data due to errors in the calibrations, inappropriate allocation of calibration equations to profiles due to variable horizon depths, spatial variation of the soil types, and other errors described by Sinclair and Williams (1979) and Haverkamp *et al.* (1984). Measurements near the A-B horizon boundary of the podzolic soil would also be affected by the soil water content in the adjacent horizon (Wilson 1988).

This study would have benefited from the inclusion of measurements to separate evaporation from transpiration. The method described by Russel (1939) and further tested by Evett *et al.* (1995), would be suitable. In this method, undisturbed soil cores are collected and weighed after any vegetation is removed, and the cores are replaced in the field and weighed again 2–3 days later. If there was no drainage, the difference in weight would be due to evaporation alone. A separate measurement of evaporation would help clarify whether the differences in soil water content, observed at some times in this study, were due to evaporation, transpiration or some other factor.

Conclusions

Soil water content was occasionally higher under ungrazed pasture near the soil surface. This was probably due to lower evaporation rates under the ungrazed pasture. The soil-limited evapotranspiration rate for the ungrazed pasture also differed from the grazed pastures during one drying period. The pastures utilised most available soil moisture to at least 80 cm and the soil surface frequently dried below the permanent wilting point.

A simple soil water balance model described observed changes in soil water deficit although the relationship between predicted and observed soil water deficit was not as good for an ungrazed pasture as for pastures grazed at low or medium stocking rates. The data collected using neutron probes appear to be more suitable for studying changes of water content over time than for measuring absolute values of water content.

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