

Chapter 6

Soil water and root distribution characteristics of perennial grasses under drought and defoliation stresses

Introduction

Roots are a vital organ for plant growth, providing the means for water and nutrient uptake. In spite of the importance of roots they are generally not as well studied or understood as shoot systems, and have been referred to as ‘the forgotten component of pastures’ (Davidson 1978), owing to their inaccessibility.

The development of an extensive root system is essential for the establishment and continued productivity of grasses (Frank *et al.* 1996). Any reduction in root weight reduces the effective moisture and nutrient reservoir (Loreiz and Rogler 1967) and potentially the survival of the plant (McWilliam and Kramer 1968). Effective water use and deep rootedness are two ways in which plants can survive drought (Burton *et al.* 1974; McWilliam and Kramer 1968; Garwood and Sinclair 1979; Thomas 1986a).

There have been many reports of grazing reducing the root growth of perennial grasses (eg. Evans 1971). Frequent or continuous defoliation has been reported to reduce root number and branching (Robertson 1933; Albertson *et al.* 1957; Jupp and Newman 1987), root diameter (Biswell and Weaver 1933; Robertson 1933), root weight (Robertson 1933; Weaver 1950; King and Hutchinson 1976) and the depth of root penetration (Robertson 1933; Weaver 1950; Ruby and Young 1953; Cook *et al.* 1958). The effect of defoliation upon a plant depends on the proportion of the shoot removed and the frequency of defoliation (Troughton 1957).

Movement of water in unsaturated soils is slow, therefore plants need high root densities to increase or

maintain rapid water uptake (Turner 1968b). Drought has been reported to increase root growth in some pasture species (Molyneux and Davies 1983; Volaire and Thomas 1995), with the additional growth coming from lateral root initiation and elongation (Jupp and Newman 1987) and sometimes a strong vertical extension (Molyneux and Davies 1983).

Hydrological models are becoming more common with the increased use of computers and availability of better and more interactive models. They provide an alternative means to explore large volumes of soil water data from the traditional statistical methods.

In general, the effects of defoliation on a plant's root system are well documented. The effect of drought or soil water deficit is also reasonably well studied. However, the interaction of drought and defoliation stress has received minimal attention. The aim of this chapter is to investigate the effects of defoliation intensity during drought on soil water, root distribution and rooting depth of perennial pasture grasses and to assess the potential of the hydrological model WaterMod for exploring soil water data.

Materials and methods

Trial design and treatments

Details of the trial site preparation, establishment, design, rain-out shelter and treatments are described in detail in Chapter 3. The particular methods relating to this chapter are described below.

Measurements

Moisture retention curves

Volumetric soil moisture content was determined with undisturbed soil cores on pressure plates for each of the five soil horizons described in Chapter 3. Tensions used were 50, 100, 300, 1000, 3000, 10×10^3 and 15×10^4 cm. The data were plotted and power curves fitted to produce soil moisture characteristic curves.

Bulk densities, calculated when calibrating the neutron probes (Appendix 2), were used to determine the water content at saturation. Field capacity and wilting point were determined as the volumetric water contents at tensions 100 and 15×10^4 cm respectively.

Soil profile water

Neutron probes (Model 503 DR) were calibrated for volumetric soil water at a site adjacent (within 50 m) to the drought trial. The neutron probes were calibrated (Greacen *et al.* 1981) for each 10 cm depth to 90 cm, then every 20 cm depth to 140 cm. The method used to calibrate the neutron probes and the calibration equations are presented in Appendix 2.

Aluminium neutron probe access tubes were placed into the SS experimental block in August 1994 and into the SA experimental block in September 1994. The access tubes were installed (Prebble *et al.* 1981) using an auger and a steel corer bevelled on the inside (Wilkinson and Burke 1995) to prevent compaction of the surrounding soil. Access tubes were placed in all plots of one replicate with six check access tubes placed in the second replicate, one for each moisture and defoliation combination.

Soil water measurements were generally taken prior to and the day after each watering event at all depths calibrated. To illustrate the change in soil water during each 6-month season, colour contour graphs (Greenwood 1996a) for each plot were prepared using Spyglass®.

The total profile water and the water content at each depth were assessed. As the soil water content was generally not recorded for all plots on the same day, only those times when all plots were assessed within 1 day of each other were used for comparisons across all treatments. The water content was calculated as the sum of the stored soil water (mm) in each layer to 140 cm.

The water content at each depth and the total soil profile water were analysed over time using the statistical package Genstat 5 (Genstat 5 Committee 1987). As there was only one replicate of data, the highest level interaction was used as the error term. Each assessment through time was dependent, hence the degrees of freedom in the time stratum were reduced using the Greenhouse–Geisser factor (Greenhouse and Geisser 1959). Contrasts were used to compare differences between moisture treatments.

Root mass and distribution

Root samples were collected at the start and finish of both experimental seasons. The samples were collected manually using steel corers (Wilkinson and Burke 1996) to a depth of 80 cm and divided into 10 cm sections. Cores were taken from the area between four plants inside the plot buffer row. The samples were stored in plastic bags in a cool room until processing.

Prior to washing, the samples were soaked overnight in water to assist separating the roots from the soil. The roots were washed using semi-automated washing buckets similar to those of Welbank *et al.* (1974). A 500 μm sieve was used to separate the roots from the soil. The roots were dried in an oven at 100°C and weighed.

The root weight data were analysed as a complex split plot with the strata ordered: moisture and defoliation, species, depth, and time. As there was only one replicate of data, the highest level interaction was used as the error term. The analysis was conducted using the statistical package Genstat 5 (Genstat 5 Committee 1987). As each assessment through depth was dependent, the degrees of freedom in the time stratum were reduced using the Greenhouse–Geisser factor (Greenhouse and Geisser 1959). The data were square root transformed following examination of residual and normality plots. Contrasts were used to compare differences between moisture treatments.

Effective rooting depth

The effective rooting depth of the plants in each plot was calculated by fitting \log_e curves (Gerwitz and Page 1974) to the root mass data described above. A root mass of 0.005 mg/cm^3 was used to indicate rooting depth.

The maximum effective rooting depth was assessed as a split plot, with moisture and defoliation in the upper stratum, using the statistical package Genstat 5 (Genstat 5 Committee 1987).

Hydrological models

WaterMod[©] (Greenhat Software 1997 Version 2) is a hydrological model, written by I. M. Johnson, capable of exploring soil water dynamics. The model is based on the Richard's equation (eg. Jury *et al.* 1991) to describe the movement of water through the soil profile. The Richard's equation is derived by combining mass balance with Darcy's law relating to the movement of water through the profile.

The main components of WaterMod are rainfall and/or irrigation, runoff, transpiration, evaporation, infiltration and through drainage. Data inputs include soil profile details, root distribution and rooting depth, rainfall and/or irrigation schedule and pan evaporation. Soil profile details include saturation point, field capacity, wilting point, hydraulic conductivity, the air entry water potential and a dimensionless constant *b* (described below). The model can be run for crops (including sowing date) or for established perennial pastures. WaterMod predicts the movement of water through the soil

profile, evapotranspiration, transpiration and the growth limiting factor (the ratio of actual transpiration to potential evapotranspiration which indicates periods of water stress).

Root distribution and rooting depth data collected during the experiment, were used in the model. The water regimes applied and measured pan evaporation were also used, as were the calculated values for the saturation point (θ_{sat}), field capacity (θ_{fc}) and wilting point (θ_w). The air entry water potential (Ψ_{ae}) and b were determined. Ψ_{ae} is the matric potential for saturated soil at the point where the pores are just about to drain. 'b' is an empirical parameter or a 'positive dimensionless constant' (Thornley and Johnson 1990) and generally referred to as the 'soil-b parameter'. The air entry water potential was determined by firstly plotting the relationship between $\ln(\psi_m)$ and $\ln(\theta_{sat}/\theta)$ and fitting a straight line (Equation 6.1).

$$\ln \psi_m = \alpha + \beta \ln \left(\frac{\theta_{sat}}{\theta} \right) \quad 6.1$$

Where ψ_m is the soil water tension (cm) and θ is the water content (m^3/m^3). The slope of the line β is equal to b . The y-intercept (α) was used to calculate ψ_{ae} (Equation 6.2).

$$\psi_{ae} = e^\alpha \quad 6.2$$

The predicted volumetric water content was compared with the volumetric soil moisture measured with the neutron probe. Any input data that was not collected and could not be solved empirically was estimated, such as hydraulic conductivity. The same soil characteristics were used for all runs, whilst the plant characteristics were unique for each species-moisture regime combination.

Results

Moisture retention curves

The moisture retention curve for each of the soil horizons described in Chapter 3 is presented in Figure 6.1. The volumetric water contents for saturation point, field capacity and wilting point are shown in Table 6.1. As soil depth increased, the water content at saturation, field capacity and wilting point also increased. The range in plant available water content was greater in the 12–26 cm zone and least in the 26–108 cm region.

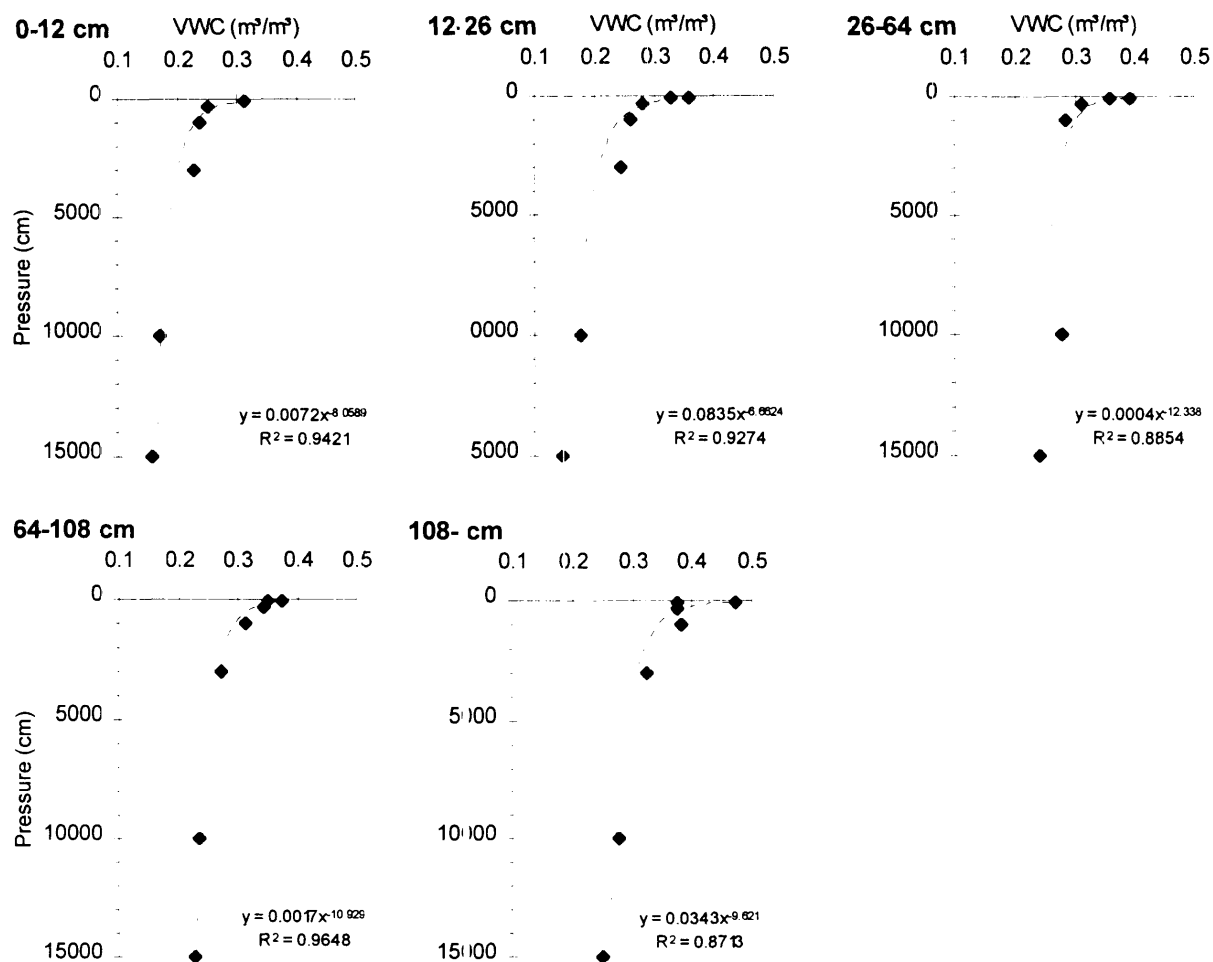


Figure 6.1: Moisture retention curves for each of the five soil horizons. A power regression has been fitted to the points.

Table 6.1: The volumetric water content (m^3/m^3) at saturation, field capacity and wilting point for each of the five soil horizons.

| Soil horizon | θ_{sat} | θ_{fc} | θ_{w} |
|--------------|-----------------------|----------------------|---------------------|
| 0-12 cm | 0.42 | 0.31 | 0.16 |
| 12-26 cm | 0.37 | 0.33 | 0.15 |
| 26-64 cm | 0.37 | 0.36 | 0.24 |
| 64-108 cm | 0.43 | 0.35 | 0.23 |
| 108-150+ cm | 0.52 | 0.38 | 0.25 |

Soil profile water

The data collected from the plots with the check tubes (neutron probe access tubes) were compared with the data from the corresponding treatments in replicate 1. Comparisons were conducted to investigate whether the one replicate data were representative of the total plot area. The comparisons indicated that the responses were similar, hence the check tubes will not be discussed further.

Spyglass contour graphs

The Spyglass® contour graphs showing volumetric water content over time and depth for the six perennial grass species in the SS and SA seasons are presented in Figure 6.2 and Figure 6.3. The data were averaged over the drought and defoliation treatments. The decline in soil water in the upper 60 cm was distinct during the SS season, and less defined in the SA season. In general, the soil surface was drier in SA than SS, with cocksfoot and weeping grass consistently having the driest surfaces of the species. In SS, the change in water content was less in perennial ryegrass and cocksfoot below 50 cm than the other species. The differences were less distinct in the SA season.

In SS, weeping grass and phalaris had high root activity to 70 cm. Tall fescue was less active in this region, but together with phalaris, its uptake to a depth of approximately 100 cm was more consistent. Cocksfoot was highly active to approximately 50 cm and perennial ryegrass to 60 cm. In SA, tall fescue, phalaris and weeping grass again had the most active root systems at depth (to about 80 cm).

Water content in the three moisture treatments during both seasons is shown in Figure 6.4 and Figure 6.5. The data are averaged over the species and defoliation treatments. The differences between the two drought treatments were greater in SS than SA. The soil profile in the 10% SS drought plots dried more quickly than the 40% SS drought plots, with more drying at the surface and to 80 cm depth. The 10% SA drought plots also dried slightly quicker than the 40% SA drought, however the profiles dried to similar contents at the surface and at depth. The non-stress moisture treatment plots were consistently wetter than the drought treatment plots, with little change in water content below 50 cm in either season. While drying did occur in both seasons, the plants in the non-stress moisture treatment plots were more successful in removing water to 50 cm in the autumn period of the SA season.

At the start of the SS and SA seasons, soil water was above field capacity at depths below 65 cm. As the SS season progressed, the soil dried in the drought treatments, so that only depths below 100 cm and 85 cm remained saturated in the 10% drought and 40% drought plots respectively at the end of the

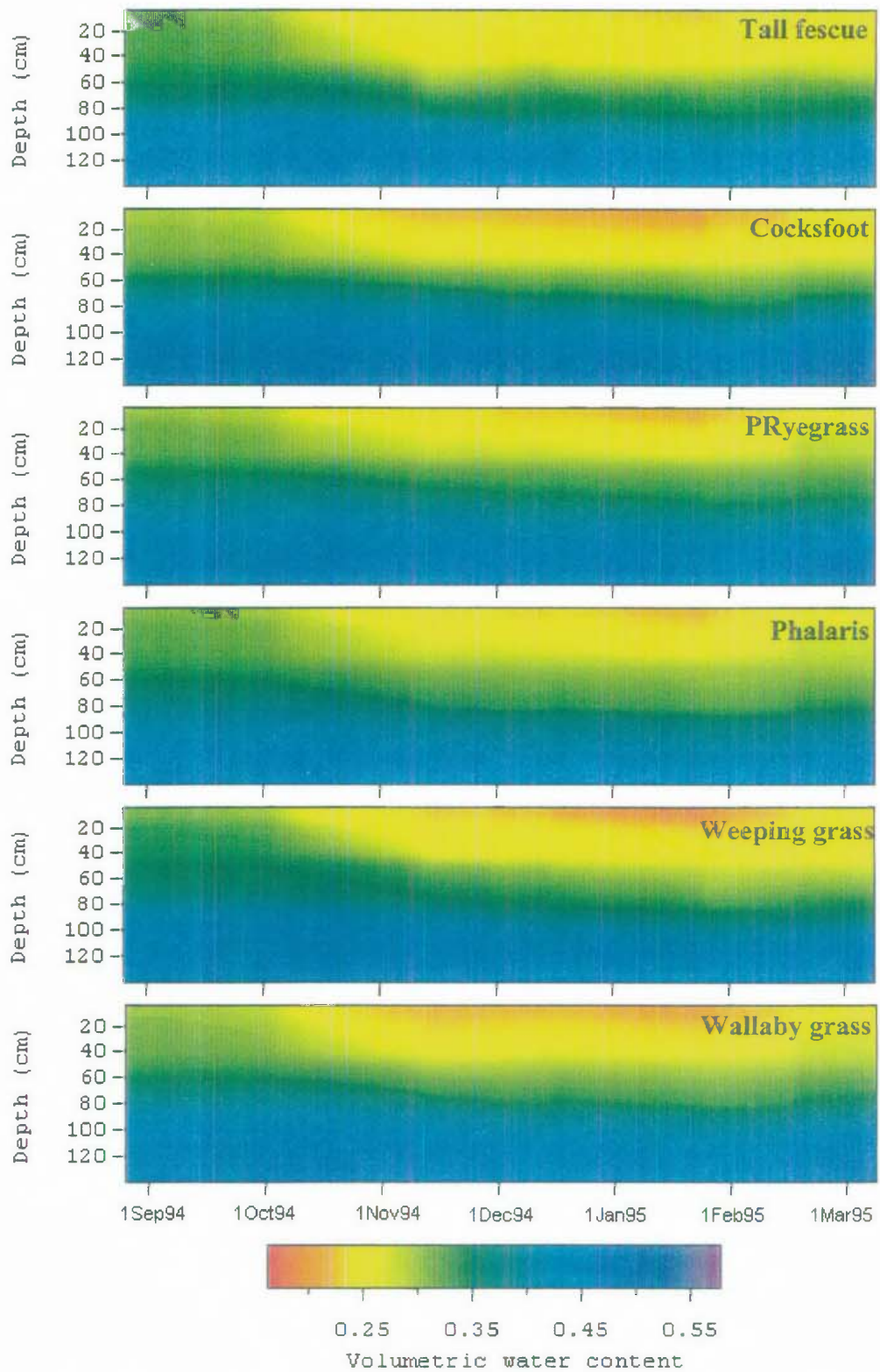


Figure 6.2: Volumetric water content of six perennial grass species during the Spring–Summer season. The images indicate changes in volumetric water content over time and depth. Data are averaged over the drought treatments and defoliation intensities.

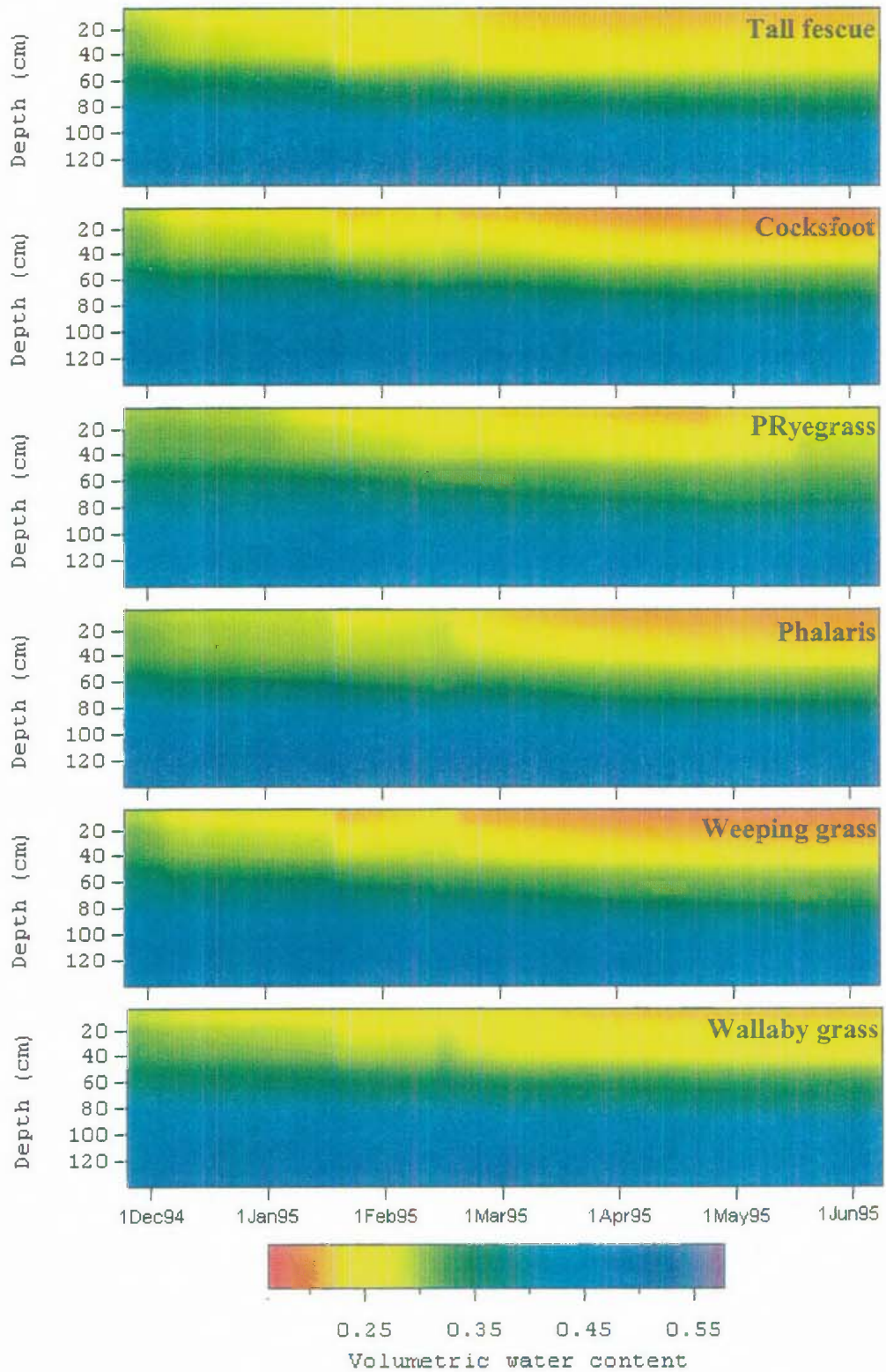


Figure 6.3: Volumetric water content of six perennial grass species during the Summer–Autumn season. The images indicate changes in volumetric water content over time and depth. Data are averaged over the drought treatments and defoliation intensities.

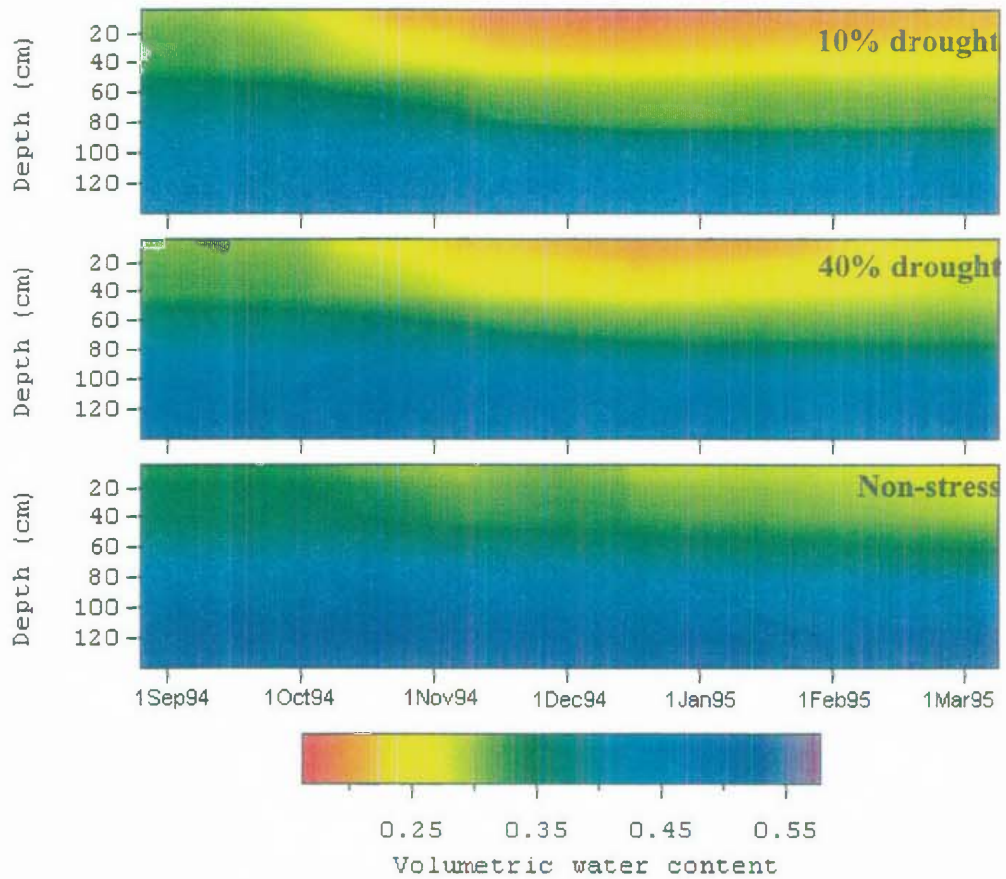


Figure 6.4: Volumetric water content of the three moisture treatments, 10% drought, 40% drought and non-stress, during the Spring–Summer season. The images indicate changes in volumetric water content over time and depth. Data are averaged over species and defoliation intensities.

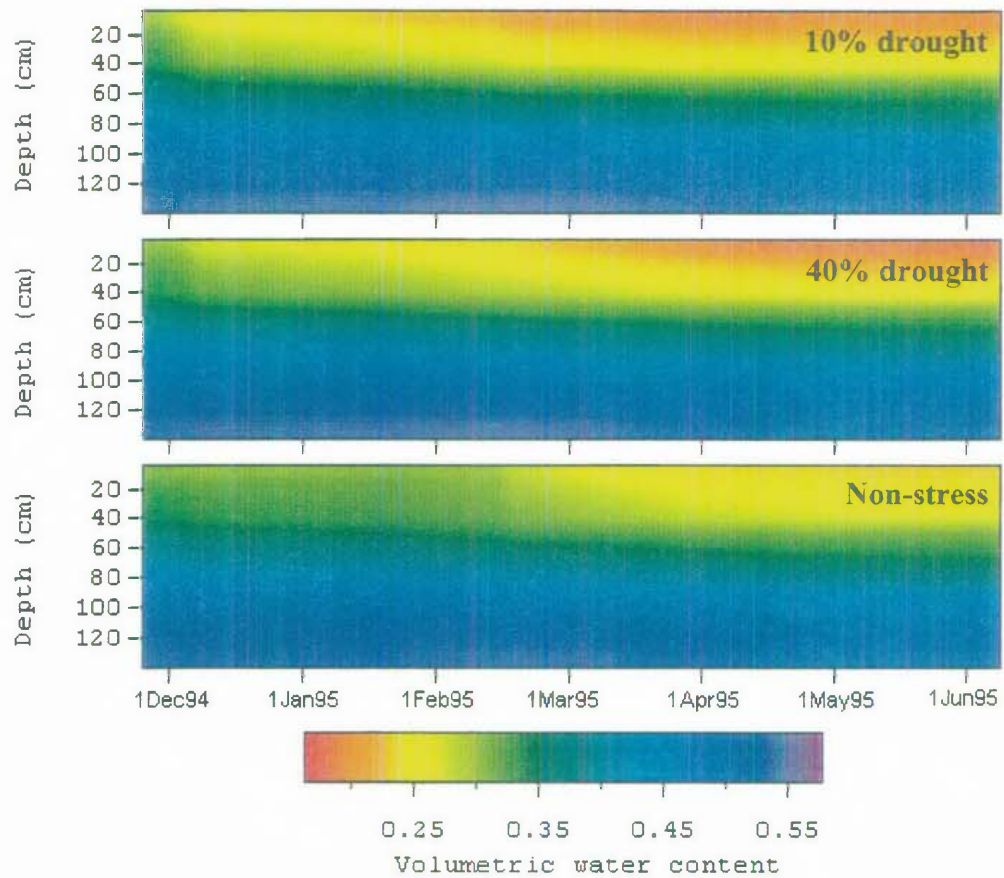


Figure 6.5: Volumetric water content of the three moisture treatments, 10% drought, 40% drought and non-stress, during the Summer–Autumn season. The images indicate changes in volumetric water content over time and depth. Data are averaged over species and defoliation intensities.

season. During the SA season, the profile dried to within the available limits to 75 cm depth in the drought plots and 85 cm depth in the non-stress moisture treatment plots. Depths below this remained above field capacity.

Defoliation regime had little effect on the soil water content during either the SS or SA season (data not shown).

Total profile water

There were no differences in the soil profile water contents of the non-stress moisture treatment plots at the start of both seasons, while the profile water contents in the two drought plots were up to 30 mm wetter at the commencement of the SA season. There was a moisture effect in the SS season: the non-stress moisture treatments having a greater water content than the drought treatments (main effect, $P < 0.05$). However, there was no main effect of moisture in the SA season (data not shown).

There were significant moisture-time and defoliation-time interactions in both seasons, and a species-time interaction in SS. In general, the significant differences were the response of the treatments through time, not the effect of the treatments at any one time.

The moisture-time interactions for both seasons are presented in Figure 6.6. There was a decline in soil water content during both seasons, the differences greater in the SS season. In SS, the profile water content was a minimum in mid-December in both drought treatments. The non-stress moisture treatment reached minimum water content at the end of the season. The rise in soil water content during January-February was due to significant 'rainfall' events in both drought treatments. In SS, the three moisture treatments had significantly different responses through time, with all contrasts between pairs of moisture treatment; significant ($P < 0.001$). In SA, the water content declined throughout the season, reaching a minimum volume in June in all treatments. The contrast between the 40% drought and the non-stress moisture treatment plot was not significant, while the contrasts between the 10% drought treatment and each of the other two treatment plots were significant ($P < 0.05$).

The defoliation-time interaction ($P < 0.01$) for both seasons is presented in Figure 6.7. There were no differences in soil water content in plots defoliated at either intensity at any time during either season, however their response during the season varied. In SS, the change in water content was similar under both defoliation treatments during the first two months of the season and greater in the moderately

defoliated plants in the latter months ($I < 0.001$). The water content rose to greater extent following the significant January–February watering. In the SA season, the soil water content declined in the moderate defoliation plots faster than in the severe defoliation plots during the entire season ($P < 0.01$).

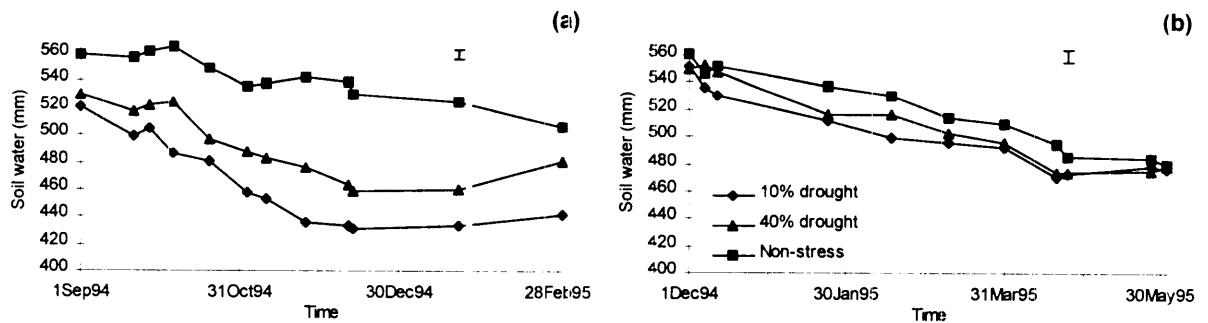


Figure 6.6: Total soil water to 140 cm during two droughts, 10% drought and 40% drought, and a non-stress moisture treatment for the six months of (a) Spring–Summer ($P < 0.001$) and (b) Summer–Autumn ($P < 0.05$). Data are averaged over defoliation intensity and species. The 1% and 5% l.s.d.s (within a moisture treatment) are shown on the Spring–Summer and Summer–Autumn season figures respectively.

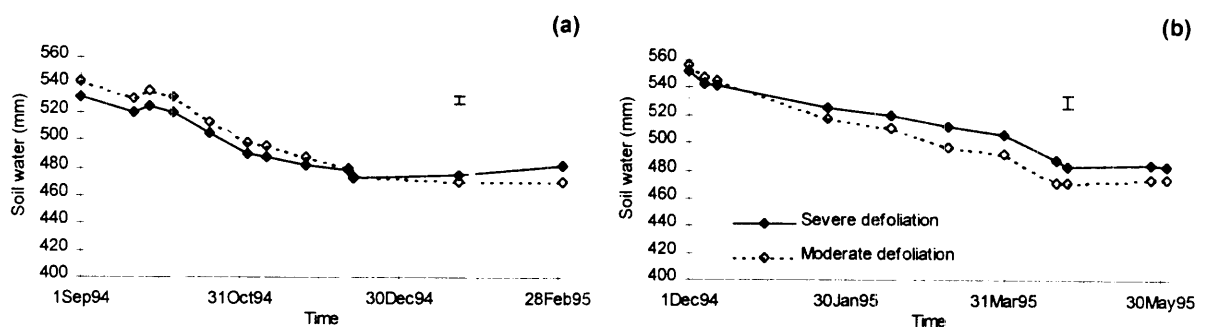


Figure 6.7: Total soil water to 140 cm during the six months of (a) Spring–Summer ($P < 0.001$) and (b) Summer–Autumn ($P < 0.01$) at two defoliation intensities, severe and moderate. Data are averaged over moisture regime and species. 1% l.s.d.s (within a defoliation treatment) are shown on each figure.

There were no significant differences in the soil water content of the six species at any time during the six months of the SS season. However, the change in content during the season varied ($P < 0.001$). The species–time interaction is presented in Figure 6.8. The soil water content declined in plots of all species throughout the season, reaching minima in mid–December. The water content continued to decline in weeping grass until late January. Following the significant watering in January–February, in both drought treatments, the water content increased significantly in the cocksfoot plots only. The range in soil water content between the species increased as the season progressed. After six months of treatments, cocksfoot and perennial ryegrass had the wettest profiles, while weeping grass and phalaris had the driest profiles. The response through time was similar for cocksfoot and perennial ryegrass until January. Similarly the other four species had similar responses until mid–December. Following mid–December, weeping grass responded differently with the decline in water content continuing until February.

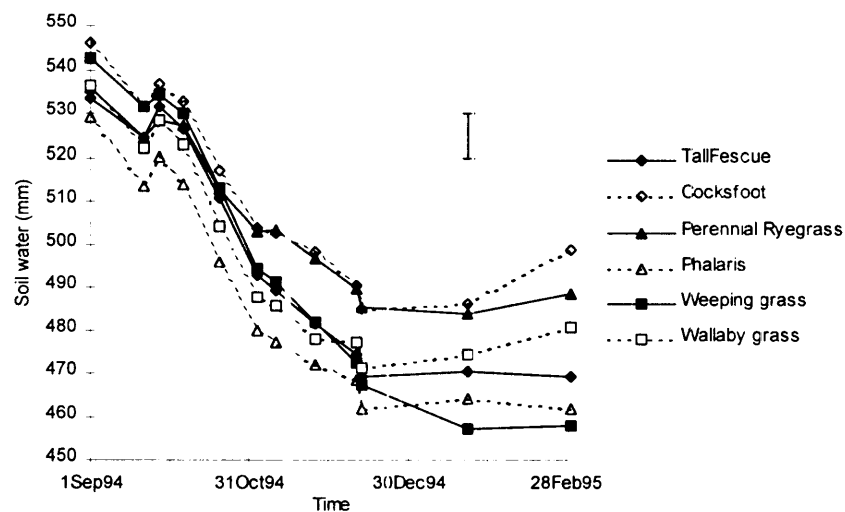


Figure 6.8: Total soil water to 140 cm of six species during the six months of Spring–Summer ($P < 0.001$). Data are averaged over defoliation intensity and moisture regime. The 1% I.S.D. (within a species) is shown on the figure.

Volumetric water content by depth

There were significant moisture effects at most depths to 80 cm in SS but only at 10 cm in SA (Figure 6.9). The non-stress moisture plots consistently had the greatest water content and the 10% drought plots the driest. The 40% drought plots were generally not significantly wetter than the 10% drought plots.

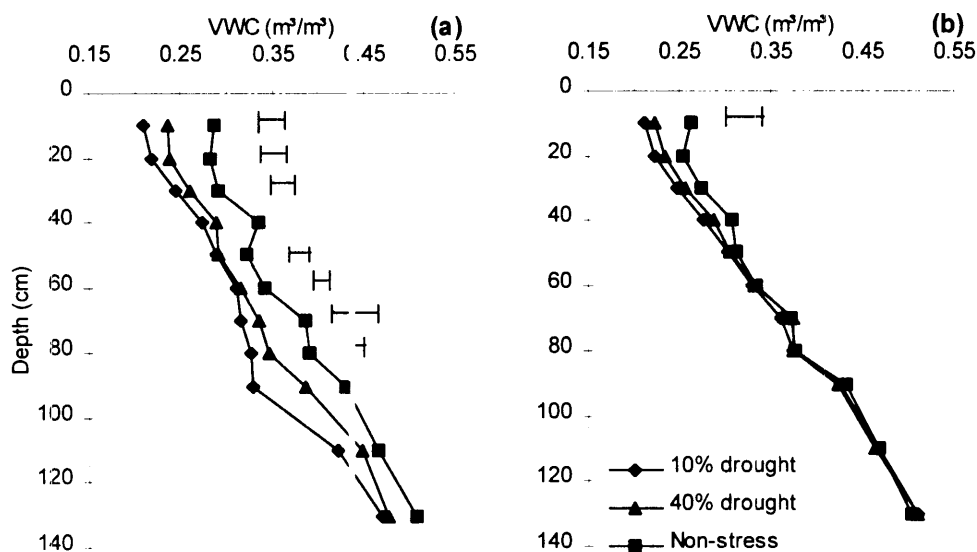


Figure 6.9: Volumetric water content during the (a) Spring-Summer and (b) Summer-Autumn seasons. Data are averaged over species, defoliation intensity and time. 5% l.s.d.s are shown where significant.

In SS, there were significant moisture-time interactions at all depths, while in SA, the interactions were significant at the 10 cm and 20 cm depths only. The interactions for depths 10, 30, 60, 90 and 110 cm for both seasons are presented in Figure 6.10. There were differences between moisture treatments, at individual times, at the 10 cm depth only in both seasons. However, the response of the moisture treatments, through time, was significant at all depths in SS. Contrasts between pairs of moisture treatments were significant for all comparisons, at most depths, to 70 cm ($P < 0.05$). At depths 80–90 cm, the contrast between the 40% drought and non-stress moisture treatments was not significant, however the contrasts between the 10% drought and the other treatments were significant ($P < 0.05$). At depths below 100 cm, the contrast between the 10% drought and non-stress moisture treatments were significant ($P < 0.05$), while the 40% drought was intermediate and not significantly different to either. In SA, contrasts between all pairs of moisture treatments were significant at 10 cm

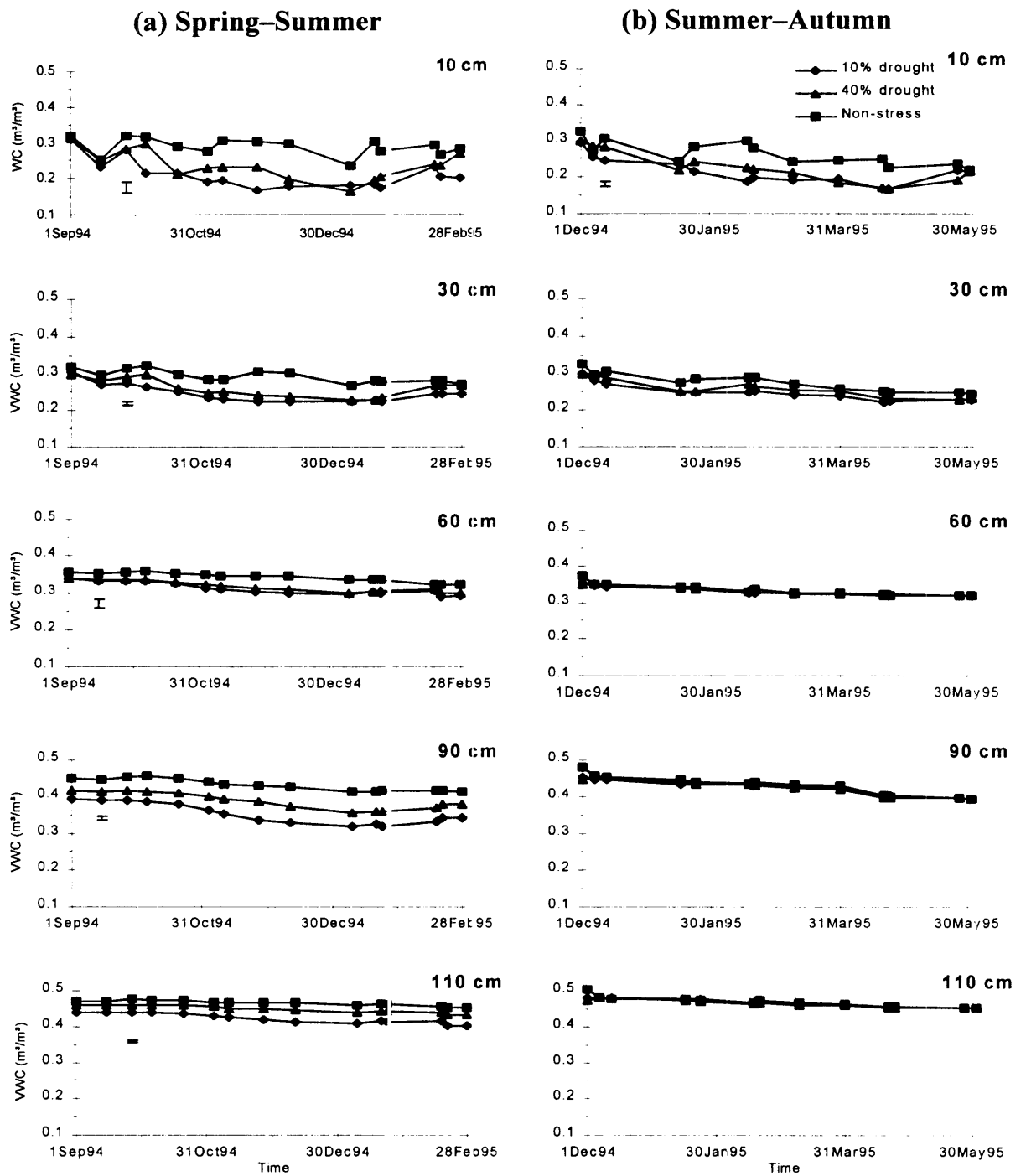


Figure 6.10: Volumetric water content (VWC) in plots at three moisture regimes, 10% drought, 40% drought and non-stress, at 10, 30, 60, 90 and 110 cm depths during the (a) Spring–Summer and (b) Summer–Autumn seasons. The data are averaged over species and defoliation intensity. 1% L.S.D.s (within a moisture treatment) are shown when significant.

($P < 0.001$). At the 20 cm depth, the contrast between the 10% drought and the non-stress moisture treatment was significant ($P < 0.01$), while the response of the 40% drought was not significant to either.

Root mass and distribution

The average root weight of individual species varied at the start of both seasons (main effect, $P < 0.01$). In SS, phalaris, perennial ryegrass and tall fescue had the highest root weights, while perennial ryegrass, tall fescue and cocksfoot had the highest root weights at the start of the SA season. The range in species' root weights was greater in SS than SA. There were no differences between species' root weight after six months of treatments in either season (data not shown).

There was a moisture–depth interaction during the SS season ($P < 0.05$). Although there were no differences in root weight between the three moisture treatments at any depth, the roots of the 10% drought plants had a greater proportion in the upper 30 cm compared to the other treatments (data not shown). Contrasts between the 10% drought treatment and the non-stress moisture and 40% drought treatments were significantly different ($P < 0.05$), while the non-stress and 40% drought plants were similar.

Moisture regime did not affect species' root weight at either assessment during the SS or SA season, however their interaction with time was significant (Figure 6.11). During the SS season, either the root mass of the drought effected plants declined or the non-stress moisture treatment plots increased ($P < 0.001$) in all species except cocksfoot and weeping grass. During the SA season, the root weight of plants of all species, except tall fescue, declined ($P < 0.05$) in either one or both drought treatments. In tall fescue, the root weight of the non-stress moisture plants declined, while the root mass of cocksfoot declined in all three moisture treatments.

Defoliation intensity did not affect root weight, however the defoliation–species–time interaction was significant in both the SS ($P < 0.001$) and SA ($P < 0.05$) seasons. The interactions for both seasons are presented in Figure 6.12. In the SS season, there was a decline in root weight in either one or both defoliation treatments of the introduced species ($P < 0.001$). Similarly during the SA season, the root weight of all species, except tall fescue, declined under either or both defoliation regimes ($P < 0.05$).

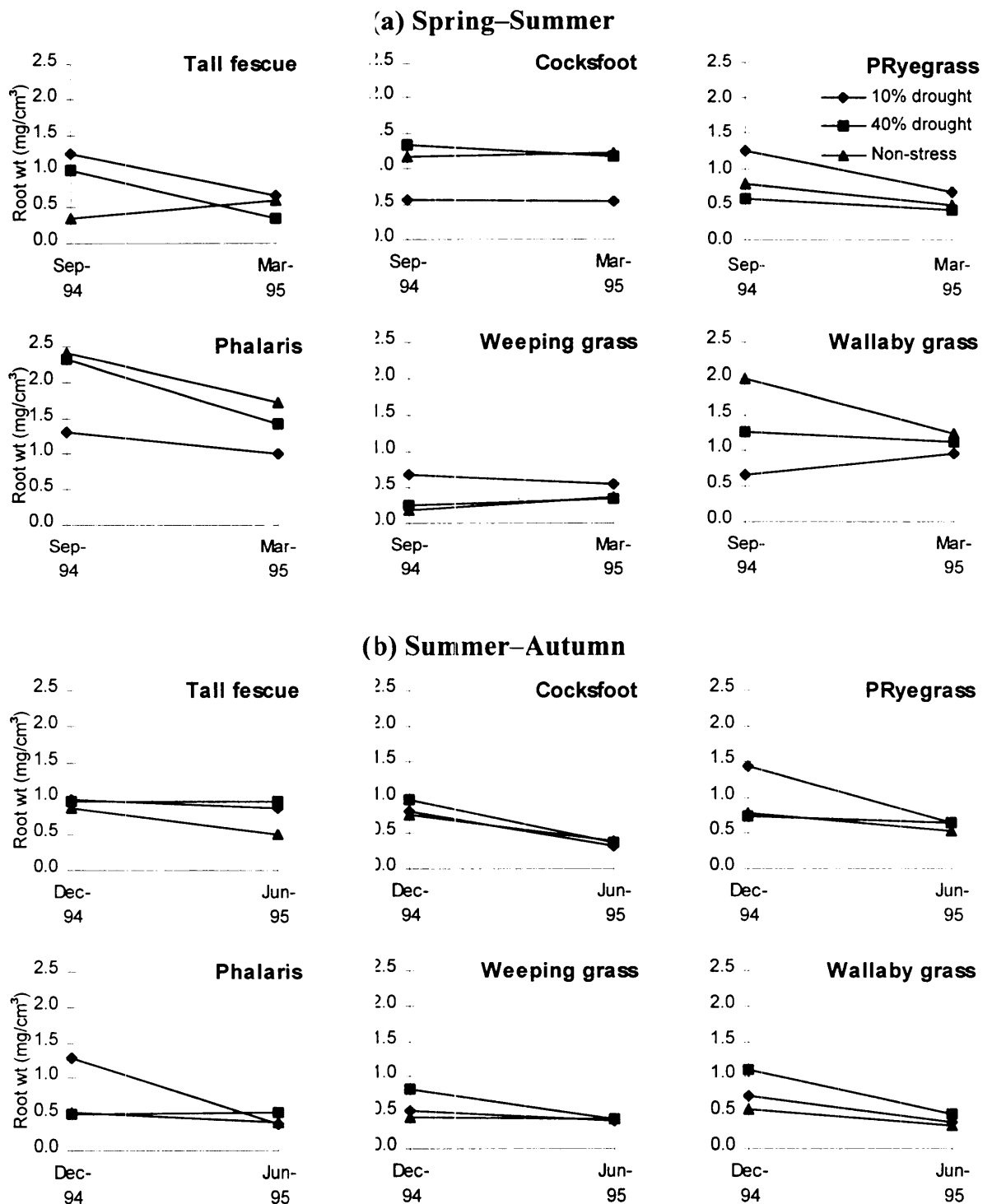
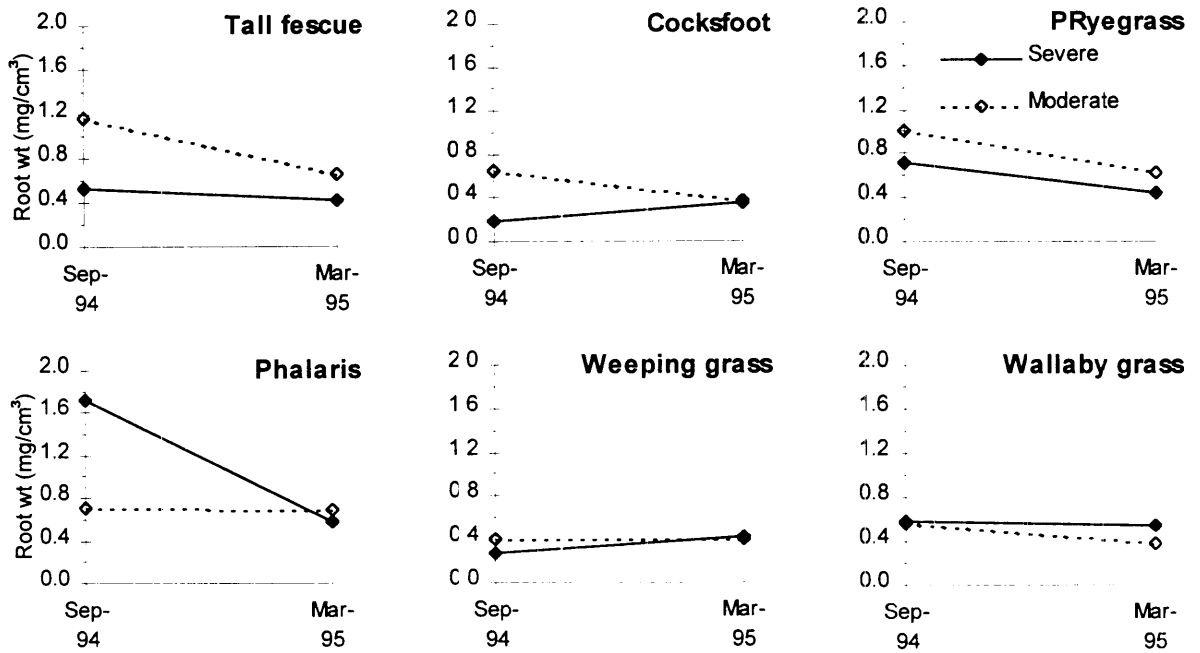


Figure 6.11: Root weight of perennial grass species during the (a) Spring–Summer ($P < 0.001$) and (b) Summer–Autumn ($P < 0.05$) seasons at three moisture regimes, 10% drought, 40% drought and non-stress moisture. The data are averaged over defoliation intensity and depth, and are back transformed.

(a) Spring–Summer



(b) Summer–Autumn

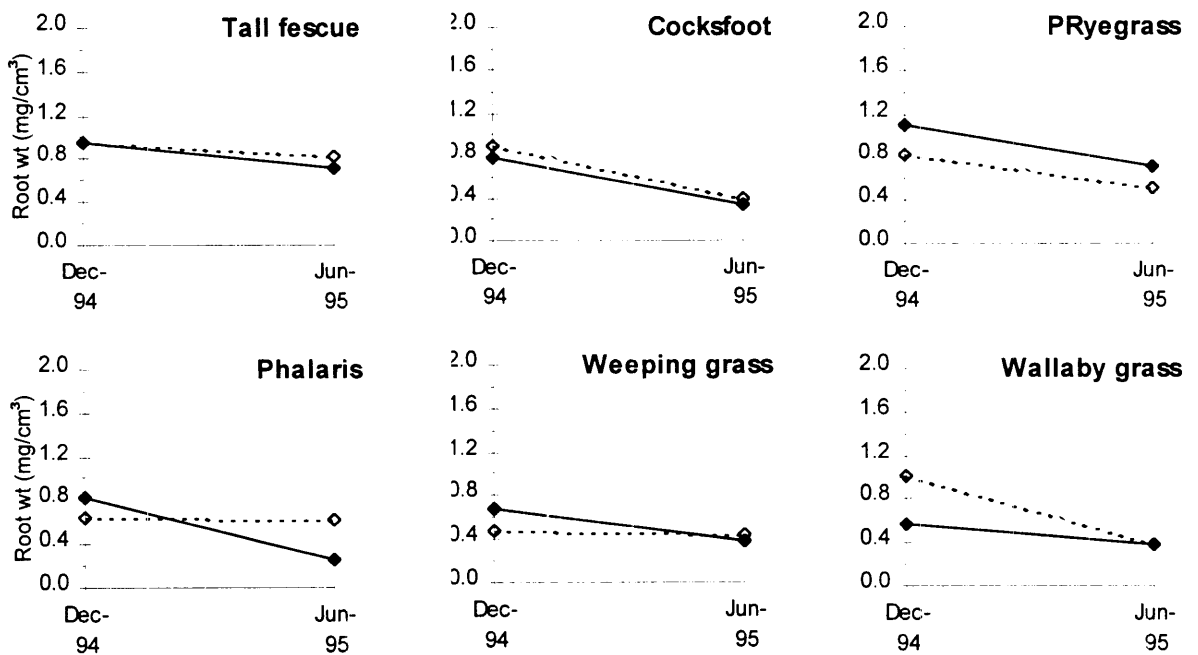


Figure 6.12: The response in root weight of perennial grasses at two defoliation regimes during the Spring–Summer ($P < 0.001$) and the Summer–Autumn ($P < 0.05$) seasons. The data are averaged over moisture regime and depth and are back transformed. Severe: severe defoliation, Moderate: moderate defoliation.

The species–depth–time interaction was significant in both seasons and is presented in Figure 6.13. In general there was a reduction in root mass in the upper 40 cm during the 6–month experimental period in both SS ($P<0.01$) and SA ($P<0.05$). There was little change below 40 cm in either season, except in phalaris, perennial ryegrass and wallaby grass which had differences in the 60–80 cm zone during SA. The root weights of cocksfoot and weeping grass were not affected by the SS treatments. In general, the greatest reductions in root weight occurred in the top 0–10 cm. The root mass in the 60–80 cm zone was greater in perennial ryegrass, phalaris and wallaby grass at the start of the SA season than the SS season. The extra root mass was lost during the season.

Over 90% of the root weight was in the upper 40 cm at the start of the SS season, except phalaris which had 85% (untransformed data). The proportion in the upper 40 cm had declined in all species except tall fescue and cocksfoot by the end of the season. There were less roots in the upper 40 cm at the start of the SA season, than at the start of the SS season. However the proportion was still greater than 88% in all species except wallaby grass and phalaris which had 80% and 83% of their roots in the upper 40 cm respectively. By the end of the season, the proportion of roots in the upper 40 cm had declined in tall fescue and perennial ryegrass, increased in cocksfoot, phalaris and wallaby grass and remained the same in weeping grass.

Effective rooting depth

In SS, phalaris, tall fescue and wallaby grass had the greatest rooting depths of the six species (main effect, $P<0.01$), being significantly greater than cocksfoot, the shallowest rooting species. The other species were not significantly different. There were no differences in species' rooting depth in the SA season. Species' rooting depths for both seasons are shown in Figure 6.14.

The rooting depth of the 10% drought plants was significantly deeper than the other treatments, while the 40% drought plants had the shallowest rooting depth (main effect, $P<0.05$). There was no effect of moisture in SA (data not shown).

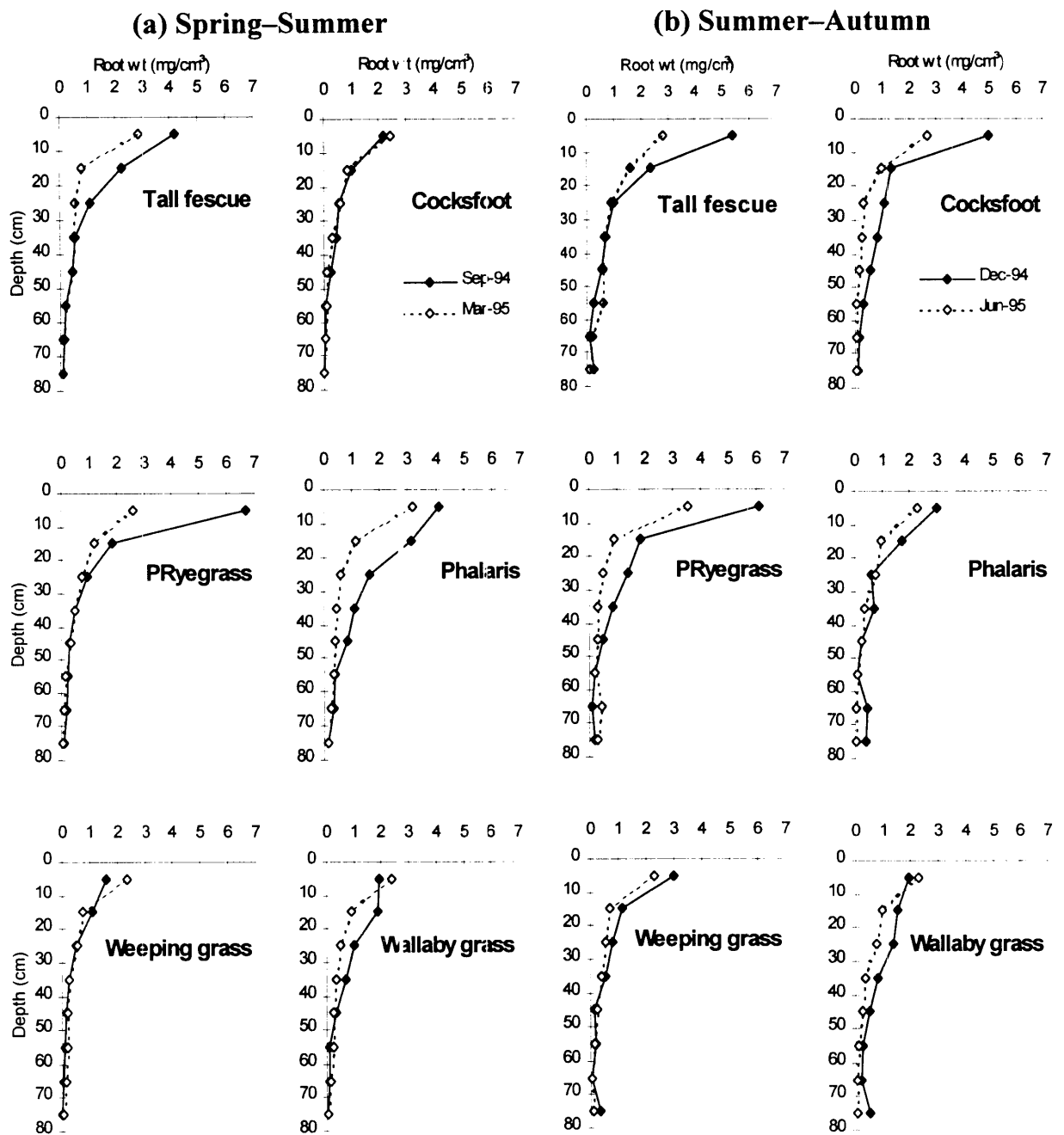


Figure 6.13: The root mass of six perennial grass species at the start and end of the Spring-Summer ($P < 0.01$) and Summer-Autumn seasons ($P < 0.05$). Data are averaged over moisture and defoliation treatments. The data are back transformed.

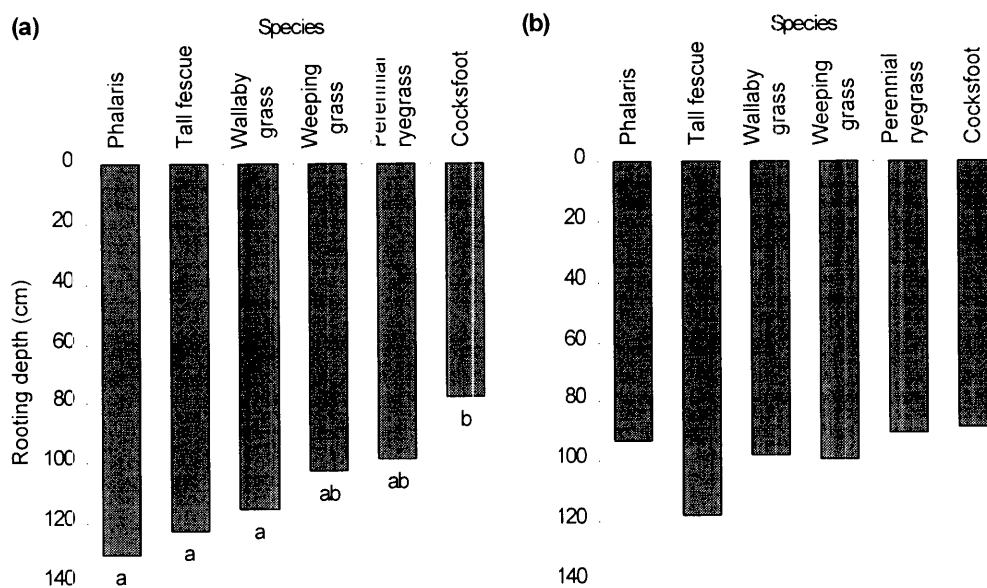


Figure 6.14: Maximum effective rooting depth of six perennial grass species during the (a) Spring–Summer ($P<0.01$) and (b) Summer–Autumn ($P>0.05$) experimental seasons. Like letters indicate no significant difference ($P<0.01$).

Hydrological models

The model was run for a 2-month period (2 September – 1 November 1994) to explore the level of agreement between the observed and predicted soil water values. Two species were used, weeping grass and perennial ryegrass, under two moisture regimes, the 10% drought and the non-stress moisture treatment. Comparisons between the predicted and calculated volumetric water contents at different times during runs of WaterMod are presented in Figure 6.15–Figure 6.18.

The model was effective in modelling the volumetric water contents of the test plots through time, with only small differences between the measured and predicted values. The greatest differences between the measured and predicted volumetric water contents were generally at depths 110–130 cm.

Differences in water use and regions of rooting activity were evident between species and treatments. The 'saw tooth' effect, indicating change in soil water, was obvious near the soil surface in the four test plots, however it was the 50–60 cm depth which indicated the greatest differences in rooting activity between the four test plots. For example, the roots of weeping grass (Figure 6.15e) were more active than those of perennial ryegrass at 50–60 cm (Figure 6.17e).

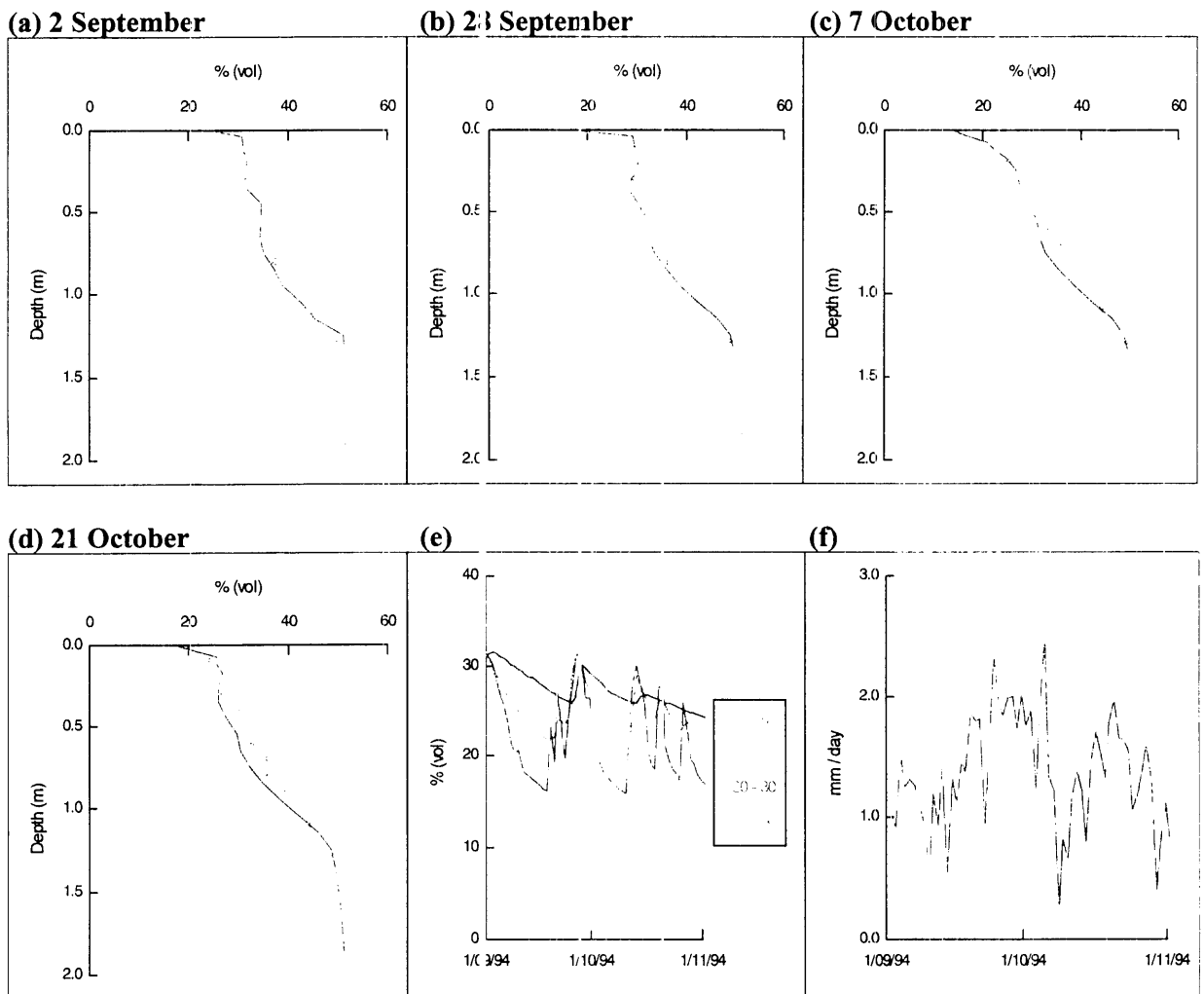


Figure 6.15 : Output from the hydrological model WaterMod showing soil water status and transpiration of weeping grass under the severe defoliation—10% drought treatment combination during the period 2 September – 1 November 1994 of the Spring-Summer season. Outputs include (a–d) predicted (—) and measured (*) volumetric water content during the season, (e) water content through time at four depths and (f) transpiration.

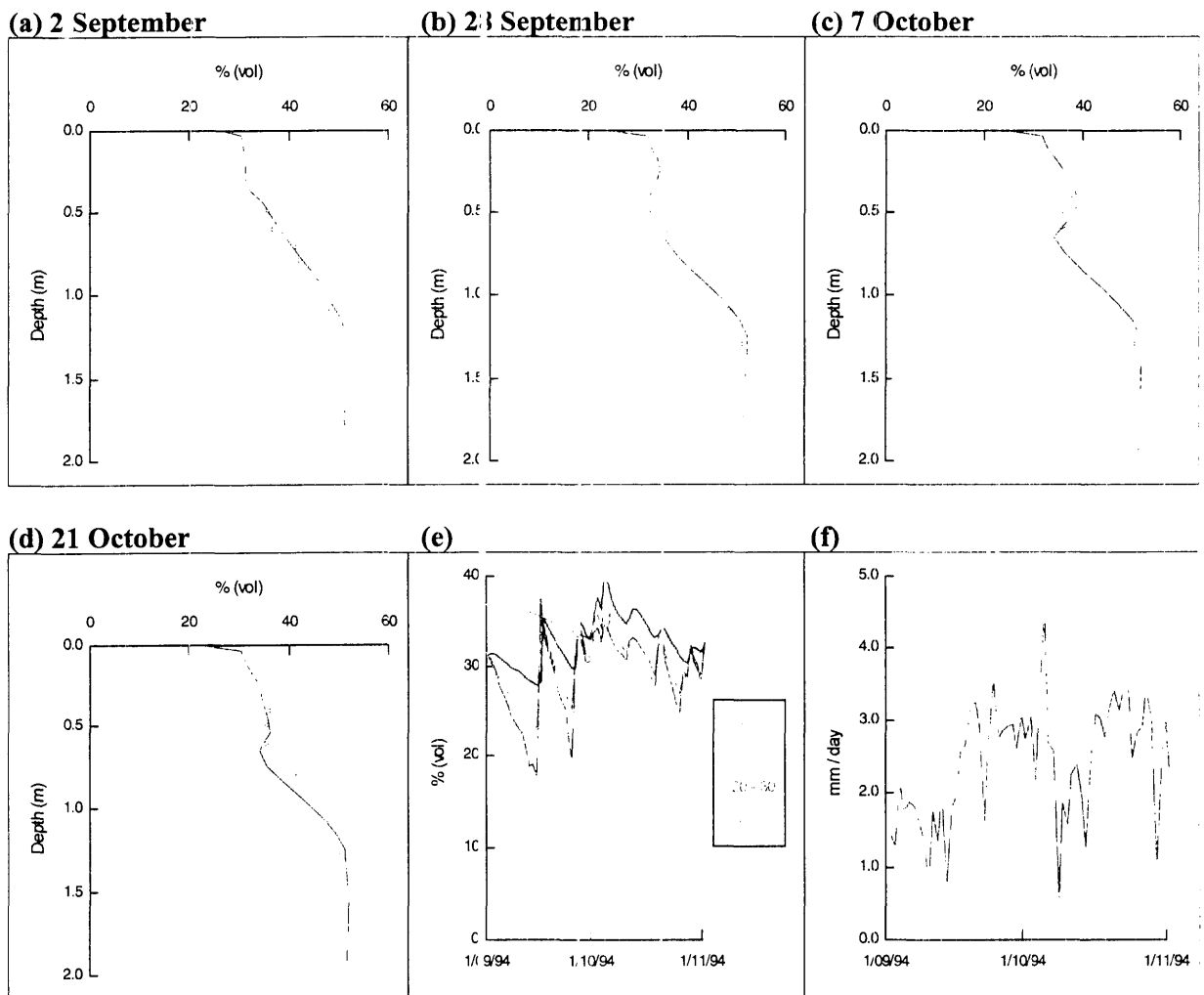


Figure 6.16: Output from the hydrological model WaterMod showing soil water status and transpiration of weeping grass under the severe defoliation—non-stress moisture treatment combination during the period 2 September – 1 November 1994 of the Spring–Summer season. Outputs include (a–d) predicted (–) and measured (*) volumetric water content during the season, (e) water content through time at four depths and (f) transpiration.

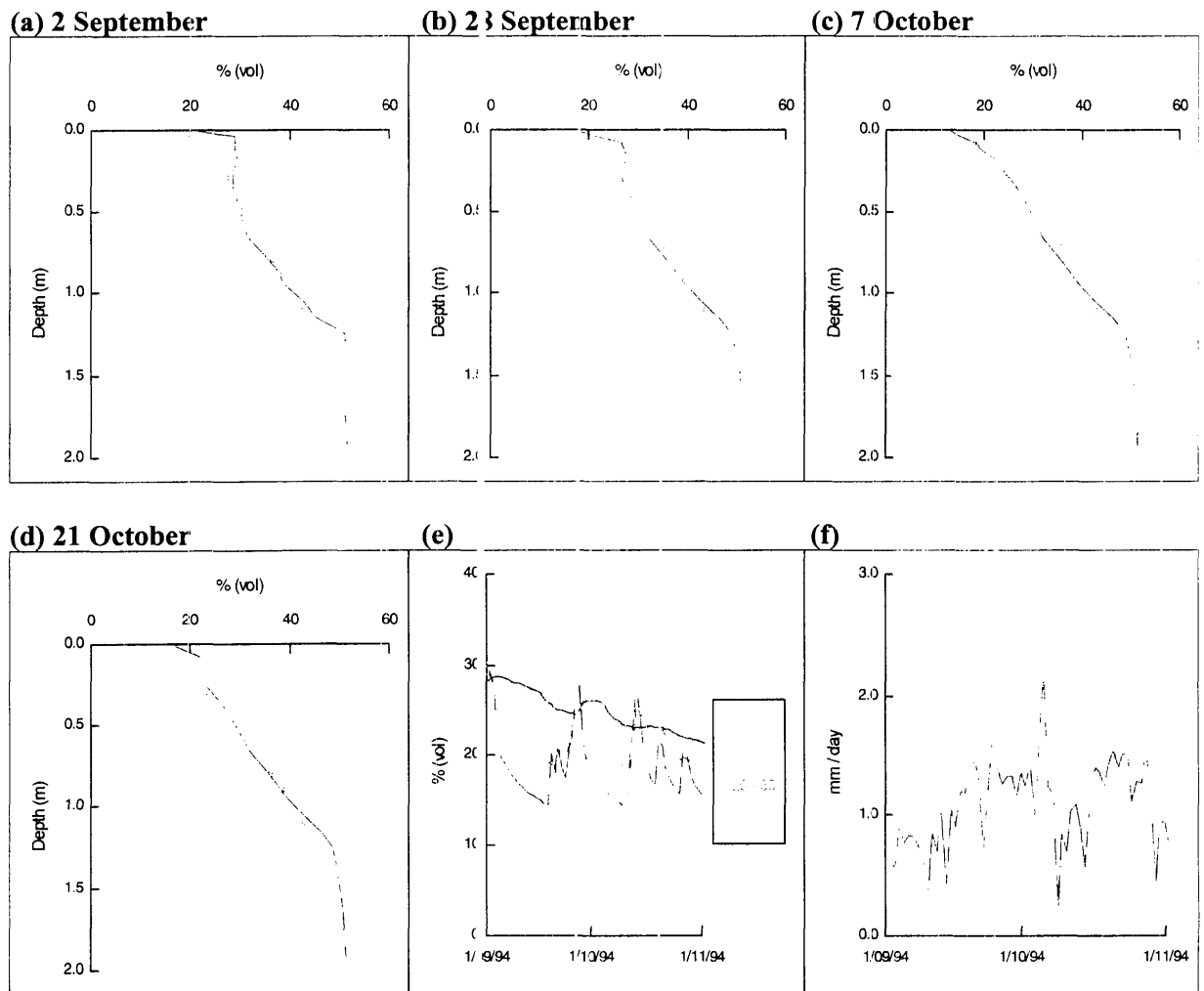


Figure 6.17: Output from the hydrological model WaterMod showing soil water status and transpiration of perennial ryegrass under the severe defoliation—10% drought treatment combination during the period 2 September – 1 November 1994 of the Spring–Summer season. Outputs include (a–d) predicted (–) and measured (*) volumetric water content during the season, (e) water content through time at four depths and (f) transpiration.

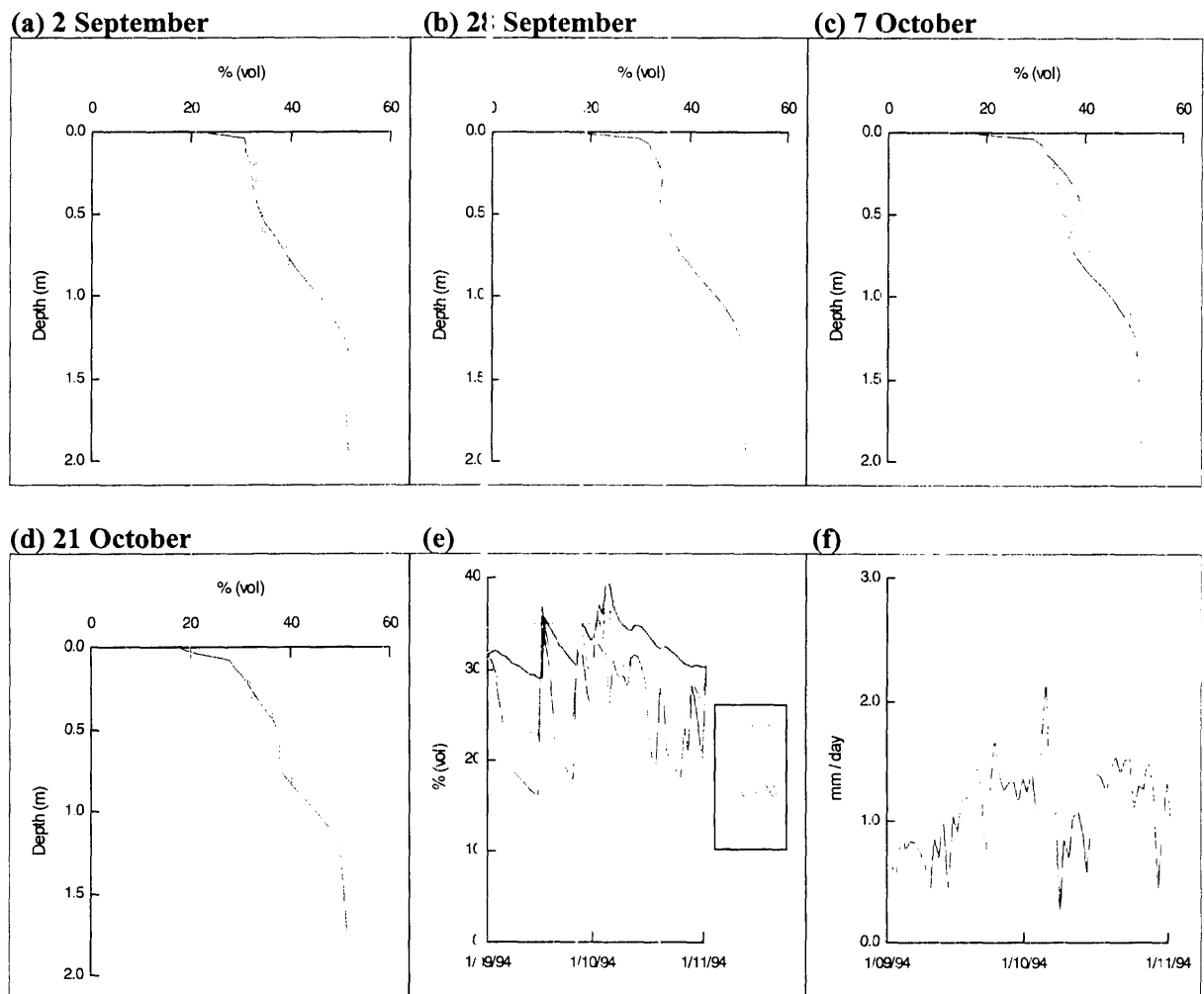


Figure 6.18: Output from the hydrological model WaterMod showing soil water status and transpiration of perennial ryegrass under the severe defoliation—non-stress moisture treatment combination during the period 2 September – 1 November 1994 of the Spring–Summer season. Outputs include (a–d) predicted (–) and measured (*) volumetric water content during the season, (e) water content through time at four depths and (f) transpiration.

The transpiration rates of weeping grasses were sensitive to the moisture regime, with the plants in the non-stress moisture plots having higher transpiration rates than those severely defoliated. The transpiration rates of the two perennial ryegrass plots were similar.

WaterMod was effective in showing the movement of water down the soil profile. It also highlighted that drainage below 90 cm was slow compared to the change in soil moisture in the active root zone 0–60 cm. WaterMod was sensitive to values of hydraulic conductivity, rooting depth and ground cover, especially as there was no litter covering the soil surface in this study.

Discussion

It is recognised that analyses with one replicate are not ideal, particularly when working with data that are naturally variable, such as soil water and root mass data. However, due to limited assistance and a large number of treatments, it was not possible to sample both replicates in this experiment. Analysis of one replicate data using of the highest order interaction as the error term is acceptable in this situation. Although it was assumed that the highest order interaction was not significant, if it had been, then the test would have been more conservative, that is, only the effects and/or interactions which were highly significant would remain so.

Soil profile water

The regions of maximum root activity varied with season and moisture treatment. While some of the change in soil water recorded during this study would have been due to evaporation and drainage, the majority would have been due to root activity. Assuming this, there was root activity in all species to 50 cm. Changes in water content below this depth varied with species. For example, the colour contour graphs suggested that weeping grass had high root activity to 70 cm during SS, whilst phalaris and tall fescue had root activity to approximately 100 cm (Figure 6.2). In SA, these three species again had the most active root systems at depth (Figure 6.3). Phalaris has been reported to be more effective at drying soil profiles than both cocksfoot and annual ryegrass in north eastern Victoria (Ridley *et al.* 1997).

The greatest differences in soil water content occurred during the SS season. There were few differences during the SA season, except near the surface (0–20 cm). Cocksfoot and weeping grass had the driest surfaces of the six species in both seasons suggesting either greater root activity, higher evaporation from the soil surface, a higher proportion of roots at the surface or the ability of these

species to remove more water at the surface.

The change in total profile water content varied with each moisture treatment during SS. In SA, the profile water content in the non-stress and 40% drought treatment plots responded similarly while the 10% drought treatment plots were different. When assessed as individual layers, the differences in response of the three moisture treatments varied (Figure 6.10). In the top 70 cm, the three moisture treatments dried at different rates. At depths 80–90 cm, the change in soil profile water in the 40% drought and non-stress moisture treatments were similar, while the 10% drought plots dried quicker. Although the soil water content was greater than field capacity at depths greater than 100 cm, the 10% drought treatment plots dried the quickest and the non-stress moisture treatment plots the slowest, while the 40% drought plots were intermediate. Thus, the differences between the three moisture regimes decreased with depth.

The 10% drought plots dried quicker than the 40% drought plots in SS, possibly as the highest growth rates generally occur during spring, together with high evapotranspiration. There was little change in soil water below 50 cm in the non-stress moisture treatment plots in either treatment, however the plants were more successful in removing water from the soil to 50 cm depth during SA, possibly due to greater root development. Frasier and Cox (1994) reported large changes in the soil profile water content in the 0–60 cm region due to Lehmann lovegrass, with minimal changes below 90 cm. On an annual cycle, water accumulated in the soil profile during the winter months and was utilised during the growing season (March–June). The depletion during the spring and summer period supports the results presented in this chapter.

The non-stress moisture plots had significantly higher water contents than the drought plots in the SS season. There was no effect of moisture in the SA season. Similarly, there were moisture interactions at depth in the SS season, but not in the SA season. The lack of differences during the SA season, compared to the SS season, could be due to the combination of a wet soil profile at the start of the season and lower growth rates and evapotranspiration.

Cocksfoot and perennial ryegrass had the wettest soil profiles at the end of the season (Figure 6.8), suggesting that they used less water, however the differences were not significant. The greater water contents in the cocksfoot and perennial ryegrass plots corresponds with the lack of recovery in the green foliage index (discussed in Chapter 4) and the number of plants which died (plant death will be discussed in detail in Chapter 7).

During the SS season, phalaris and weeping grass were most effective in drying the soil profile. The greatest total change in profile water occurred in weeping grass. It is well established that phalaris is a deep rooted species (eg. McWilliam and Krarner 1968) and effective at removing soil water from depth (Pook and Costin 1971). Weeping grass is a persistent species and increases in abundance following drought (Whalley and Huxtable 1993). The results from this study suggest that weeping grass also has an active and deep root system. Garwood and Sinclair (1979) found that the ranking of species on their soil water usage changed with cutting frequency. For example, when cut every six weeks, tall fescue used the most water and cocksfoot the least, while perennial ryegrass had the greatest soil water deficits and rough-stalked meadow grass had the least when cut every 3 weeks. In this study, the moderately defoliated plants tended to use more water than those severely defoliated, however, there was no effect of defoliation intensity on the water usage of individual species during either experimental season in this study. The lack of interaction could be due to the small numbers of plants per plot and the wetness of the profile at the start of the experiment

Root mass and distribution

There was a wide range in root weights across the species at the start of both experimental seasons, but the range was reduced after six months of treatments. There were neither defoliation intensity nor moisture regime effects (averaged over the other treatments) on root weight or distribution, however, there were interactions, mostly with time.

Root weight declined during the experiment in both seasons, with the greatest changes generally occurring in the upper 40 cm of the soil profile. Although the distribution of roots down the soil profile did not change due to different defoliation or moisture intensities, the proportion of roots in the upper 40 cm increased (by 2–4%) in tall fescue and cocksfoot and declined in the other species (by 3–4%) during the SS season. During the SA season, the proportion of roots in the upper 40 cm increased (by up to 11%) in cocksfoot, phalaris and wallaby grass and declined in tall fescue and perennial ryegrass (by 9–10%). Although roots tend to concentrate in the upper layers (Troughton 1957) with the greatest proportion usually in the 0–10 cm zone (Garwood and Sinclair 1979; Miller 1991), the distribution of the roots varies with the level of drought resistance (Burton *et al.* 1954). Burton *et al.* (1954) found that drought susceptible species had 94% of their roots confined to the 0–60 cm zone of the soil profile, while the drought-tolerant species had only 65–69% of their roots in this layer. In a pot experiment conducted on cocksfoot seedlings, Voltaire and Thomas (1995) reported that drought (80 days no water) decreased root density in the 0–40 cm zone while the root density below 40 cm

increased throughout drought. Following rewatering, root density increased rapidly in the upper 50 cm.

The zones of maximum root activity and regions with the greatest proportion of roots are consistent. For example, the colour contour graphs indicated that phalaris had consistent water uptake to 100 cm in the SS season. Phalaris also had on average 85% of the root mass in the upper 40 cm region, while the other species had over 90%.

There was no change in root mass at any depth during SS in either cocksfoot or weeping grass. The ability to maintain a greater root mass at the surface, irrespective of the treatments imposed could account for the greater drying which occurred in the plots of these species during the SS season. During the spring months (September–November) there appears to have been root growth at depths below 60 cm in the SA block plants prior to the start of the experimental season (Figure 6.13). Ridley and Simpson (1994) found that the highest root growth rates occurred to 126 cm in spring and were associated with the maximum period of shoot growth. The extra root mass acquired during spring was lost during the SA season, which may explain the lack of moisture effect during the SA season. Klapp (1943, cited in Troughton 1957) found that defoliation reduced root weight in the lower soil layers to a greater extent than the upper layers. Root growth rates vary with season. In summer–dry temperate regions there is virtually no growth of roots of perennial grasses in summer, while rapid root growth occurs during autumn and spring (Jacques 1956; Ridley and Simpson 1994). Short–term annual weather fluctuations and long–term climatic cycles may also override or mask the effects of grazing (Hyder *et al.* 1975; Wilson 1989, both cited in Milchunas and Lauenroth 1993).

Few authors have reported no effect of grazing on root mass, as found in this study, however Matthew *et al.* (1991) found that root mass and production were relatively insensitive to grazing management. Seasonal fluctuations in root production were found to be large in comparison to those produced by grazing management (Matthew *et al.* 1991) and only when defoliation was drastic did it overwhelm seasonal variation (Roberts and Hunt 1936, cited in Troughton 1957). Matthew *et al.* (1991) suggested that the lack of difference in root production, due to varying defoliation severity, could be due to quick adaptation of the plants to the grazing regime or that the defoliation interval was too great to have an effect on established swards. The effect of increased stocking rate on root mass or length near the surface is inconclusive with some reports of reduced mass near the surface (eg. King and Hutchinson 1976; Langlands and Bennett 1973), others increased mass (eg. Schuster 1964; Lorenz and Rogler 1967) and another no effect (Greenwood 1996b).

The literature on roots tends to be somewhat inconclusive. This may be due to some experiments being conducted in pots, while others are conducted in the field. The age of the plants, sampling technique (eg. soil corers, augers and mesh bags), methodology (eg. sieve size, live versus dead roots and root versus roots plus rhizomes) and the type of measurement (eg. root length, root replacement and root mass) may also lead to inconclusive results. Other factors such as variations in soil within an experimental site, limited replication, and small samples (used to represent a large area) would add to the normally large variation in root assessments.

There are three possible reasons for the lack of differences found in this study. Firstly, the lack of defoliation intensity effect on root weight could possibly be due to the cutting frequency (7–15 days) being too regular. Some studies have compared 3 week and 6 week grazing intervals, calling defoliation every 3 weeks 'frequent' (eg. Garwood and Sinclair 1979). Pook and Costin (1971) reported that there were differences in the amount of phalaris roots and rhizomes in the grazed and ungrazed areas to 50 cm, but the amounts were similar at 75–90 cm depth. The pasture was 8 years old at the time of assessment. Ruby and Young (1953) reported that decreasing cutting intensity compensated for increased frequency in root mass in the upper 30 cm of soil. Frequent cutting also reduced root weight at depths 30–60 cm.

It is possible that the lack of differences found in this study could be due to the lack of differentiation between dead and live roots. Some of the dead roots may even have been from the previous pasture. Without distinguishing between live and dead roots, overestimation is likely. The life length of roots varies with species (Troughton 1981), management (Weaver and Zink 1946) and the decomposition rate (Weaver 1947). Perennial ryegrass has been reported to have short lived roots, tall fescue intermediate and cocksfoot long lived roots (Troughton 1981). The longevity of roots varies with species from a few months in perennial ryegrass (Garwood 1967) to six years or more in *Nardus stricta* (Tatarinova 1961, cited in Troughton 1981). The differences in life span and rate of decay could confound root mass, as measured in this study, as there was no distinction between live and dead roots.

The third reason for the lack of difference between the defoliation regimes could be that many of the studies conducted on roots are from experiments with mature swards following several years of grazing treatments (eg. Albertson *et al.* 1953; King and Hutchinson 1976; Langlands and Bennett 1973; Pook and Costin 1971). Defoliation may have a greater effect on mature swards with established root systems and the effect more pronounced after several seasons of treatment application. As the

swards used in this study were still establishing, they may not have had well developed root systems, therefore defoliation may have had little effect as the roots were trying to grow and explore all soil available as quickly as possible. That is, there may have been preferential partitioning to the roots during early development. The main effect of defoliation on roots and other underground organs is the reduction in growth (Troughton 1957), however, compared to the reductions in growth of the tops, the loss in root mass is only relatively small.

Effective rooting depth

The value of deep rooting in drought survival is well documented (eg. McWilliam and Kramer 1968; Garwood and Sinclair 1979; Thomas 1986a; Burton *et al.* 1954) and further supported by the SS season results of this study. Roots of phalaris have been found as deep as 2 m in subsoil containing moisture (McWilliam and Kramer 1968). Perennial ryegrass has been reported to have superficial root development, with almost total exploration of the top soil (0–30 cm), but with limited extension of roots into the subsoil (30–90 cm) (Pooch and Costin 1971). Phalaris roots in a phalaris–subterranean clover pasture however did not fully exploit the topsoil, but they did have a strong vertical extension of deep roots into the subsoil (Pooch and Costin 1971). Heavy grazing has been reported to significantly reduce root extension of grasses (Schuster 1964).

The data are again consistent between measurements in this study. Phalaris, tall fescue and weeping grass had the most active root systems (greatest changes in soil water) of the six species tested and were the deepest rooted (in the SS season).

Where there was copious water available, as in the non–stress moisture plots, the plant roots did not need to grow towards water. In the non–stress moisture treatment plots, roots were active to 50 cm. This is the region rich with nutrients and often water (Jacques 1956). Jacques (1956) suggested that young roots near the surface supply mineral foods and water to the plant and act as storage organs while the roots which extend downwards are to supply water. Davidson (1969) found that the lowest root–shoot ratios occurred where nitrogen, phosphorus and soil moisture were non–limiting, that is, both the roots and shoots grew under non–limiting conditions; the shoots growing to a greater extent.

Several other methods were attempted to estimate rooting depth, however they were not successful. The other methods were colour contour graphs, soil moisture extraction curves and daily water loss as described in Frank and Bauer (1991). Maximum effective rooting depth, using the Spyglass[®] colour contour graphs, was estimated as the maximum depth where there was no change in volumetric soil

water content. Rooting depth estimated from extraction curves involved graphing two extraction curves from assessments late in each experimental season. The maximum rooting depth was determined as the depth where there was no change in soil moisture content (that is, the point where the two curves met). The contour graphs were insensitive to small changes that would be likely at maximum depth, while rooting depth using extraction curves were difficult because of possible confounding due to drainage. Estimating the rooting depth of the non-stress moisture plants was more difficult as the profile was constantly wet at depth due to water being applied every 2–3 days. Frank and Bauer (1991) defined root activity as daily water loss ≥ 0.095 mm/100 mm soil depth increment. Daily changes of 0.15 mm and 0.2 mm/100 mm were used, but distinguishing between drainage and water use was difficult. Knowledge of hydraulic conductivity for the soil may have helped distinguish between the two. With a better understanding of the soil profile and general hydrology, the soil water levels could be better monitored so that saturation did not occur as it did in this case.

The shape of \log_e curves fitted to root mass data and the degree of fit is dependent on the distribution of the roots, with not all root distributions having a \log_e distribution. While the ranking of most species in this study followed those suggested in the literature, cocksfoot was ranked lower in this study than reported by Thomas (1986a). Grass roots have been reported at depths greater than 80 cm (Burton *et al.* 1954; McWilliam and Kramer 1968; Pook and Costin 1970; Garwood and Sinclair 1979; Frank and Bauer 1991). Similarly, spaced plants have been reported to have deeper rooting systems than swards (Pavlychenko 1942, cited in Troughton 1957). With this information, the values determined from fitting curves to the root data are most likely underestimating the rooting depth. Garwood and Sinclair (1979) reported that the rooting depth of 2 year old swards of cocksfoot, perennial ryegrass and tall fescue (averaged over defoliation frequency) were 85 cm, 80 cm and greater than 100 cm respectively. These values are similar to those calculated in this study which further supports the theory that rooting depth was underestimated.

Hydrological models

Soil water data is one of the more difficult sets of data to explore, partly because of the large volume of data, and interacting processes such as transpiration and drainage. In general, traditional statistical methods are not as effective on these types of data sets due to correlations through depth and time. For this reason, WaterMod[®] was used to investigate the soil moisture data and test the potential effectiveness of using models to identify differences between species and treatments. Models are becoming more common with the increased use of computers and availability of better and more

interactive models.

WaterMod effectively modelled soil water in the plots tested in this study when compared to the neutron probe measurements. The greater differences between the predicted and measured soil water contents at depth could be due to errors in parameter values (eg. hydraulic conductivity) or possibly increased error in the neutron probe readings. Soil water near saturation can be difficult to measure with the neutron probe.

Prior to using a model it is important to know which parameters and inputs are required to run it so that the appropriate data can be collected. This is especially important where substantial data inputs are necessary or the model is sensitive to the data correctness. For example, in this study hydraulic conductivity was not measured, hence it had to be estimated. Runs with different hydraulic conductivity values indicated that WaterMod was sensitive to small changes. However, with this in mind and provided the remaining data are accurate, WaterMod could be used to estimate an unknown or difficult to measure parameter, such as hydraulic conductivity. For example, hydraulic conductivity can be calculated in the field, however the data are difficult to collect and often have large variation (M. McLeod, pers. comm.). Models, such as WaterMod can be used to test the effectiveness of a value or to estimate likely values.

Hydrological models, such as WaterMod have potential as effective tools to peruse large volumes of water data. WaterMod's most unique feature is being able to see the predicted movement of water through the soil profile on a daily basis. The effects of infiltration, following rainfall or irrigation, and drainage can be identified, as well as the regions of maximum root activity.

Conclusions

1. The effects of the drought and defoliation treatments on soil water were greater during the SS than the SA season, possibly due to high spring growth rates combined with high temperatures.
2. Although there were few differences in soil water content of the three moisture regimes at different depths at any one time, the rate at which the three profiles dried varied. The differences between the three moisture treatments decreasing with depth.
3. Defoliation intensity had little effect on soil water content, root mass and distribution, or rooting depth in either the SS or the SA season.

4. The plants appeared to utilise the water in the soil profile to similar proportions irrespective of the moisture regime during the SA season.
5. Root growth occurred below 60 cm during spring (September–November), prior to the start of the SA experimental season, however the extra root mass was lost during the SA season. The root weight declined during the experiment in both seasons, generally in the upper 40 cm of the soil profile. There was no change below 40 cm in the SS season, while during the SA season there were reductions in root weight at depths below 60 cm in phalaris, perennial ryegrass and wallaby grass.
6. Neither defoliation intensity nor moisture regime affected the root weight of the species during either season. However in the SS season, the 10% drought plants had more roots in the upper 40 cm than the other moisture treatments. In SS, phalaris, tall fescue and wallaby grass were the deepest rooting species and cocksfoot the shallowest rooting species. There were no differences in the SA season.
7. WaterMod was effective in graphically showing the movement of water in the soil profile on a daily basis. The model was also effective in showing infiltration following rainfall/irrigation, drainage and estimating the region of maximum root activity.