Soil Water Studies on Small Lucerne Plots*

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Abstract

Lucerne (*Medicago sativa* L.) was grown in a field trial under four soil water depletion (SWD) levels, viz. 15 %, 35 %, 55 % and 75 %. Texturally the experimental soil ranged from a sandy loam to a sandy clay loam. Soil water content was measured at five depths with mercury manometer tensiometers, Bouyoucos gypsum blocks and Colman moisture cells. From these measurements irrigation scheduling was done and actual evapotranspiration (ET_a) rates calculated for the different moisture treatments.

Introduction

In the Winter Rainfall Region of South Africa, lucerne (*Medicago sativa* L.) is grown either in rotation with wheat under dryland conditions or under irrigation in pastures in combination with grasses and other legumes. In the former region information on the water use characteristics of lucerne under different soil water regimes is inadequate to assist in irrigation design and scheduling. Furthermore, the proper management of water resources has become of top priority, thereby requiring more accurate estimates of actual evapotranspiration (ET_a).

Well-watered lucerne has been shown to consume water at very high rates, which could exceed the pan evaporation (E_o) rate (Van Bavel 1967, Rosenberg 1969a, Snaydon, 1972a). Evapotranspiration rates for irrigated lucerne were found to be as high as 12 mm/d (Rosenberg 1969a, 1969b). Snaydon (1972b) found maximum production of dry matter in autumn at an ET_a/E_o ratio of 1,5. Under irrigation practices involving more limited water supply, Vittum *et al.* (1963) reported that lucerne yields obtained under 85 per cent depletion were not different statistically from those under wetter water regimes. They concluded that forage crops like lucerne are able to use water held in the soil at low water pressures (-200 to -400 kPa) and still maintain the same growth rate.

Nieuwoudt (1965) found actual water consumption of lucerne to range from about 700 mm to 1070 mm in the Olifants River Valley (Western Cape Province). He also reported ET_a/E_o ratios ranging from 0,58 to 1,01. In a five year irrigation experiment with lucerne in the south western Cape Province (Oudtshoorn) seasonal water use values were established for lucerne ranging from 370 mm to 660 mm, depending on the treatment. Seasonal ET_a/E_o ratios ranged from 0,39 to 0,71. The latter mean included a peak of 0,99 for the main hay production period (D.J. Beukes, unpublished data). Shalhevet *et al.* (1976) reported gross water application amounts of 615 mm to 1120 mm with 5 and 12 irrigations, respectively. In all cases the wetting depth was 1200 mm.

Materials and Methods

An irrigation experiment with lucerne (*Medicago Sativa* L.) was conducted on the Welgevallen Experimental Farm of the University of Stellenbosch (latitude 33° 56' longitude 18° 53'). The treatments consisted of allowing lucerne to extract soil water to a specific depletion level of plant available soil water (SWD level) before an irrigation was applied to fill up the soil water reservoir to field water capacity (FWC). Four levels, viz. 15 %, 35 %, 55 % and 75 % were used, each on a plot of 9 m x 7,5 m. The primary objective was to determine the finer details of methods and instruments for measuring soil water (Beukes, 1974). Secondary objectives, which will be dealt with in this paper, were to determine the changes in soil water content and soil water pressure as well as the water use characteristics of lucerne, under the different soil water regimes.

The experiment was laid out on an alluvial terrace. The soil is classified as a Rietvlei series of the Westleigh soil form (MacVicar *et al.* 1977). The thickness of the A-horizon is 460 mm. The soft plinthic B-horizon overlays at 1500 mm depth a coarse sandy to gravelly layer. The latter layer is in turn underlaid by a boulder bed. During winter a water table is present at 1800 mm depth. The mean bulk densities of the A and B-horizons are respectively 1,40 and 1,41 g cm^{-3}. Texturally the A-horizon is sandy loam while the B-horizon is a sandy clay loam. The experimental soil is a typical soil on which pastures are established in this region.

Climatic data were obtained from a weather station situated 300 m from the experimental site. Highest day temperatures are experienced during January (28°C) and February (29,5°C). The greatest amount of wind is registered from November till January at a mean velocity of 188 km per day. During the growing season, which lasts from 15 September to the end of April the following year, the mean rainfall is 236 mm and mean United States Weather Buro (USWB) class A pan evaporation is 1500 mm.

Disturbed soil samples and undisturbed soil cores (cylindric, 53,8 mm diameter; 30 mm high) were taken from each experimental plot at 100 mm intervals down to 1650 mm depth for all the necessary physical and chemical soil analyses. Field water

*Excerpt from MSc (Agric)-thesis of DJ Beukes, University of Stellenbosch capacity was determined at different depths on the experimental plots according to the standard field procedure (Wilcox, 1962; Beukes, 1978). The permanent wilting percentages were determined at 1520 kPa on the soil cores with the pressure membrane apparatus. A small pit was dug on the side of each plot to measure the root depth of a number of representative lucerne plants. From these results a mean root depth of 1370 mm was calculated. This value was taken as the possible water extraction depth of the lucerne. The latter depth was divided into five zones with instruments installed in each zone. Soil water was measured with mercury manometer tensiometers, Bouyoucos gypsum blocks (Bouyoucos, 1961) and MC-310 A soil moisture cells (Colman and Hendrix, 1949).

The gypsum blocks and moisture cells were calibrated in the normal way (Colman 1952). All the instruments (including the tensiometers) were installed in the centre of each plot at 150, 300, 610, 910 and 1220 mm depth and read daily at 08h00. The readings were converted to percentage soil water, using the appropriate water retentivity and calibration curves. Water pressure values for the gypsum blocks and moisture cell readings were obtained from the water retentivity curves.

For the purpose of irrigation scheduling at the different SWD levels, the water percentages representing the latter levels were subtracted from the measured percentages. The results were multiplied by the respective soil bulk densities and depth increments to yield the quantities of plant available water, in mm, for each depth zone. These quantities were subsequently added up for the whole soil profile to yield total plant available water (TAW) above or below the specific SWD level. When the latter TAW values were zero or negative the proper amount of irrigation water was applied to replenish TAW from the attained depletion level to FWC.

Actual evapotranspiration (ET_a), or crop water use, was calculated, taking the general water balance equation into consideration:

$$ET_a = R_{eff} + I + (SW_1 - SW_{i+1}) + (C - D) - R_o \qquad (1)$$

The terms effective rainfall (R_{eff}) and irrigation (I) were neglected because soil water content (SW), and hence TAW, was measured before (SW_1) and after (SW_{i+1}) an irrigation or rain. The contribution of R_{eff} and I to the ET_a term was, therefore, taken into account by the values of SW_1 and SW_{i+1}. It was not always possible to follow this approach for rainfall incidences, especially with the start of the rainy season at the end of April. Effective rainfall, taken as rainfall times 0,70, had then to be included in the equation. The groundwater table (GWT) was deeper than 4000 mm during the growing season so that capillary supply (C) from GWT was neglected. The applied irrigation water amounts were, as previously stated, calculated to fill up TAW to FWC. A mean drainage rate of 0,6 mm/d was measured at FWC for all four plots. Therefore, water loss by deep drainage (D) was such a small component of the water balance equation that it could be neglected. Lateral drainage was prevented by screening each lucerne plot with vertically placed plastic sheeting which extended from the soil surface down to the boulder bed. There was no runoff (R_o) from the plots. The water balance equation that was consequently used for the major part of the growing season was:

$$ET_a = SW_1 - SW_{i+1} \qquad (2)$$

ET_a (or crop water use) was, consequently, calculated for each plot by obtaining the difference in TAW between consecutive measurements of soil water. Soil water depletion, therefore, was affected primarily by ET_a.

Water was applied by a microjet system. Irrigation scheduling was done mostly by tensiometer. Soil water pressures for the shallower depths of measurement of the 55 % and 75 % depletion levels were often much lower than −85 kPa, which was outside the measuring range of the tensiometers. In the latter cases soil water content values, obtained from the gypsum blocks or moisture cells, were used.

Until the lucerne was 16 months old and well established, the experimental plots received 31 mm water every 10 days. Thereafter the differential irrigation treatments were enforced. Harvesting was done on all plots at about 10 per cent flowering. Since the practice was to irrigate the lucerne immediately after cutting, the date for the latter was changed sometimes to coincide with the attainment of a specific SWD level.

Although observations were done over three growing seasons, thereby including the previously mentioned establishing period, it was only during part of the 1972/73-season and the complete 1973/74-season that the irrigation treatments were successfully applied. Results from the latter season only will be used to demonstrate the various aspects of the treatments.

Results and Discussion

Irrigation scheduling and evapotranspiration

Table 1 depicts some relevant irrigation data for the irrigation season lasting from October 1973 to April 1974. The ET_a values in the sixth column correspond to the irrigation season of each SWD level.

TABLE 1
IRRIGATION DATA

SWD level (%)	Number of irrigations	Mean irrigation frequency (days)	Mean amount per applic. (mm)	Gross irrigation (mm)	ET_a accord. to irrig. season (mm)	Pan evaporation 1/10/73–30/4/74 (mm)	Rainfall 1/10/73–30/4/74 (mm)
15	29	7	38	1102	1393	1666	127
35	17	10	62	1054	1255		
55	8	25	122	976	1008		
75	5	38	143	715	919		

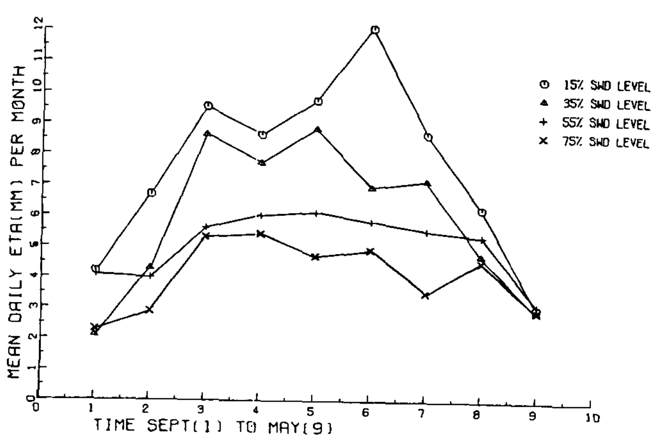

Figure 1
Evapotranspiration rates at different soil water depletion levels, for the period 25/09/73 to 23/05/73

TABLE 2
MEAN DAILY ET_a/E_o RATIOS PER MONTH

Month	ET_a/E_o at SWD level (%) of 15	35	55	75
Oct.	0,98	0,73	0,53	0,46
Nov.	0,94	0,76	0,65	0,63
Dec.	1,06	0,78	0,78	0,59
Jan.	1,08	0,83	0,59	0,49
Feb.	1,08	0,71	0,60	0,58
Mar.	1,13	0,93	0,70	0,50
Apr.	1,00	0,87	0,87	0,86
May	0,88	0,76	0,93	0,85
Mean ET_a/E_o for season	1,02	0,80	0,71	0,62

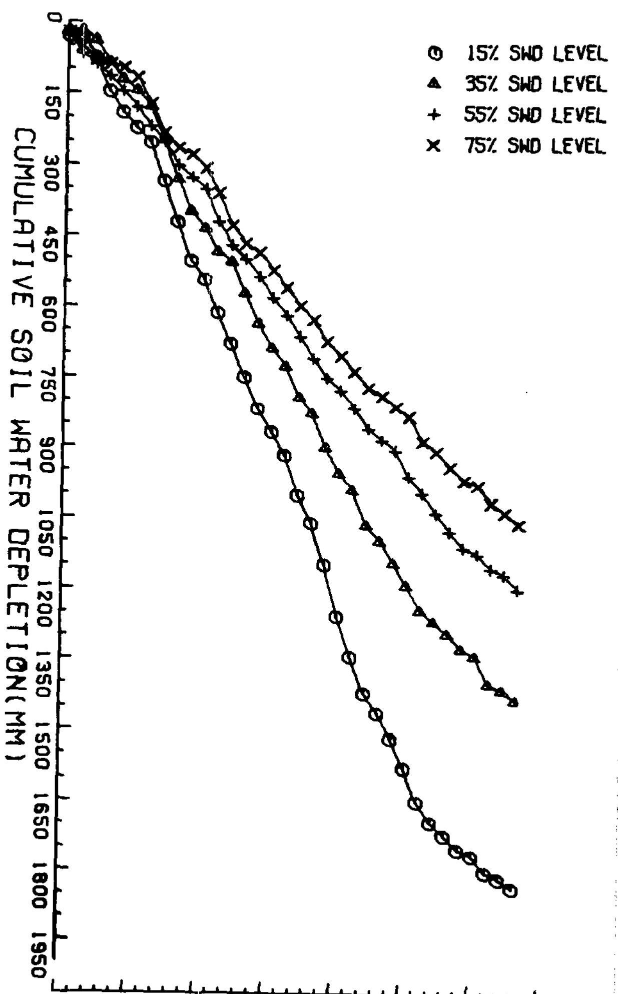

Figure 2
Cumulative soil water depletion

By decreasing the SWD level from 75 % to 15 % both the irrigation frequency and the amount of water per irrigation decreased. The 75 % SWD level required 5 irrigations of 143 mm each while the 15 % SWD level needed 29 irrigations every 7 days at 38 mm per application. Under the climatic conditions that prevailed at least 1100 mm and 700 mm of water were required, respectively, by a 15 % and a 75 % SWD level. These results compare favourably with those reported by Shalhevet *et al.* (1976).

Mean daily ET_a values per month are presented in Figure 1 for the period September to May. The results show that when the level of soil water depletion was increased from 15 % to 75 %, ET_a and, consequently, ET_a/E_o were decreased. Seasonal ET_a followed the typical parabolic trend of atmospheric demand, causing lower water use values at the start and end of the growing season. Seasonal mean ET_a rates for the SWD levels (in decreasing order) were 4,0, 5,2, 5,9 and 7,6 mm/d, with a peak of 12,0 mm/d during February for the 15 % SWD level (Figure 1).

Cumulative soil water depletion, or total crop water use, is shown in Figure 2. These data indicate that, for a growing season lasting from October to May, cumulative SWD was equal to 1829 mm and 1055 mm, respectively, for a 15 % and a 75 % SWD level. From the data reported by Nieuwoudt (1965) a mean water use value of 911 mm of water can be calculated for a 50 % SWD level for the period October to March. In Figure 2 a cumulative SWD value of 957 mm is arrived at by the end of March for a 55 % SWD level.

Mean daily ET_a/E_o ratios per month are given in Table 2. The typical parabolic trend was absent because ET_a/E_o ratios did not decrease during April and May. A possible explanation was that ET_a was increased, relative to pan evaporation, because of higher soil water contents which were caused by more frequent rainfall during these months. By this time, the effects of the various irrigation treatments were cancelled out to a large extent. The seasonal ET_a/E_o of 1,02 for the 15 % SWD level (Table 2) indicated that the ET_a rate was equal to that of pan evaporation. At this SWD level soil water was not a limiting factor so that crop water use was primarily a function of prevalent climatic conditions. The seasonal ET_a/E_o ratios compare favourably with those reported by Nieuwoudt (1965) and Shalhevet *et al* (1976). In the present study a 75 % SWD level required 715 mm of irrigation water and induced an ET_a/E_o ratio of 0,62. Shalhevet *et al* (1976) reported a mean ET_a/E_o ratio of 0,63 when the irrigation amount was 737 mm of water.

Figures 3(a) to 3(d) depict fluctuations in percentages of soil water at different depths for the various SWD levels. For the sake of clarity only values at three of the five depths, viz. at 150 mm, 610 mm and 1220 mm, are included in the figures. Incidences of irrigation and rain are also indicated.

These figures are included primarily to demonstrate the differences in soil water regimes brought about by the various SWD levels. For example, at all depths the frequency of soil water fluctuations was much higher and their magnitude much smaller for a 15 % than for a 75 % SWD level. While for the former level changes in soil water were restricted mainly to the top 600 mm of soil (Figure 3(a)), these changes extended down to 1220 mm depth for a 75 % SWD level (Fig. 3(d)). In other

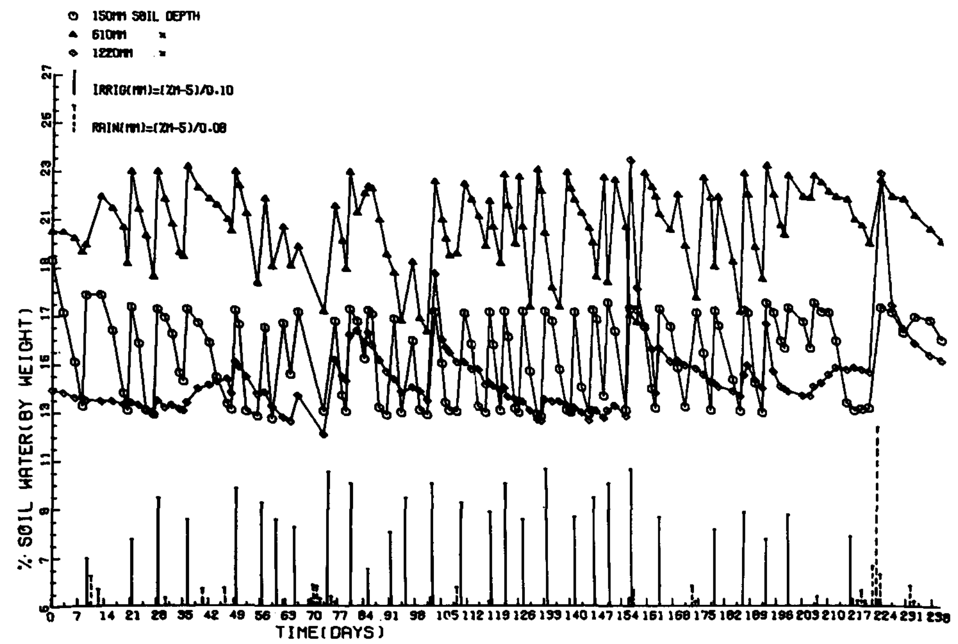

Figure 3(a)
Soil water fluctuations for the period 25/09/73 to 23/05/74 — 15% SWD level

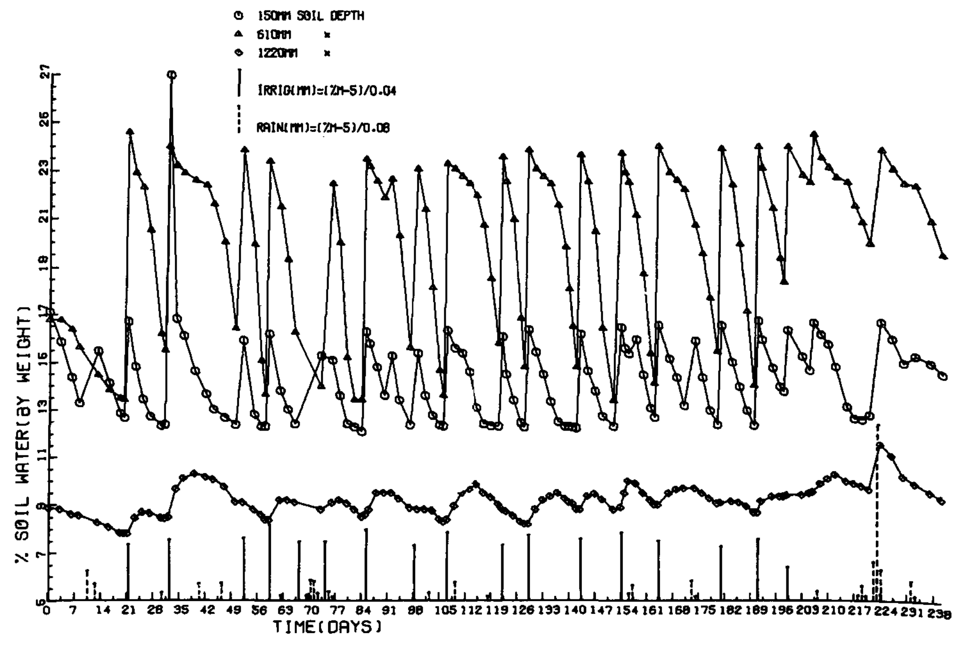

Figure 3(b)
Soil water fluctuations for the period 25/09/73 to 23/05/74 — 35% SWD level

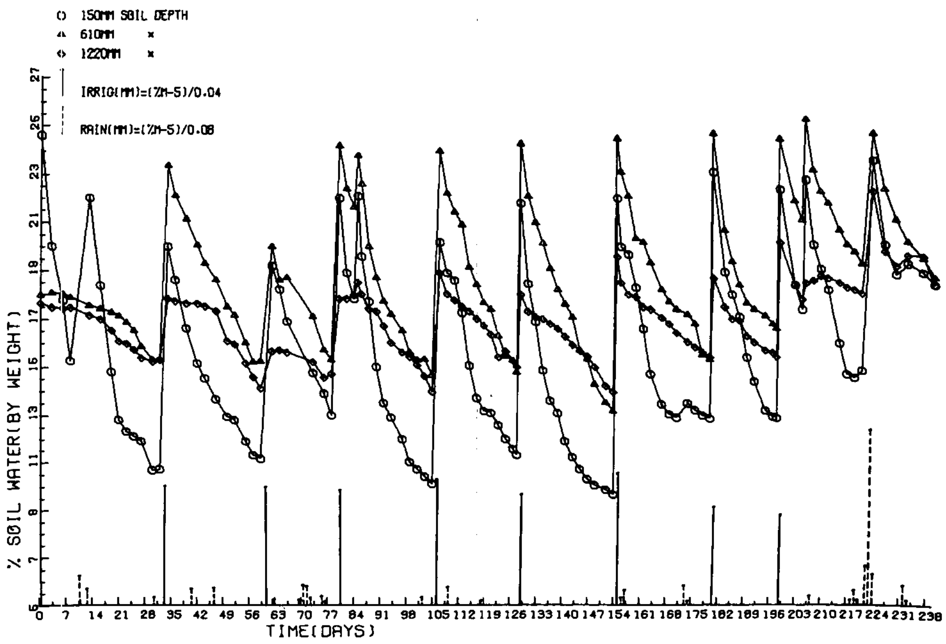

Figure 3(c)
Soil water fluctuations for the period 25/09/73 to 23/05/74 – 55% SWD level

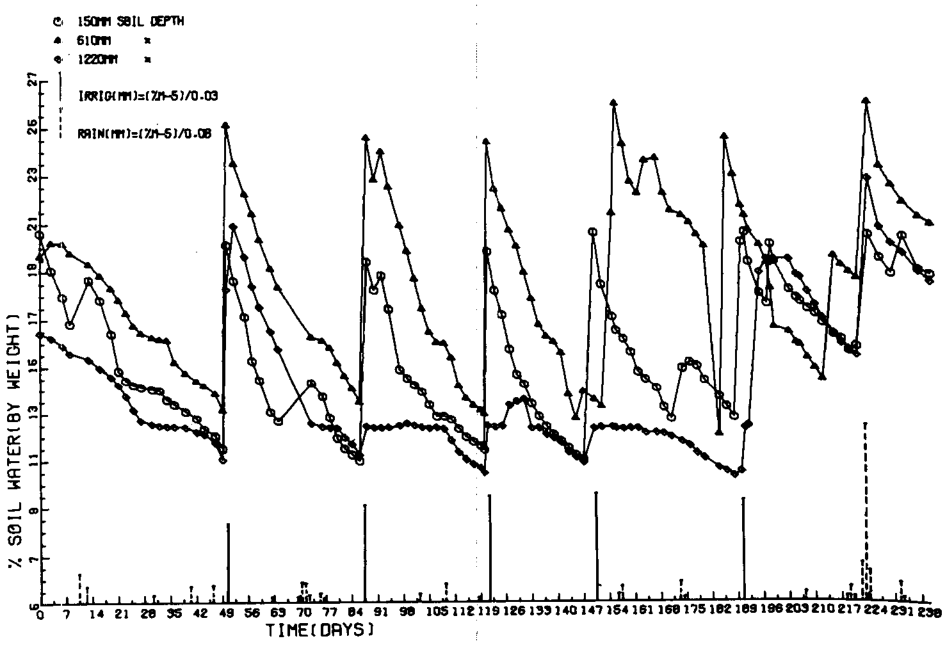

Figure 3(d)
Soil water fluctuations for the period 25/09/73 to 23/05/74 75% SWD level

words, with increasing SWD level the soil depth to which soil water depletion took place also increased. In Figures 3(b) to 3(d) the irregularities in soil water patterns at the beginning and end of the growing season were caused by higher incidences of rainfall. The low soil water percentages at 1220 mm depth in Figure 3(b) were caused by a sandy layer with a low water retention capacity.

Water extraction (expressed as a percentage of the total) at the different depths of measurement, and at the point of time when a specific SWD level was attained, is given in Table 3. These percentages are the means calculated from values at all attainments of SWD levels. The standard errors for these means are included also in Table 3.

These results follow the same trends as those reported on the fluctuations of soil water content under the various treatments. At a low SWD level the major part of soil water was extracted from the top soil layers, as compared to a high level where water extraction occurred from the entire soil profile. For example, percentages of water extraction were 93,54 and 61,65, respectively, from the 0–610 mm soil layer, for a 15 % and 75 % SWD level. Except for the former level, the larger part of water extraction occurred from the deeper soil layers,

TABLE 3
PERCENTAGE EXTRACTION OF SOIL WATER AS A FUNCTION OF THE SWD LEVEL

Soil depth (mm)	% Extraction ± standard error at SWD level (%) of			
	15	35	55	75
150	37,71 ± 1,63	16,97 ± 0,55	20,42 ± 0,71	14,83 ± 0,69
300	24,21 ± 2,57	14,02 ± 0,72	16,21 ± 0,92	20,28 ± 0,93
610	32,08 ± 2,60	45,42 ± 1,05	25,39 ± 0,80	26,54 ± 0,14
910	6,01 ± 1,56	15,26 ± 0,59	20,85 ± 0,69	23,43 ± 0,81
1220	0,00 ± 0,00	8,34 ± 0,61	17,13 ± 0,64	14,92 ± 0,99

TABLE 4
MEAN SOIL WATER PRESSURES (SWP) AT TIME OF IRRIGATION

Soil depth (mm)	SWP (kPa) ± standard error at SWD level (%) of			
	15	35	55	75
150	−47,9 ± 5,8	−70,9 ± 5,6	−366,7 ± 76,7	−660,8 ± 69,0
300	−11,4 ± 1,4	−23,1 ± 5,8	−179,2 ± 36,9	−390,8 ± 24,8
610	−12,6 ± 0,7	−17,2 ± 2,0	−117,8 ± 23,8	−476,7 ± 48,1
910	−11,0 ± 0,5	−36,4 ± 3,1	− 59,9 ± 9,2	−922,5 ± 97,6
1220	− 8,8 ± 0,5	−10,8 ± 0,4	− 54,1 ± 9,0	−377,5 ± 48,2
Mean SWP for profile	−18,3	−31,7	−155,5	−565,7
Mean deviation (mm) from SWD level	− 4,5	− 3,7	+ 2,4	+ 9,8
Available water (mm) above SWD level	29,0	59,0	126,0	156,0

viz. 610 and 910 mm. This is contradictory to the general pattern of extraction, i.e. a high extraction value in the top soil layer and decreasing values with an increase in depth. For a complete cover crop like lucerne, where direct soil evaporation from the topsoil is practically zero, soil water extraction should rather be a function of the root distribution pattern.

Soil water pressure

Table 4 presents mean soil water pressure (SWP) values calculated from data whenever a specific SWD level was attained. The standard errors of the means are also given.

A 15 % and a 75 % SWD level, respectively, were reached at depth-weighted mean SWP values of −18,3 and −565,7 kPa. The table also shows the mean deviation from the aimed soil water depletion at the time of irrigation. Theoretically these values should be equal to zero but for a field experiment of this kind that goal is not easily achieved. For the 15 % and 35 % SWD levels mean deviations were −4,5 mm and −3,7 mm of water, respectively. The negative signs indicate that the SWD levels were exceeded in actual fact by these amounts. Mean deviations from the intended soil water depletion for the 55 % and 75 % levels were +2,4 mm and +9,8 mm of water, respectively. These positive signs, particularly that of the 75 % SWD level, indicate that the SWD levels aimed at were not yet reached and some more water than should have been, was still available in the soil. These higher water contents were caused by the fact that the time intervals between consecutive irrigations were longer than the production period for lucerne hay. Since a plot was irrigated after harvesting, an irrigation was due sometimes before the SWD level was reached.

The SWP profiles in Figures 4(a) to 4(d) were selected as typical examples of the changes in SWP with time and depth between successive irrigations.

In these figures, the SWP line on the extreme left hand side depicts the pressure profile one day after an irrigation and the last line on the right hand side the situation immediately before the next irrigation. The amounts of available water (in mm) left in the soil profiles above the aimed depletion levels are also indicated by the values in brackets (upper right hand corner). These figures illustrate that major changes in SWP for the 15 % SWD level (Figure 4(a)) took place only to a depth of 300 mm and for the 75 % SWD level (Figure 4(d)) down to 1220 mm depth. The latter findings correspond to those reported on soil water fluctuations and water extraction patterns. In actual fact, the characteristic SWP profiles are verified by the extraction data in Table 3.

Although SWP in the upper soil layers for the 75 % SWD level was much higher and, consequently, water was more available there, the lucerne continued to withdraw water from the soil layer at 910 mm depth, resulting in a decrease in SWP. The same observations were made for the 35 % SWD level (Figure 4(b)). These findings are in contrast with the passive water uptake theory (Gardner and Ehlig, 1963) which requires that the water pressure in the xylem of the plant be highest at the root tips and decrease in the direction of the stem. However,

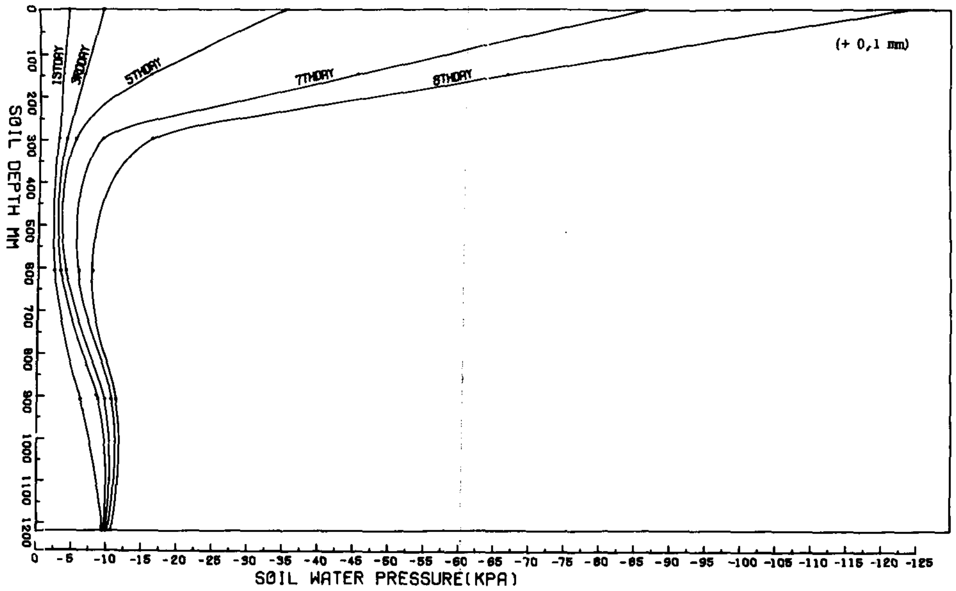

Figure 4(a)
Soil water pressure profiles – 15% SWD level: 8 days (05/02/74 to 12/02/74)

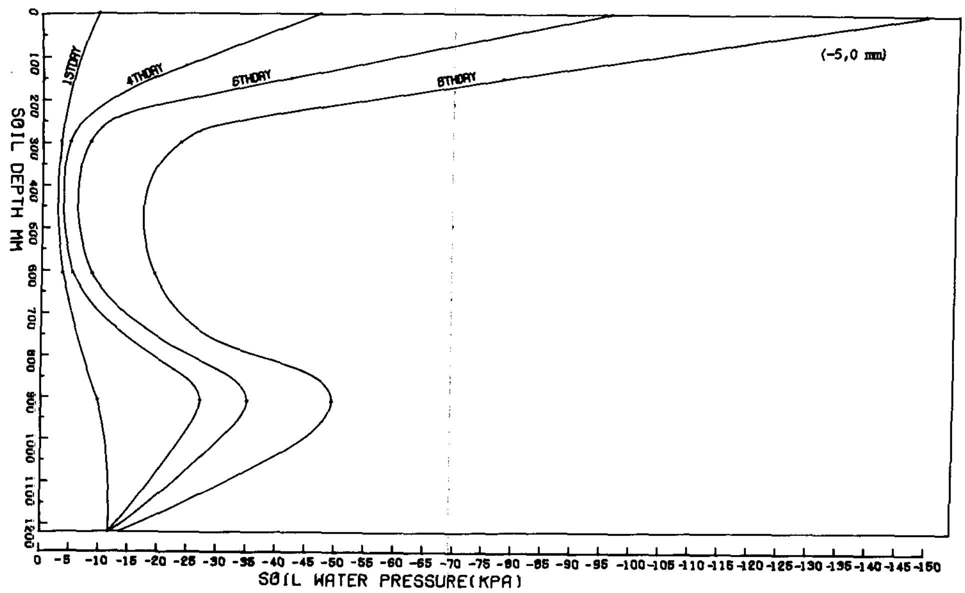

Figure 4(b)
Soil water pressure profiles – 35% SWD level: 8 days (01/01/74 to 08/01/74)

a decrease in soil pH was observed on the 75 % SWD level plot between 300 and 610 mm depth which possibly restricted root growth. Relatively stronger root development could have been expected below this region. Unfortunately, root distribution studies were not carried out to prove such a suggestion. The same extraction patterns were reported by other research workers. Kohl and Kolar (1976) found that lucerne roots withdrew soil water in the lower portion of the root zone (where soil water pressure was between −700 and −1000 kPa), while the upper portion of the profile was above −200 kPa. Van Riper (1964), over two seasons, measured higher water extraction by lucerne in the 610–1525 mm than in the 0–300 mm soil layers.

Except for the 75 % SWD level, the largest changes in SWP between successive irrigations took place in the top 300 mm of soil for all SWD levels. As a result, larger variation in SWP values at time of irrigation could have been expected in the top soil layers, a fact that is proved by the higher standard errors (Table 4) of the means.

Lucerne hay yields

Six cuttings per plot were made during the experimental season under discussion. To submit the yield data to statistical analysis it was decided to regard the number of harvests per SWD level

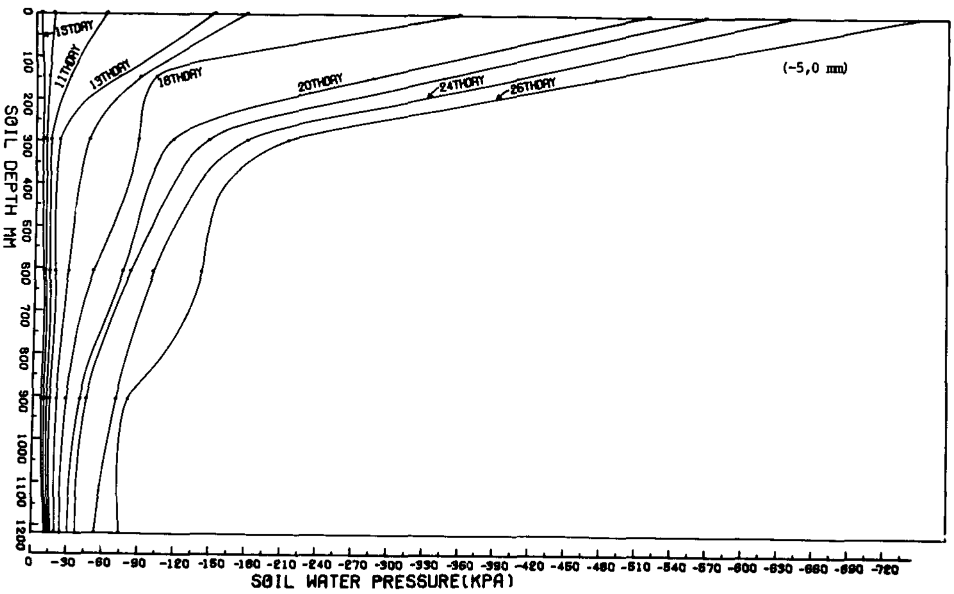

Figure 4(c)
Soil water pressure profiles — 55% SWD level: 26 days (14/12/73 to 08/01/74)

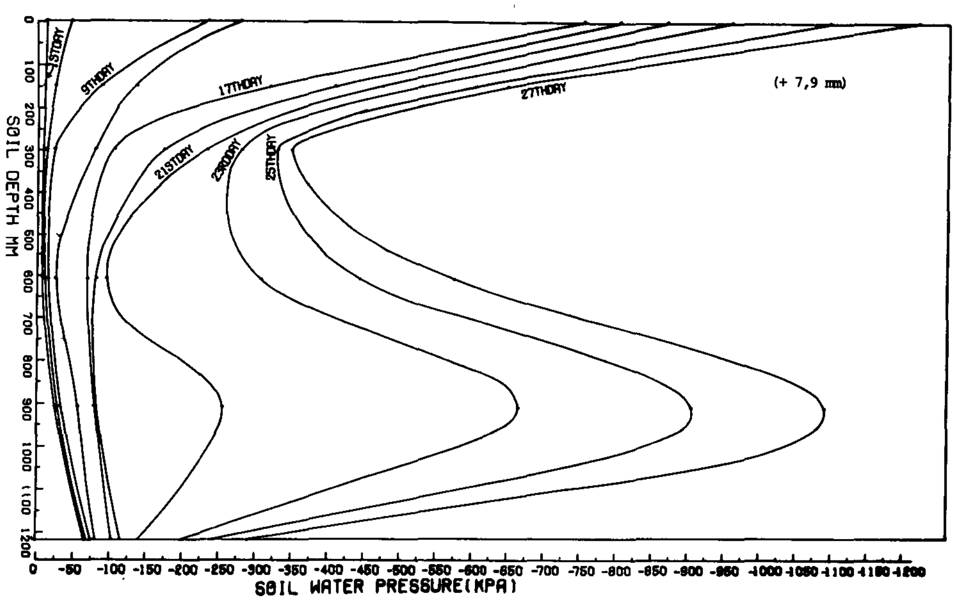

Figure 4(d)
Soil water pressure profiles — 75% SWD level: 27 days (24/01/74 to 19/02/74)

as replicates. The post-treatment yields were to be expressed as percentages of the pre-treatment values in order to compensate for any variation that did exist. A regression analysis was then performed. Unfortunately, this approach ignored the possibility of yield against time interactions. Statistical evidence of treatment effects were proved in two cases. Firstly, when yields were expressed per unit of time, i.e. in terms of the growth rate and, secondly, when expressed per unit of irrigation water, i.e. in terms of water use efficiency. In the former case masses per cutting ranged from 145,1 to 106,4 kg $ha^{-1}d^{-1}$ for a SWD level range of 15 % to 75 %. In the latter case yields ranged from 29,2 to 36,3 kg ha^{-1} mm^{-1} water for the same SWD range. Although the order of magnitude of these values was somewhat different from that of Shalhevet *et al* (1976), the trend was the same. Mean masses per cutting of 5,367 and 4,330 t ha^{-1} for a 15 % and a 75 % SWD level, respectively, were obtained, with yields of the other two treatments intermediately. These yield data, however, were statistically not significant.

Conclusions

In this study it was shown that:

(a) Under the climatic conditions that prevailed irrigation requirements were established of 1100 mm and 700 mm of water, respectively, for a 15 % and a 75 % SWD level.

(b) A direct relationship exists between the soil water regime and the amount of water consumed, and that with a 15 % SWD level the rate of actual evapotranspiration was equal to that of pan evaporation.

(c) Soil water extraction and, consequently, changes in water content and water pressure (SWP) were restricted to a much shallower depth with a 15 % than with a 75 % SWD level. Under conditions of high soil water depletion while the lucerne was extracting water from soil layers where SWP was high it continued to withdraw water from deeper layers of lower SWP.

(d) A decrease in the SWD levels, i.e. the maintenance of increasingly higher soil water regimes, was found to be accompanied by:

- an increase in growth rate of lucerne;
- a decrease in the water use efficiency term (i.e. production of less lucerne hay per unit of water applied); and
- an increase in hay production per unit area, although this finding could not statistically be verified, probably because of lack of data.

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