EFFECTS OF RDI ON APPLE TREE (cv. Royal Gala) GROWTH, YIELD AND FRUIT QUALITY IN A HUMID ENVIRONMENT

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To my Beloved Son Kahlil
who fills my life with joy

and In Memory of my Husband.

ABSTRACT

The feasibility of using Regulated Deficit Irrigation in the humid environment of New Zealand was evaluated on trees of apple cv. Royal Gala (*Malus domestica* Borkh.). The study was carried out in a glasshouse experiment and a field experiment. In the glasshouse experiment, it was evaluated the pattern of soil water extraction by the winter mutant of lucerne (*Medicago sativa sensu lato*) ASR13R from a 'synthetic' soil layered in the same way that it occurs in the research orchard, under trickle and sprinkler irrigation. Results indicated that lucerne extracted soil water at a high rate and explored deep areas of soil.

The field experiment was conducted during two consecutive seasons (1987-1989). Lucerne as under tree cover and black polyethylene mulch were compared with conventional herbicide strip to control excess of water in the root zone of the crop that would otherwise promote vegetative growth. These treatments were applied in combination with an irrigation schedule divided into three Phases. In Phase I, water was withheld, in Phase II RDI was compared with full irrigation, and during Phase III which coincided with the rapid fruit growth, all treatments received the full irrigation rate. During the first season, RDI and full irrigation treatments were based on 25% and 100% replacement EPS (evaporation in the planting square) respectively. In the second season, after a 50% of the soil water content in the top 600 mm of soil, between Drainage Upper Limit and the Lower Limit was reached, full irrigation treatments were replenished to the DUL, while RDI treatments received 25% of that amount. Results showed that under the conditions of this study evaluation of crop water requirements based on soil moisture measurements was more reliable than those based on pan evaporation.

The degree of reduction of summer pruning obtained under lucerne X RDI treatment, reflected levels of soil and plant water deficit similar to those obtained in arid environments. Results confirmed my hypothesis that by using lucerne as under tree cover, a RDI strategy can be used in this environment. In contrast. black plastic mulch appeared to maintain soil moisture rather than prevent its accumulation. Nevertheless, effects were obtained which reflected positively in fruit growth and yield. Similar results were obtained under the control treatment, although it was less effective for in reducing tree vigour. The latter treatment, however, can be implemented in most orchards at no cost and generate important savings.

Apple fruit growth proved to be relatively insensitive to water deficit imposed during early stages of growth, whereas vegetative growth was checked. Restoring full irrigation to coincide with rapid fruit growth stimulated growth of RDI fruits resulting in higher yield under control and plastic X RDI. Lucerne showed higher rates of water use that were not compensated by the irrigation which affected fruit growth and size. Results showed that fruits from RDI treatments were firmer, accumulated higher T.S.S. and had lower bruise susceptibility than fruits from fully irrigated treatments. Fruit quality remained higher after 10 weeks of cool storage.

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LITERATURE REVIEW

1.1. *Introduction*.

New Zealand has a good reputation as an exporter of high quality fruit, which in a world market subjected to enormous fluctuations, requires a commitment to keep up to date the use of techniques that allow production of more fruit of the highest quality.

Under favourable conditions of soil moisture and climate common to most horticultural areas, the recent trend towards more intensive planting, without a concomitant shifting to dwarfing root stocks, necessitates the use of appropriated techniques to control tree vigour which do not reduce fruit quality.

Quite extensive research (Chalmers *et al.* 1981; Mitchell and Chalmers, 1982., Chalmers *et al.* 1983) has demonstrated that vegetative growth can be effectively controlled if the plants are supplied with a reduced proportion of the maximum water demand in the initial stage of rapid vegetative growth. This period of water deficiency coincides with a slow stage of fruit growth. Such irrigation strategies have been described as Regulated Deficit Irrigation (RDI) based on the fact that the rationale calls for a relatively precise water deficit to be created in the plant using the irrigation schedule.

In New Zealand, soils that receive heavy rains in winter and early spring, hold high amounts of water in this critical stage. Consequently, vigorous vegetative growth take place. This raises the need to investigate ways of controlling soil water in the root zone. Specific soil management techniques may provide this requirement, but whether such treatments can be combined with a strategy of limited irrigation and whether they make it economically feasible to use the advantages of this irrigation strategy is still unexplored.

In this study two alternative ways of controlling soil water are examined. First, the soil was sheltered from rainfall with a black polyethylene film and secondly, evapotranspiration was increased around the root zone of the crop during spring with a permanent sward of lucerne. To examine these alternative soil management strategies, two experiments have been carried out. A glass house experiment was designed to examine in detail the water movement and pattern of water extraction by lucerne in a model soil constructed as an analogue of soil found in the Massey orchard. A field experiment was conducted over two seasons to thoroughly evaluate the effect of the two soil management treatments compared to a conventional herbicide strip. All treatments were applied in combination with irrigation scheduling to investigate the applicability of RDI in a humid environment and their effect on yield and fruit quality of Royal Gala apples.

1.2. *Irrigation.*

1.2.1. *Introduction.*

The basic aim of irrigation is to supply plants with water at the correct times and amounts to optimise yield. The classical ideas which assumed water is equally available to crops within a certain range of soil moisture (Veihmeyer and Hendrickson, 1950), led to irrigation regimes in which the plant was irrigated at intervals to replenish the soil to "field capacity" followed by a period of soil water depletion to variable low levels of moisture. However, since the 1950's new approaches and commercially available devices have been developed for scheduling irrigation which permit the farmer to evaluate the supply of water for crops more accurately and improve the irrigation practices in general (Elfving, 1982).

1.2.2. *Irrigation Methods.*

At the present time, the most common methods of irrigation in horticulture are sprinkler and trickle (Griffiths, 1989). In sprinkler irrigation the area over which the water enters the soil is equal to the total area (Bresler, 1977). The pattern of water distribution depends of the characteristics of the sprinkler.

Sprinklers have the advantage of producing an uniform and complete wetting of the surface soil (Uriu and Magness, 1967). Because sprinkler eliminates the soil and topography as important factors in water distribution, it can be desirable when adverse conditions of these two factors are present (Bishop *et al.* 1967).

Thus, one of the principal advantages of a sprinkler is the high degree of water control. The system can apply water to soil at rates lower than, or equal to, infiltration rates. It is usually recommended, however, to apply water at rates below the minimum intake rate of the soil to avoid ponding and runoff (Christiansen and Dais, 1967).

Trickle irrigation is a system initiated in Israel (Black, 1976) based on the principle of maintaining high soil water potential by increasing the frequency of application of small amounts of water (Bucks *et al.* 1979). Since water is applied frequently, the infiltration process dominates over the extraction processes (Rawlins, 1973). Water is applied in the form of small continuous drops or small streams or micro sprays, the form being dependent of the type of applicator or emitter which may be quite variable (Bucks *et al.* 1981). In this method of irrigation, the emitter is placed directly upon or close to the soil surface, which makes the area where infiltration occurs very small compared with the total surface of soil, in contrast with the sprinkler in which it is assumed that the infiltration area will be approximately equal to the entire soil surface (Bresler, 1977).

Bresler *et al.* (1971) observed that during trickle irrigation, a radial area of ponded water usually developed under the emitter. He pointed out that this area is initially small, but the radius increases with time and that water from the emitter can infiltrate the soil through this area or evaporate to the air instantaneously. One of the advantages of trickle irrigation systems is the fact that it minimizes fluctuations in soil water content due to the maintenance of high soil water potential. This also has the advantage of minimizing the salt concentration of the plant available water (Patterson and Wierenga, 1974). In addition, trickle irrigation may be used to irrigate only a portion of the root system and control its growth (Black and West, 1974; Black and Mitchell, 1971, 1974). Mitchell and Chalmers (1983) comparing the performance of point emitter and microjet, found soil moisture under the microjet was more uniformly distributed than under the point emitter. Hence, greater control of root growth was obtained under the point emitter. However, a problem associated with heavy soils was the excess of water under the point emitter which caused death of the roots and a concomitant damage to the tree.

1.2.3. ***Crop Water Requirements.***

The crop water requirement is equivalent to the rate of evapotranspiration (ET) necessary to sustain optimum plant growth (Zein El-Abdin *et al.* 1973). In order to fulfil optimum growth, the crop must be disease-free and the soil conditions such as fertility and water must be optimum. The crop water requirement is expressed as ET_{crop}, and the units are $mm.day^{-1}$ or $inches.day^{-1}$. The way in which RDI is usually scheduled, is based upon the principle that a predictable plant water deficit will be obtained if a reduced proportion of potential evapotranspiration is replaced at close intervals (i.e. 1-2 days). Obviously, such an approach requires accurate assessment of ET.

1.2.3.1. *Methods of Estimating Evapotranspiration.*

The methods of estimating evapotranspiration include direct and indirect measurement, and modelling techniques. Sharma (1985) grouped the methods according to the approach followed, in three classes: a) water balance methods, b) micrometeorological methods and c) plant physiological methods.

Before considering the different methods it is important to define some terms. Burman *et al.* (1983) defined evapotranspiration (ET) as the process by which water is transferred from the earth's surface to the atmosphere. Sharma (1985) defined potential evapotranspiration (E_p) as the upper limit of the ET rate from a given soil-vegetation unit under a given set of meteorological conditions. The first expression for E_p was developed by Penman (1948) and cited by Sharma (1985) as follows:

$$\lambda E_p = \frac{sR_n + \lambda f\,(\mu_2)[e_s(T_a) - e_a]}{s + \gamma} \tag{1.1}$$

where

s is the slope of the saturation vapour pressure-temperature curve at the mean temperature

R_n is the net radiation

γ is the psychrometric constant

μ_2 is the wind speed

e_s (T_a) is the surface saturation vapour pressure at air temperature T_a

e_a is the vapour pressure of air at a given height (usually 2m)

λ is the latent heat of vaporization.

In this expression E_p is the ET that occurs when the vapour pressure at the evaporating surface is at saturation point (Van Bavel, 1966). Burman (1983) argued this definition has caused varied interpretation because it is not restricted to a standard surface. Thus, it is important to include reference to a standard surface in potential ET to avoid confusion and facilitate interpretation (Burman, 1983).

Definitions of E_p with reference to a specific vegetation are denominated reference ET or ER. Two definitions are widely used: 1) Doorenbos and Pruitt (1977) defined ER as the rate of ET from an extensive surface of actively growing green grass cover of uniform height (8-15 cm), completely shading the ground, and not short of water. 2) Jensen (1971) defined ER as "the upper limit or maximum ET that occurs under given climatic conditions within a field having a well watered agricultural crop, with an aerodynamically rough surface, such as lucerne, with 30 to 50 cm top growth".

Sharma (1985) pointed out that under the same environmental conditions ER with respect to lucerne is greater than ER of grass. The crop coefficient K_c is a constant accounting for soil and plant effects such as crop physiology, degree of cover, etc. throughout the growing season. Doorenbos and Kassam (1979) have indicated that in the same season and in the case of annual crops, the degree of cover is the most significant parameter affecting the crop factor (K_c), while for perennial crops K_c does not vary markedly.

1.2.3.1.1. *Water Balance Methods.*

Included among these methods are the soil water methods and lysimeters. Soil water depletion is equated with ET (Reicosky *et al.* 1977). Soil water depletion methods are based on the soil water balance equation (Gardnier *et al.* 1986) as follows:

$$\Delta S = P + I - R - ET_a - D \qquad (1.2)$$

where,
ΔS = change in soil water storage,
P and I= precipitation and irrigation respectively,
R = surface runoff,
ET_a= actual ET,
D = drainage.

An error in ET may arise if drainage is not measured (Robins *et al.* 1954). Robins found considerable drainage losses from a fine sandy loam for 8 days following irrigation. Tanner (1967) emphasized in most humid areas soil water depletion measurements rarely provide reliable estimates because of frequent rains and resulting drainage. However, if estimates of drainage error are reliable, soil water depletion can be used. During periods without rain when drainage ceases, ET can be calculated from the changes in soil water storage in the root zone as follows:

$$\int_{t1}^{t2} ET\,dt = \int_{t1}^{t_2} \int_{0}^{z} d\theta /\delta t) dz dt \qquad (1.3)$$

where θ is the soil volumetric water content and z is the lower boundary of the water extraction by roots and is assumed constant with time (Sharma, 1985). Soil water storage (W) may be evaluated over the profile with the neutron probe technique. Sharma signaled it is not feasible to detect changes of less than 5-10 mm of soil water storage in the profile, thus measurement of soil water for periods of less than a week may be meaningless unless evaporation rates are very high.

Lysimeters are devices enclosing a volume of soil, which may be planted to vegetation and isolated from the surrounding soil. Since a complete control of water input and output can be done, lysimeter provides a suitable way to estimate ET, and also to check on the adaptability of micrometeorological methods for calibrating empirical formulas used to estimate ET (Sharma, 1985).

1.2.3.1.2. *Micrometeorological Methods.*

Jensen (1974) explained that no single method to compute ET using meteorological data is universally satisfactory without a proper local calibration. These methods estimate ET from the meteorological variables of temperature, radiation, humidity and wind velocity , measured at or above the evaporative surface (Sharma, 1985). The instrumentation required for these methods is extensive and costly which make them more suitable for research than practical use.

1.2.3.1.3. *Plant Physiological Methods.*

Among this group are methods developed by plant physiologists in an attempt to estimate the transpiration as a major component of the soil-plant-water relationships (Sharma, 1985).

1.2.3.1.3.1. *Chamber Methods.*

This group includes closed and ventilated chambers, and are operated by assessing the changes in air humidity passing through a chamber enclosing a sample of plant or plant community. In the close system, the increase in humidity of the air chamber is measured over a short period of time (Reicosky and Peters, 1977). In the ventilated chamber, the air is continuously passed through the chamber and the out-coming humidity is measured by the difference from the incoming air stream. Denmead and Rose (1984) have indicated that it has been almost impossible to overcome some problems related to these chambers. Wind speed, net radiation, temperature and vapour pressure are strongly modified within the chamber which makes it difficult to reproduce the natural microclimate. For example, Decker *et al.* (1962) constructed a "tent" of polyester film 3 m in diameter, for measuring the transpiration of Tamarix shrubs. Both temperature and vapour pressure were higher inside the tent than outside, and the net effect of the altered environment was to depress transpiration of test plants by 15-20%.

Among the chamber methods, porometers are more popular. The stomatal resistance to water vapour diffusion can be measured by diffusion porometry. Basically the instrument consists in a small chamber which is clamped over the leaf or group of leaves and the rate of flow of water vapour from the plant material is recorded (Sharma, 1985). Through an appropriate calibration, stomatal resistance is calculated and also the transpiration rate in an indirect way. The latest instrumentation measures stomatal conductance, and calculates stomatal resistance plus transpiration rate.

1.2.3.1.3.2. ***Tracer Techniques.***

In order to overcome microclimate effects on transpiration measurement with the use of chambers, tracer techniques have been developed (Huber, 1932 as cited by Rutter, 1968). This method consists in measuring the linear velocity of the transpiration stream by labelling with a soluble compound or introducing a heat pulse and then examining the rate of transfer of the marker by the transpiration stream. With the heat pulse technique, the heat is applied for a few seconds at a fixed level on a trunk and the velocity of the transpiration stream is calculated from the time taken for the heat to reach a thermojunction or thermistor at a short distance from the application point (Ladefoged, 1963). Water fluxes are calculated by solving equations describing the transport of heat by convection and conduction in the stem. If water flow J is determined for an element of the stream with area dA,then the volumetric flow F is given by

$$\rho = fJdA \tag{1.4}$$

The major problem arises in quantifying the effective cross sectional area of the stem involved in the water conduction. Cohen *et al.* 1981 proposes, however, that with an appropriated calibration, this technique may give an accurate field measurement.

1.2.3.1.3.3. *Other Plant Physiological Methods.*

Several studies over the past 40 years have established the relationship between soil water and girth changes through simultaneous measurements of daily and weekly soil moisture and diameter increments or decrements (Fritts, 1958; McClurkin, 1958; Berman and Kozlowsky, 1962; Kozlowsky and Winget, 1964). By measuring variation in the diameter of the tree trunk with dendrometers, changes in stem diameter can be translated into transpiration rate with an adequate calibration.

1.2.3.2. *Modelling of Evapotranspiration.*

1.2.3.2.1. *Models for Potential and Reference ET.*

Many empirical models relating climatological data and ET have been developed. Some of them are used for practical hydrological applications (Doorenbos and Pruitt, 1977; Burman *et al.* 1980). Sharma (1985) pointed out that instead of empirical models, an approach oriented to a process would be preferable to determine critical processes and factors under different conditions. Sharma (1985) grouped the models according to the approach used to calculate E_p. Thus, when water is limited ET is less than E_p, in this case ET is modelled either by consideration of the process related to water flow in the soil-plant-atmosphere system or empirically through correlations. The first group of models are described as process-oriented models and the second, correlation-based models (Sharma, 1985).

1.2.3.2.1.1. *Process Oriented Models.*

1.2.3.2.1.1.1. *Combination Equation Models.*

Included in this group are methods that combine energy balance methods and aerodynamic transport of water vapour. The first of these is the Penman equation (1948). Most other models in this group are related to the Penman equation (Van Bavel, 1966; Monteith, 1965; McIlroy, 1984). Van Bavel (1966) showed that E_p calculated by the Penman equation for lucerne was much different than for grass. The application of these models should be restricted to short vegetation since the Penman calculation of E_p assumed a green grass crop cover of uniform height, covering the ground completely, well supplied of water and under non-advective conditions. For use in forests, the most acceptable is the Penman-Monteith expression (Monteith, 1965) which assumed a negligible surface resistance (r_c=0) or canopy resistance, as follows,

$$\lambda E_p = \frac{s(R_n - G) + \rho C_p [e_s (T_a) - e_a]/r_a}{s + \gamma} \qquad (1.5)$$

where

$[e_s(Ta)-e_a]$= the water vapour deficit of the air above a saturated surface,
G = heat flux of the ground,
R_n= net radiation,
C_p= specific heat of air at constant temperature,
T_a= air temperature,
ρ = air density,
r_a= aerodynamic resistance,
e_s and e_a= saturation and ambient vapour pressure.

The Penman-Monteith equation is applicable when the soil or vegetation surface is covered with water, for which the E_p represents the maximum rate of ET from a soil or vegetation surface.

1.2.3.2.1.1.2. *Net Radiation Models.*

Several workers (Slatyer and McIlroy, 1961 and Davies and Allen, 1973), defined the equilibrium evaporation E_{eq}, which is the minimum potential ET in the absence of the water vapour deficit near the evaporative surface thus,

$$\lambda E_{eq} = [s/(s+\gamma)]\ (R_n\text{-}G) \qquad (1.6)$$

Since this equilibrium evaporation defined the lower limit of evaporation from any wet surface, it can be used to measure E_p within canopy, from a soil or a short vegetative surface without wind effects (Sharma, 1985).

Priestley and Taylor (1972) as cited by Sharma (1985) developed a model for describing E_p from short vegetative surfaces as follows:

$$\lambda E_p = \eta \, [s/(s+\gamma)](R_n - G) \tag{1.7}$$

where

η = Priestley and Taylor evaporation coefficient with a mean value of 1.26. This coefficient is supposed to include the aerodynamic component of the combination equation which varies with the vegetative surface and restricts the use of Priestley and Taylor model to short vegetative surfaces.

1.2.3.2.1.2. *Correlation Based Models.*

Included in this group of model are methods based on the relation of ET to radiation, temperature, humidity and evaporation (Tanner, 1967).

1.2.3.2.1.2.1. *Radiation Model.*

Makking (1957) proposed the formula:

$$E_p = C\, f(R_I) \tag{1.8}$$

where,

R_I= incoming short wave solar radiation expressed in mm/day since radiation is assumed to be related to the evaporative power of the atmosphere

C= empirical factor

Currently, R_I is easily measured with the meteorological instrumentation available.

1.2.3.2.1.2.2. *Temperature Model.*

Temperature models use temperature alone or in combination with relative humidity. Tanner (1967) indicated that these methods are more suitable to monthly estimates and are not reliable for short periods.

Linear and non-linear models based on temperature have been developed. Among the former, perhaps the most widely used is the Blaney-Criddle method (1950), whilst a non-linear model commonly used was developed by Thornwaite (1948).

1.2.3.2.1.2.3. *Humidity Models.*

Tanner (1967) pointed out these models are based on some modification of one of the oldest of aerodynamic models, the Dalton method as cited by Tanner (1967)

$$E_p = f(\mu z)(e_0 - e_z) \tag{1.9}$$

where

e_0= saturation vapour pressure corresponding to the surface temperature

e_z = vapour pressure at the same temperature

$f(\mu)$= a wind expression often=0 and it is derived for local conditions.

Sharma (1985) claimed humidity models are restricted because data on water vapour pressure are not as readily available as temperature or radiation.

1.2.3.2.1.2.4. *Evaporation Models.*

These are most widely accepted mainly due to the high correlation between pan evaporation and evaporation or ET from vegetation, soil and water bodies (Tanner, 1967). Among many types of evaporation pan, the class "A" is the most commonly used. Data illustrating the effect of pan size and installation are provided by McIlroy and Angus (1964).

Doorenbos and Pruitt (1977) presented a relationship between E_p and pan evaporation (E_{pan}) as follows:

$$E_p = K_p E_{pan} \tag{1.10}$$

where,

K_p= pan coefficient which should be derived locally by correlation for a given vegetative surface. These workers indicated that E_{pan} gives better estimates of E_p over periods longer than a week.

1.2.3.2.2. *Models for Actual Evapotranspiration.*

Sharma (1985) divided these models in correlation based and process oriented models, in the same way as the models for E_p.

1.2.3.2.2.1. *Correlation Based Models.*

Among this group are models based on crop coefficient and models based on the soil water deficit.

1.2.3.2.2.1.1. *Models Based on Crop Coefficient.*

Jensen (1968) proposed a model based on the concept of potential ET and a crop coefficient. The reference crop must have a fully developed root system and sufficient leaf area and soil moisture to ensure that ET is limited by meteorological conditions. For such a crop, ET is related to E_p (which is called reference ET or ER) by the formula:

$$ET = K_c ER \tag{1.11}$$

where,

K_c = crop coefficient

Crop coefficient is a dimensionless parameter which includes effects of resistance to water movement from the soil to the evaporating surface, resistance to diffusion of water vapour from the soil to the evaporating surface through the laminar boundary layer, resistance to turbulent transfer to the atmosphere and the relative amount of radiant energy available as compared to the reference crop (Jensen, 1974). Usually, crop coefficients are related to a reference crop.

Doorenbos and Pruitt (1977) presented crop coefficients for a great variety of crops and even though they emphasized the use of local data, they also suggested crop coefficients that were generally applicable.

1.2.3.2.2.1.2. *Models Based on Soil Water Deficit.*

Many empirical relationships between E/E_p and soil water content or soil water potential have been proposed to take into consideration the reduction in ET due to a soil water deficit (Sharma, 1985). Ritchie (1981) used the term "extractable water" θ' instead of "available water" and defined as

$$\theta' = (W-W_m)/(W_f-W_m) \tag{1.12}$$

where,

W = soil water storage in the rootzone

W_f = water storage at field capacity

W_m = minimum observed water storage. Both, W_f and W_m are experimentally measured.

Ritchie proposed that E/E_p should equate to 1 until water is depleted to a critical value (θ'_c) below which E/E_p decreases linearly until $E/E_p = 0$. The critical value for many crops ranges between 0.25 to 0.35 and therefore the value may be approximated by 0.30. Sharma (1985) pointed out that this approach should be treated as site and crop specific.

1.2.3.2.2.2. *Process Oriented Models.*

1.2.3.2.2.2.1. *Models Based on Surface Resistance.*

The effects of restricted water availability are reflected through canopy resistance r_c, for wet canopies $r_c=0$, while models for partially wet canopies are more complex. In the case of dry surfaces r_c can be calculated from stomatal resistance r_s and leaf area index (LAI) as follows:

$$r_c = r_s/LAI \tag{1.13}$$

While stomatal resistance may be related to soil water deficit (Tan *et al.* 1970; Sceicz *et al.* 1973; Russell, 1980) or to plant water potential(Ψ_P) (Rutter, 1975) or to Ψ_P and environmental variables such as vapour pressure deficit, light and temperature (Jarvis *et al.* 1981). Since most of the r_s and Ψ_P relationships are highly species specific, it is unlikely a universal relationship between E/E_p to predict r_s will ever be found (Sharma, 1985).

1.2.3.2.2.2.2. *Models Based on the Root Extraction Function.*

These models are based on the assumption that the rate of water extraction by a root system is equal to the water loss from the plant. Feddes *et al.* (1976) proposed that the required root depth data and the transpiration be calculated by integrating a bulk sink term (S_r) over the rooting depth z as follows,

$$ET = \int_{o}^{z} S_r(z,t)d_z \qquad (1.14)$$

where

S_r is a bulk sink term related to volumetric soil water content. Sharma (1985) explained that S_{rmax} represents the sink term value for unlimited water conditions. Root water uptake under limited water supply conditions can then be deduced, based on water availability. The same author pointed out that much work is needed in developing techniques for estimating spatial distribution of effective root density and its dynamic under different soil conditions.

1.2.3.3. *Estimation of Irrigation Requirements.*

Determination of the amount of water required for irrigation (R) is the final step and involves combining ET with effective rainfall and other water amounts if supplied by irrigation (Burman *et al.* 1983). The effective rainfall is that portion of rainfall that contributes to the ET requirements of a crop (Hershfield, 1964). Doorenbos and Pruitt (1977) defined crop water requirement as the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields, under non-restricting soil conditions, including soil water and fertility, and achieving full production potential under the growing environment

$$R = ET - P_e + \text{(other requirements)} \qquad (1.15)$$

Where P_e is rainfall and other requirements include extra water required for leaching of harmful salts, for crop cooling or frost protection, germination of seeds, for fertilizer or pesticide application or for soil temperature management.

A considerable proportion of natural precipitation, or water applied by overhead irrigation can be intercepted by vegetation foliage. Most of the intercepted water does not enter the soil or vegetation and is evaporated directly. Interception is usually measured as the difference between gross precipitation and that reaching the soil. Zinke (1967) estimated that for forests, values of annual interception range from 10-40% of the total precipitation; which also may cause a reduction in effective rainfall.

1.2.3.3.1. *Allowable Soil Water Depletion.*

Several studies have tried to determine the permissible water deficit in the root zone that does not adversely affect the crop yield, quality or both. Veihmeyer and Hendrickson (1950) through a series of trials with plants grown in pots and in the field, established an hypothesis that water is equally available from field capacity (FC) to permanent wilting point (PWP). In contrast, Taylor (1952) observed a linear decrease in yield of sugar beet with increasing soil water tension and conclude that Veihmeyer's hypothesis was untenable.

Rogers and Goode (1953) recommended irrigation when 50% of the available water in the root zone had been depleted, but the detection of this deficit in the plant remained as a major problem. Taylor (1965) clearly noted that irrigation should take place while the soil water potential is still high enough to supply plants at the rate required to satisfy the evaporative demand, thereby avoiding stress that may depress yield or quality of the crop.

The timing of irrigation of deciduous fruit trees depends on many factors such as amount of available water, soil factors as depth, physical characteristics, transpiration rate, climatic conditions, time of the year, stage of development of the fruit, and factors such as water quality, accessibility of the water source and even the scheduling of other management activities (Hagan *et al.* 1967).

Assaf *et al.* (1974) obtained the highest yield in apples trees in Israel using treatments in which irrigation was applied whenever available water in 0-60 cm layer decreased to 40% during the main fruit growth period. Doorenbos and Kassam (1979) proposed 50% depletion as a "safe" criterion for a wide range of soils and crops. Nonetheless, the level of maximum soil water tension or maximum soil water depletion that can be tolerated while maintaining potential crop growth, varies with the type of crop (Doorenbos and Pruitt, 1977), and also depends on the crop development stage. Beukes and Weber (1982) divided the apple growth in four phenological phases. Because of the lack of any strong positive effect of higher levels of water availability on growth, yield or quality, the authors concluded that 25% levels could be tolerated during early stages of fruit growth and also during the postharvest stage. Nevertheless, local data is required to provide refinements in allowable depletion criteria for crop-soil interactions in given climates (Stegman, 1983).

1.2.3.3.2. *Allowable Evapotranspiration Deficit.*

The allowable ET deficit in crops may be a suitable period of time without irrigation until crop ET falls to a given level below the potential ET rate (Stegman, 1983). One example of this is to delay the first seasonal irrigation until the ET accumulates to a given level above which the expected yield may be adversely affected. This procedure requires some production function relative to ET (Stegman, 1982).

To implement an allowable ET deficit as a timing criterion, it is necessary to have accurate estimates of ET (Rosenberg, 1969 and Blad, 1974). Stegman (1982) developed the following relationships:

$$ET/ET_m=1 \quad \text{if } A_w > b \qquad (1.16)$$

$$ET/ET_m=A_w/b \text{ if } A_w < b \qquad (1.17)$$

where

ET_m = maximum potential evapotranspiration
A_w = percentage of water available remaining in the rootzone
b = threshold percentage of water available at which ET begins to fall below ET_m rate.

Values threshold for b reported (Ritchie,1973; Hillel, 1974; Meyer and Green, 1981) range from 20% to near 50% remaining available water.

1.2.3.3.3. *Plant Approach.*

The plant approach has deserved more attention from workers because it is directly related to yield, and integrates soil water deficits and the evaporative demand of the atmosphere.

1.2.3.3.3.1. *Allowable Leaf Water Potential Depression.*

Leaf water potential (Ψ_L) is a well known parameter that reflects the diurnal oscillation of atmospheric evaporative demand. Several workers (Slatyer, 1967; Cowan and Milthorpe, 1968; Hsiao, 1973; Begg and Turner, 1976) have shown that typical diurnal patterns of Ψ_L present maximum daily values near sunrise and minimum values between midday and mid afternoon. At greater evaporative demand, lower values of Ψ_L may be exhibited in the plant. These same authors established that the degree of overnight recovery is a function of the available soil water and the resistances in the soil-plant pathway.

Physiological studies carried out by these authors and others (Acevedo *et al.* 1971; Meyer and Greene, 1981) have demonstrated that growth is a process that is highly sensitive to water stress. Photosynthesis, respiration, partitioning of assimilates, fruit setting and fruit growth have been also recognized as processes affected by water stress (Begg and Turner, 1976).

The threshold of Ψ_L at which sorghum yield becomes limited is between -1.3

and -1.5 MPa (Musick, 1976), while Stegman *et al.* (1976) established a relationship between mid-afternoon leaf water potential (Ψ_{Lm}) and the residual available water in the root zone. Predicted values for Ψ_L were obtained at different expected maximum air temperature for a wide range of available soil water. A threshold of -1.25 MPa was chosen to estimate the degree of soil water depletion that could be tolerated. The level of -1.25 MPa was previously reported for corn, by Stegman and Aflatonni (1972) as the Ψ_L below which depression in yield were likely to occur. Nevertheless, there are numerous studies which reveal substantially lower Ψ_L at high levels of available soil water (Chalmers and Wilson, 1975; Chalmers *et al.* 1983).

1.2.3.3.3.2. *Foliage-Air Temperature Difference.*

Recent developments in non-contact infrared thermometry on a commercial scale provide an alternative approach to irrigation scheduling. The method is based on a sound principle: the measurement of the last effect of a linked process that begins with a water deficit causing stomatal closure which reduces transpiration. Less heat from the incoming radiation is dissipated, and consequently leaf temperature raises (Idso *et al.* 1977).

Idso *et al.* (1977, 1978) and Jackson *et al.* (1977) proposed a stress degree day (SSD) methodology in which days are summed as in heating degree days and the SSD is obtaining by the difference between leaf temperature T_f and air temperature T_a. The measurement is taken at a time when the surface temperature of the leaf is maximum. Yield reductions in wheat were found when the total number of SSD exceeded 10-15 between irrigations.

1.2.3.3.3.3. *Plants as Indicators of Water Stress.*

This approach includes growth measurement of plant organs, leaf angle and elongation. Many problems arise, however, when using growth as a criterion for irrigation because growth is complex and strongly affected by environmental factors other than water (Haise and Hagan, 1967).

Nevertheless, stem growth is affected by water stress, as demonstrated by Gates (1955) on tomatoes; Vaadia and Kasimatis (1961) on grapes and Uriu *et al.* 1964) on peaches. Also, Verner *et al.* (1962) established that trunk growth was a suitable indicator for timing irrigations. He recommended the measuring of stem rate growth using dendrometers and applying irrigation when the trunk growth rate fall below 80% of frequently irrigated trees.

1.2.3.3.3.4. *Phenological Variation in Crop Sensitivity to Water Stress.*

Since plant responses to water stress are the result of a complex interaction of many physiological processes which may in turn be affected differently by plant water deficits (Vaadia and Waised, 1967), considerable research effort has been applied to detect periods and processes sensitive to water stress during plant growth. Several workers (Vietz, 1966; Rawitz, 1969; Acevedo *et al.* 1976; Hillel and Huron, 1973) studying the role of water in promoting growth and stimulating yield, have found evidence that yield of crops is increased when irrigation is supplied in an adequate frequency and amount to prevent water stress at any time during the growing season. Schneider *et al.* (1969) found however, that irrigation during early spring resulted in vigorous growth of wheat, while severe water stress during heading and grain development restricted yields. In this work the idea of timing of a deficit when its impact on yield is more marked was advanced.

Grimes *et al.* (1967, 1970) reported that flower production and boll set in cotton are strongly dependent on the time at which a deficit is imposed during the flowering period. They noted that water availability during flowering is a critical factor from the standpoint of fibre development. In some crops such as lucerne and other forage crops, which endure water deficit, Downey (1972) has indicated there is a lack of evidence of water stress sensitive periods during growth. Nevertheless, there are crops, in which such periods are well defined and water deficit can enhance yield or quality. Among these Doorenbos and Kassam (1979) listed cotton, safflower, soybeans, pineapple, canning tomatoes and sugar cane. It seems that in annual crops the effect of water stress may be strongly inhibitory of yield. Robins and Domingo, (1953) and Denmead and Shaw (1961) found that a deficit during tasselling or pollination in corn had a strongly negative effect on yield.

Some authors (Hall and Butcher, 1968; Jensen, 1968; Hanks, 1974) have claimed that different stages of plant growth are interdependent, and that water stress in one stage acts in a multiplicative way to reduce yield, while other proposed effects are additive on subsequent stages in reducing yield (Flinn and Musgrave, 1967; Hiller and Clark, 1971; Stewart *et al.* 1977).

In perennial crops, Powell (1974) found a decrease in fruit set of apple trees if water stress was imposed early in the season. Powell (1976) found that extension shoot growth stopped first in the drier treatment and later in the irrigated plot. Several studiees reported in citrus (Hilgeman *et al.* 1959, 1974; Marloth, 1950; Beutel, 1964; Shalhevet *et al.* 1976) found that the second phase of fruit growth (during which about 70% of total fruit growth take place) is a water stress sensitive period. They noted also that blooming and fruit set were sensitive. On the other hand, Magness (1953) found water stress exerted an inductive effect on fruit bud initiation. Mitchell *et al.* (1986) reported a similar response in Barlett pears.

Slatyer (1967, 1973, Hsiao (1973) identified cell enlargement as a key process with respect to sensitivity to water stress. These workers made the important observation that only small water deficit may be required to reduce leaf area and other growth events involving cell enlargement. Begg and Turner (1976) pointed out that water stress affects physiological as well as ontogenic processes differentially which contributes to the differential sensitivity of crops at varied stages of development.

Hsiao *et al.* (1976) divided the effects of water stress on productivity into two important categories, those that affect dry matter production and those that affect the partitioning of assimilates. Although many authors (Ritjema, 1973; Hsiao, 1976; Downey, 1976; Pruitt, 1980; Stewart, 1977; Hanks, 1974; Hanks and Retta, 1976 and others) relate water stress to yield through the effect on dry matter production. Less attention has been paid to assimilate partitioning in relation with water stress.

1.2.3.3.3.5. *Development of the Concept of Regulated Deficit Irrigation.*

Lack of information about the allocation of photoassimilate in perennial crops led to Chalmers *et al.* (1978) to investigate the process by which the peach tree distributes the total annual increment in dry weight and the proportion of this that goes to the fruit. Results established that a competitive interrelation exists between the growth of root, frame growth and fruit. They proposed assimilate distribution between organs and tissues was finally controlled by the growth of the roots. This important hypothesis led these workers to study management systems that could derive advantages from controlling root growth. An hypothesis was developed that vegetative growth in excess of the need for a satisfactory number of fruit buds was a disadvantage with respect to growth of the fruit and other aspects of management, such as high density planting and winter pruning.

In an attempt to define water requirements for peaches, Chalmers *et al.* (1981) analysed strategies for irrigation of fruit crops. First, they defined a system of low irrigation frequency as being adapted to low root density and high root volume. These systems were considered more suited to a relatively low level of management, plentiful water supply and low tree density. Trees grown under such systems were expected to be late in bearing and required a high volume system of irrigation, such as flood or sprinkler. A second system was defined for trees with high root density and low root volume. The latter system was expected to produce smaller trees and consequently be more adapted to higher density plantings. It was also proposed to be of great importance for high density plantings without dwarfing root stocks because high root density and between tree competition restricted tree size (Chalmers, 1980).

Considering also that vegetative growth occurred mainly in spring while the growth of many fruits takes place in summer and autumn, making these chronological separate events, Chalmers *et al.* (1981) examined the possibility of controlling vegetative growth using water stress. It was hypothesized that ample water supply could be provided in late summer with little effect on vegetative growth because fruit growth suppressed the vegetative growth by competition (Chalmers and Wilson, 1978). On the other hand, vegetative growth was vigorous and competed strongly with fruit growth in spring and early summer. Vegetative growth would be restricted by water stress during this time, and Chalmers *et al.* (1981) hypothesized that the deleterious effects of water stress on fruit growth at that time could be balanced by benefits to fruit growth by reduced competition from vegetative growth.

On the basis on these premises, Chalmers *et al.* (1981) used three irrigation treatments which were applied to peach trees during different fruit growth stages. These stages were identified from the bimodal pattern of dry weight growth of peach fruit described by Chalmers and Van Den Ende (1975). In this work two periods of increasing dry weight growth by the fruit (DWI and DWIII) separated by a period of decreasing dry weight growth (DWII) were identified. In the context of this work DWI and DWIII were identified as periods of increasing assimilate demand by the fruit whereas assimilate demand decreased during DWII. Periods of highest assimilate demand have been identified as the most sensitive to water stress and consequently the following irrigation treatments were proposed:

a) full irrigation applied daily, in which trees would not be exposed to a water deficit

b) deficit irrigation applied during DWII, which applied water stress to the tree only during periods of low sensitivity of the fruit

c) deficit irrigation applied during DWII, which applied water stress as in (b) but also during DWI when assimilate demand by the fruit was high but vegetative growth competed strongly.

Results can be summarized as follows:
1) Deficit irrigation during DWI and DWII checked the unwanted vegetative growth and the resulting loss in productivity was not significant because of reduced competition to fruit.
2) Checking vegetative growth reduced the potential for subsequent vegetative growth and fruit growth during DWIII was enhanced by reducing vegetative competition when all treatments received full irrigation.

These principles continued to develop in subsequent studies (Mitchell and Chalmers, 1982, 1983; Chalmers *et al.* 1983) but it was not until 1984, when Mitchell *et al.* 1984 first used the term regulated deficit irrigation (RDI), and established RDI as an irrigation strategy which favoured the use of stages in fruit development as an appropriated basis for scheduling irrigation.

Chalmers *et al.* (1981) demonstrated that when RDI was applied during the first and second stage of fruit growth and returned to full irrigation in the third stage, vegetative growth was reduced whereas an increase in fruit size resulted. Combining reduced irrigation with high density planting was highly effective in reducing the annual increase of the tree trunk cross sectional area.

Beukes and Weber (1982) divided the apple growth into four phenological phases as follows :
1) first 40-50 days after full bloom,
2) 40-50 days after full bloom until end of shoot extension,
3) end of shoot extension until harvest and,
4) post harvest phase.

They found an increase in shoot growth by increasing Total Available Water

(TAW) in Phase 2 and a linear increase in fruit circumference by increasing TAW in Phase 3. Beukes and Weber results confirmed the previous work of Chalmers *et al.* (1975, 1981) and are in agreement in three relevant aspects:
a) the increase in water available in phase 3 of fruit growth affected the fruit size positively;
b) the results contrast with much earlier emphasis on the negative influence of soil water stress and,
c) vegetative growth may be reduced by a regulated water deficit.

Chalmers *et al.* (1984) summarized the advantages of RDI as follows:
a) RDI controls tree vigour reducing the need of summer pruning to a minimum with a concomitant reduction in costs
b) RDI increases fruit size and yield
c) RDI reduces the total volume of water used and increases the water use efficiency
d) RDI allows high plant densities.

Application of RDI to pear trees gave additional support to this irrigation strategy (Mitchell *et al.* 1984). The use of three different levels of water deficit applied in stages of rapid vegetative growth and slow fruit growth showed that the fruit grew no more slowly during the RDI period, but once the full irrigation was applied in the subsequent period, the fruit tended to grow at a faster rate. Shoot growth was effectively controlled by RDI. The evaluation of effects of tree spacing and irrigation on fruit set, size and yield demonstrated that both management treatments enhanced fruit set, fruit growth and yield. Based on these results the authors proposed that spacing and water supply operate in a synergistic mechanism to reduce the vegetative growth and increase fruit growth.

Lötter *et al.* (1985), irrigated Granny Smith apples at four different levels of TAW during each of four phenological phases, already defined (Beukes and Weber, 1982). They reported more vigorous shoot and trunk growth during the second phase under the highest level of TAW, whereas at lower TAW level most of the shoot extension growth was completed during phase I. A decrease in levels of TAW during phases 2 and 3 of fruit growth resulted in decreased fruit size, however, for all TAW levels the biggest increment in fruit circumference growth was produced during phase 2. These authors recognized Phase 3 as a critical stage in terms of requirements of high water supply and recommended higher TAW levels during Phases 2 and 3, which differs from Chalmers *et al.* (1981) who found that is unnecessary to apply water at optimum rate during a chronologically similar period in peach trees. It should be remembered, however, that physiologically these periods were defined differently. Chalmers *et al.* (1981, 1984) have always used the rate of fruit growth to define the need for full irrigation. The present authors have mixed requirements for fruit and vegetative growth which may have resulted in the suppression of fruit as well as vegetative growth.

The use of a period of withholding irrigation in the initial stages of fruit development and rapid vegetative growth, was added to the RDI irrigation strategy by Mitchell *et al.* (1986). This addition was mainly justified on the basis of the seasonal rainfall distribution and the concomitant increase in soil water stored during winter and spring. A simultaneous evaluation of the withholding period with tree spacing showed this treatment to be an effective way to accelerate the drying out of the root zone and to enhance the inhibitory effect of water deficit on shoot growth.

Finally, in New Zealand, Irving and Drost (1987) applied the RDI strategy on Cox's Orange Pippin apple. The water deficit was imposed on Phase 1 and 2 of fruit growth. When the deficit was imposed on Phase 1, a marked reduction in shoot growth was obtained. A lesser reduction occurred when the deficit was imposed on Phase 2. Regulated deficit irrigation had positive effect on vigour reduction but such effects were not reflected on crop yield.

It is now recognized that vegetative vigour is inversely related to fruitfulness and that irrigation management oriented to optimise the proper balance between these two variables is a major determinant in orchard productivity (Jerie *et al*, 1989). Systematic research in this area is now required in order to calibrate the strategy in different environments and fruit crops in which sensitivity to water stress in different growth stages may quite variable.

1.2.3.4. *Irrigation Timing.*

Considerable evidence has been accumulated, regarding the importance of a proper timing of irrigation application (eg. Rawitz, 1969; Acevedo *et al.* 1971; Hillel and Guron, 1973; Al-Ani and Bierhuizen, 1971; Garnier and Berger, 1987). Timing of irrigation should be adjusted to soil water depletion according to crop requirements which vary with the evaporative demand, root depth, size of the soil reservoir and the water holding capacity of the soil (Clothier *et al.* 1987).

When the soil dries, water uptake by plants becomes more difficult (Hanan, 1972; Hillel, 1974). If during drying, evaporative demand is high, the plant responds reducing transpiration in order to maintain tissue hydration (Garnier and Berger, 1987). Denmead and Shaw (1962) showed that high transpiration rate depleted soil water rapidly, and increased the resistance to water movement. Alternately, if the transpiration was low, the soil water was slowly depleted until the moisture was low. Consequently, there is no a fixed optimum interval between irrigations or any fixed soil water potential (Ψ_S) at which to start irrigating. Vermeiren and Jobling (1984) recommended irrigation should be applied as often as required to maintain Ψ_S at a level that allows maximum transpiration under the local atmospheric conditions.

One method of determining the interval between irrigation is to start watering when a given level of water deficit or evaporation has been reached . Campbell and Campbell (1982) have described a procedure to set what they called the "full" and the "refill" points in the soil. The full point was defined as FC for the given soil and the refill point, the Ψ_S below which crop production was decreased.

Field capacity can be determined for the particular soil and Campbell and Campbell (1982) recommended the refill point be set at the minimum value of soil water content (θ) that allows the water potential and resistance to water flow from roots to transpiring surfaces to be negligible compared with the other resistances of the system. This means that if soil water content is monitored, it is necessary to convert the value to water potential. This may be done using a water release curve or by simultaneous measurement of Ψ_S with tensiometers (Hanks and Ashcroft, 1980). For practical purposes Ψ_S is difficult to determine, therefore it is recommended that the soil water content be monitored and the irrigation be set somewhere between the full and the refill points following a record-keeping scheme (eg. Jensen, 1970).

Doorenbos and Pruitt (1977) devised an irrigation scheme based on field water balance to be used under any conditions for a sprinkler irrigation. Water available for the crop is calculated from the equation:

$$W_e = W_b + P_e + G_e - ET_{crop} \text{ in mm/month} \tag{1.18}$$

where,

W_b = initial soil water stored
P_e = rainfall
G_e = ground water depth

Tables were provided with values of rooting depth, fraction of water available and readily available soil water for different crops and soils. Taking these values it is possible to calculate the allowable soil depletion for ET of crop.

These same authors defined the allowable soil water depletion as the fraction of the total soil water available between FC and PWP that remains in the root zone and allows unrestricted evapotranspiration. Thus, the total soil water available was defined as the depth of water stored in the root zone between FC and PWP. Depth of irrigation is the amount of water in mm per unit land area necessary to bring the soil to FC.

Recently, Buss (1989) proposed a technique to schedule irrigation specifically designed for permanent horticultural plantings. In this technique the readily available water was defined as the volumetric soil water content which could be held between a matric potential of -0.008 MPa and -0.04 MPa. To determine the timing of irrigations, the total θ within the root zone was divided into three stages based on the rate at which θ changed in a drying cycle as follows :

1) saturation and drainage
2) readily available water (RAW) and,
3) decrease in RAW.

Changes in stage 1 were attributed to drainage and evaporation, while in the other two stages were due to ET. The water content left in the root zone, when the soil was fully wet was called the drainage upper limit (DUL), and the boundary between stages 2 and 3 was called the lower limit (LL) of plant available water, below which the plant experiences induced stress, following the definitions of Ritchie (1981).

The DUL was considered important to adjust the refill amount and thus avoid over-irrigation. It was recommended the LL be determined by inspection of the relation between volumetric water content and the ratio of actual to potential ET or other indicators of water stress in the plant.

The concept of RAW as presented in this work contrasts with the term Plant Available Water (PAW). The first term defines the amount of water present between the DUL and the LL summed over the root zone. The lower limit represents an index or indicator of the onset of stress rather than the onset of damage to plant as was the permanent wilting point to the PAW.

Obviously, the irrigation interval in this scheme is adapted to the specific crop in a given set of conditions.

1.3. *Soil Water Regime.*

1.3.1. ***Introduction.***

Soil water plays an important role in the water supply and aeration of the root system, and also influences the biology of soils and nutrition of fruit trees (Tamasi,1986). Soil physical properties determine the amount of water that can be stored and the depth and area where the bulk of the root may spread (Fochessati,1986). If water is applied in excess of the amount the soil can hold and the soil has any physical impediment to water movement, water will be blocked and produce waterlogging. In the absence of any impediment to movement, water will be lost by deep percolation. In both cases negative effects on root development may occur. In the first situation, a reducing environment around the roots may arise, in the second water and nutrients will be lost to the roots (Clothier and Scotter, 1983).

1.3.2. ***Soil Water Availability.***

The well known parameters FC and PWP defined limits between which water was supposed to be available to the plant, but are now considered ambiguous. Attempts have made to correlate FC with some other soil properties, such as soil suction, but Gardner (1966) pointed out there is not an unique single value that can be used. With the development of knowledge in the field of unsaturated flow processes in the soil, FC has been recognized as arbitrary and not a physical property of the soil that is independent of the measurement (Hillel, 1980).

Additionally, the term PWP which was introduced by Hendrickson and Veihmeyer (1945) as the value of soil wetness in the root zone at the time plant wilts is also considered arbitrary since estimates for a given soil and different crops may vary. These two terms have now been replaced with the more dynamic concepts of the DUL and LL (Ritchie, 1981) which can be used to obtain the extractable water capacity, i.e. DUL-LL.

In the field LL is determined for a crop which has reached its maximum vegetative size without stress and grown on stored water until LL is reached (Ritchie, 1981). Reid *et al.* (1984) used the term LL as the θ at which plant water uptake apparently ceases, and plants are distressed by drought. He found good agreement between estimates of available and extractable water, and proposed that DUL and LL may be useful indicators of the water available to the crop. Nevertheless, Reid emphasizes that the concept of available soil water, which applies only to 60 cm depth, underestimates actual water use, whereas if extractable water is extended to 1.0 m depth, it performs better. Reid specified that in some situations the time required for a soil to drain to the DUL can lead to errors in the water balance equations, and suggested the use of equations that relate drainage rate to the θ in excess of the DUL.

Rickards and Cossens (1966) compared laboratory with field estimates of DUL and they obtained a poor correlation between them. This could be due to textural layering below the depth where the measurement was taken such as Clothier *et al.* (1977) have identified in the situation of a coarse layer underneath an uniform layer of fine texture.

A more refined procedure was used by Buss (1989) by applying the terms DUL to an specific upper limit of soil volumetric θ when the soil was fully wet but in a drained state. The LL was assessed by inspection of the relationship between volumetric θ and the ratio of actual to potential ET. On the basis of these estimates over the root zone depth, Buss introduced the term Readily Available Water Capacity (RAWC), and indicated that within this range of available water, the plant is not exposed to severe damage for water stress.

1.3.3. *Water Distribution in the Soil.*

In irrigated soils the type of irrigation application and the intrinsic soil characteristics are crucial factors in the way soil transmits water. In furrow, flood or sprinkler systems, irrigation consists of a short period of infiltration followed by a long period of redistribution, evaporation and water extraction by the plants (Bresler, 1977). In addition, the pattern of water distribution by sprinkler is additionally determined for characteristics of the sprinkler and the ability of the soil to store water (Griffiths, 1989). During, the period of redistribution large fluctuations in the soil water content occur in the soil, which are factors which can affect plant growth and yield (Bresler and Yaron, 1972).

With trickle irrigation, such fluctuations are minimized because the system applies water to the soil in small amounts at short intervals. The water distribution pattern depends upon the ability of the soil to transmit water within the root zone (Clothier and Scotter, 1983)

The preceding discussion makes a consideration of the wetted profile under trickle irrigation relevant. If infiltration occurs into a dry soil, a clear boundary is formed between the wetted zone and the dry zone at the wetting front (Bresler and Russo, 1975). The wetting front in trickle irrigation indicates the boundaries of the irrigated soil volume (Bresler *et al.* 1971).

Bresler (1977) compared wetting fronts in two soils, a loam and a sandy soil receiving different total amount of water. He found the sandy soil had greater ability to transmit water, but lower soil water holding capacity. Also, he noted a wider wetting pattern in both soils was produced at the higher water application rate. Wider spread in the surface soil resulted in a less movement in depth for a given amount of water. Higher application rates produced a less wetter soil volume because pores were rapidly filled with water.

McAuliffe (1985) studying the wetted profile under trickle irrigation of six soils in New Zealand, found in most cases a clear horizontal gradient of water content decreasing from the point of application. The gradient was more marked in soils with high capillarity. In these soils drainage losses were estimated as high as 50% in the first 12 hours after application.

1.3.4. *Soil Water Storage and Water Extraction.*

The total volume of water available at a given time for a plant depends upon the available or extractable θ and the volume occupied by the roots (Taylor and Klepper, 1978). Under normal conditions, roots extract water from different soil layers with varied physical properties (Taylor *et al.*1972) .In general,the removal of water tends to be faster from the soil surface and as the water is depleted from this area, the uptake will increase progressively in deeper layers (Huck and Hillel, 1983).

In annual crops, root growth was restricted to the wetted area of the soil profile (Swain, 1984). Black and West (1974), however, demonstrated that apple trees with only 25% of the root in a well watered soil and the rest of the root in soil at wilting point, were able to absorb 75% of the amount absorbed by trees with all the roots in soil at FC. Based on these results they concluded that orchard trees should be able to perform well if only 25% of the root system was well watered.

If the soil is uniformly wet, the water absorption pattern is mainly determined by the root distribution and the resistance in the pathway from the soil to the root (Belmans *et al.* 1979). Hillel and Talpaz (1976), found roots tend to proliferate in the zones with greater moisture. Fresh roots formed in new soil layers only if the root parent was in adjacent layers, in a way that indicated roots 'tracked' the wet areas of soil.

It is interesting to note that the pattern of water extraction adjusts to soil water flow (Hillel, 1980). Usually the soil extends below the root zone. Water will flow within, through and below the root zone, and some capillarity upward movement may also occur. Several workers have developed models of soil moisture extraction by roots (Nimah and Hanks, 1973; Hillel *et al.* 1975; Reicosky and Ritchie, 1976; Taylor and Keppler, 1976). One can conclude from these studies that water uptake is a dynamic process in which the root does not depend entirely upon the soil water conduction to the areas where extraction is taking place and resistance to water movement is continuously increasing. The root also actively grows to reach moist areas of soil (Belmans *et al*,1979).

Garnier *et al.* (1986) confirmed the above conclusion in a study of water uptake in peaches. They observed maximum water loss occurred in the upper 60 cm of soil if the soil was well watered. The wet treatment maintained the same pattern of water extraction throughout the experiment while in the dry treatment the water uptake shifted towards the deeper layers.

1.3.5. *Controlling the Soil Water Budget.*

McAuliffe (1985) pointed out that in arid regions, such as Israel, the entire plant water requirement is provided by the irrigation system, and root growth approximately follows the pattern of soil water distribution. However, in areas such as New Zealand, where rainfall supplements the irrigation, plant root distribution is less likely to reflect the soil water content, and will tend to occupy an extensive volume as the crop matures.

Mature vines of kiwifruit have an extensive pattern of rooting (Hughes *et al.* (1986); Clothier *et al.* 1987). In mature apple tree, it has been found (Rahardjo, 1989) in Havelock North, New Zealand, that the highest root density occurred in a 2-3 m radius from the tree probably due to overlapping roots from adjacent trees. These roots also extended beyond 1500 mm depth. This degree of root extension is an expression of vigorous vegetative growth, as defined by

Chalmers (1985). Accordingly, management oriented to restrict root growth might be expected to reduce tree vigour.

Of the approaches proposed to control the soil water budget, one of the simplest is the manipulation of soil water content, by partial wetting of the soil using irrigation management (Bresler, 1977). Cultural practices associated with the management of the ground surface,however, such as cover crop, weed control, mulching, etc, can have a great influence on the soil water budget as well as affecting development of the root system through effects on the volume of soil which may be utilized by the roots (Fochessatti, 1986).

Black and Mitchell (1970) compared the soil water use under a vigorous sward of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*), an herbicide strip and, trashy cultivation. They obtained higher water use for trees under ryegrass in spring, which could assist in overcoming waterlogging in shallow orchard soils.

Plastic films of different thickness and colours also have been used. Mulching with a plastic film can cover the soil for long time, preventing weed growth, loss of heat and water, and erosion. Bacon (1974) found the effects of black plastic mulching on apple trees prevented evaporation and retained soil moisture and increased yield, although it increased soil temperature. Similar results were reported by Mage (1982), who compared a plastic soil cover with permanent grass sod under apple trees.

Other workers have proposed the use of a grass mulch under tree cover (Chiusoli, 1971; Todeschini, 1971). The grass cut was left on the ground through the year forming a cover of increasing thickness. The resulting sod improved soil structure by increasing decomposition and soil respiration and facilitated the solubility and availability of nutrients. Coker (1958) studying the effect of the sod-system of orchard management in contrast to bare soil, on root formation in apple trees, pointed out that with a grass sod many of the thicker tree roots grew upwards into the sod where they branched off thickly. In deeper zones of the soil a higher density of fine roots developed under bare surface. Large quantities of absorbing roots, however, grew under the grass only if the soil moisture was satisfactory, if the soil dried root number decreased thereby checking tree growth. Richards and Cockroft (1972) found that root concentration of irrigated peach trees was more influenced by site characteristics than soil management treatment.

Bergamini (1976) explored the possibility of using other plants as under tree cover in orchards, such as red clover (*Trifolium pratense*), blue grass (*Poa pratensis*) and lucerne (*Medicago sativa*). The roots of clover and lucerne, and particularly lucerne, suppressed the development of peach seedlings.

Hayman and McBride (1984) compared pasture and lucerne behaviour under irrigation with the following results:
a) Lucerne demanded less frequent irrigation than pasture. Due to its deep tap root, lucerne was able to recover water from irrigation that percolated beyond the reach of pasture;
b) Lucerne transpired at the higher rate which indicated that in a soil with high water content, lucerne used the water at a faster rate.

From the preceding studies, one can conclude that plastic mulch and lucerne might be suitable to exclude winter rain and use winter rain respectively.

1.4. *Plant Responses to Water Deficits.*

1.4.1. *Leaf Water Potential.*

1.4.1.1 *Diurnal Pattern.*

Although, soil water potential may be useful to evaluate water stress, it is only an indirect parameter for describing the plant water status (Rudich *et al*, 1981). For a long time, Ψ_L has been accepted as a measurement of plant water status (Barrs, 1968; Boyer, 1967; Hsiao *et al.* 1976). Research reports (e.g. Slatyer, 1967; Cowan and Milthorpe, 1968) repeatedly show a diurnal pattern of Ψ_{L}, the minimum daily value of which decreased with the soil water availability. Smart and Barrs (1973) explained that the shape of diurnal pattern is similar between different perennial horticultural species. The daily minimum Ψ_{L}, however, depends upon the plant size.

Goode and Higgs (1973) studying water potential and its component osmotic ($\Psi\pi$) and pressure potentials (P) in apple leaves of irrigated and non irrigated trees obtained a considerable diurnal change in Ψ_{L} (from 0.1-0.2 MPa before sunrise to 1.5-2.5 MPa) after midday, even when the soil moisture tension was low. A similar response was obtained in irrigated and non irrigated trees which showed that Ψ_{L} is very dependent upon the evaporative atmospheric demand. Smart and Barrs (1973), demonstrated that diurnal variation in environmental parameters such as radiation, temperature,saturation vapour deficit and insolation, accounted for 74 to 99% of diurnal variation in Ψ_{L} in peaches, prunes, citrus and grapes.

The diurnal pattern of Ψ_{L} obtained by Olsson and Milthorpe (1983) in peach trees reached maximum daily values after sunrise, which did not change markedly during the drying cycle. Minimum values were obtained in the early afternoon and more closely reflected the decrease in soil water potential as drying progressed.

1.4.1.2. ***Seasonal Changes.***

1.4.1.2.1. ***Pattern Related to Soil Moisture.***

Chalmers *et al.* (1983) also found that diurnal minimum values in Ψ_{L} in peach trees paralleled those in soil water potential. Meanwhile, maximum values changed less with the soil water potential decrease during the drying cycle. The effect of drought on diurnal Ψ_{L} of peach trees was somewhat different. Midday leaf water potential (Ψ_{Lm}) in peach decreased sharply accompanied by a gradual decrease in predawn leaf water potential (Ψ_{Lp}) values as the soil water was depleting (Xiloyannis *et al.* 1980). The same classical pattern of Ψ_L change, have been described by numerous other workers (e.g. Garnier and Berger, 1987; Torrecillas *et al.*1988; Larsen *et al.* 1989).

In almond trees (Torrecillas *et al.* 1988), Ψ_{Lp} in an irrigated treatment was consistent through the growing season whereas in a rainfed treatment it decreased gradually, parallel with soil water as stress accumulated.

Xiloyannis *et al* (1988) showed that Ψ_{Lp} of irrigated peach trees varied over small range, while in non irrigated trees it decreased steadily to -1.5 MPa after 50% of available soil water in the top 90 cm was depleted. This decrease continued as soil moisture decreased further. Values of Ψ_{Lm} reflected atmospheric conditions more closely than the soil water status and no marked differences were obtained between irrigated and non irrigated trees. Moreover, Ψ_{Lm} was almost the same when the soil moisture approached PWP, but stomata closed in non irrigated trees suggesting the operation of osmoregulation mechanisms to maintain turgor. These workers concluded that Ψ_{Lp} is a useful parameter for defining plant water status and available soil water. Nonetheless, a relationship between the soil parameter and Ψ_L measured during the day was found in peach, and kiwifruit.

Seasonal study of Ψ_{Lm} in pear trees subjected to wet, normal and dry treatments (Brun,1985), revealed that the dry treatment was significantly different to normal and wet treatments. In the dry treatment Ψ_L decreased steadily after full bloom and continued as soil water was depleted.

In general, the influence of soil drying appears to be more accentuated on midday Ψ_{Lm} than in Ψ_{Lp}. However, after a given threshold in soil water availability is reached, Ψ_{Lp} reflects the soil water stress (Garnier and Berger, 1987).

Stephenson *et al.* (1989), showed that young leaves of macadamia trees wilted at values of Ψ_L less than -2.4 MPa. Whereas mature, hardened leaves developed stress symptoms at -4.1 MPa. It was concluded that when the minimum value was reached in mature leaves some physiological damage might have occurred. This conclusion was due to irreversible damage detected in the leaves at less than -5 MPa.

Several studies (Goode and Higgs, 1973; Davis and Lackso, 1978, 1979a, 1979b; Jones *et al.* 1979) have shown apple trees have a marked capacity to adapt to slowly imposed deficits. This was deduced partly from smaller differences in Ψ_L between irrigated and non irrigated trees through the season (Jones *et al.* 1983). Similar results were obtained by Lakso *et al.* (1984). The latter found young leaves were more sensitive to water stress while mature leaves adjusted to deficit without dramatic changes in Ψ_L. Lackso *et al.*(1984) proposed that leaf area development appeared to be more sensitive to changes in water status than stomatal behaviour in osmotically adjusted leaves. Hence, this sensitivity difference could be used with advantage to manipulate water deficit in apple trees. Moderate levels of water stress can be maintained to inhibit shoot growth while allowing photosynthetic activity in mature leaves.

1.4.1.2.2.*Pattern Related to Phenological Phase.*

Chalmers *et al.* (1984), measured Ψ_{Lp} and Ψ_{Lm} on pear trees subjected to three levels of irrigation applied at different stages of the growing season. Even though, water was withheld at the start of the irrigation period, (during which Ψ_{Lp} and Ψ_{Lm} were reduced) the lowest Ψ_L values were obtained during the fruit maturation stage, despite the fact at this stage the trees were receiving full irrigation. This result was explained by environmental effects interacting with increased transpiration associated with elevated rates of photosynthesis required for rapid fruit growth. Fujii and Kennedy (1985) found in apple trees elevated photosynthetic rate during blooming period and during the rapid fruit growth.

1.4.2. *Stomatal Resistance, Conductance and Transpiration.*

The internal water deficit of plants is controlled by the rate of water uptake by the roots and the rate of transpiration (Kozlowsky, 1968). As a water deficit develops, physiological processes are altered and subsequently growth and yield are reduced (Hagan *et al.* 1967).

Apparently, stomatal closure of many species is obtained in response to dryness of the air independently of the Ψ_L (e.g. Cohen and Cohen, 1983; Kauffman and Elfving, 1976). However, Garnier and Berger (1987) observed a progressive reduction in stomatal conductance instead of an 'on' and 'off' reaction, as the soil water content decreased. The daily pattern increased as radiation increased, reaching a peak in the early morning and then decreasing gradually during the rest of the day.

In many cases, stomatal resistance seems to be relatively unaffected by decreasing Ψ_L until a threshold value is reached at which stomatal closure increases sharply over a narrow range of Ψ_L (West and Gaaf, 1976., Hsiao, 1973). The validity of this statement was confirmed by Hopmans and Schouwink (1986). They reported leaf stomatal conductance of non-irrigated trees was significantly lower than in irrigated trees. The depression in stomatal conductance observed at minimum values of soil water potential led these workers to propose the existence of a threshold of Ψ_L at which stomatal conductance is reduced. Studies on avocado and citrus also have revealed that a reduction in Ψ_L below -1 MPa initiated stomatal closure (Kriedeman, 1986).

Stomatal closure was induced in non irrigated peach trees at low levels of soil moisture and Ψ_L (Xiloyannis *et al.* 1980). Young *et al.* (1981) found that stomatal closure occurred in peach seedlings when Ψ_L dropped below -2.6 MPa and no apparent correlation existed between stomatal closure and turgor pressure.

Xiloyannis *et al.* (1988) reported results in which stomatal conductance responded to water deficit in the soil according to the species. While in peach trees the stomatal conductance decreased as soil moisture reached 25-30% of the available soil moisture, kiwifruit plants reacted by a sudden drop in transpiration at levels at 50% soil moisture. In contrast, olive trees continued transpiring even at low levels of soil moisture. Larsen (1989) compared transpiration rates in different species and found the highest rates in apple. followed by peach, while apricot, olive and grape exhibited a similar rate which was lower than apple and peach.

Levels of water deficit that cause stomatal closure would be expected to depress photosynthesis concomitantly (Brix, 1962). Throughton (1969), presented evidence that stomatal closure is the primary cause of depressed photosynthesis under water-limiting conditions. Therefore, the depression will also occur at a Ψ_L threshold that elicits a stomatal response. Tan and Buttery (1982a, 1982b) studied stomatal conductance, transpiration, photosynthesis and leaf water potential in peach seedlings exposed to different watering regimes. They found a critical value for Ψ_L below which stomatal resistance increased rapidly. Since actual water loss continued to decline steadily during this phase, they suggested that water loss, photosynthesis and presumably growth will start to decline as soon as water stress appears.

Jones and Rawson (1979), pointed out that the threshold water stress of plants depends on plant size, root volume and evapotranspirative demand. For instance, net photosynthesis and stomatal resistance of peach seedlings subjected to mild water stress returned to normal after rewatering (Hand *et al.* 1982). Where the seedlings were subjected to severe stress,however, net photosynthesis recovered only after a time lag, and growth was severely altered.

A report on macadamia trees indicated that stomatal conductance was sensitive to water deficit and decreased slowly until Ψ_L reached -2 MPa when stomata closed (Stephenson *et al.* 1989). These authors argued, however, that stress was too great at this Ψ_L because when this value was reached, since flower abscission and leaf expansion had already been severely affected.

Olson and Milthorpe (1983) found no clear relationship between stomatal conductance and Ψ_L of peaches. This was interpreted to indicate that Ψ_L, may have only a small effect upon stomatal conductance. Similar behaviour of stomatal conductance without corresponding differences in Ψ_L was reported by Jones *et al.* (1983).

The daily pattern of stomatal conductance in peach trees showed higher values early in the day, followed by a decrease towards sunset (Chalmers *et al.* 1983 and reference therein). Leaves in the upper layers, exposed to more irradiance exhibited higher stomatal conductance. In this study, a differential sensitivity to Ψ_L according with the stage of fruit development was reported. Stomatal conductance reduced more in DWII stage of fruit growth than in DWIII stage for a given lowering in Ψ_L.

1.4.3. ***Stem Water Potential.***

Diurnal variation in stem water potential (Ψ_S) for irrigated and non irrigated apple trees showed the same pattern as Ψ_L (Powell,1974). Hence, a depression was observed at midday, which increased with the evaporative demand. The degree of depression was greater in droughted trees. Powell (1976) reported in Cox'Orange Pippin apple that dependence of Ψ_S on the evaporative demand was not constant throughout the season. In the evening the falling evaporative demand was not followed by a corresponding rise of Ψ_S in the dry plots. Stem water potential lagged behind Ψ_L (Powell and Thorpe, 1977) and did not fall as low as Ψ_L, i.e. the recovery of Ψ_L follows Ψ_S. Other workers (Klepper and Cecatto, 1968; Smart and Barrs, 1973), have reported the same diurnal pattern of Ψ_S (Garnier and Berger, 1987).

1.4.4. *Growth*.

Kozlowsky (1958) reported that a negative water balance in trees may reduce growth, cause leaf abscission, dieback, sun scorch and death. In addition, water deficit in leaves influenced carbohydrate supply through effects of increasing resistance to CO_2 diffusion.

Water stress may arise when the plant is exposed to a soil water deficit (Levitt, 1972). However, the internal water deficit in plants is controlled by the rate of water uptake by the roots and the rate of transpiration (Kozlowsky, 1968). As a water deficit develops, physiological processes are altered and subsequently growth and yield are reduced (Hagan *et al.* 1967).

1.4.4.1. *Vegetative Growth.*

1.4.4.1.1. *Root*.

Waynick and Walker (1930), as cited by Kriedeman and Barrs (1981), stated that dry soil severely limited root growth in citrus trees. Marsh (1973) has indicated, that soil water stress may lead to increased depth of rooting. Hilgeman and Sharp (1970) reported in oranges an increase in the proportion of feeder roots caused by water stress, not an increase in rooting depth. This resulted in an apparent increase in total weight of feeder root and a net effect of water stress on reduction in the top:root ratio, mainly due to a large concomitant reduction in top growth. Similar results in apple and citrus have been reported by Rogers (1939) and Levy *et al.* (1978) respectively. Rogers (1939) also explained that apple roots are very sensitive to moisture stress and growth is retarded long before wilting point is reached.

Goode and Hyrycz (1964) found that moisture stress changed the configuration of the apple root system. They reported that watered trees concentrated more than twice the root weight in the top soil zone (0-150 mm) and below that zone the proportion was reversed in non irrigated trees. Total tree weight was similar in both treatments. The authors concluded the apple tree shows capacity to adapt its root system to irrigation practices. Similar results were obtained with apples by Cripps (1971) who found the root systems in non irrigated trees extended to greater depths than those of well watered trees. Water stress consistently lowered top/root ratio.

Several workers (Kramer and Kozlowski, 1960; Cockroft and Olson, 1972) have shown that as result of water stress and high soil temperatures, roots of fruit trees do not grow in summer. Richards and Cockroft (1975) observed that a Ψ_S of -0.5 MPa had no effect on root elongation, but at a Ψ_S of -1.5 MPa root elongation ceased. Hence, these workers suggested that low frequency irrigation and high transpiration rate which produce a fast soil drying and slower root growth would result in high root concentrations in the surface soil.

1.4.4.1.2. *Stem and Shoot.*

Effects of reduced vegetative growth with increased water deficit were associated with a decline in Ψ_L. Chalmers (1987) reported that shoot extension ceased at values of -0.5 and -2.0 MPa at dawn and midday respectively. Hilgeman (1951; Hilgeman and Sharp, 1970) obtained reduction in trunk growth of citrus trees in proportion to the reduction in water applied. Goode and Ingram (1971) studying growth of apple trees under different irrigation regimes, found that in deficit treatments trunk growth rate was not affected during the first season, but appeared affected in successive seasons. Whereas the effect on shoot growth occurred in the first season. In long term, the most marked effect, however, was on shoot number rather than on shoot elongation. Assaf *et al.* (1974, 1975) obtained low shoot and trunk growth in a dry irrigation regimes. A graded soil water deficit was associated with a similar response in relative growth of the trunk cross sectional area. Powell (1976) showed evidence of a relationship between irrigation and the final shoot length reached by shoots of apple trees. It appeared that elongation ceased first in the dry plots and last in the irrigated which had a proportionately longer period of growth. Chapman (1973) demonstrated that watering regimes did not affect shoot number but length. Rate of growth of shoots on stressed trees declined over the time while in well watered trees shoots continued to grow for much longer.

In irrigation trials on avocado trees, Lahav and Kalmar (1972, 1982) found that a 28% reduction in annual water application led to 25% reduction in trunk growth. On the other hand, only an 8% decrease in fruit size occurred at harvest, whilst fruit number was not affected. Furthermore, when Mosak (1977) subjected avocado trees to water deficit in the latter half of the season, a reduction in trunk growth was obtained with only a slight reduction in fruit size, and no differences in yield. Both of these studies suggested that water deficits alter partitioning of assimilates in favour of the fruit and against the trunk or vegetative growth.

Trees usually respond to reduced irrigation by reduced vegetative growth. Mitchell *et al.* (1984) used three levels of RDI in pear trees. In the period of slow fruit growth, irrigation was applied to replace 92%, 47% and 23% of evaporation over the planting square. During rapid fruit growth, full irrigation was given to all treatments. Results showed that RDI in pears slowed trunk growth, shortened branch elongation, reduced the weight of pruned wood but that fruit size was increased. Thus, RDI treatment was shown to reduce vegetative vigour while yield was increased. Interpreting these results in terms of assimilate partitioning the data indicated that a reduced proportion of assimilate was allocated to vegetative growth.

1.4.4.1.3. *Reproductive Growth.*

1.4.4.1.3.1. *Fruit Set.*

Information on the effects of water stress on fruit set in deciduous fruit trees is limited. Hanan (1972) found water stress caused serious effects on bud initiation, formation and maturation, Skepper and Vincent (1962), found a reduction in fruit set in apricot and prune trees as result of water stress. Powell (1974), comparing irrigated and non irrigated trees obtained in the earlier group a higher fruit set and a higher number of fruitlets retained.

Chalmers *et al.* (1981) reported that fruit set was reduced by severe water stress. Using the RDI strategy, however, resulted in increased fruit set per unit tree size, when severe water stress was avoided in peaches and pears. They also indicated that RDI combined with high density planting markedly stimulated fruit set, growth and yield, as compared with low tree density and full irrigation.

Proebsting *et al.* (1977) comparing trickle and sprinkler irrigation on their effects on fruit and growth, found that apple trees under trickle started to set flowers and bear fruit at an earlier age than sprinkled irrigated trees. Results were interpreted to suggest that trickle irrigation restricted root growth to a smaller root volume, which changed the growth pattern to less shoot and stem growth. The authors proposed photo assimilates were diverted in favour of fruit growth.

1.4.4.1.3.1. ***Fruit Growth and Yield.***

A large number of reports exist to show that, in general fruit growth and yield are enhanced by reduced water stress and/or increased irrigation. More recently, however, attention has focused upon potentially beneficial effects of transitional and, or marginal water deficits on these growth attributes. This section will concentrate on these reports.

Kriedeman (1986) pointed out that once fruit is set the yield is dependent upon applied water and recommended to manage the orchard on the basis of a sensible compromise between imposition of water stress that favours reproductive development and the relief of such stress during key stages in the season to ensure a high quality crop.

Hilgeman (1959) reported that water stress should be avoided at blooming and fruit set and also during the second stage of citrus fruit growth, since rates of fruit growth and final size may be diminished. In 1974, Hilgeman reported that fruit on citrus trees irrigated on both sides grew at a faster rate compared with trees irrigated at alternate sides. Already Beutel (1964) had observed that irrigation stimulated growth of navel oranges and lemon, since in three subsequent days after irrigation, fruit grew at faster rate and tended to slow down thereafter.

Bielorai and Levy (1971) found that grapefruit yields were significantly reduced when the number of drought days, defined as days in which soil water potential was below 0.1 MPa, exceeded 60.

The response of apple trees to different soil moisture conditions was studied by Goode and Ingram (1971). (These authors obtained a higher yield in irrigated apple trees than in non irrigated trees, but no positive effect of irrigation on fruit size was reported.) The highest marketable crop was obtained from trees watered when the soil moisture tension reached 20 cm. This was a medium rather than the minimum water tension in this experiment. Further, the treatments that were watered when the tension reached 50 cm in the top 300 mm of soil, resulted in the greatest increase in marketable crop per unit of water applied.

(Assaf *et al.* (1974) found a linear correlation between the percentage of apple fruit with diameter greater than 6.5 cm and the number of days in which the 0-60 cm layer of soil was subjected to less than 30% available water during the main period of fruit growth. These workers emphasized the importance of frequent irrigation to maintain the available water well above 30% in the top soil layer in order to obtain maximum fruit size. /

Positive effects on fruit size and yield have been reported by Chalmers *et al.* (1981) combining RDI strategy with increased root competition (high density planting) in peach trees. The application of the same strategy to pears (Mitchell *et al.* 1984) also resulted in an increase in yield.

Beukes and Weber (1982) applied three levels of total available soil water to Granny Smith apples. The treatments were applied in each of four phenological phases described earlier (Section 1.2.3.3.5.3). These workers found the optimum sequence of water levels for optimum yield was one with a deficit during the first and fourth phenological phases and the highest water level in the third phenological phase. These results agree with those of Chalmers *et al.* (1984, 1986) and Mitchell *et al.* (1984, 1986, 1989).

Lötter *et al.*(1985) evaluated the effects of different levels of total available soil water on fruit size and yield of apple trees. The treatments were also applied in different phenological phases. Negative effects on yield were obtained when water stress was applied in phase 2 and 3, but no adverse effects resulted when the stress was applied during phases 1 or 4. The apparent contradiction between these and former results probably lies in differences between the stage of physiological development defined by arbitrary stages of phenological development.

Using RDI in apple trees, Irving and Drost (1987) obtained no significant differences in crop yield as a result of the irrigation treatments. Goodwin and Jerie (1989), however found RDI produced a positive effect on yield of grapevines, as more bunches per vine were obtained with consistent bunch weight.

1.4.5. *Fruit Quality.*

1.4.5.1. *Total Soluble Solids and Acidity.*

Assessment of the effect of soil moisture on fruit quality has been mainly relegated to a minor role in determining quality, except for stress situations, even when water deficit regimes may affect quality in positive ways (Proebsting, 1970). Thus, several workers (Hendrickson and Veihmeyer, 1929; Morris *et al.* 1962; Uriu *et al.* 1964; Cahoon and Donoho, 1967) reported that apple fruit from dry plots had higher percentage of soluble solids (T.S.S) which might reflect a lower moisture content in the fruit.

Assaf *et al.* (1975) evaluated the effect of six irrigation regimes on quality of apples. At harvest time, the fruits from the dry treatment had the highest T.S.S., whereas the fruits from the extreme wet treatment had the lowest T.S.S. Differences among the rest of the treatments were not significant. Nevertheless, when expressed in terms of fruit size the highest T.S.S. yield was obtained in a treatment in which the water regime also caused the biggest fruit size.

In experiments in which different levels of irrigation in apples were studied, Guelfat'Reich *et al.* (1974) obtained the highest T.S.S. at harvest and during storage, and the best shelf life in those treatments which were irrigated two weeks after the soil reached PWP. Fruits from these treatments also showed the lowest acid content. On the other hand, these fruits were of smaller fruit size and for that reason of reduced marketability.

Guelfat' Reich and Ben-Arie (1979) studied the effects of frequency of irrigation in addition to effects of trickle or sprinkler irrigation systems on fruit quality of a diverse range of fruits. In sprinkler and trickle experiments with apples, they was found that T.S.S. content was significantly higher when the amount of irrigation was reduced. Within the trickle irrigation treatment, reduced irrigation resulted in higher T.S.S. In the same study, however, pears under trickle irrigation resulted in lower T.S.S.. Effects on apricots were not significant, while in grapes reduced irrigation accelerated fruit ripening. The general effect of frequent irrigation and large amounts of water was to reduce T.S.S. of the fruit and increase acid content. Effects observed at harvest persisted during storage. It was proposed that increased irrigation amounts could be causing inflation of cell size, fragility of cell walls and dilution of cell content. Another proposed explanation was possible nutrient leakage from the root zone caused by frequent and increased irrigation.

Proebsting *et al.* (1984) examined the effect of a moderate water deficit in apple trees maintained throughout the growing season on fruit quality at harvest and storage life. Trees were sprinkler or trickle irrigated. Within the trickle irrigated treatments, water was applied at 100%, 75% and 50% ET. In the sprinkler treatment it was applied at 100% and 75% ET. Fruits from trickle irrigated trees were lower in moisture content and acidity and higher in T.S.S than sprinkler irrigated fruits. There was no interaction between harvest date and storage in relation to the irrigation treatment. Moisture content did not change during storage, whereas T.S.S. increased during early part of the storage.

Evaluation of the effect of RDI on apple quality by Irving and Drost (1987) resulted in a higher T.S.S. content in fruits from all RDI trees than in the control trees.

1.4.5.2. *Fruit Size.*

Many workers have shown that one of the first manifestations of reduced growth, as a result of soil water deficit, is reduced fruit growth (Lord *et al.* 1963; Uriu, 1964; Goode, 1972; Proebsting, 1970).

Guelfat' Reich and Ben-Arie (1979), examining the effect of trickle versus sprinkler irrigation on the fruit quality of several commodities found a size reduction of apple, grapes, apricots and pears when the irrigation was reduced three weeks before harvest. Positive effects in the keeping quality of fruits under the same treatment were obtained, but because of reduced size, fruits were not as marketable. In contrast, fruits from heavily irrigated trees exhibited a poorer keeping quality.

Several workers (Felsdtein and Childers, 1957; Landberg and Jones, 1981; Lord *et al.* 1963) concluded that fruit maturing under a moisture deficit are smaller, have low water content and higher soluble solids (Assaf *et al.* 1975; Drake *et al.* 1981.) than fruits receiving ample water.

Proebsting *et al.* (1984) designed experiments to evaluate effects of RDI on fruit quality and storage life of apple. Results showed that fruits from RDI trees had equal fruit size and storage life when compared with non deficit irrigated trees. It is important to emphasize that deficit treatments were:

1) 75% ET replacement through the season
2) 50% ET in June-July and then 100% ET until harvest

These results contrast with numerous reports in which RDI significantly and positively affected fruit size (Chalmers and Van Den Ende, 1984; Chalmers *et al.* 1981; Mitchell and Chalmers, 1982; Mitchell *et al.* 1986, 1988, 1989). In most of these works, emphasis has been given to the application of RDI in a proper timing in order to obtain positive increment in size of the fruit. Thus, the lack of any positive effect of RDI on fruit size as reported above by Irving and Drost (1987) might be due to extension of RDI into the stage of rapid growth of the fruit, during which time water supply should not be in deficit. These are aspects of apple irrigation which deserve further attention.

Adato and Levinson (1988) subjected avocado trees to a 30% reduction in the quantity of water applied which resulted in more fruits per tree and greater yield, and the largest individual fruit size. Annual fruit growth, however was also increased indicating that is not enough to reduce the levels of water applied, proper timing of the deficit in coordination with fruit growth is necessary for optimum results.

1.4.5.3. *Colour.*

An early report by Kumashiro and Tateishi (1967) indicated that low soil moisture increased red colour of apples. A contrasting effect of irrigation on colour was obtained by Lord *et al.* (1963). In general, there is lack of information on possible effects of water deficit inducing treatments such as RDI on colour. Nevertheless, colour effects might be expected as an indirect effect through the control of vegetative growth. If vegetative growth was controlled the negative effects of shading on blush colour development would be avoided. Jackson *et al.* (1971, 1977a, 1977b) found that shading individual fruits and entire bearing trees, adversely affect red colour development, size and storage quality. Seeley *et al.* (1980) indicated that in red varieties such as Delicious, adequate levels of radiant flux density are needed, not only to enhance red colour development, but also to ensure flesh quality. Morgan *et al.* (1984) pointed out the apple cultivar 'Gala' attracts more returns if red blush development is maximized. He found that summer pruning increased the percentage of red blush and fruit fresh weight, but did not affect background colour.

Proebsting *et al.* (1984) comparing sprinkler and trickle at moderate levels of water deficit on quality of Red and Golden Delicious apples, found that skin colour, regardless of the variety, was usually higher with trickle than sprinkler. Red skin colour did not change during storage in any of the irrigation treatments. These results support a general hypothesis that water deficits that reduce vegetative growth might be expected to enhance colour.

1.4.5.4. *Firmness*

Quality fruit must be firm. In their experiments with apples and pears, Hendrickson and Veihmeyer (1942) obtained fruit that were softer from wet plots than moisture stressed plots. Nonetheless, provided the stress was not severe, the differences tended to even out during storage and subsequent ripening. Apples firmness has been reported not to be affected by irrigation (Lord *et al.* 1963). Guelfat'Reich *et al.* (1974) in their experiments with different irrigation regimes in apples also found no consistent differences in fruit firmness except in the driest treatment in which fruits were significantly firmer than the other treatments at harvest and subsequent shelf life and during storage. Similar findings were reported by Assaf *et al.* (1975). Only extreme wet and dry treatments showed differences in fruit firmness at harvest, being firmer in the dry treatment in which fruits were small. When fruits of equal size were compared treatments resulting in the biggest fruit size and yield, also resulted in the highest firmness.

Guelfat'Reich and Ben-Arie (1979) studying effects of frequency and amount of sprinkler and trickle irrigation on keeping quality of apples, obtained higher fruit firmness and keeping quality in fruits in which the amount of irrigation was reduced. Conclusions from these experiments were as follows: frequent irrigation and large amount of water reduced fruit firmness, which persisted during storage.

Degree of fruit firmness seemed more related to fruit size than to irrigation in reports by Amen and Mika (1983). While small fruit exhibited the highest firmness, no differences between irrigated and non irrigated fruits were detected. In another treatment, however, increasing planting density resulted in smaller sized fruit which showed decreased firmness at time of harvesting.

Proebsting *et al.* (1984) and Irving and Drost (1987) found no differences in fruit firmness in apples from RDI trees as compared with non-deficit irrigated trees. Assaf *et al.* (1984) applied six irrigation treatments which received the same amount of water but differed in the volume and surface area irrigated. No differences, between these treatments, were obtained in yield, growth, fruit size and crop load. Trees from two water stressed treatments, however, showed lower yield, smaller fruit size of higher firmness and T.S.S. than the former treatments.

Erf and Proctor (1989) in their experiments using trees under tent-like canopy covers and trees receiving natural rainfall obtained fewer fruit, lower total fruit weight, higher T.S.S. and firmer fruit from trees with covers.

1.4.5.5. ***Bruise Resistance.***

Bruising is an inevitable consequence of handling. Thus, in quality evaluation, it is important to consider the resistance of fruit to bruising. Diener *et al.* (1982) obtained no change in bruise susceptibility as the fruit matured, when specific bruise volume, which eliminates the effect of fruit weight and variations in fruit drop, was used to study this attribute.

Lack of change in bruise resistance with storage time led Holt and Schoorl (1984) to conclude that this parameter is not useful to evaluate the durability of the commodity or indicate textural changes. Contrasting results by Klein (1987) indicated that bruise susceptibility increased with the lateness of harvest and decreased with storage time. The former was related to the degree of ripeness. He explained his results in terms of changes in turgor, as sugar increases during ripening, turgor increases and so does bruise susceptibility. With storage time water is lost by the fruit decreasing turgor, and bruise susceptibility as well.

1.4.5.6. ***Keeping Quality and Incidence of Disorders***

Guelfat'Reich *et al.* (1974) reported an inferior keeping quality in storage of fruit subjected to wet regimes. The occurrence of physiological and pathological disorders such as bitter pit and scald was lower in fruits from the drier treatments and very high in the wet treatments.

Poorer keeping quality also has been associated with heavily irrigated trees (Guelfat'Reich and Ben-Arie, 1979). These authors proposed heavy irrigation caused leaching of nutrients from the root zone which caused a mineral imbalance of the fruit or alternately effects on cell turgor and susceptibility of cell walls to disruption. Proebsting *et al.* (1984), however, suggested that irrigation had no effect on storage and that changes in the fruits were the same independent of irrigation. Lötter *et al.* (1985) recommended an 85% TAW level during stages 2 and 3 of fruit growth despite the negative influence of a high soil water regime on incidence of watercore, superficial scald and bitter pit.

1.4.6. *Relative Sensitivity to Water Deficit.*

1.4.6.1. *Physiological Processes.*

Hsiao (1973) pointed out that physiological processes vary in their response to water stress. Some, such as cell enlargement are highly sensitive, others such as photosynthesis and respiration are moderately sensitive, while others like as irreversibly membrane damage are relatively insensitive to water stress. Therefore, the first change that can be expected as plant Ψ of the plant decreases, is a slowing down of shoot and leaf growth. A reduction in protein synthesis and stomatal closure would follow and as a consequence transpiration and CO_2 assimilation would be reduced. A series of associated processes would then be affected and plant growth and development would be suppressed.

Hsiao (1973) and Boyer (1976) proposed that water deficits decrease photosynthesis through effects on total conductance of CO_2 by stomata, a reduction in cellular water content, an increase in solute content, a change in enzymatic activity, or through indirect effects on photosynthetic and respiratory mechanisms. In the context of this study it can be postulated that mild to moderate water stress may alter many plant processes, some of which could enhance a variety of aspects of orchard management, before gross fruit production is seriously reduced.

1.4.6.2. *Assimilate Partitioning.*

Plant performance as a whole is the result of interactions between the assimilate producing regions (sources) and utilising regions (sinks). The coordinated activities between sinks determine the amount of photo assimilate available for growth and storage (Daie, 1988). The amount of assimilate produced reflects the integration and the magnitude of each activity in response to alterations in the environment. Depending upon the species, multiple sinks may be identified at any stage of development. Vegetative sinks include 'growth' sinks, such as meristems, roots, young leaves, stem and shoots, and 'storage' sinks as root tubers and other storage tissues. 'Reproductive' sinks are flowers, fruit and seeds (Daie, 1988).

Priestley (1976) explained that growth or dry matter accumulation of any sink is influenced by the extent to which sinks of similar or different tissue type compete for substrates from a common source. He proposed that growth regulators are capable of influencing this relationship both by direct control of sink growth rate and by regulating the vascular connections between sources and sinks.

Differences in water potential of the various plant parts also influence translocation flow, (Daie, 1988), with regions at lower water potential receiving disproportionately large amounts of assimilates (Lang and Thorpe, 1986).

1.4.6.2.1. *Sink Growth*

Despite lower photosynthetic rates under water-deficit conditions, reproductive sinks may not be dramatically affected (Asana *et al.* 1963; Barlow *et al.* 1982). Sink organs seem to be relatively insensitive to water deficit conditions and the mechanism that accounts for this has been studied by Westgate and Boyer (1985), who showed that maize kernel growth was supported by reserves of carbohydrates. Quatter *et al.* (1982), presented evidence that kernel growth rate of maize was not significantly altered if severe water stress did not occur during early to mid-phases of the grain-fill period. These findings are consistent with observations by Chalmers *et al.* (1984) who found fresh weight and dry weight growth rates of pear fruit were increased when plant water status was decreased.

1.4.6.2.2. *Sink Metabolism*

Once sucrose is loaded into the phloem elements, the destination of assimilates depends upon the mobilizing ability of various competitive sinks (Gifford and Evans, 1981; Daie, 1985). Daie (1988), proposes that the plant has two alternatives to maximize the sucrose gradients. First, the plant can increase sucrose concentrations in the phloem elements at the site of loading (source). Secondly, it may lower sucrose concentrations at the site of unloading (sink). The first alternative would mean an increase in the load for transportation in the phloem, but without strong sinks mobilizing sinks for storage or utilization, a feedback mechanism may be activated increasing the starch accumulation in the mesophyll cells. Thus, it seems that decreasing the effective sugar concentration in the sink region is a more appropriate alternative. Evidence supporting this alternative show that vegetative (Meyer and Boyer, 1981) and reproductive sinks (e.g. Mitchell *et al.* 1984; Chalmers *et al.* 1984; Mitchell *et al.* 1986 and others) continue growing under water deficit conditions. This means that sink organs maintain their ability to mobilize assimilate. If enhanced sucrose unloading rates are maintained, the feedback mechanism prevents the sucrose building up in leaves.

Daie (1988) concluded that consistent and recognizable alterations in growth, development and metabolism and consequently assimilate partitioning, occur when the plants are subjected to water deficit conditions. However, the knowledge of the cellular and molecular nature of responses and 'how' plants 'sense' the environment and a response is elicited, is still limited. Current evidence (Daie and Wyse, 1985; Patrick *et al.* 1986) suggest that turgor serves as the "signal" and changes in turgor will lead to alterations in assimilate partitioning.

1.4.6.2.3. *Regulation of Growth and Assimilate Partitioning in Fruit Trees.*

In a fruit tree, different sinks are related through competition, irrespective of the source (Priestley, 1976). The roots systems growth may fail if the tree crop supports a heavy fruit load (Smith, 1976) whereas removal of shoots increased fruit set (Quinlan and Preston, 1971). On the other hand, if fruit set on a spur is high, bourse shoots may fail to develop unless the fruits are thinned and within a spur, individual fruits compete so only a few reach maturity. Heavy fruit loads lead, in extreme cases, to reduced vegetative vigour (Barlow, 1963), poor root growth and failure to initiate fruit buds for the subsequent season.

In citrus trees, Kauffman (1977) showed that water stress reduced top growth, by which the tree reached a more favourable top:root ratio when undergoing water stress. In apple trees, Chapman (1973) demonstrated that water stress affected the amount of assimilate going to leaves, since dry matter production and leaf area were reduced by 90% in trees receiving irrigation fornightly compared with leaves of daily irrigated trees.

Hilgeman (1974) found that trunk growth sometimes was not reduced by low levels of irrigation and this coincided with years when fruit yields were reduced. This was interpreted in terms of a competition for photo assimilates between trunk and fruit, which resulted in annual variation in trunk growth inversely related to fruit yield. Goode and Hyrycz (1964) obtained similar results in apple trees. In years when the trees carried large number of fruits, trunk growth was depressed in all irrigation treatments. When the fruit loads were light, trunk growth was generally much greater than in trees receiving less water, but smaller than in well watered trees. Moreover, trunk growth was still much greater under light fruit load than in well watered trees carrying a heavy fruit load.

Maggs (1960), however, considered that the proportion of annual vegetative growth increment converted into shoot growth is maintained within narrow limits. He assumed that growth adjustments occur mainly between leaves and roots. In *Vitis vinifera*, water deficits inhibited shoot, leaves and tendril growth, but no differences between organs in sensitivity to water deficit, or in partitioning of growth, was detected (Schultz and Matthews, 1988).

1.4.6.2.3.1. ***Role of Root Growth in Control of Vegetative Growth and Assimilate Partitioning.***

Vyvyan and Rogers (1934) proposed that over a period, root and shoot increments are in balance. Thus, a decrease in root growth will consequently be balanced by reduced shoot growth. Later, Vyvyan (1957) showed that there was a constant ratio between the annual increments of stems and roots.

More precisely, a linear relationship is invariably obtained between the log of shoot weight (W_s) and the log of root weight (W_r) (Chalmers, 1989) which according to Wareing (1950) means there is a constant ratio between the relative growth rate of shoot and root. The latter author proposed this indicated a strong physiological link existed between the relative growth of roots and shoots. Support for this point of view has been provided by numerous experiments in which part of the shoot or root has been removed.

For example, studies with pine and birch seedlings (Wareing, 1950) revealed that removal of foliage induced a compensatory growth in shoot to reestablish the shoot:root ratio. The existence of a homeostatic mechanism operating to restore the balance between shoot and root, which is characteristic of a given set of environmental conditions was found to be an allometric relationship of the following form:

$$\log W_s = \log b + K \log W_r \qquad (1.19)$$

This relationship holds for many plants (Chalmers and Van Den Ende, 1975; Richards, 1981; Geisler and Ferree, 1984; Throughton, 1976) and led to Chalmers (1989) to postulate that for a particular environment the relative growth rate (RGR) of the root system limits the potential for vegetative growth. In the allometric equation, the slope K expresses the relationship between the RGR of shoot and roots as follows,

If $K < 1$ ratio top:root decreases as the plant grows
If $K > 1$ ratio top:root increases as the plant grows

In peach trees the top:root ratio increased in absolute value, from 1 to 4 as the tree matured (Chalmers and Van Den Ende 1977). During the same period, the proportion of dry weight (d.wt) allocated to vegetative growth of the top declined from 70% in a young tree to 30% in a mature tree. The proportion of annual d.wt increment allocated to root growth declined from 10% to 1%, while the allocated to shoot declined from 40% to 10%. Consequently, the top:root ratio increased. The decline in the proportion of the d.wt increment allocated to vegetative growth could be due to either, a decrease in sink potential of the vegetative tree, or an increase in sink potential of the fruit (Chalmers, 1989). Sink potential of the fruit, appears to be endogenously controlled and independent of the tree size or age (Jerie and Chalmers, 1976). It follows, therefore, that decrease in proportion of d.wt allocated to vegetative growth was due to a decrease in the competitive sink potential of vegetative growth rather than to an increase in sink potential of the fruit. Considering, that shoot growth and root growth appeared to be linked by a homeostatic mechanism, Chalmers and Van Den Ende (1975) proposed that root growth which had declined to the greater degree had become the rate limiting process.

Chalmers (1989) has reviewed the state of hypothesis and evidence on the role of root growth in assimilate partitioning and its relation to overall productivity. By interpreting data of Brouwer (1963) and Drew and Ledig (1980) who found that a compensatory growth of top was followed by growth of roots or vice versa; Chalmers proposed that growth of roots or shoots are sequentially related in time. Richards (1986) proposed these mechanisms are closely coordinated and largely mediated by root-produced cytokinins.

Since vegetative growth is linked to root growth, and the growth of non vegetative organs such as fruit and seeds is endogenously controlled (Chalmers *et al.* 1985), it is likely that management systems tending to control root growth will modify the assimilate partitioning in favour of vegetative growth, (Maggs, 1963; Chalmers *et al.* 1975; Avery, 1975; Avery *et al.* 1979; Geisler and Ferree, 1984).

1.4.6.2.3.2. ***Role of Fruit in Assimilate Partitioning.***

Chandler (1934) was among the first to record that fruiting apple trees yielded more dry matter per unit surface area than those without fruit. Maggs (1963) pointed out the annual growth of an apple tree, in the vegetative condition, is distributed in a definite pattern between leaves, stems and roots, which is modified by the presence of a crop. As a result of his experiments, which compared effects of deblossoming and defruiting on growth, he concluded that cropping depressed growth activities of the plant and the removal of crop brought a rapid recovery. The growth pattern of the tree was changed with the crop. Cropping trees produced 50% more leaf as a proportion of the vegetative increment, 50% less root, and 50% less total dry matter (vegetative growth plus crop) per unit leaf area than deblossomed trees.

Several experiments (Maggs, 1963; Head, 1967, 1968, 1969) have demonstrated that trees allowed to bear a crop showed a reduction in the amount of new roots while an opposite effect occurred in deblossomed trees. It seemed that fruiting also reduces the proportion of total growth increment going to roots. This reduction was evident even in light crops and suggested that root growth was even more sensitive to competition than shoot growth.

Chalmers and Wilson (1978) reported that during periods in which d.wt accumulation by the fruit was occurring, growth of limbs was depressed, this also indicates an effect of competition from developing fruit for assimilate demand.

Avery *et al.* (1979) proposed sink demand is lower in the absence of fruit and a lower photosynthetic supply is needed. The reverse situation occurs in the presence of fruit. When not bearing fruit, extra growth of shoots and other meristems provides alternative sinks, which compete for root factors and assimilates but possibly not to the same extent as the fruit.

1.4.7. *Use of Water Deficit to Manipulate Plant Growth.*

Recent intensive systems of fruit tree culture require small trees that will crop heavily in the early years and make only limited amounts of vegetative growth (Luckwill, 1970). A great deal of research has been conducted in the search for methods to control growth and stimulate cropping in such relatively young trees. In this and other application management systems aim to manipulate plant growth to obtain less vegetative growth and higher yield. The most recent techniques developed include the use of water deficits to manage plant growth.

1.4.7.1. *Manipulation of Root Growth.*

Chalmers (1987a) has proposed that there are at least three mechanisms which can be used to manipulate growth using water deficit. First, root growth can be suppressed by controlling the wetted root volume.

In a series of experiments (Chalmers *et al.* 1981) tree density, summer pruning and RDI were compared as methods to control tree vigour and productivity in peach orchards. The authors found: 1) the roots of peach trees planted at high densities did not grow into the root zone of adjacent trees. 2) the tree vigour was strongly related to the within row spacing (Van Den Ende and Chalmers, 1983) and 3) the less vigorous vegetative growth was obtained when trickle irrigation restricted root size (Mitchell and Chalmers, 1981). Although all methods inhibited tree growth, the most effective was high tree density combined with RDI. In addition, high tree density combined with RDI markedly stimulated fruit set, growth and yield, while RDI during DWI and DWII stages of fruit growth reduced tree size significantly. From these and earlier results (Chalmers and Van Den Ende, 1975) the authors proposed that root growth or size may be the variable controlling vegetative vigour and fruitfulness. That is, RDI has a direct effect on root growth and this has a concomitant effect on the growth of the top.

By controlling the wetting pattern of soil through the use of drip irrigation it is possible to alter the root volume of peach trees (Chalmers, 1983). In a reduced volume, the root system is more dense and concentrated than under conventional irrigation (Mitchell and Chalmers, 1983). If roots do not grow in dry areas of soil or become physiologically inactive, then RDI could be an effective method to control root growth (Chalmers *et al.* 1983).

The effectiveness of other approaches to control vegetative growth by limiting root growth, such as root barriers provide support for the above hypothesis.

For instance, Richards (1986) proved the effects of root restriction technique on newly planted peach trees. By the use of hilling and root barriers, the root was restricted to volume of 0.5, 1.0 , 2.0 and 3.0 m^3. Vegetative vigour and tree size decreased with decreasing root volume. A dramatic increase in flowering was obtained in the two smallest root volumes. The final fruit yield, however, was slightly lower for the smaller root volumes which was due to reduction in fruit size rather than in fruit number. For the larger root volumes, fruit size was reduced to the same level as in the small volume. It was obvious that in larger root volume there was not restriction for top growth, this competed with the fruit, causing a reduced fruit size with the years. The author concluded root restriction is an effective technique to reduce tree size, but fruit production may be limited due to the negative effect on fruit size. Consequently, root restriction can not be considered as a technique to reduce tree vigour. Its effects contrast with the positive effects of RDI on fruit size and yield. Proebsting *et al.* (1989) evaluated the effect of restricted root volume in young peach trees and found reduced leaf conductance, water use, and shoot growth which was similar to the effect of deficit irrigation applied throughout the season deficit. Finally, in nature, restricted root growth may occur if soil has layers of high mechanical impedance (Willat and Olson, 1982). In such cases, root growth will be confined to the top layers and affect the normal configuration of the root system. In peach trees, Cockroft and Wallbrink (1966) also found root restriction due soil conditions. Such root conditions restrict tree size and tend to make trees more fruitful and precocious (Chalmers, 1990 personal communication).

1.4.7.2. *Differential Sensitivity of Competing Physiological Processes to Water Deficits.*

The second way in which RDI can be used to manipulate growth is by manipulating plant Ψ and thereby selecting between physiological processes with different sensitivities to water deficit.

Considering that cell enlargement is highly sensitive to low plant Ψ whereas other processes are less sensitive (Hsiao, 1973), Chalmers (1987) proposed that periods of vegeative growth activity be identified and manipulated by using a period of low Ψ_L.

Although expansion fruit cells should be equally sensitive to low Ψ, Chalmers (1989) proposed that fruit cells are stronger solute sinks and therefore would attract water strongly. Since the approach of RDI is to lower Ψ and suppress shoot growth early during the growing season, this also serves to eliminate the competitive effect of the shoot growth on the fruit growth.

In a study with pear trees, Chalmers (1986) found that a plant water deficit that decreased Ψ_L during mid November (when shoot extension was the predominant growth activity) inhibited shoot elongation. Nevertheless, although Ψ_L was reduced, compared to the control during this period, fruit fresh and dry weight was stimulated, thereby establishing unequivocally that fruit growth at that time was considerably less sensitive to decrease Ψ of the plant. During the subsequent period of full irrigation while Ψ_L of the RDI treated trees was higher than in the control. The mechanism by which Ψ_L was increased remains uncertain but this effect, probably combined with reduced competition from vegetative growth, probably accounts for the subsequent stimulation of fruit growth and yield (Chalmers *et al.* 1986)

Finally, the RDI strategy (Chalmers and Van Den Ende, 1975), exploits seasonal changes in the sensitivity of fruit and vegetative growth to water stress which are a function of the phenological separation of the most active periods of these processes. It is a very important point, overlooked by others who have studied RDI (Lötter *et al.* 1985) that when active, fruit growth is also severely inhibited by reduced Ψ of the plant. The plant should be subjected to RDI only during stages of slow fruit growth and rapid vegetative growth. If this is done, vegetative vigour is reduced, and the return of the plant to full irrigation in the periods of rapid fruit growth stimulates fruit growth.

1.5. ***This Study.***

Regulated Deficit Irrigation, in arid and semiarid regions, has been sufficiently proven as a management strategy that reduces vegetative growth. Thus, expectations and questions arise regarding the possibility of using this technique for a wider range of fruits and environments. In a humid environment such as New Zealand, where high rainfall during winter and early spring saturates the water holding capacity of the soil and spring rain reduces net ET, the potential for RDI will be reduced. To be successful RDI requires the plant be exposed to a water deficit in the initial period of rapid vegetative growth, when the water demand is low. In this study, therefore, I sought to investigate whether alternative soil management techniques might be suitable to control excess of soil water in the root zone, making the use of RDI feasible in this environment. In addition, it was necessary to further evaluate effects on fruit growth, yield and quality since this area still requires clarification. The alternatives studied were a sward of lucerne chosen for its ability to extract water from deep areas of the soil and for its high transpiration. This was considered to be an economic way of drying out the soil of the root zone, in early spring at a fast rate. The other alternative evaluated was a rainfall shelter of black polyethylene covering the soil surface directly to prevent water infiltration during winter and early spring.

CHAPTER 2

GENERAL MATERIALS AND METHODS

2.1. Introduction.

Taking into consideration the ample positive effects of the RDI technique on deciduous fruit trees, as shown in the literature review, and the humid climate of Palmerston North,New Zealand; it was concluded that the application of RDI strategy was mainly subjected to find techniques that allow us to have a soil water deficit in the rootzone of the trees in spring. Hence, the use of soil management techniques orientated to control the soil water budget was an important aspect to be investigated. One possibility was the use of a black plastic mulch as a rain shelter in order to prevent the water accumulation in the soil during the winter and early spring. On the other hand, a plant as lucerne, with known characteristics of high rate of transpiration and deep tap root, offered the possibility of its use as under tree cover which might at a fast rate, to deplete the water available for the crop. In this study two soil management techniques, in contrast with a conventional bare soil, were evaluated as alternatives to facilitate the application of RDI.

2.2. Plant Material.

In the glasshouse and in the orchard experiment a winter active mutant of lucerne (*Medicago sativa sensu lato*) AS13R was used.

The experimental plant used in field study was apple cv Royal Gala (*Malus domestica Borkh*) which is a New Zealand bred hybrid of Kidd's Orange and

Golden Delicious. Trees budded on the semi dwarf roostock MM106 were planted in 1985 as feathered maidens, FKV (free of known virus) material.

2.3. Environment.

2.3.1. Climate.

The climate in the area of this study, based on data from 1954 to 1984 at Station E05363, Grasslands Division, DSIR, Palmerston North present a pattern with the following characteristics:

a) Rainfall with a total of 968 mm, of which approximately 50% fall during main growing period, October to March. The number of rainy days per month and the monthly average are about the same throughout the year, although December and February record the highest and lowest average respectively. The lowest number of rainy days which is 9, occurs in February;

b) Annual pan evaporation is 945 mm from which 706.3 are evaporated during growing season. Figure 2.1 shows the typical monthly water balance in Palmerston North. Water excess occurs from April to September, and a soil water deficit usually is presented from October to March.

c) Daily mean temperature of 11.6 °C. Mean maximum and mean minimum air temperatures, 17.4 and 8.9 °C registered in the months of February and July respectively.

2.3.2. Soil.

The soil of the experimental area is a Manawatu fine sandy loam in the NZ genetic system (a Dystric Fluventic Eurochrept sandy mixed mesic in the US

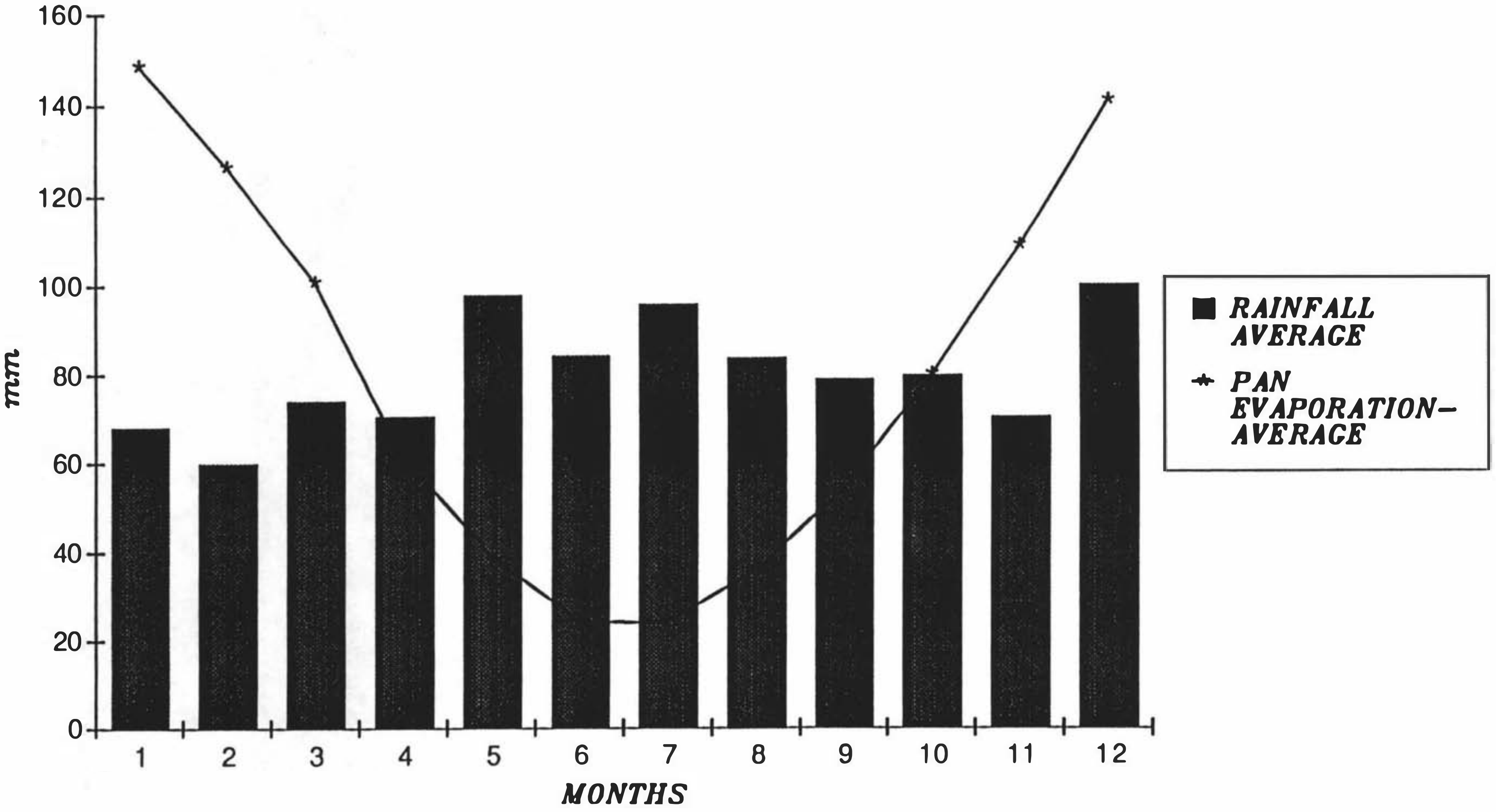

Figure 2.1. Monthly water balance for Palmerston North, New Zealand.

Soil Taxonomy) as described by Clothier *et al.* (1973). The soil profile is subdivided into three layers 0-50 cm fine sandy loam, 40 cm of fine sand with gravely coarse sand beyond 90 cm.

Retentivity curves obtained with the Hayne's apparatus and pressure plate are presented in Figure 2.2 (a) for three textural elements of the soil profile.

Field estimates of TASM in the top 600 mm was 126.1 mm . Laboratory estimates of RASM of 95 mm has been reported by McAuliffe (1985) and a retention efficiency of about 35% after 12 hours.

2.4. Field Trials.

Field experiments were conducted at Massey University, Fruit Crops Unit orchard, Palmerston North, New Zealand. The experiment was initiated during 1987 and conducted for two complete seasons.

Trees were planted in 1985 at spacing 2 x 4 m and trained to a "central leader" or free standing system. Dormant pruning was carried out to control tree shape. Thinning of fruit was carried out following commercial standards.

2.4.1. Experimental Layout.

The experiment was laid out in a split-plot design. Two rows with 34 trees in each one were the main plots. Each experimental main plot was split into two subplots at which level irrigation strategies were applied. Every subplot contained three soil management plots, each one containing five trees. The two end trees on every soil management plot were left as guard trees. The soil management treatments were randomized.

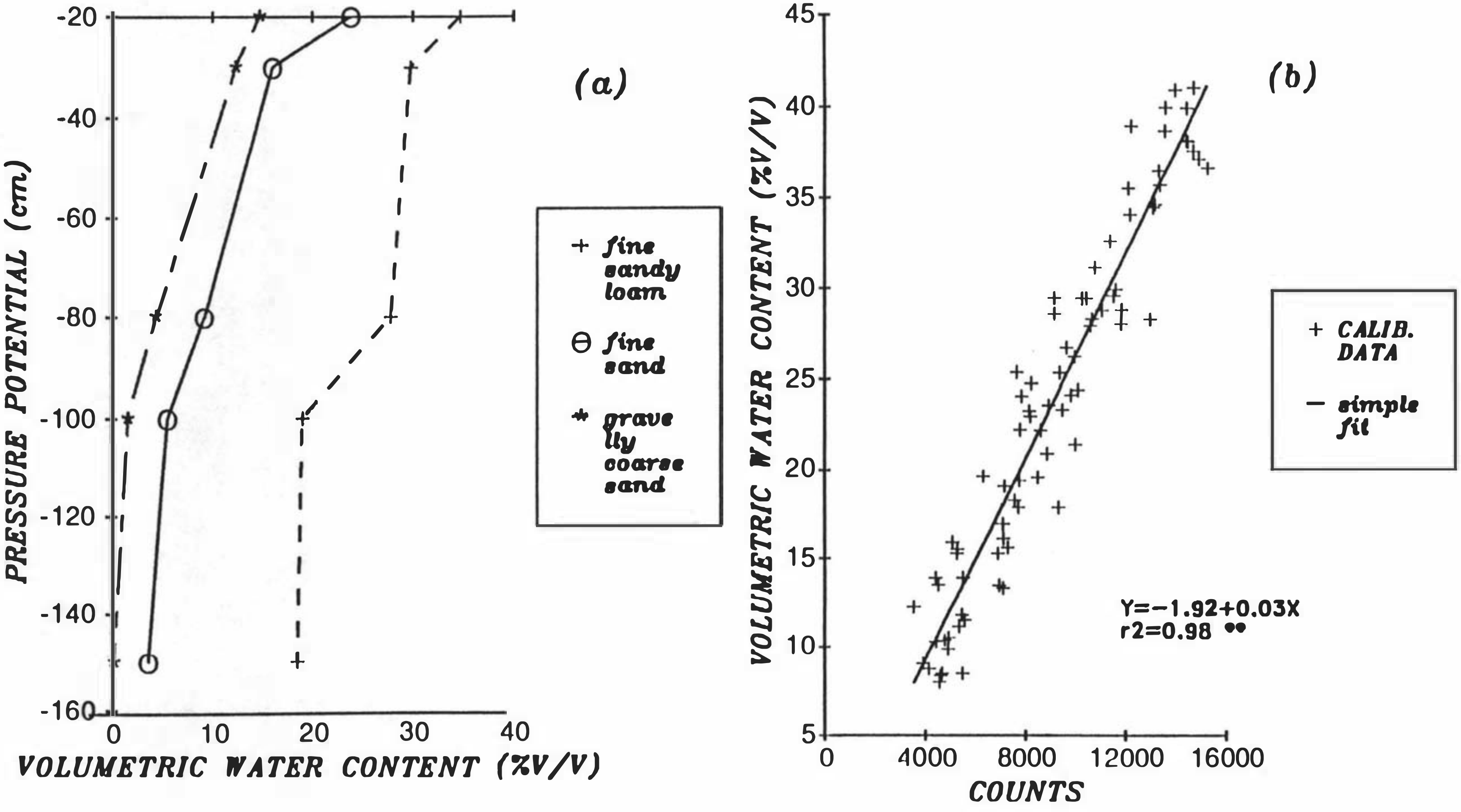

Figure 2.2. (a) Retentivity curve for the three textural elements of the Manawatu fine sandy loam and (b) field calibration of neutron probe at Massey orchard.

2.4.1.1. Soil Management Treatments.

Soil management treatments were as follows:

a) a permanent sward of lucerne was planted as an under tree cover,

b) a rain shelter of black heavy grade polyethylene film directly covering the soil surface,

c) herbicide strip was used as control treatment.

Treatments were established in April 1987. Lucerne was also planted in the alleyways between rows.A slight tree-line bank and centre-row drain was created to prevent water ponding on the plastic surface.

To lay the polyethylene film, a trench 50 cm depth was cut at 1 m distance from the trees in both sides of each row. Two plastic film sheets 2 m wide were extended along the row, from the tree line towards the trench and buried laterally to cover the wall of trench. Soil was then packed around the plastic and the trench was refilled with soil. Along the tree line the plastic bands were overlapped and glued. Plots receiving the other treatments were trenched at 1m from the trees at the same depth as the plastic treatments.

2.4.1.2.Irrigation Strategies.

Plants were trickle irrigated using four 8 liter/h Turbo-Key drip emmitters per tree placed at 50 cm from the tree and connected to the main line through pipes 50 cm long.

Irrigation strategies consisted of:

a) a withholding period until 20 Nov and 8 Dec in years 1987 and 1988, respectively, when soil water was partly depleted and full irrigated in other times, this treatment was called Full Irrigation;

b) a withholding period followed by regulated deficit irrigation during slow stage of fruit growth, until 17 Jan and 13 Jan in years 1988 and 1989 respectively and full irrigation the rest of the time, this treatment was called Regulated Deficit Irrigation (RDI).

The witholding period common to all treatments was called Phase I. The period in which either is given RDI or full irrigation was called Phase II. The subsequent period in which full irrigation is replaced to RDI treatments and continued in the rest of treatments until harvest, is called Phase III.

Except plastic treatment, all the treatments were exposed to the incidence of natural rainfall. However, during Phase III, the plastic was rolled up to allow rainfall in these treatments as well thus all treatments received the same water input in this phase.

2.5. Data Collection.

2.5.1. Collection of Soil Moisture Data.

Access tubes 1.10 m long were driven into the soil at distances of 350, 450 and 750 mm from the two middle trees in every plot forming a grid radiating away from the trees in a line in the tree row and normal to the tree row (Figure 2.3). A total of 12 access tubes were used in every plot for determination of soil moisture by the neutron scattering method.

Soil moisture was collected using a neutron depth moisture gauge obtained from Campbell Pacific Nuclear Corporation (model 503DR, Martinez, California, US).

2.5.1.1. Field Calibration.

Field calibration of the neutron probe was carried out as the access tubes were installed. Samples were taken at 100 mm intervals, from 300-1000 mm depth in

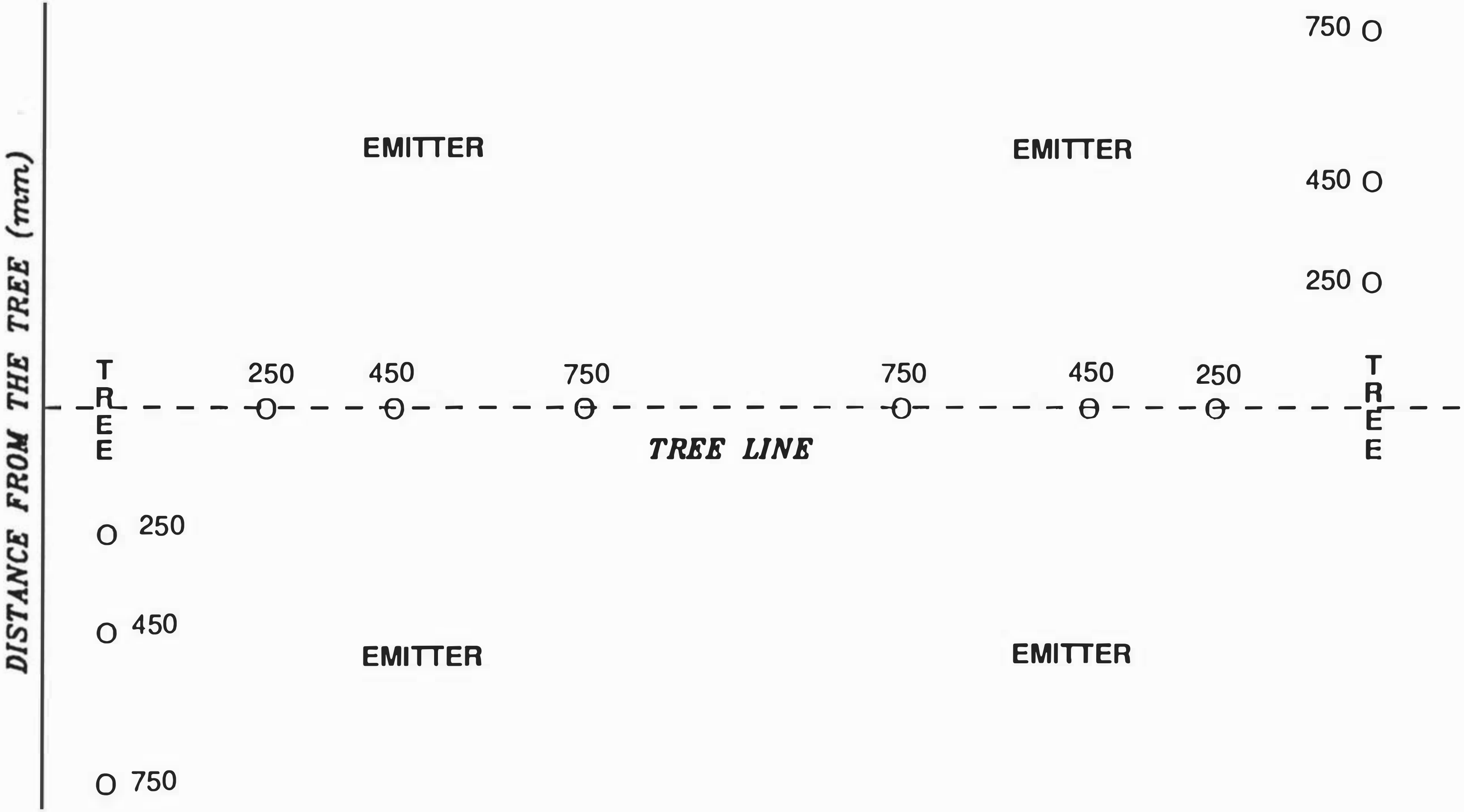

Figure 2.3. Layout of drip emmitters and access tubes for neutron probe measurements.

ten holes randomly chosen among the total soil sites where access tubes were placed. Core samples were oven dried at 105 °C for 2-3 days until constant weight was achieved. The core samples were used to determine bulk density and gravimetric water content. Volumetric water content was calculated by multiplying the bulk density by the gravimetric water content. A linear regression was fitted between the volumetric water content and the absolute count. Calibration equation is presented in Figure 2.2. (b).

Standard count readings were taken weekly by placing the instrument on top of the case. The square root of the average of the last standard count and the square root of the difference between the current standard count and the previous one were calculated. If the product of these square roots was much lower than the difference between the two counts, the gauge was considered to be working properly. During the time of this study, all the measurements of standard count were clustered around the same value indicating that the performance of the instrument was stable and correct which allowed to use the calibration equation without modifications.

2.5.1.2.Field Data.

The calibration equation was incorporated to the calibration menu of the instrument which permitted the soil moisture to be read directly in terms of volumetric water content. Volumetric water content was monitored at 100 mm intervals throughout 300-1000 mm depth using a counting interval of 16 seconds. The measurement taken at 300 mm depth was assumed to represent the water content from 0-300 mm which may affect the precision of the soil water content reported here.

2.5.2. Collection of Plant Data.

2.5.2.1. Trunk Circumference.

The circumference of all trees was measured each winter with a metric tape at a marked point 20 cm above ground. Data was used to calculate cross sectional area.

2.5.2.2. Shoot Length.

The length of tagged shoots was measured with scale ruler twice a week in the three middle trees of every plot from the 6th week after full bloom until growth ceased. The number of tagged shoots was different in every season.

2.5.2.3. Fruit Data.

Fruits of uniform size were tagged on the three middle trees of every plot. Fruit diameter was measured twice a week, starting on 6th week after full bloom and continuing until harvest. The number of tagged fruits was different in every season. Measurement was made with a caliper and all measurements were converted to fruit volume by assuming the fruit was spherical. All graphs and data presented were derived from the fruit volume calculations.

At maturity, all fruits were harvested in three separate pickings, graded by size and counted to determine yield. Twenty fruits with average weight of 140 g were selected from every tree to assess parameters of fruit quality. Five were evaluated at harvest time. The remaining fifteen were kept in cool storage at about -2 °C for a period of ten weeks after which same parameters of quality were evaluated.

At harvest and after storage five fruits were weighed. A sample of three fruits was used to assess flesh firmness and total soluble solids and the other two were used to measure background colour and bruise resistance respectively. Fruit firmness was determined, after removing a slice of skin from two equatorial opposite sides of the fruit, with a fruit pressure tester Efegi Model 327 and 8mm plunger. Juice expressed from two opposite sides of the same fruit were used to measure total soluble solids using a portable refractometer calibrated 6.2% sucrose solution.

Bruise resistance was evaluated by dropping a crystal ball of 17.8 g through a crystal glass tube 75 cm long onto one point in the equatorial area of the fruit which gives a constant impact energy (E) of 0.15 J. After impact the apples were allowed to stand for 24 hrs to let the bruise to develop. The bruise diameter was measured in two perpendicular directions with a caliper. The average diameter of the bruise was called d. Bruise susceptibility was evaluated in terms of the diameter of the bruise according Banks et al. (1990).

2.4.2.4. Plant Water Status Data.

Leaf water potential was measured in a pressure chamber (Scholander *et al.* 1964). Two mature shade leaves from the terminal node of twigs of two middle trees in every plot were enclosed in small plastic bags lined with moist towel paper prior to excision to avoid water loss. Precautions were taken to minimize the time between leaf excision and making a pressure chamber measurement. The time at which measurements were made varied in each season.

Leaf conductance and photosynthesis were determined using a Lycor Li-6200 Portable Photosynthesis System. This instrument comprises a CO2 analyzer coupled to a leaf temperature thermocouple, a humidity sensor and a quantum sensor, which allowed several parameters to be evaluated in the same leaf namely: stomatal resistance and conductance, the temperature of air and leaf, relative humidity and net photosynthesis. Measurements were taken using four sun leaves in each one of the two middle trees in every sample plot.

2.4.2.5. Data Analysis.

Data was analysed using a Prime and Network computer system at Massey University. Software used were SAS, Minitab, Microsoft Chart 3 and XyWrite III. For data obtained in orchard the statistical analysis was done using a multivariate analysis of variance. Due to the limitations imposed by two main blocks the experimental design was restricted to two degrees of freedom for the main effects (irrigation) and four degrees of freedom for interactions (irrigation x soil management). A high number of observations were therefore obtained to ensure the confidence level of the measurements was high before making the comparison.

CHAPTER 3

GLASSHOUSE EXPERIMENT: INTERACTION BETWEEN IRRIGATION METHOD AND LUCERNE ON SOIL WATER REGIME

3.1. *Introduction.*

Traditionally, lucerne has been used as a forage crop. Its behaviour under irrigation has confirmed its ability to extract water from deeper layers of the soil (Hayman and McBride, 1984) and offers little resistance to ET when well watered. There is limited information, however, about the use of lucerne as a sward under the tree cover in orchards (Bergamini, 1976).

As one of the major aims in this work, it was proposed to use lucerne as a water competitor of the main crop. Whether this is an effective approach to irrigation management, or whether lucerne affects the pattern of water uptake of the system is not well understood. This experiment was designed to evaluate the behaviour of lucerne while not in competition with the crop, growing on a 'synthetic' soil, layered to create an analogous of Manawatu fine sandy loam which exists in the Massey orchard. Irrigation was provided by sprinkler or point emitters alternately.

Specifically this study aimed to:
a) compare the soil water distribution pattern after irrigation for the trickle and sprinkler;
b) determine the lucerne water uptake pattern under a wide range of soil moisture;

c) develop a soil moisture balance.

3.2. *Materials and Methods.*

3.2.1. *The Soil Profile.*

A 'synthetic' soil profile was constructed with a combination of layers of uniform soil. For this purpose a stainless steel cylindrical tank 1.20 m height, 1.36 m diameter was used. The tank had an opening at the bottom in which was placed a plastic screen to allow free drainage. Five access tube 1.10 m long were fixed in the tank, four of them at 0.40 m from the edge and one in the centre.

Soil was layered from bottom to top using 200 mm gravelly coarse sand, 530 mm fine sand and 350 mm of silty loam. The soil was air dried and added in layers of 100 mm. The soil was packed and then samples were taken for bulk density. Care was taken to pack the soil to a bulk density of about 1.4 Mg/m^3. Final bulk density was 1.4 Mg/m^3.

Once the soil profile was established, lucerne seeds were sown. Hand watering was given periodically during crop establishment. Irrigation treatments were initiated when an homogeneous crop cover was developed which occurred approximately one month after planting.

3.2.2. *Irrigation.*

3.2.2.1. *Sprinkler Irrigation.*

A slightly modified sprinkler was placed in the centre of the tank. This sprinkler converted the spray into water droplets and adjusted the application radius to approximately the internal area of the container. Uniformity of water distribution was evaluated using cans randomly distributed over the surface.

the input of water to the soil. Twenty four hrs after irrigation, water content was assessed with the neutron probe. Measurements were carried out at 100 mm intervals from 250 to 950 mm depth. The neutron probe assessment was conducted at one day intervals until lucerne showed visible wilting symptoms.

Variable amount of water was applied in 9 different wetting and drying cycles. The volume of water outflow was recorded to allow water balance to be calculated. At the end of each cycle lucerne was clipped to determine dry matter yield.

3.2.2.2. *Trickle Irrigation.*

The single sprinkler was replaced with eight drip emitters of 8 l/hr capacity. The emitters were placed equidistant along a loop of irrigation pipe placed on the surface of the tank. Water was applied in small amounts at two day intervals in order to study the soil wetting pattern and prevent drainage. After drainage was initiated the amount of water output was monitored to estimate soil water balance.

3.3..*Results.*

3.3.1. *Soil Water Content.*

3.3.1.1. *Sprinkler Irrigation.*

Drainage and ET of the lucerne crop resulted in profiles of water content as reported in Figure 3.1., showing a higher water retention in the top 250 mm of soil. This corresponded to the layer of finer textured soil. Mean values of 21.5 % water content were obtained in the top 250 mm 24 hrs after drainage ceased, which indicated the maximum amount of water this soil layer can hold.

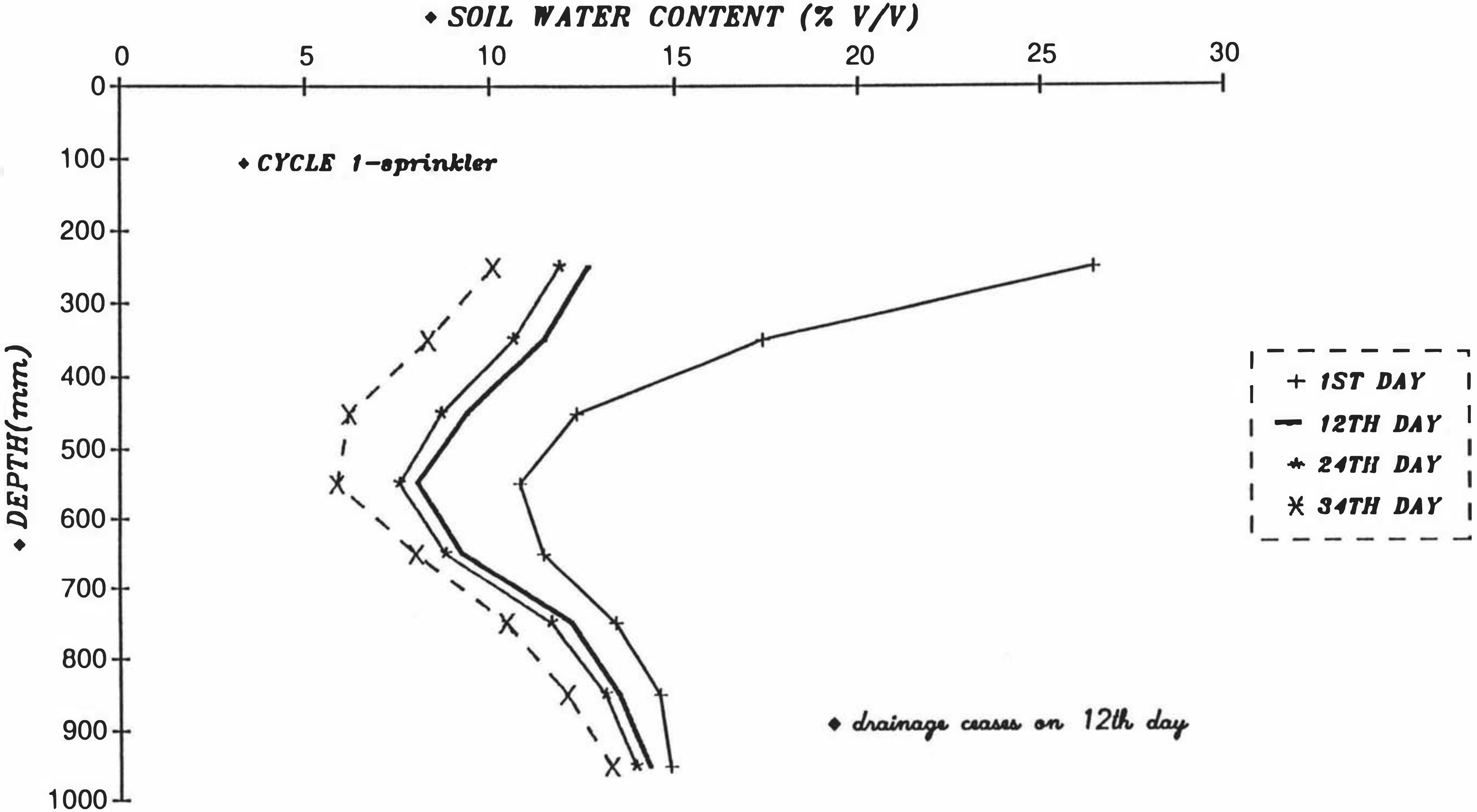

Figure 3.1. Profiles of water content of a "synthetic" soil analogue of Manawatu fine sandy loam under sprinkler irrigation.

A maximum value of water content of 26.4 % was recorded in this layer 24 hrs after application of 18.5 mm of water and a minimum value of 9.1% was obtained on 16th day after drainage ceased. When the maximum value was measured in the top soil, water outflow occurred in the bottom of container, suggesting this value exceeded the saturation point of the top layer.

Considering the mean value obtained after drainage stopped as the soil water reserve and subtracting the minimum value measured on day 16, it could be calculated that in this period 37% of the soil water reserve in the top layer was used.

The variability in θ of layers from 850-950 mm depth ranged from 16.9 % to 11.1 % with a mean of 15% +/- 1 % 24 hrs after drainage stopped (Figure 3.1). This range of values extended below the water content at which drainage ceased suggesting the presence of active lucerne roots in this depth of soil. From Figure 3.1 it can be observed that water extraction proceeded uniformly along the soil profile.

3.3.1.2. *Trickle Irrigation.*

A significantly mean water content of 13.99% in the top 250 mm was measured 24 hrs after drainage stopped. This figure coincided with the value obtained in sprinkler irrigation, which showed this is the maximum value of water content the soil can hold in this layer. During the first 7 days there were a non significant decrease in water content in the top 650 mm of soil but a significant decrease in the bottom layers. This indicates lucerne crop was extracting water from this area of soil. During the 16 day period occurred a significant decrease in θ along the soil profile, which continued until the plant showed visible wilting signs. The major decrease during this period, took place in the upper layers, whereas towards bottom layers a significant decrease continued to day 27 then it was apparent the plant had exhausted the available moisture.

Table 3.1. Water content (θ) profile during a drying cycle after irrigation with point emitters.

Depth(mm)	Day 1^{z}	Day 7	Day 16	Day 27	SE
0-250	13.99 a^{y}	13.07 ab^{x}	11.55 bc	10.40 c	0.78
250-350	8.92 a	8.39 ab	7.61 bc	6.66 c	0.39
350-450	8.31 a	7.71 ab	7.18 bc	6.42 c	0.30
450-550	9.16 a	8.56 ab	8.07 bc	7.20 c	0.33
550-650	11.16 a	10.39 ab	9.83 b	8.47 c	0.39
650-750	13.93 a	12.68 b	11.98 bc	10.31 c	0.43
750-850	16.29 a	14.78 b	13.96 b	12.48 c	0.34
850-950	17.16 a	15.98 b	15.41 b	14.00 c	0.25

^{z} Days after irrigation.

^{y} Mean separation between days by LSD, 5% level.

^{x} Means with same letter are not significantly different.

These results suggest the plant with its deep root was able to extract water along the soil profile. It allowed lucerne to resist a relatively long period without irrigation. These results agreed with those reported by Hayman and McBride (1984) who found lucerne recovered irrigation water at soil depths beyond possible use for grass.

3.3.1.3. *Comparison Between Irrigation Systems in Relation to Drainage.*

In cycles in which water was applied in sufficient amount to initiate some drainage (Table 3.2), the measurement of water content in the top 450 mm of soil was significantly higher in sprinkler than in trickle irrigation.

Table 3.2 . Water content (θ) profile at time drainage initiated and ceased as measured with the neutron probe.

Depth	Drainage initiates		Drainage ceases	
(mm)	Sprinkler	Trickle	Sprinkler	Trickle
0-250	19.62 a^{z}	15.16 b^{y}	16.37 b	13.99 b
250-350	11.33 a	9.68 b	9.78 b	8.92 b
350–450	8.59 a	8.85 a	7.50 b	8.22 b
450-550	9.38 a	10.08 b	7.95 c	9.16 c
550–650	11.66 a	12.04 a	10.18 b	11.16 b
650-750	14.36 a	14.99 b	12.56 c	13.93 c
750-850	15.06 a	17.36 b	13.90 c	16.30 b
850-950	15.49 a	18.32 b	14.66 c	17.16 d

^{z} Mean separation between treatments by LSD, 5% level.
^{y} Means with same letter are not significantly different.

Nevertheless, an inverse situation was obtained from 450 mm depth down in the profile. It is apparent from these results that the irrigation method affected the water distribution pattern giving a wetter top soil under sprinkler. Similar results were obtained when the maximum soil water retention was compared at the time drainage ceased. The water distribution in the profile presented the same pattern described at the time drainage started but the maximum water retention was the same. However, when the total storage of the soil profile of both times was compared, no significant differences were obtained between irrigation methods. This suggests the amount of water the soil can hold at saturation is a soil characteristic which is independent of the water application system.

3.3.2. *Soil Water Storage* (W).

The evolution of W is presented for layers from 0-350,350-550, 550-750 and 750-950 mm depth. To determine W at a given depth of soil, the measurement of water content (θ) from neutron probe was multiplied by the change in depth (z), thus

$W=\Sigma\theta\Delta z$ and total storage (W_t),

$$W_t = \Sigma\theta\Delta z = \int_0^{350} \theta\delta z + \int_{350}^{550} \theta\delta z + \int_{550}^{750} \theta\delta z + \int_{750}^{950} \theta\delta z$$

and the change in water storage over time is given for the difference in the soil water storage between the periods of time considered,

$$\Sigma W_{(t1-t2)} = \Sigma\theta\delta z_{t1} - \Sigma\theta\delta z_{t2}$$

The following analysis considers only the change in water storage during the period in which no irrigation was added nor drainage occurred. Thus the changes in soil water storage may be mainly attributed to the evapotranspiration of lucerne. The analysis is based on the total of nine wetting and extraction cycles with sprinkler versus four similar cycles using trickle irrigation.

3.3.2.1. *Sprinkler Irrigation.*

From Figures 3.2 and 3.3 it can be noted that on these occasions the application of 12.49 and 7.58 mm of water respectively resulted in an excessive amount of water at the top 350 mm during the first 11 days of cycle 1 and 2. This was not reflected in lower layers.

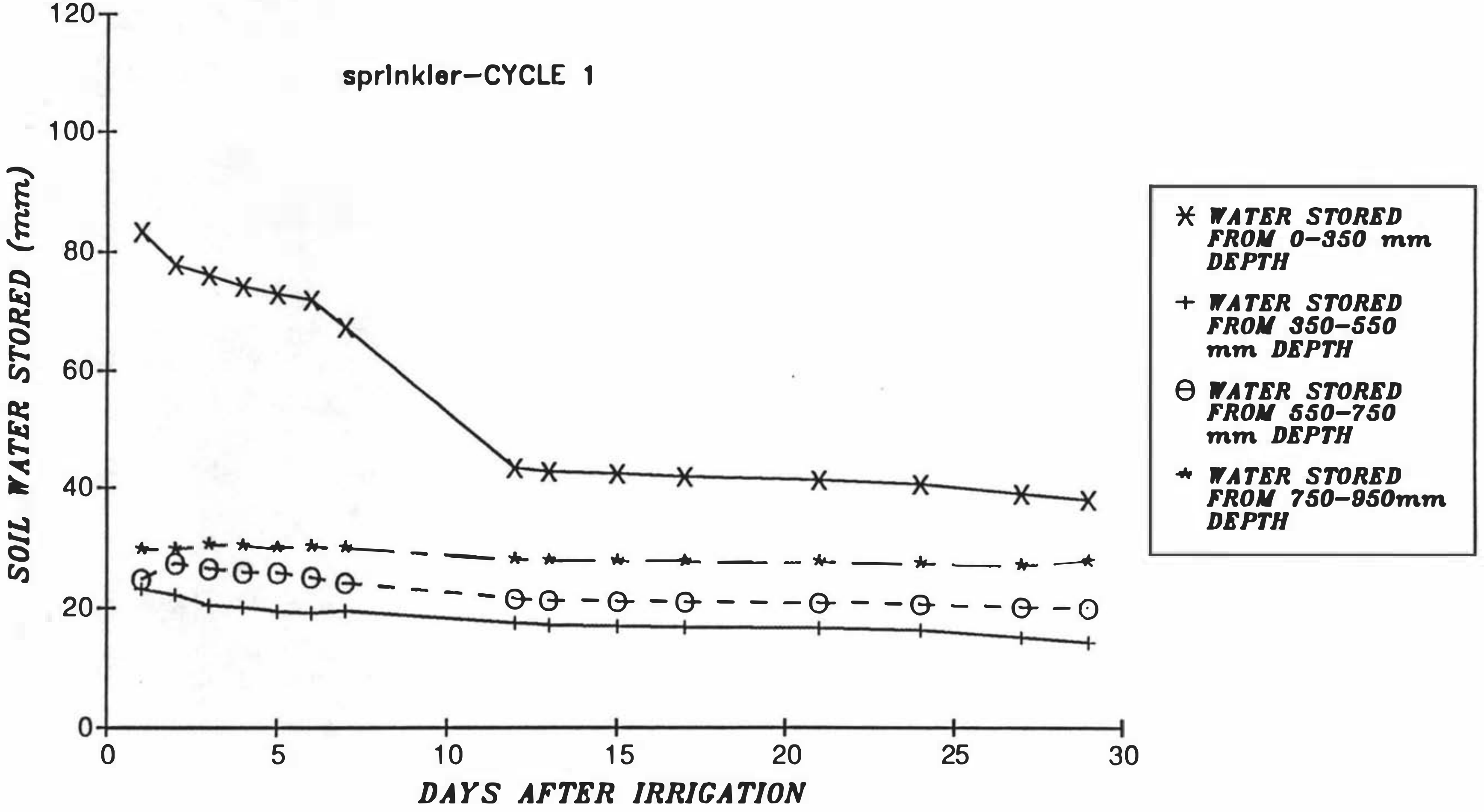

Figure 3.2. Changes in the amount of water stored between 0-350, 350-550, 550-750 and 750-950 mm depths of a "synthetic" soil profile during the extraction period following irrigation by sprinkler.

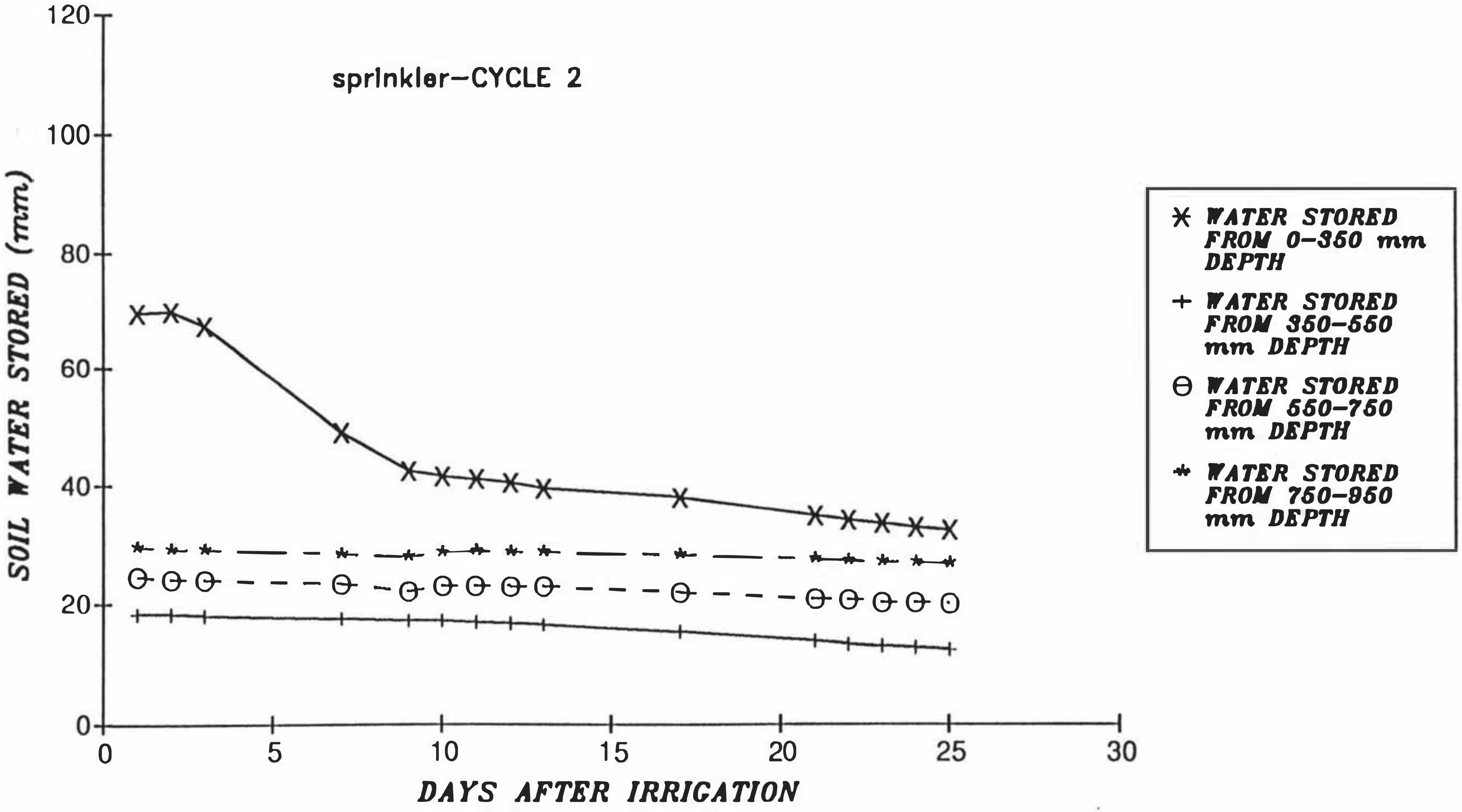

Figure 3.3. Changes in the amount of water stored between the depths 0-350, 350-550, 550-750 and 750-950 mm depths of a "synthetic" soil profile during a drying cycle after sprinkler irrigation.

Inasmuch as the same pattern was obtained in successive cycles, Clothier (personal communication, 1990) suggested the neutron probe overestimated the water content of top soil and this was exacerbated when the soil was wet. Therefore, it became necessary to disregard the period in which erroneous measurement was occurring and to do this, the periods of water extraction were extrapolated towards the y axis. Thus, the intercept with the y axis represents the maximum amount water the soil can hold and any water in excess of that amount will be drained. The day at which drainage ceased was considered the first day of water extraction. Table 3.3 shows the proportion of water extracted for lucerne under the two irrigation systems.

3.3.2.2. *Comparison Between Irrigation Systems in Relation to Root Water Extraction.*

Considering lucerne formed a close cover and the experiment was runned under controlled conditions, thus evaporation could be similar, a comparison of the water extraction obtained in similar time periods with the two application systems was estimated.

Table 3.3 and Figure 3.4 show the total amount of water extracted at each depth and period and the proportion of water extracted with respect to the total uptake for the plant in the period.

By adding the percentage of water extracted from 0 to 550 mm depth, it was estimated that in the initial period the plant used up 76% of the water from top 550 mm of soil. By the 2nd period (6th-16th day), the participation of upper layers (0 to 350 mm) in the water uptake became significantly lower with respect to the proportion obtained in the previous period. A compensatory increase, however, in the absorption from 550 to 950 mm depth occurred. Thus, when the water supply in the top soil was adequate, the roots extract water from that layer, but as soil dried out the pattern of water uptake shifted towards deeper layers of soil.

3.3.2.3. *Trickle Irrigation*

During the initial period under trickle irrigation (Table 3.3 and Figure 3.5)

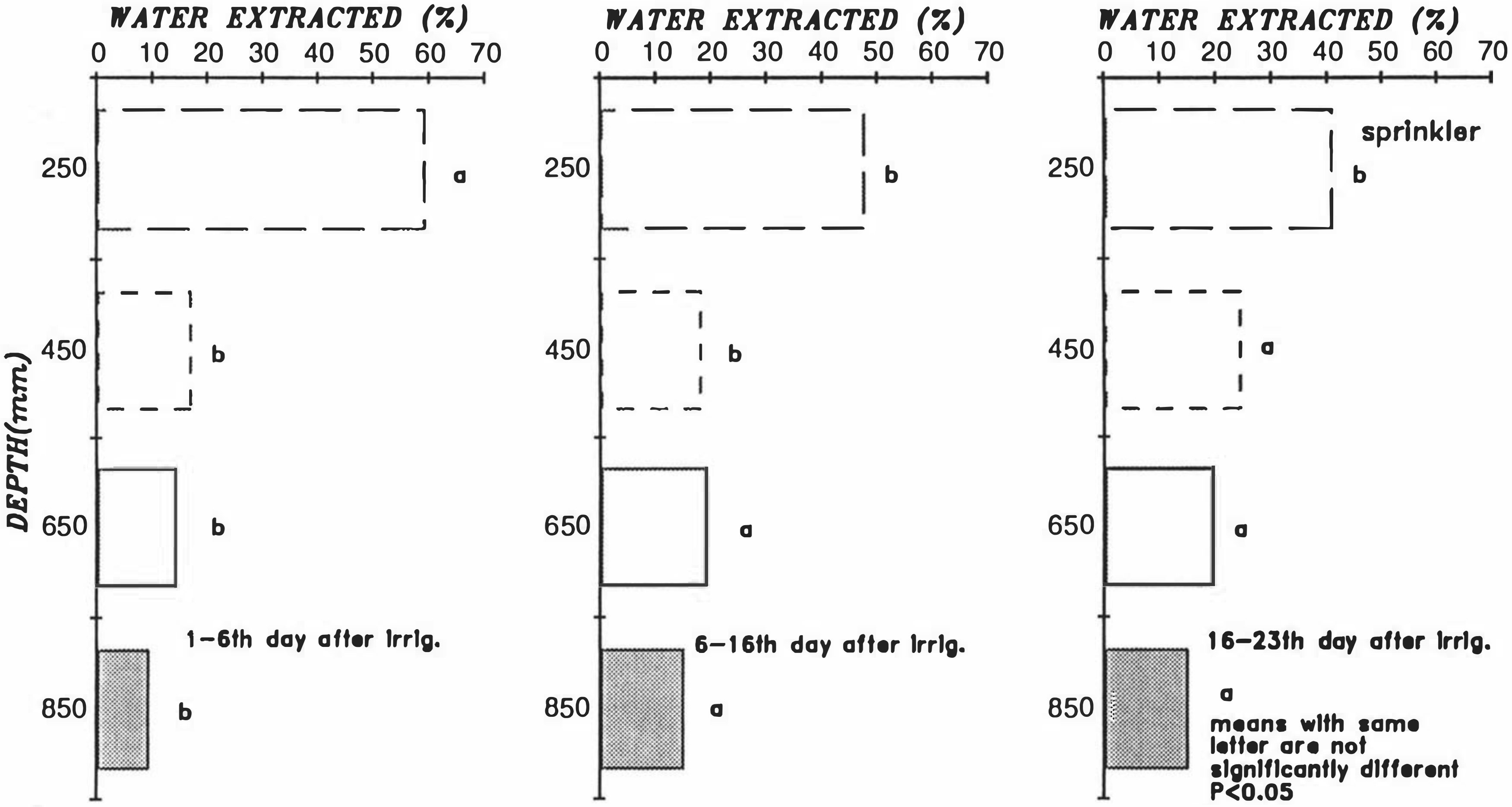

Figure 3.4. The proportion of water extracted from layers between 0-350, 350-550, 550-750 and 750-950 mm depth during a drying cycle after sprinkler irrigation.

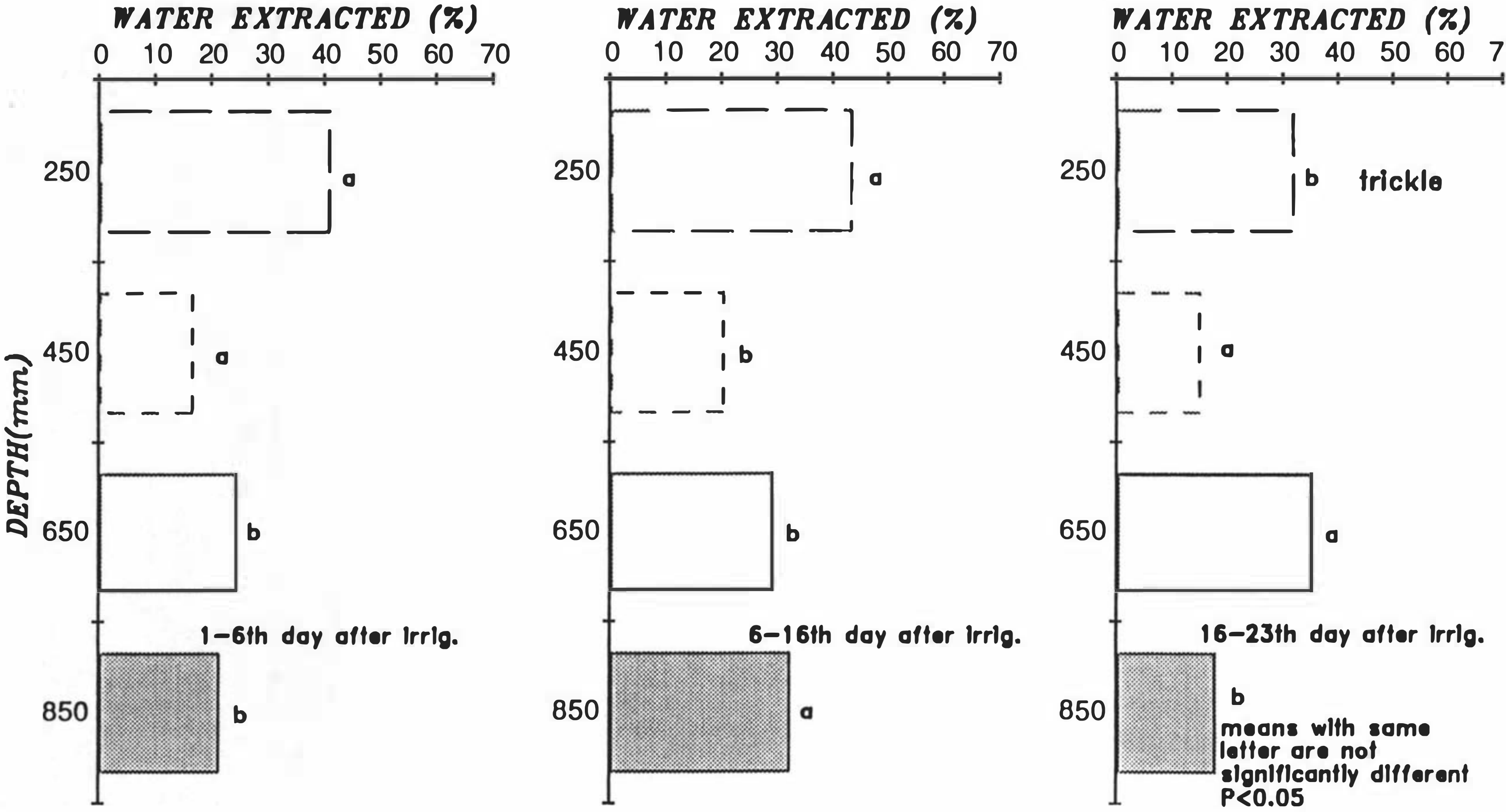

Figure 3.5. The proportion of water extracted from layers between 0-350, 350-550, 550-750 and 750-950 mm depth during a drying cycle after trickle irrigation.

In the second period there was a no significant change in the proportion of water uptake from top 350 mm but a significant increase in the lower layers took place. Further decrease in the participation of upper layer in the water uptake was observed in the 3rd period. A highly significant increase in uptake, however, occurred from layers between 550-750 mm.

Table 3.3. Soil water storage change between soil depth intervals during extraction periods of sprinkler and trickle irrigation.

	Periods					
	1-6 days^{z}		6-16 days		16-23 days	
Depth (mm)	Total W (mm)	Percent	Total W (mm)	Percent	Total W (mm)	Percent
Sprinkler						
0-350	4.59 a^{y}	59.26 a	2.55 b^{x}	47.60 b	3.59 a	40.86 b
350-550	1.11 b	17.12 b	1.16 b	18.22 b	2.28 a	24.53 a
550-750	0.85 c	14.27 b	1.02 b	19.23 a	2.03 a	19.57 a
750-950	0.44 b	9.35 b	0.78 ab	14.95 a	1.48 a	15.04 a
Trickle						
0-350	5.12 a	41.12 a	4.38 ab	43.41 a	3.75 b	31.84 b
350-550	1.88 a	16.85 a	1.78 a	20.43 b	1.97 a	15.22 a
550-750	2.20 a	24.55 b	2.26 a	29.26 b	3.28 b	35.21 a
750-950	2.17 a	21.47 b	2.30 a	32.28 a	2.14 a	17.88 b

^{z} Days after irrigation.

^{y} Mean separation between periods by LSD, 5% level.

^{x} Means with same letter are not significantly different.

3.3.3. *Soil Water Balance.*

In this experiment the only water input was irrigation which ensured the amount of water supplied per day was controlled. Measurement of the volumetric content plus the determination of water outflow permitted the daily water use for the plant to be calculated.

Since it was observed that during periods in which drainage was occurring that neutron probe readings were excessively high, the rate of extraction in this initial period calculated from this data was also too high, which was considered erroneous. Thus, linear regression equations were fitted for total water stored and for the storage for every depth and time, disregarding the period in which drainage was occurring. The correlation coefficients were in the range of 0.94 to 0.99, thus the data from the two irrigations was pooled for further comparisons.

The results of test of significance of difference in slope and intercept between the two irrigation systems are shown in Table 3.4. The intercept represents the maximum water content the soil can hold and any addition of water above that will initiate water movement or drainage. The analysis showed the maximum storage capacity of layers between 0 to 350 mm in trickle irrigation was significantly higher than in sprinkler irrigation. There was no significant difference in the water storage of the bottom layers.

Neither the slope representing the rate of water extraction from individual layers, nor the slope obtained for the total storage was significantly different between irrigation systems.

Table 3.4.Comparison between regression lines for soil water storage (W) over time after sprinkler and trickle irrigation.

	Sprinkler		Trickle	
Depth(mm)	Intercept	Slope	Intercept	Slope
0-350	53.55 a^{z} *	-0.66 a^{y}	71.86 a *	-0.63 a^{y}
350-550	20.28 b	-0.32 a	29.85 b	-0.29 a
550-750	27.33 b	-0.36 a	41.06 b	-0.43 a
750-950	31.50 b	-0.21 a	48.19 b	-0.35 a
Total	132.50 *	-1.53^{NS}	190.20 *	-1.70^{NS}

[z] Mean separation between treatments by LSD, 5% level.

[y] Means with same letter are not significantly different.

[*,**] Significance at 5 % (*) and 1 % (**) levels.

Although in the Table 3.4, the mean separation between layers is not shown, the slope of layer from 0 to 350 was significantly higher than that for the other depths in both irrigation treatments. Exceptions were the 550 to 750 mm layer under trickle irrigation and the 750 to 950 mm layer for sprinkler.

Estimates of average daily water use considering all the neutron probe readings in both wetting and extraction cycles resulted in mean values of 2.37 +/- 0.33 mm for sprinkler irrigation and 2.11 +/- 0.22 mm for trickle irrigation. There were no significant differences between irrigation systems but values were higher than those obtained from regression equations (slope of total storage against time in Table 3.4).

3.3.1. ***Water Use Efficiency***

The efficiency of irrigation expressed in terms of millimetres of water necessary to produce one kilogram of dry matter was not significantly different. The values obtained were as follows:

1) sprinkler irrigation 16.09 +/-2.17 mm
2) trickle irrigation 13.22 +/-3.25 mm.

When efficiency was calculated using the slope of the regression equation described above (between soil water storage and time over the extraction period), the amount of water necessary to produce one kilogram of dry matter declined to 8.30 +/-0.34 mm and 11.22+/-0.38 mm in trickle and sprinkler respectively.

3.4. ***Discussion.***

The discrepancy between the results obtained using the slope of regression equations and the rate of water extraction estimated using the soil water balance equation may be attributed to the error in the neutron probe found in readings in top soil when the soil was wet. The sensitivity of the neutron probe varies with the depth, and in the top soil, because thermal neutrons may be lost (Shirazi and Isobe ,1975). When the 'sphere of importance' is intersected by the soil surface there is a rapid scape of neutrons from the soil mass giving readings which indicate a lower than actual moisture content when the air is drier than the soil (Visvalingam and Tandy, 1972). In the conditions of this experiment during periods succeeding each irrigation the lucerne sward, which formed a close cover of the soil appeared to retain a higher relative humidity in the atmosphere between the soil and the free air than was present in the air itself. This layer can absorb small quantities of thermal neutrons and introduce a further error in the relationship between thermal neutron activity and the volumetric water content. In this experiment, this effect appeared to have overestimated the water content values in the upper soil layer, especially in the period subsequent to the irrigation.

]The study of soil water content profiles during wetting showed as Clothier *et al* (1977) had reported, that the wetting front moves in the fine sandy loam until it is saturated and then moves along the fine sand. Results of Table 3.4 showed that the top layer had a greater water retention capacity at the time when drainage ceased as indicated for the intercept values. The ability to transmit water and the low water holding capacity of the sandy soil in contrast to a lower water movement in the upper loam layer was also reported by Bresler (1977).

The drying pattern showed water uptake was mainly located in the top soil when the soil was wet but shifted towards the lower layers as soil dried out. This is in agreement with previous report by Garnier *et al* (1985) for apples, and Hayman and McBride (1984) for lucerne, who demonstrated that lucerne extracted water from deep soil only after water from shallow layers had been utilized.

A higher slope for layers from 0 to 350 mm (Table 3.4) showed the rate of water extraction was higher in the top soil. It explains the shifting in pattern of water uptake for lucerne even when only 5% of the storage had been used from this layer, as happened under sprinkler irrigation. Similar results were obtained by Huck and Hillel (1983) who indicated that water uptake tends to be faster from top layers of soil and as water is depleted the uptake progresses to lower layers. The shifting in water uptake from upper to deeper soil layers suggests the root system extended well throughout the soil profile. Nevertheless, during sprinkler irrigation maximum extraction took place in the top 500 mm of soil which indicates the maximum root density was also located there.

Since the beginning of the drying cycle, the water extraction under trickle irrigation extraction was more evenly balanced between top and bottom layers. Nonetheless, participation of top layer of soil was greater when the soil was wet and lessened as soil dried out. Since trickle treatment was applied after six months of sprinkler irrigation and seven months after planting, it could be expected that lucerne roots would have extended towards deeper layers. Additionally, the greater storage in bottom layer under trickle irrigation at the time drainage ceased as compared with the storage in the sprinkler irrigation (intercept of Table 3.4), showed the trickle irrigation produced a more balanced water distribution in the soil profile than the sprinkler irrigation. These results corroborates results of other authors (Bresler *et al*, 1971). This factor considered in conjunction with the effects of trickle irrigation on root development and pattern of water use were the main factors in the selection of trickle irrigation system for the main trial.

These results confirm Belmans *et al* (1979) findings that if water distribution is uniform the pattern of absorption is determined by the root distribution. This explains why in the first period of extraction under trickle irrigation a balanced water uptake existed, which was changed when water supply was depleted in top layer.

It can be concluded that root water extraction is a dynamic process and lucerne demonstrated capacity to adjust the pattern of water uptake according to the soil moisture. As water was depleted from one area roots progressively explored deeper areas. These properties are important in the choice of lucerne

CHAPTER 4

SEASON 1987-1988

4.1. *Introduction.*

The transferability of a crop technology developed in one set of environmental conditions to another with completely different conditions depends upon an adequate calibration. It is important to determine which are the most critical variables one needs to control in order to obtain the beneficial effects of novel technology. The performance of RDI in the dry environments of Australia has been proven to be an excellent technique to control tree vigour while producing increases in yield of orchard trees (Chalmers *et al.* 1981; Mitchell and Chalmers, 1982; Chalmers *et al.* 1983). In theory, RDI could be adopted in humid environments if certain questions could be answered appropriately. These include: how to create a water deficit in the trees at the initial flush of vegetative growth when the soils are holding large amounts of water. What approach is the best to adopt to schedule the irrigation? What are the appropriate dates to interrupt the period of RDI in order to avoid negative effects on fruit yield ? Does RDI affect fruit quality? The preceding literature review and glasshouse experiment confirmed the ability of lucerne to extract water from depth within the soil profile. As a possible alternative, this experiment aimed to use lucerne as an under tree cover in the orchard to ascertain if lucerne could be used to create a soil water deficit in the root zone of the crop. Alternately, the experiment also evaluated the efficiency of a black polyethylene mulch as a rain shelter to prevent rainfall accumulating in the soil.

4.2. *Objectives.*

This experiment aimed to:

1) determine the effect of two soil management techniques, namely a lucerne sward and a black polyethylene film compared to a conventional herbicide strip to control soil water.

2) evaluate the effectiveness of pan evaporation as a parameter to determine RDI irrigation strategies in the environment of this study.

3) evaluate crop performance under RDI in interaction with soil management techniques.

4) evaluate the effects of these treatments on fruit quality.

4.3. *Materials and Methods.*

4.3.1. *Weather.*

The average rainfall during the growing season 1987-1988 was 2.64 mm/day giving a total of 396 mm, of which 250.28 mm fell during the first 109 days of the growing season (Table 4.1). Days with precipitation exceeding 10 mm were distributed throughout the season with a maximum on one day of 27 mm on day 137 after full bloom (a.f.b.). The longest period without rain occurred between day 115 and 129 a.f.b. Total pan evaporation was 679.4 mm of which 439.11 mm were evaporated during the first 109 days a.f.b. Evaporation averaged 4.53 $\text{mm}\cdot\text{day}^{-1}$ showing a regular pattern during the growing season. Days with higher values occurred towards end of season. The highest value of daily pan evaporation of 8.6 mm was recorded on day 137 a.f.b.

Table 4.1. Climatic data for Palmerston North during season 1987-88 (Summary by periods).

Dates	Total Days a.f.b.	Total Rainf (mm)	N°days Rainf> (10 mm)	Daily Average Class A Pan Evap (mm)
28 Sep-23 Oct	26	84.1	5.0	3.25
24 Oct- 2 Nov	36	6.6	0.0	3.26
3 Nov- 8 Nov	42	5.1	0.0	4.98
9 Nov-15 Nov	49	27.0	2.0	4.09
16 Nov-25 Nov	59	7.0	0.0	5.63
26 Nov- 3 Dec	67	23.0	0.0	4.50
4 Dec- 9 Dec	73	42.0	2.0	2.77
10 Dec-18 Dec	82	5.2	0.0	4.99
19 Dec-29 Dec	93	45.4	3.0	5.29
30 Dec- 7 Jan	102	2.7	0.0	5.68
8 Jan-22 Jan	117	4.2	0.0	5.66
23 Jan-27 Jan	122	0.0	0.0	7.24
28 Jan- 5 Feb	131	13.1	1.0	4.86
6 Feb-12 Feb	138	78.5	3.0	4.16
13 Feb-22 Feb	144	46.7	0.0	5.68

Source: Grasslands Division, DSIR, Palmerston North, New Zealand.

4.3.2.*Prediction of ET Crop by Pan Evaporation.*

Considering the variable climatic conditions and the problems associated with operating the irrigation equipment, an irrigation schedule based strictly on ET was not practical. Consequently, an irrigation schedule based on historical evaporation data was devised. This parameter was selected for its known high correlation with ET of vegetation (Tanner, 1967) and on the basis that a predictable plant water deficit would be obtained if a given proportion of potential evapotranspiration was replaced at close intervals. A comparison between reference crop ET and measurements of accumulated soil water deficit was carried out to evaluate the effectiveness of the arbitrary irrigation schedule.

Reference crop ET was calculated using the Doorenbos and Pruitt (1977) correlation model based on pan evaporation. Values of K_p were obtained from tables (Doorenbos and Pruitt, 1977) prepared for a Class A pan placed in short green grass area. Local daily records of relative humidity (assuming a 10-m green crop on the windward side of the pan) and 24-hr wind run obtained from DSIR, Grassland Division, Palmerston North, were used to select K_p from the tables. Values of K_p were multiplied by daily records of pan evaporation (1.10) to obtain E_p. ET_{crop} and $ET_{lucerne}$ were calculated using equation 1.11. Values of K_c for crop were selected from tables (Doorenbos and Pruitt, 1977) for the young orchards with a tree cover of 50%. These values ranged from 0.95 to 1.08 during Phase I and from 1.00 to 1.20 during Phase II and III. The same tables were used to obtain the crop coefficient for lucerne (K_L), these values were less variable throughout the growing season and ranged from 0.85 to 1.05. For plots sown to lucerne treatment, total ET was assumed to be that for $ET_{lucerne}$. This assumption was based on the fact that lucerne, during the experiment formed a full cover which may be assumed to represent the upper limit of ET under these climatic conditions.

4.3.3. *Irrigation.*

The following irrigation strategies, summarized in Table 4.2, were used: a) A period until 55 days a.f.b. (20 of November 1987), during which irrigation was withheld followed by RDI treatments which received 25% replacement of EPS (evaporation over the planting square), as defined by Mitchell *et al.*(1984), based on pan evaporation of the long term climatic data. This period extended to 111 day a.f.b. (16 January, 1988), and was followed full irrigation (100% replacement EPS) until the end of season, plus rainfall. b) Full irrigation treatments received 100% replacement of EPS plus rainfall after the withholding period. Irrigation was automatically set to be applied at one day intervals according to general orchard practice.

Table 4.2. Irrigation treatments during season 1987-1988.

Treatment	Phase I Withholding Period	Phase II RDI Period	Phase III Full Irrig. Period
Full Irrigation			
Plastic	No Rainf	100% EPS	Rainf+100%EPS
Control	Rainf	Rainf+100%EPS	Rainf+100%EPS
Lucerne	Rainf	Rainf+100%EPS	Rainf+100%EPS
RDI			
Plastic	No Rainf	25% EPS	Rainf+100%EPS
Control	Rainf	Rainf+25%EPS	Rainf+100%EPS
Lucerne	Rainf	Rainf+25%EPS	Rainf+100%EPS

4.3.4. ***Estimation of Net Water Input.***

Net water input was obtained by adding the daily rainfall data (for the treatments receiving it) and the water supplied by irrigation. Rainfall was reduced by 10% to account for the portion lost through evaporation (Zinke, 1967).

4.3.5. ***Predicted Water Deficit.***

Prediction of water deficit for each treatment was obtained by subtracting the respective total water input per treatment from the calculated ET_{crop} or $ET_{lucerne}$.

4.3.6. *Soils.*

Records of volumetric water content were obtained for all the plots at one week intervals during the growing season, using the neutron scattering method.

4.3.6.1. *Stored Soil Water.*

Measurements of θ taken at different depths were used to calculate the water content between two depths z_1 and z_2, i.e. θ_{12}. The measurement from depth z_1, θ_1 and from z_2, namely θ_2 were used in the formula as follows:

$$\theta_{12} = (z_2.\theta_2 - z_1.\theta_1)/(z_2 - z_1) \qquad (2.1)$$

where q is volumetric water content measured by neutron probe (% V/V).

Assuming most of the roots were in the top 600 mm of soil, the water stored in the soil was calculated for the top (0 to 600 mm) and bottom (600 to 1000 mm) layers respectively. The following mathematical expression was used to calculate soil water storage (W):

$$W_{top} = 300\theta_{0\text{-}300} + 100\,\theta_{400} + 100\theta_{500} + 100\theta_{600} \qquad (2.2)$$

$$W_{bottom} = 100\theta_{700} + 100\,\theta_{800} + 100\theta_{900} + 100\theta_{1000} \qquad (2.3)$$

$$W_{total} = W_{top} + W_{bottom} \qquad (2.4)$$

4.3.6.2. *Soil Water Volume.*

The volume (Q) of water stored in two layers of soil was calculated taking in account the distances from the tree at which access tubes were located (250, 450 and 750 mm). The volume of water stored at each distance was calculated using the following mathematical expression:

$$V= \int_{0}^{r} 2\pi r W(r) d_{r} \qquad (2.5)$$

where r is the radial distance of the access tube with respect to the tree.
if I is the water input (rainfall or irrigation) then the rate (Q) of water used in the interval of time 1 (t_1) to time 2 (t_2) is equal to:

$$Q= Q_{t1}-Q_{t2}+I \qquad (2.6)$$

4.3.7. *Collection of Plant Data.*

4.3.7.1. *Plant Water Status.*

Two shaded leaves, randomly selected in the middle portion of the tree, were sampled to determine leaf water potential with the Scholander pressure bomb. The diurnal pattern of Ψ_L was measured for one complete fine day using the two middle trees in each plot during Phase I, II and III.

4.3.7.2. *Photosynthetic Rate and Stomatal Conductance.*

Two fully exposed leaves from the middle section of the tree were sampled in every plot to assess rate of photosynthesis and stomatal conductance. The diurnal pattern of these two parameters was measured simultaneously with Ψ_L using a Li-cor 6200 instrument.

4.3.7.3. *Shoot Data.*

Two shoots of the two middle trees of every plot were tagged and their length measured twice a week until harvest.

4.3.7.4. *Fruit Data.*

Four fruits of uniform size were tagged on the three middle trees of every plot and their diameter measured twice a week from the 46th day a.f.b. until harvest.

4.4. *Results.*

4.4.1. *Weather Season 1987-1988.*

4.4.1.1. *Phase I.*

Figure 4.1 reveals the pattern of rainfall and evaporation from full bloom to the day on which harvest was initiated (day 148 a.f.b.). The data shows that all treatments except the plastic mulch received a total of 84.1 mm rainfall during the first 26 days of the growing season. Although incidence of rainfall decreased, an additional 42.7 mm fell between day 26 to 55, at which time the withholding period was curtailed.

4.4.1.2. *Phase II.*

The rainfall pattern during Phase II (Figure 4.1) occurred in two peaks between the 6th and 8th of December (day 72-74 a.f.b.) and 19th to 29th of December (day 80-90 a.f.b.). However, a dry period followed until the end of Phase II.

4.4.1.3. *Phase III.*

The dry spell initiated on day 90 a.f.b. extended until day 127 a.f.b. (Fig 4.1) associated with an increase in E_p. During this period all plants experienced a water deficit, requiring irrigation. Figure 4.1 also shows that significant rainfall occurred from day 127 a.f.b. to harvest.

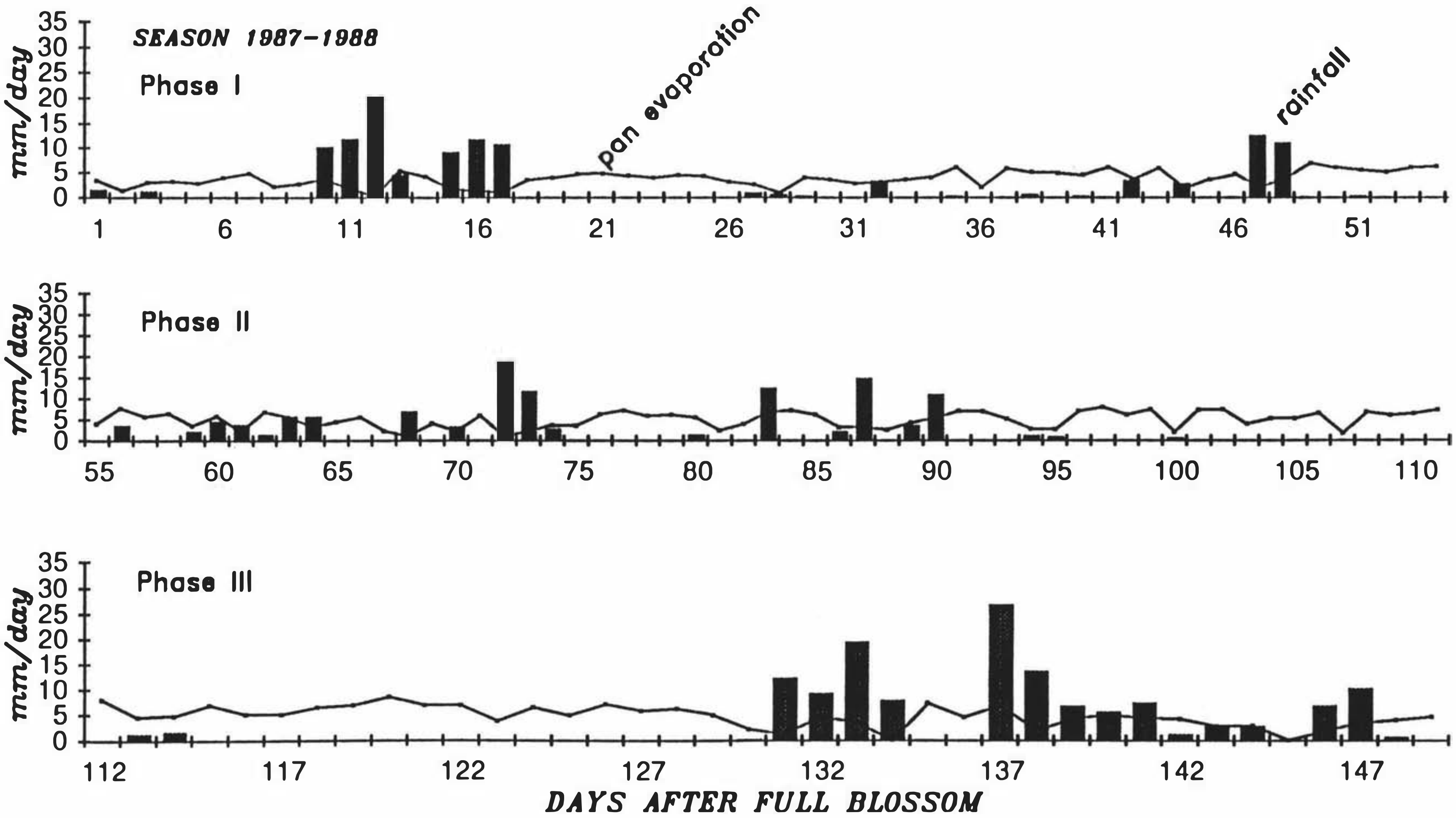

Figure 4.1. Daily water balance during growing season 1987-1988.

4.4.3. *Accumulated Predicted Water Deficit.*

The predicted water deficit accumulating for each treatment is presented in Figures 4.2, 4.3 and 4.4. The pattern of accumulation of the water deficit for plastic (Figure 4.2) shows that irrigation without rainfall was insufficient to meet the accumulated crop water demand. A different picture was obtained for control and lucerne X full irrigation treatments (Figures 4.3 and 4.4). For the former, the data indicated a water excess from days 86-96 a.f.b. and from day 137 a.f.b. to harvest. Whilst for the latter, water excess was indicated for days 70-118 and from 128 to harvest. The data for control X RDI Figure 4.3 shows the deficit had been reduced at the end of Phase III. Cumulative ET for RDI treatments indicated that net water input of Phase III might reduce the deficit of Phase II by day 128 a.f.b. in lucerne. Whereas, it could be insufficient for plastic and control treatments (Figures 4.2 and 4.3).

4.4.4. *Soil Moisture.*

4.4.4.1. *Volumetric Water Content.*

Typical volumetric water content profiles obtained in this study are shown in Figure 4.5. a,b and c. In general, higher values of volumetric water content were obtained in the top 500 mm of soil, which coincided with the layers of finer soil texture. Maximum values in the range of 34-40% were obtained in the top 500 mm with no significant differences among soil management and irrigation treatments. Minimum values as low as 8.0 % +/- 0.32 in the top three layers were recorded in control RDI treatment. This value recorded on day 122 a.f.b., when a maximum value of 32.6% in top 300 mm was obtained. Since irrigation was applied on this day and there was a wide range of soil moistures for same plot and the same time, the data suggest that wetting pattern given for the drippers was not measured from some access tubes more distant from the application point.

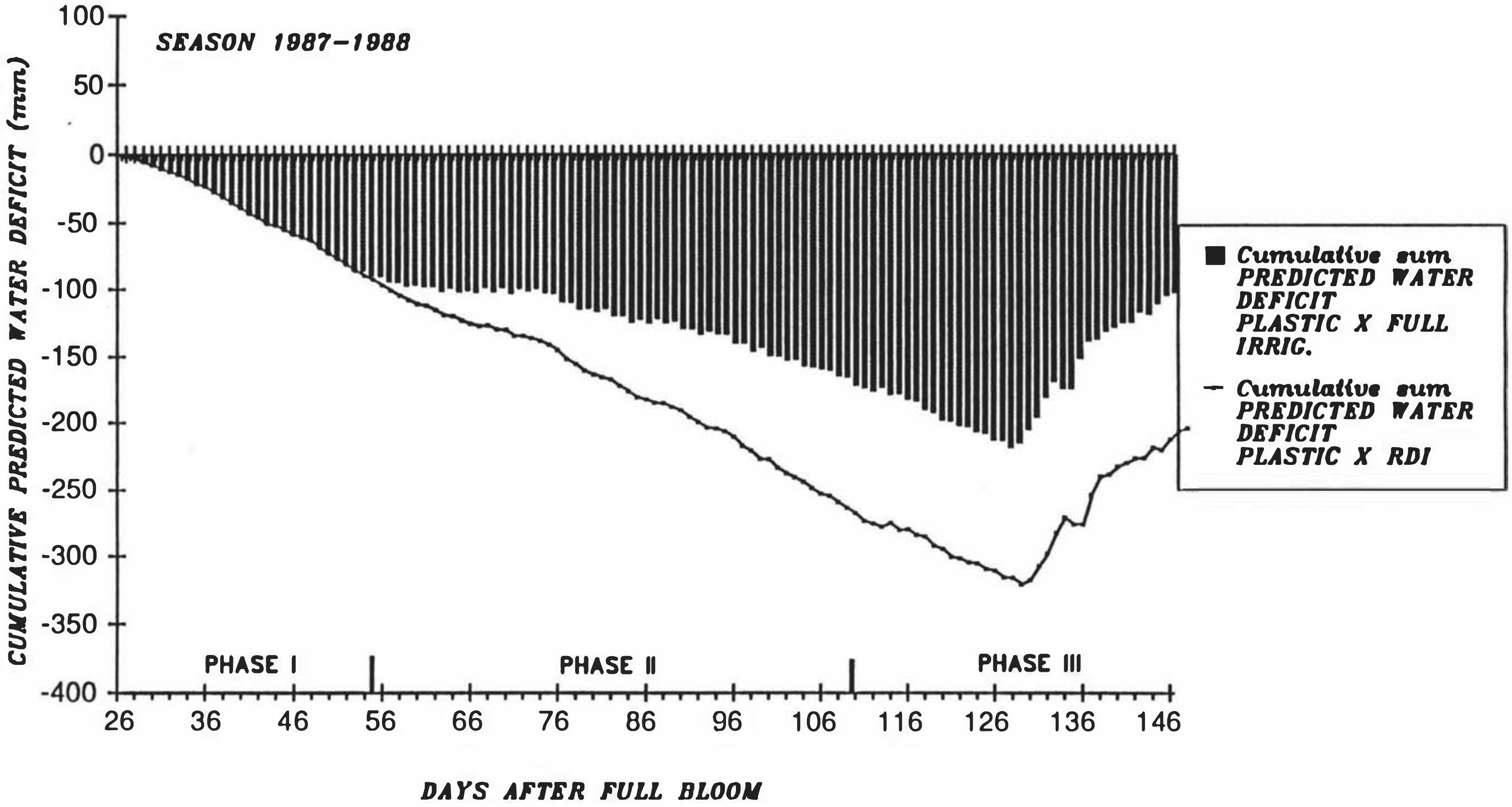

Figure 4.2. Cumulative water deficit/surplus predicted for plastic treatments during the growing season 1987-1988.

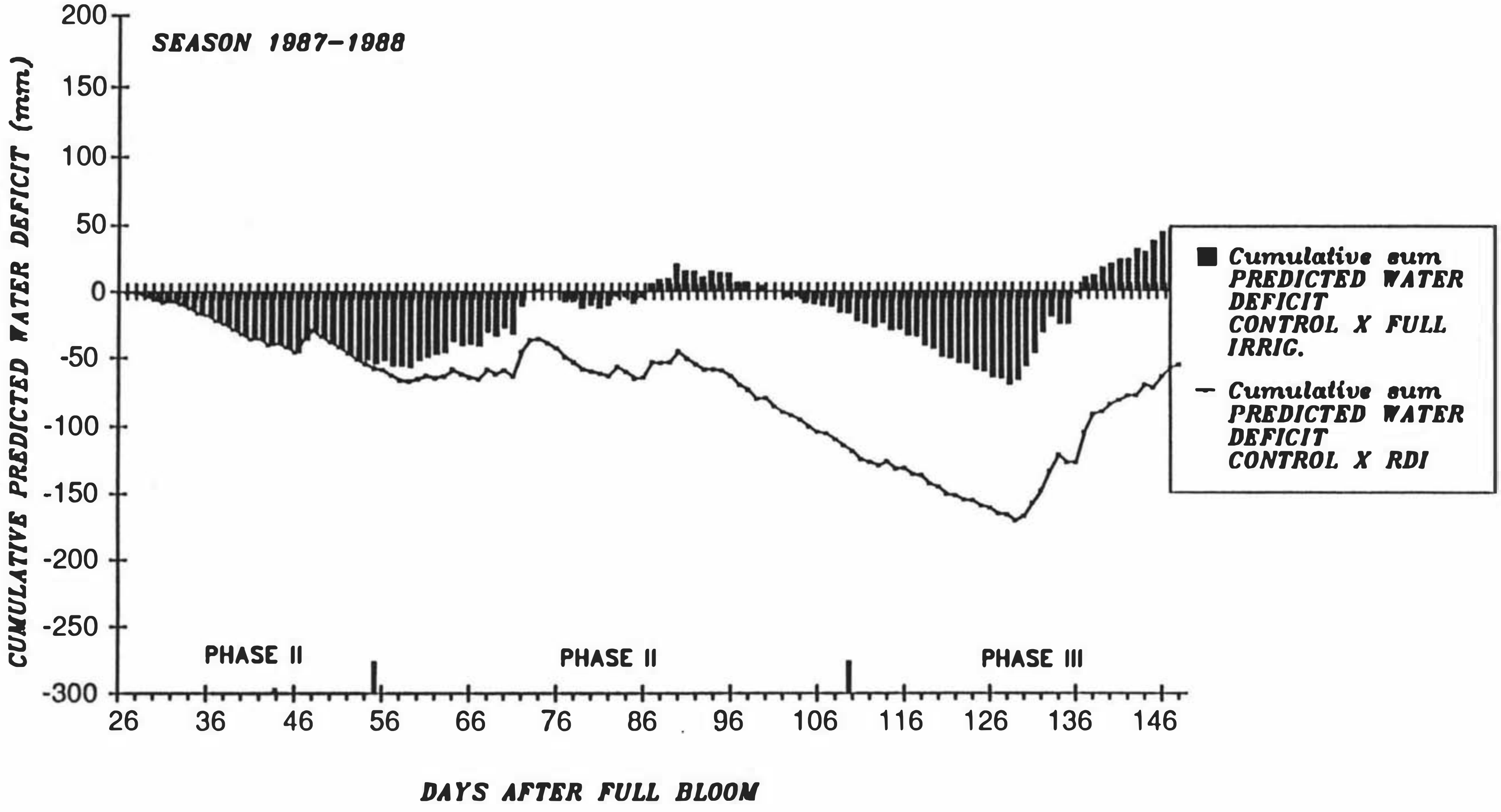

Figure 4.3. Cumulative water deficit/surplus predicted for control treatments during the growing season 1987-1988.

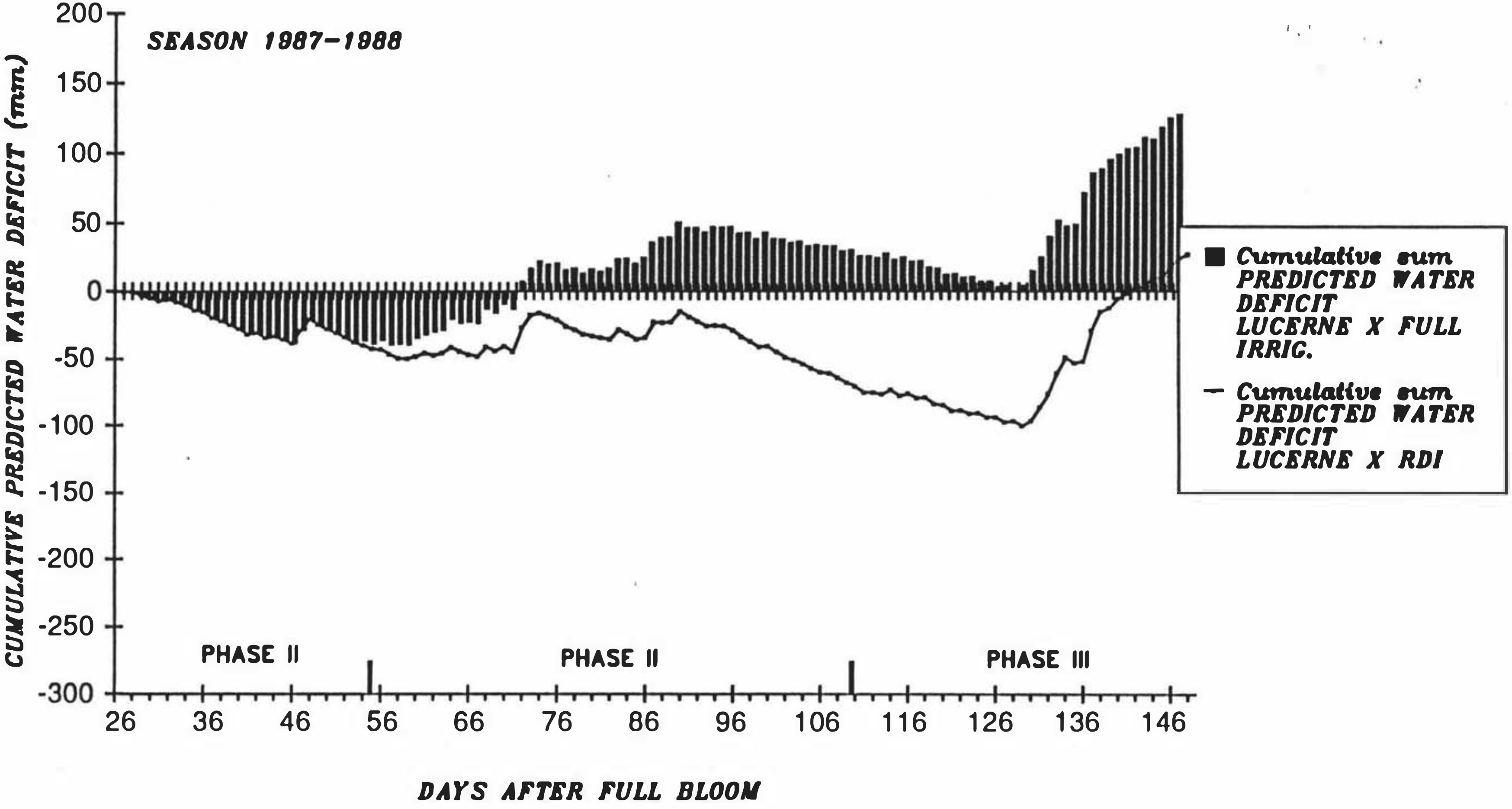

Figure 4.4. Cumulative water deficit/surplus predicted for lucerne treatments during the growing season 1987-1988.

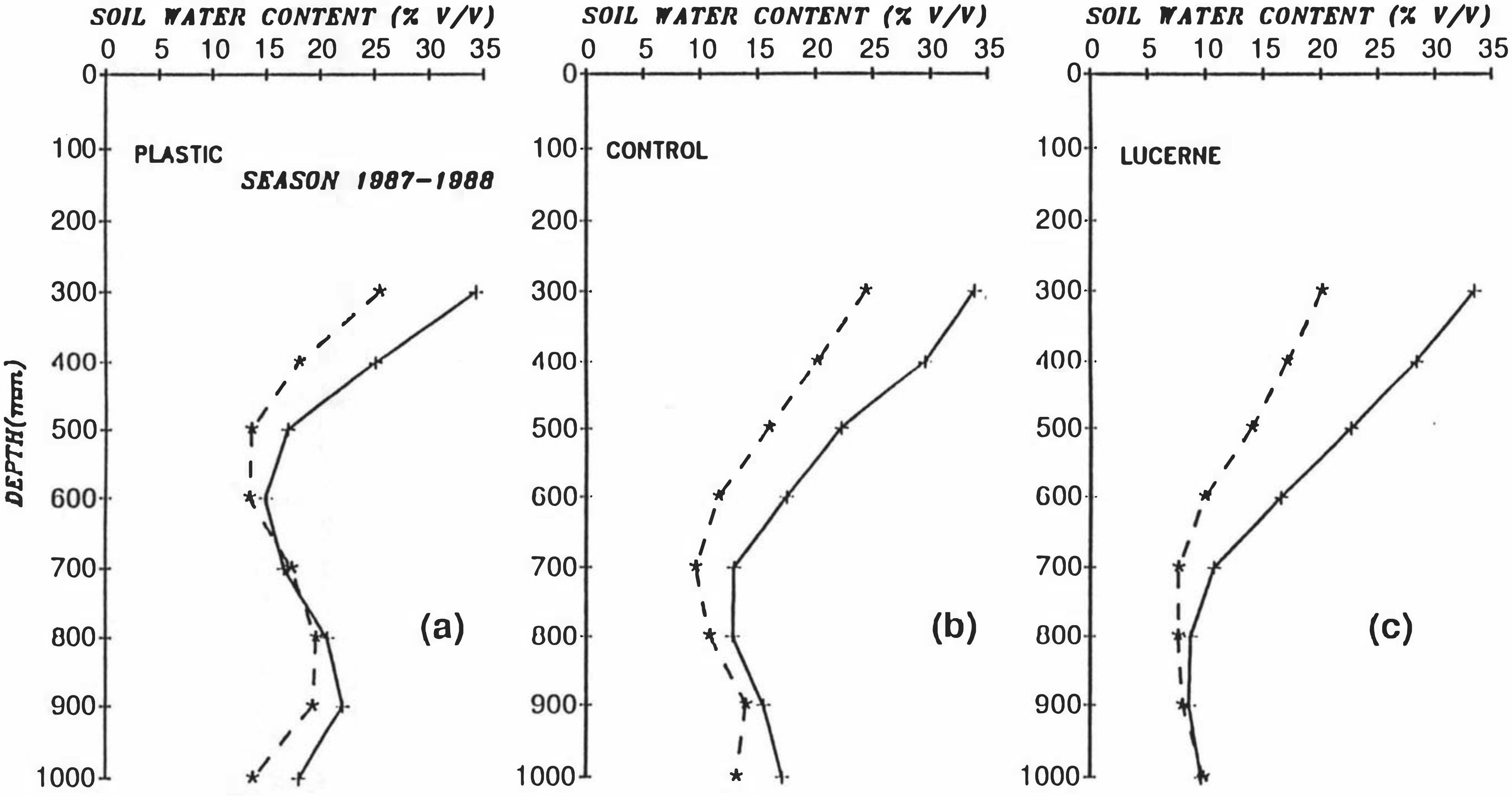

Figure 4.5. Typical soil water content profiles obtained under (a) plastic, (b) control and (c) lucerne treatments respectively during Phase I (day 36 +, day 59 *).

This situation occurred on those days when the surface soil was dry. Such was the case for day 122 when irrigation had not been applied during the previous 5 days due to an equipment malfunction. Nevertheless, the fact that access tubes were placed around the trees and well replicated ensured that mean conditions of soil moisture and their variations could be evaluated. On the other hand, this observation shows that extreme data were of limited value when explaining treatment effects. The maximum value obtained in the deeper layers was 32%. This value is higher than the appropriate value of the retentivity curve (Figure 2.2 a), which indicates that soil moisture exceeded the saturation point. The minimum value of 4.8% +/-0.1 in the soil profile was obtained in the layer from 700-900 mm depth in lucerne X RDI and full irrigation treatments. This value recorded on day 102 a.f.b., was significantly lower than in the other treatments, which suggests lucerne was extracting soil moisture from the deeper layers.

4.4.4.1.1. *Volumetric Water Content in Phase I.*

Figures 4.5 a,b and c illustrate the changes in soil water content for the period between day 36 and 59 a.f.b. during Phase I. Initially, in the layers from 0-600 mm depth (Table 4.3), no significant differences in soil water content between treatments were obtained. In the layers from 700-1000 mm, however, the lucerne treatment showed a significantly lower water content than plastic and control treatments. Since control and lucerne had received rainfall, the differences between lucerne and control can be assumed to be due to lucerne root activity in the deeper layers of the soil profile. The subsequent water extraction of this treatment from day 36 to 59 a.f.b. took place in the layers from 0-800 mm as can be observed in Figure 4.5. The plastic resulted in the lowest change in θ for this period. Considering the substantial changes observed in the other two treatments, this may also suggest the plastic retained soil moisture.

Table 4.3. Changes in soil water content (θ) during Phase I.

	θ(% V/V)					
	Plastic		Control		Lucerne	
Depth(mm)	Day 36^{z}	Day 59	Day 36	Day 59	Day 36	Day 59
300	34.32a^{y}	25.53a	33.86a	24.43a^{x}	33.34a	20.04b
400	25.14a	18.02a	29.53a	20.19a	28.22a	17.04a
500	16.95b	13.56a	22.19a	15.99a	22.58a	13.95a
600	14.90a	13.43bc	17.46a	11.60c	16.49a	9.88c
700	16.62a	17.35a	12.90bc	9.58b	10.68c	7.65c
800	20.58a	19.54a	12.80b	10.80b	8.69c	7.60c
900	22.06a	19.26a	15.46b	13.96b	8.54c	7.97c
1000	18.01a	13.74a	17.12a	13.20a	9.62b	9.77b

[z] After full bloom.
[y] Mean separation between treatments by LSD, 5% level.
[x] Means with same letter are not significantly different.

4.4.4.2. *Effects of Treatments on Total Soil Water Storage.*

4.4.4.2.1. *Phase I.*

The changes in W throughout the season are shown in Figures 4.6, 4.7 and 4.8. Results obtained during Phase I indicate that from day 26 to 59 a.f.b. a progressive decrease in W occurred in all the treatments. The initial W (Table 4.4) obtained for plastic and control treatments was not significantly different. This suggested that either plastic had not been installed early enough in the winter or had been ineffective as a barrier to control water storage. However, lucerne showed a lower W which was significant in lucerne X full irrigation. Although lucerne was probably the cause of the lower values in W, there was no previous data to support this inference.

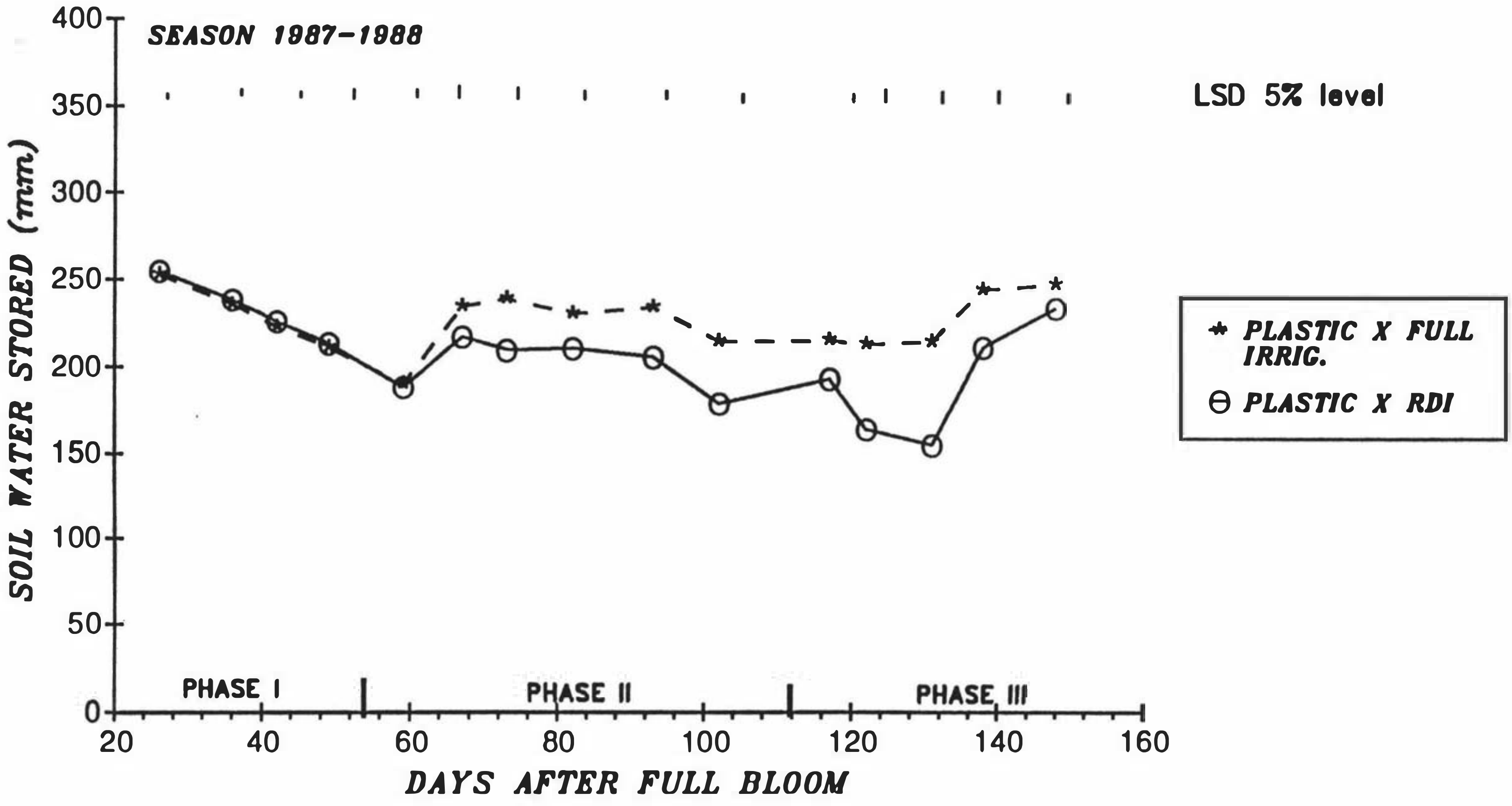

Figure 4.6. Seasonal pattern of soil water stored (W) under plastic treatments, estimated by the neutron probe.

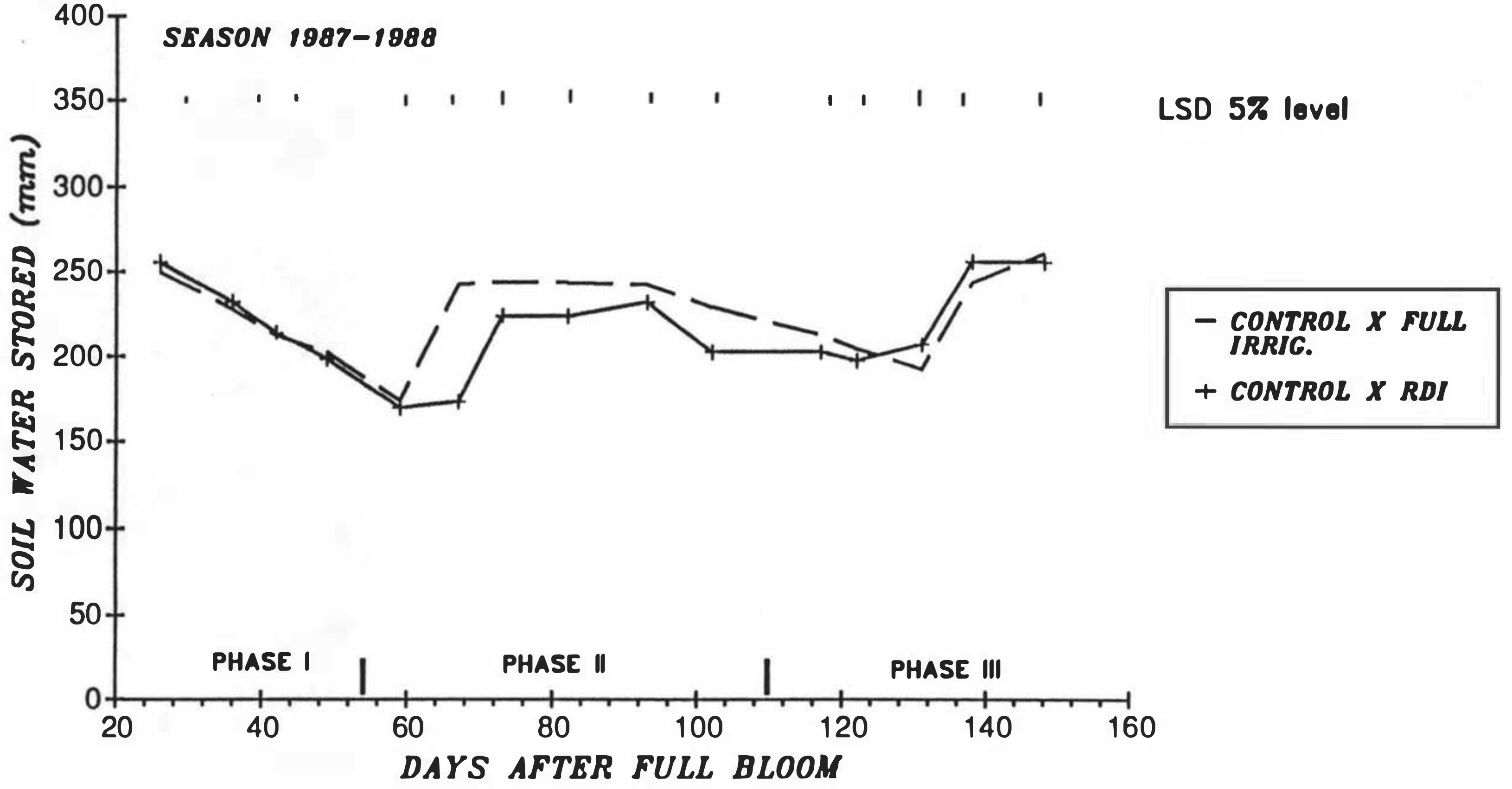

Figure 4.7. Seasonal pattern of soil water stored (W) under control treatments, estimated by the neutron probe.

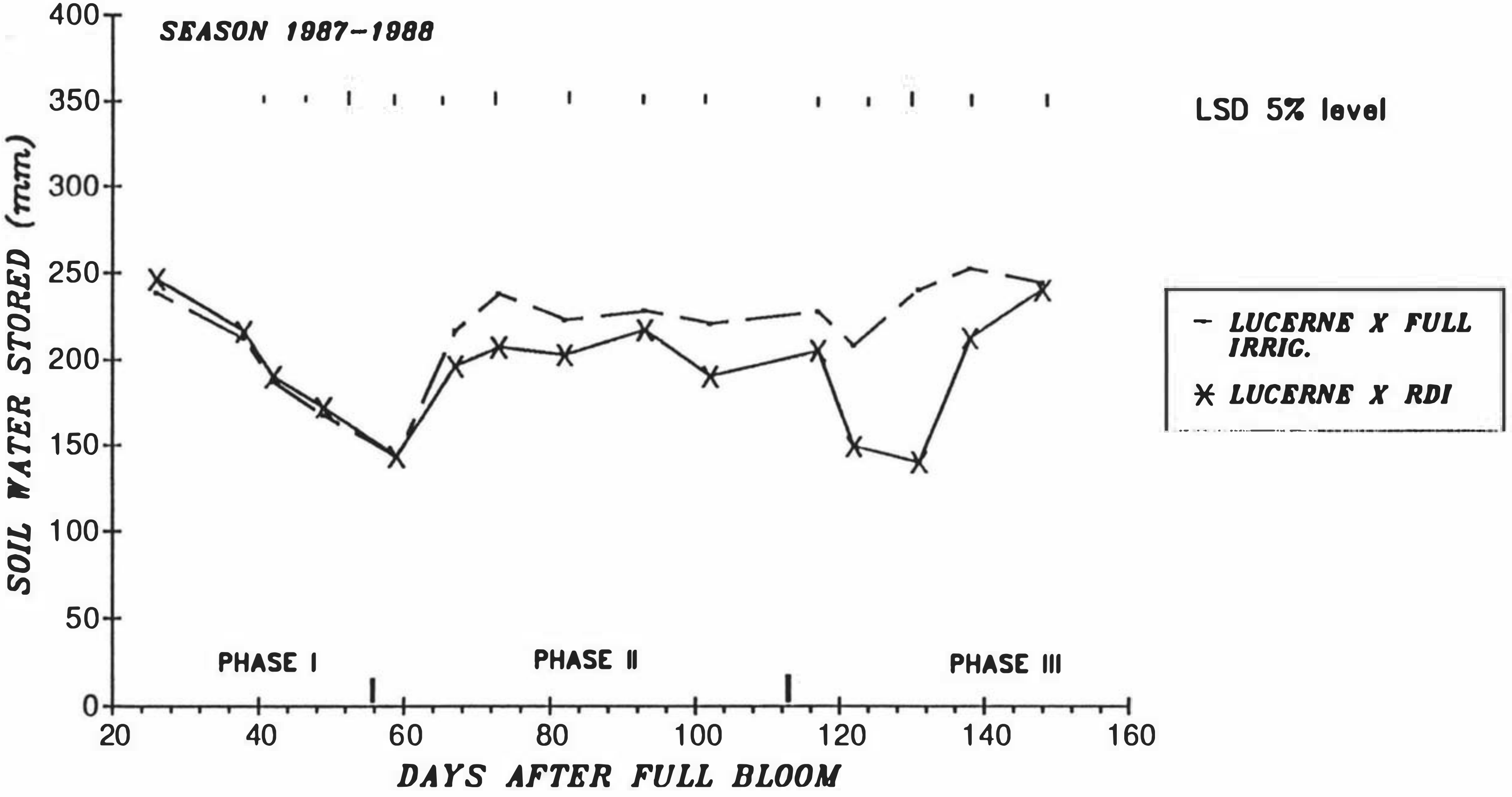

Figure 4.8. Seasonal pattern of soil water stored (W) under lucerne treatments, estimated by the neutron probe.

Table.4.4. Changes in total soil water storage (W) during Phase I.

	W (mm)		
Treatment	Day 26 a.f.b.	Day 49 a.f.b.	ΔW^{z}
Plastic X Full Irrig.	252.8 a[y]	210.8 a[x]	42.0 c
Plastic X RDI	254.9 a	213.1 a	41.8 c
Control X Full Irrig.	250.1 a	202.3 ab	83.2 b
Control X RDI	255.6 a	198.7 b	92.3 b
Lucerne X Full Irrig.	238.3 b	167.8 c	105.9 a
Lucerne X RDI	246.2 ab	172.9 c	108.7 a

[z] Data including net water input during the period.
[y] Mean separation within columns by LSD, 5% level.
[x] Means with same letter are not significantly different.

On the other hand, the largest change between days 26 and 59 a.f.b., occurred in lucerne X RDI followed by lucerne X full irrigation. Since all treatments but plastic were receiving only rainfall, differences in W were due to the surface management. The decrease in W in the plots with lucerne as under tree cover was significantly greater than plastic and control treatments. Moreover, total W for the control (herbicide strip) was reduced more than plastic mulch, though less than lucerne. This indicates that whilst lucerne was more effective than other surface management treatments in decreasing the water stored in the root zone of the crop, the plastic cover appeared to conserve soil water. In terms of the objectives of this experiment, this is unexpected and is the reverse of the desired outcome. Consequently, this result needs further investigation.

4.4.4.2.2. *Phase II.*

Although irrigation treatments were initiated on day 55 a.f.b., the differences in W between RDI and full irrigation treatments became significant under plastic and control from day 67 a.f.b. Under lucerne, this did not occur until day 73 a.f.b. (Figures 4.6, 4.7 and 4.8). Under plastic X RDI, W increased from 188.3 to 216.8 mm where it remained until day 93 a.f.b.

Although water stored under plastic X full irrigation decreased slightly during Phase II, and under lucerne remained constant, control treatment showed a somewhat different pattern. A continuous decrease in W from day 93 to 131 a.f.b. was measured for the control treatment under full irrigation, which suggested from this time in Phase II the amount of water applied was insufficient to satisfy the crop ET.

Table.4.5. Changes in total soil water storage (W) during Phase II.

	W(mm)			
Treatment	Day 67 a.f.b.	Day 102 a.f.b.	ΔW	Water Use (mm)
Plastic X Full Irrig.	234.6 a[z]	194.3 c[y]	-40.3 a	-124.9 c
Plastic X RDI	216.8 b	179.1 d	-37.7 a	-58.9 e
Control X Full Irrig.	222.5 b	228.1 a	+5.6 d	-177.4 b
Control X RDI	183.2 c	201.9 b	+18.7 b	-89.1 d
Lucerne X Full Irrig.	196.6 c	190.7 c	-5.9 d	-183.1 a
Lucerne X RDI	163.1 d	172.9 d	+9.8 c	-98.0 d

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

After irrigation treatments were initiated on day 55 a.f.b., W increased in all treatments with respect to the minimum values reached in Phase I. The changes in W from day 67 to 102 a.f.b. are shown in Table 4.5. Results indicated an overall decline in W during Phase II in plastic treatments and control and lucerne X full irrigation. The largest decrease occurred in plastic X RDI. On the other hand, W increased under RDI treatments receiving rainfall, indicating a positive soil water balance under these treatments. This would be expected to occur until the soil water potential, reduced under the preceding drying conditions, returned to the equilibrium determined by the water potential under the new conditions. Nevertheless, the pattern of water use during this period (Table 4.5) reveals the extent to which the trees were able to meet their water requirements under their respective treatments. Results (Figures 4.6, 4.7 and 4.8) indicated a decline in W from day 93 to 102 in all the treatments. This decline coincided with a dry period (Figure 4.2) during which all irrigation treatments received the same amount of water. One can therefore, infer that the decline in W reflected a change in the pattern of water extraction by the crop.

By considering the net water input during the period, the greatest water use occurred under lucerne X full irrigation. This was significantly higher than the water use of control and plastic X full irrigation. Among the RDI treatments, water use was the highest in lucerne though not significantly different from control. The lowest water use was obtained under the plastic X RDI treatment. Results show that water use was proportional to water input, with greater water use in those treatments receiving a higher input. Due to the higher input, W was higher and also the root zone wetter in these treatments. Lucerne and plastic X RDI resulted in the lowest soil water storage during the period. In terms of soil drying these results suggest that plastic became effective after the tree became an active water user. It was noticeable, owing to the high rate of water use exhibited by the lucerne X RDI treatment that this treatment was capable of maintaining a lower water storage than was possible when excluding rainfall with plastic mulch.

4.4.4.2.3. *Phase III.*

Full irrigation was given to all treatments from day 110 a.f.b. All treatments, except control X full irrigation, showed an increase in W until day 117 a.f.b. (Figures 4.6, 4.7 and 4.8). Values of W under plastic and lucerne X RDI however, declined from day 117 to 122 a.f.b. The magnitude of the decline was greatest under lucerne X RDI reaching the lowest value of the whole season on day 131. This decline coincided with a period without rainfall from day 113 to 127 a.f.b. The highest figures in W of Phase III were reached on day 148 a.f.b. These were only slightly higher than the initial values of Phase I. These results suggested that in treatments in which RDI had been applied previously, the amount of irrigation given in Phase III was insufficient to satisfy the crop water demand. Rainfall from day 128 compensated for the deficiency in stored water. Since all treatments received the same amount of irrigation water during Phase III, it follows that excepting control treatment, trees that had previously received RDI used more water during this period.

4.4.4.3. *Accumulated Soil Water Deficit.*

4.4.4.3.1. *Phase I.*

To describe more accurately the interaction between the climate, treatments and plant water use, the cumulative soil water deficit was used. For this purpose, the first day of measurements was taken as day 0. When the accumulated sum reached zero, the deficit was assumed to equal zero. Positive values were then considered as water excess and added to the drainage losses.

During Phase I (Table 4.6), the lucerne treatment resulted in the highest cumulative soil water deficit. This deficit was significantly higher than that obtained under the control and plastic. This occurred because the rate of water use was the highest under lucerne treatments. Since during Phase I, irrigation was withheld results indicated that lucerne was substantially more effective than plastic and the control in creating a soil water deficit in the root zone of the crop during this stage. Results are illustrated in Figures 4.9, 4.10 and 4.11.

Table.4.6. Accumulated soil water deficit over the planting square (ΔW) during Phase I.

Treatment	ΔW^z(mm) Day 49 a.f.b.	Rate Water Use (mm/day)
Plastic X Full Irrig.	-42.19 c^y	1.83 c^x
Plastic X RDI	-41.98 c	1.82 c
Control X Full Irrig.	-48.05 b	3.63 b
Control X RDI	-48.15 b	3.63 b
Lucerne X Full Irrig.	-70.79 a	4.62 a
Lucerne X RDI	-74.10 a	4.76 a

^{z} Change in W with respect to first day of measurement.
^{y} Mean separation within columns by LSD, 5 % level.
^{x} Means with same letter are not significantly different.

4.4.4.3.2. *Phase II*

Table 4.7 shows that all RDI treatments resulted in a significantly higher cumulative soil water deficit than their respective full irrigation treatments. By day 67 a.f.b., 13 days after irrigation treatments of Phase II were initiated, the soil water deficit showed a clear definition of effects of RDI treatments. The greatest deficit was created under lucerne X RDI treatment. This deficit was significantly greater than the deficit under plastic and control X RDI. Irrigation treatments plus 51 mm rainfall (in those treatments receiving it) caused an increase in water storage in those treatments by day 93 a.f.b. decreasing the accumulated soil water deficit with respect to the deficit accumulated at the end of the withholding period.

Table.4.7. Accumulated soil water deficit (ΔW) over the planting square during Phase II.

	ΔW^z(mm)		
Treatment	Day 67 a.f.b.	Day 93 a.f.b.	Day 102 a.f.b.
Plastic X Full Irrig.	-38.43 e^y	-39.12 b^x	-56.98 c
Plastic X RDI	-52.83 d	-56.14 a	-75.93 a
Control X Full Irrig.	-48.60 d	-16.50 c	-40.33 d
Control X RDI	-78.60 b	-46.45 b	-66.90 b
Lucerne X Full Irrig.	-61.18 c	-19.51 c	-45.49 d
Lucerne X RDI	-86.77 a	-46.22 b	-65.46 b

[z] Change in W with respect to first day of measurement.

[y] Mean separation within columns by LSD, 5 % level.

[x] Means with same letter are not significantly different.

As a result, plastic X RDI exhibited the highest accumulated soil water deficit at this stage. An apparent change in the rate of water extraction was observed from day 93 to 102 a.f.b. in all treatments (Figures 4.9, 4.10 and 4.11), which was more obvious in the plastic X RDI treatments. This change in water use may suggest an increase in fruit growth rate and may indicate the time when full irrigation should have commenced. A similar increase in the rate of soil water extraction resulting from increased fruit growth rate has been reported for peaches (Olsson, 1977).

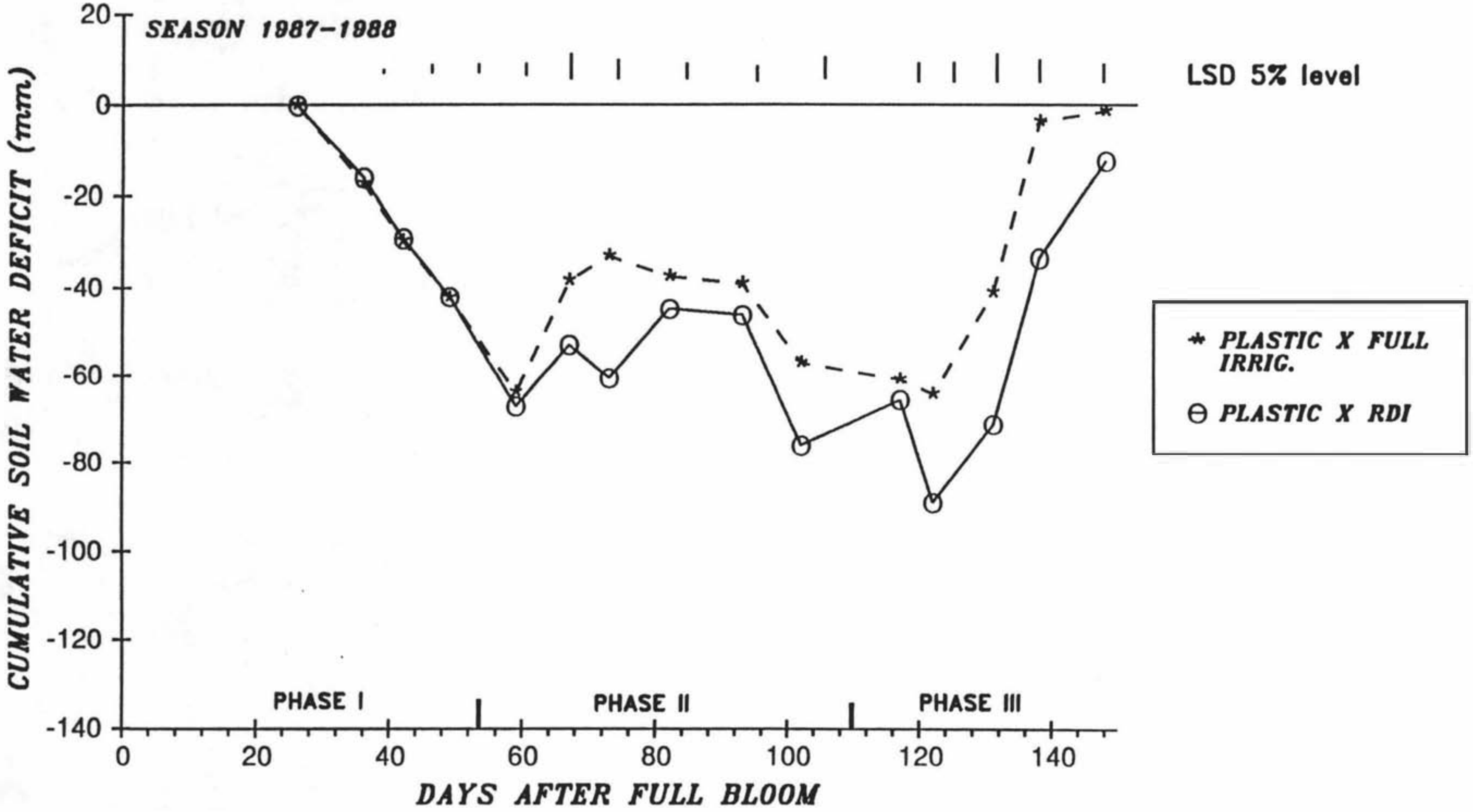

Figure 4.9. Cumulative soil water deficit obtained under plastic treatments during the growing season 1987-1988.

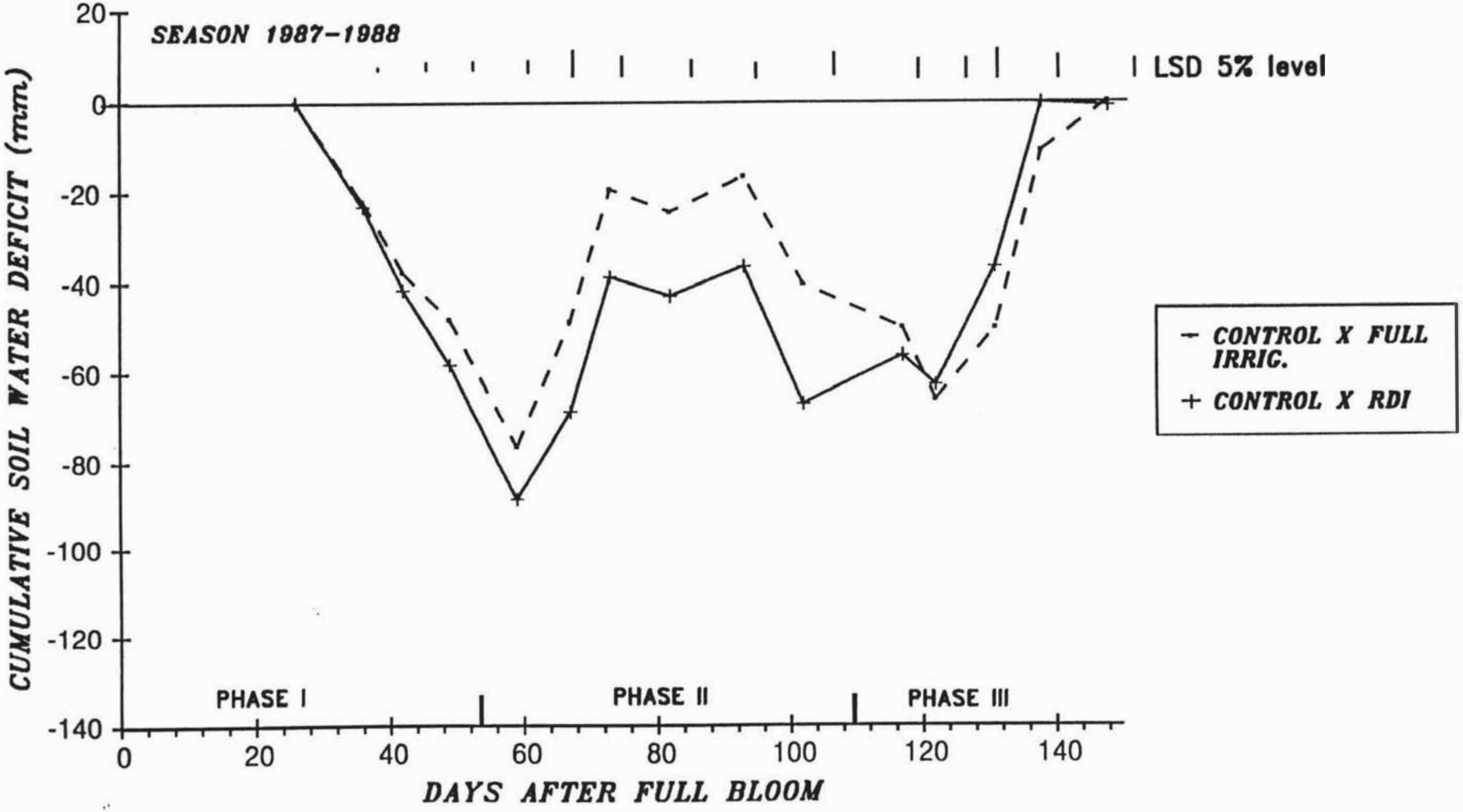

Figure 4.10. Cumulative soil water deficit obtained under control treatments during the growing season 1987-1988.

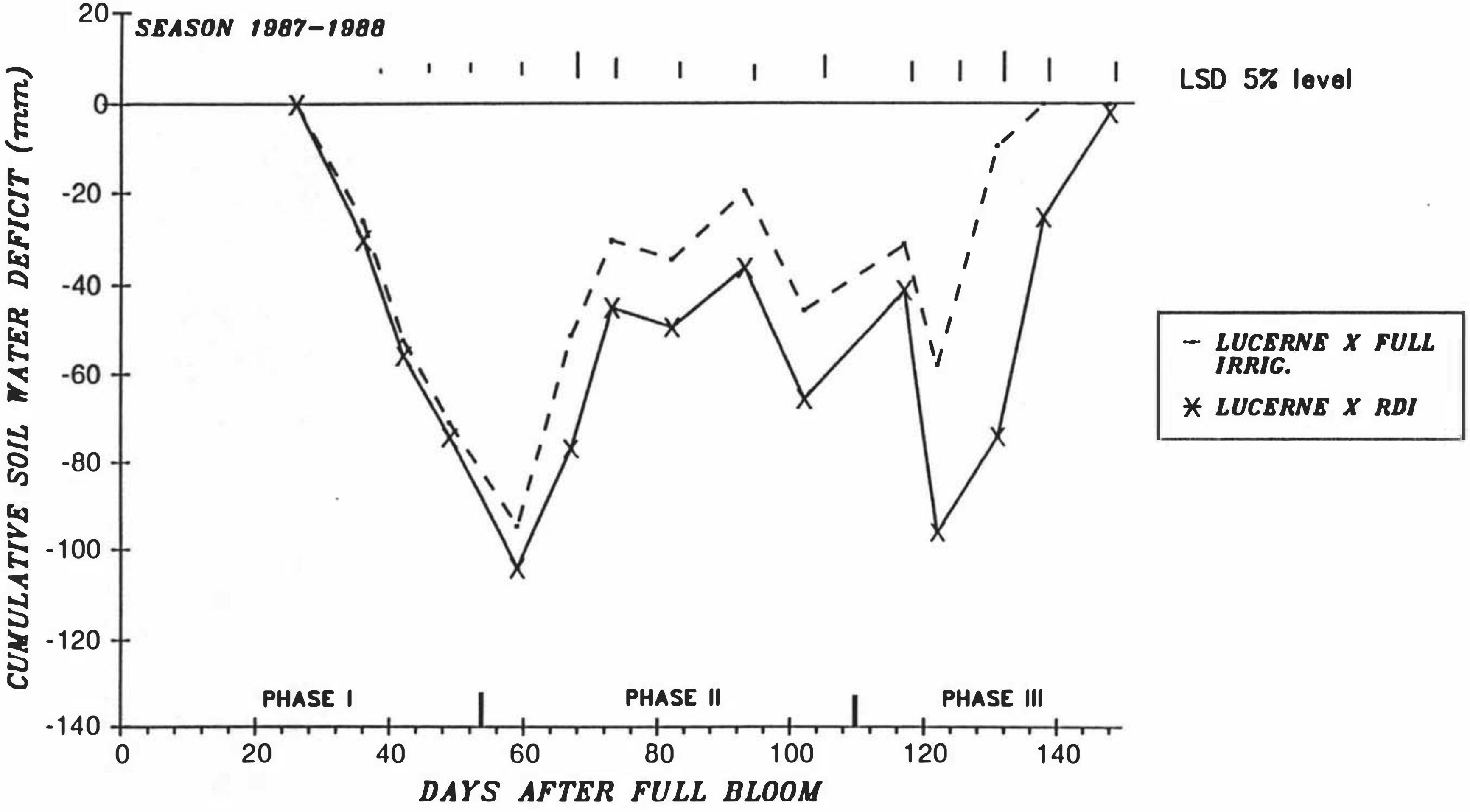

Figure 4.11. Cumulative soil water deficit obtained under lucerne treatments during the growing season 1987-1988.

4.4.4.3.3. *Phase III.*

Table.4.8. Accumulated soil water deficit (ΔW) over the planting square during Phase III.

	ΔW^{z}(mm)		
Treatment	Day 117 a.f.b.	Day 131 a.f.b.	Day 148 a.f.b.
Plastic X Full Irrig.	-60.83 ab^{y}	-41.10 b^{x}	-1.35 b
Plastic X RDI	-65.46 a	-71.06 a	-12.36 a
Control X Full Irrig.	-50.08 c	-50.12 a	-0.76 b
Control X RDI	-56.17 bc	-36.63 b	-1.03 b
Lucerne X Full Irrig.	-31.15 e	-19.96 c	-4.05 b
Lucerne X RDI	-41.11 d	-73.90 a	-2.04 b

^{z} Change in W with respect to first day of measurement.
^{y} Mean separation within columns by LSD, 5 % level.
^{x} Means with same letter are not significantly different.

Full irrigation was given to all treatments from day 110, (Table 4.8) which slightly ameliorated the soil water deficit by day 117 for all treatments except plastic X RDI. The deficit under plastic remained significant greater than the rest of the treatments. By day 131, soil water deficit increased in all the treatments except lucerne X full irrigation and control X RDI. The greatest deficit resulted in plastic and lucerne X RDI, though the difference between them was not significant. Since all treatments were receiving the same amount of irrigation, differences indicate a different rate of crop water use between treatments under full irrigation. Lucerne X RDI and plastic X RDI showed the highest rate of water use at this stage. Additionally, the data suggests that full irrigation was not enough to satisfy the high evaporative demand during this period, when period, when high values of E_p and low precipitation were experienced. Rainfall from days 138 to harvest compensated for the deficit which had become significantly lower than other treatments in plastic X RDI.

4.4.4.3.4. *Relationship Between Cumulative Predicted ET and Cumulative Soil Water Deficit Measured.*

Table 4.9 shows the determination coefficients (r^2) for linear regression between cumulative predicted ET and the accumulated soil water deficit. In Phase I, all treatments except control X RDI resulted in a r^2 which was highly significant (at 1 % level) and also of a high order (range 0.72 to 0.94). In contrast, all treatments resulted in a lack of fit to a linear regression in Phase II. Treatments in Phase III were significant at the 5% level, except the lucerne X RDI and lucerne X full irrigation.

Table 4.9. Determination coefficients (r^2) for cumulative predicted ET to cumulative soil water deficit measured.

	r^2		
Treatment	Phase I	Phase II	Phase III
Plastic X Full Irrig.	0.84 **	0.02 ^{NS}	0.66 *
Plastic X RDI	0.94 **	0.02 ^{NS}	0.62 *
Control X Full Irrig.	0.72 *	0.26 ^{NS}	0.60 *
Control X RDI	0.66 *	0.08 ^{NS}	0.60 *
Lucerne X Full Irrig.	0.80 **	0.15 ^{NS}	0.51 ^{NS}
Lucerne X RDI	0.75 *	0.45 ^{NS}	0.57 ^{NS}

$^{*, **}$ Significance at 5% and 1% levels respectively.

^{NS} = non significant

4.4.4.4 *Effect of Treatments on Pattern of Water Extraction* .

4.4.4.4.1. *Pattern with Depth.*

The proportion of the total volume extracted at depths from 0-600 and 600 to 1000 mm is shown in Table 4.10. By examining the time changes in water extraction under the different irrigation strategies, one observes the predominance of surface roots under the full irrigation treatments. This was most accentuated under lucerne full X irrigation in the period between days 117 to 122 a.f.b. (Phase III). During the period between days 59 to 67 a.f.b. (Phase II), full irrigation treatments showed a slight but not significant increase in root extraction from the bottom layers of the soil. However, plastic X RDI showed a significantly different pattern with 63% of the water withdrawn from the bottom layer. This pattern suggests the onset of water stress under plastic X RDI. Although the accumulated water deficit showed a greater deficit in lucerne and control X RDI, water extraction from the top layers was predominant. The water extraction by day 122 a.f.b. (Phase III) had returned to predominantly surface root activity.

4.4.4.4.2. *Pattern with Distance From the Tree.*

Since a detailed analysis of the effect of distance on the pattern of water extraction showed no significant changes through time, data was pooled to evaluate the effects of treatments. Figure 4.12 displays results of this analysis. In general, a greater proportion of water was extracted at 750 mm from the tree which implies a greater volume of soil explored. No significant effect of irrigation was detected on the pattern of water extraction in relation to distance from the tree.

Table 4.10. Effects of treatments on percentage of water extracted from different depths in the root zone.

Treatment	Day 26-36 a.f.b.		Day 59-67 a.f.b.		Day 117-122 a.f.b.	
	0-600 mm[z]	600-1000 mm	0-600 mm	600-1000 mm	0-600 mm	600-1000 mm
Plastic X Full Irrig.	64.9 b[y]	35.1 a[x]	51.9 b[w]**	48.1 b**	72.3 b**	27.7 c**
Plastic X RDI	65.2 b	34.8 a	37.3 c**	62.7 a**	52.5 d**	47.5 a**
Control X Full Irrig.	64.4 b	35.6 a	59.4 a^{NS}	40.6 c^{NS}	63.9 c^{NS}	36.1 b^{NS}
Control X RDI	61.5 b	38.5 a	65.3 a^{NS}	34.7 cd^{NS}	64.8 c^{NS}	35.2 b^{NS}
Lucerne X Full Irrig.	75.8 a	24.2 b	63.6 a**	36.4 c**	82.4 a**	17.6 d**
Lucerne X RDI	61.7 b	38.3 a	61.7 a^{NS}	32.5 d^{NS}	76.0 ab**	23.9 c**

[z] Depth.

[y] Percent of total volume.

[x] Mean separation within columns by Duncan's multiple range test, 5% level.

[w] Means with same letter are not significantly different.

NS, *, ** = non significant, significant at 5% (*) and significant at 1% (**) levels respectively.

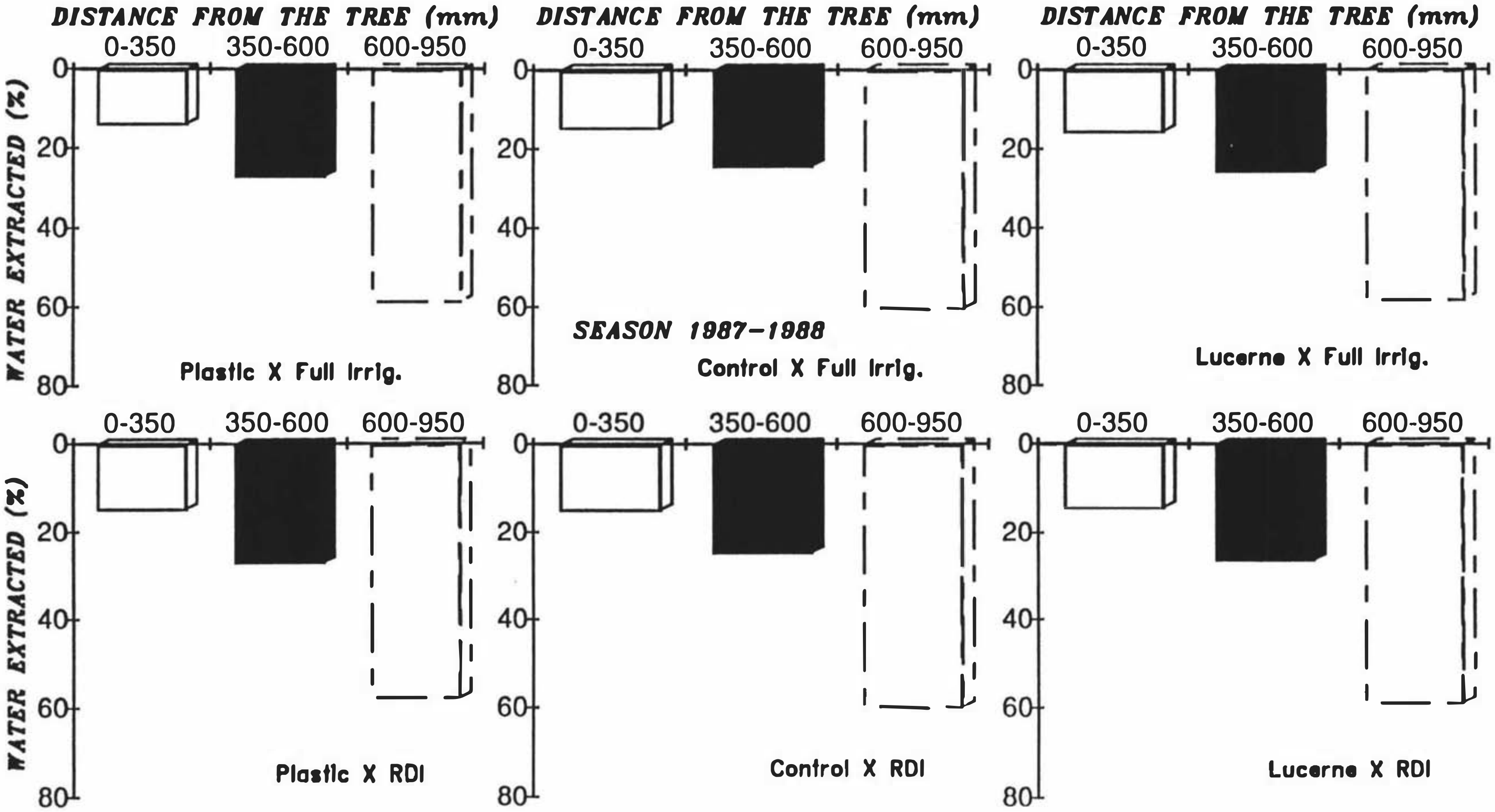

Figure 4.12. Pattern of soil water extraction with distance from the tree for treatments during a selected period.

4.4.5. *Diurnal Pattern of Leaf Water Potential.*

On day 53 a.f.b. (Figure 4.13) it can be seen that treatments that in most treatments Ψ_L became more negative from 6 am to midday, but minimum values were not reached until later in the day. In lucerne X full irrigation and RDI treatments Ψ_L continued decreasing at a considerable rate until 18 hrs. These Ψ_L values were significantly lower than the other treatments in lucerne X RDI, with a mean of -1.76 MPa. Statistical analysis indicated no significant differences in Ψ_L measured at 6 am.

The pattern obtained on 82 day a.f.b. did not reveal differences between treatments. Values of Ψ_L were in general less negative than on day 53 a.f.b. Minimum values were obtained at midday.

On day 122 a.f.b. significant differences in YL between treatments were evident at 6 am. The lowest values, which were not significantly different, were obtained in lucerne and plastic X RDI. The maximum Ψ_L was obtained for control X full irrigation. A marked decrease was obtained in all the treatments from 6 am to 10 am, reaching the minimum daily values at midday. Minimum values were significantly less negative for the three full irrigation treatments. The minimum values for all treatments were lower than those obtained on day 82 a.f.b. A recovery to less negative values, however, took place from midday to 18 hours. Since the pattern of root extraction showed that on day 122 all the treatments had returned to surface root extraction the decline in Ψ_L observed here suggests that the fruit presence might have influenced the pattern obtained on day 122 a.f.b. These results are in agreement with previous studies in which low Ψ_L may be associated with increased transpiration (Hansen, 1970; Chalmers *et al.* 1983; Erf and Proctor, 1987). Minimum values in Ψ_L were registered at 10 am on day 148 a.f.b. The pattern measured on this day did not reveal significant differences between treatments.

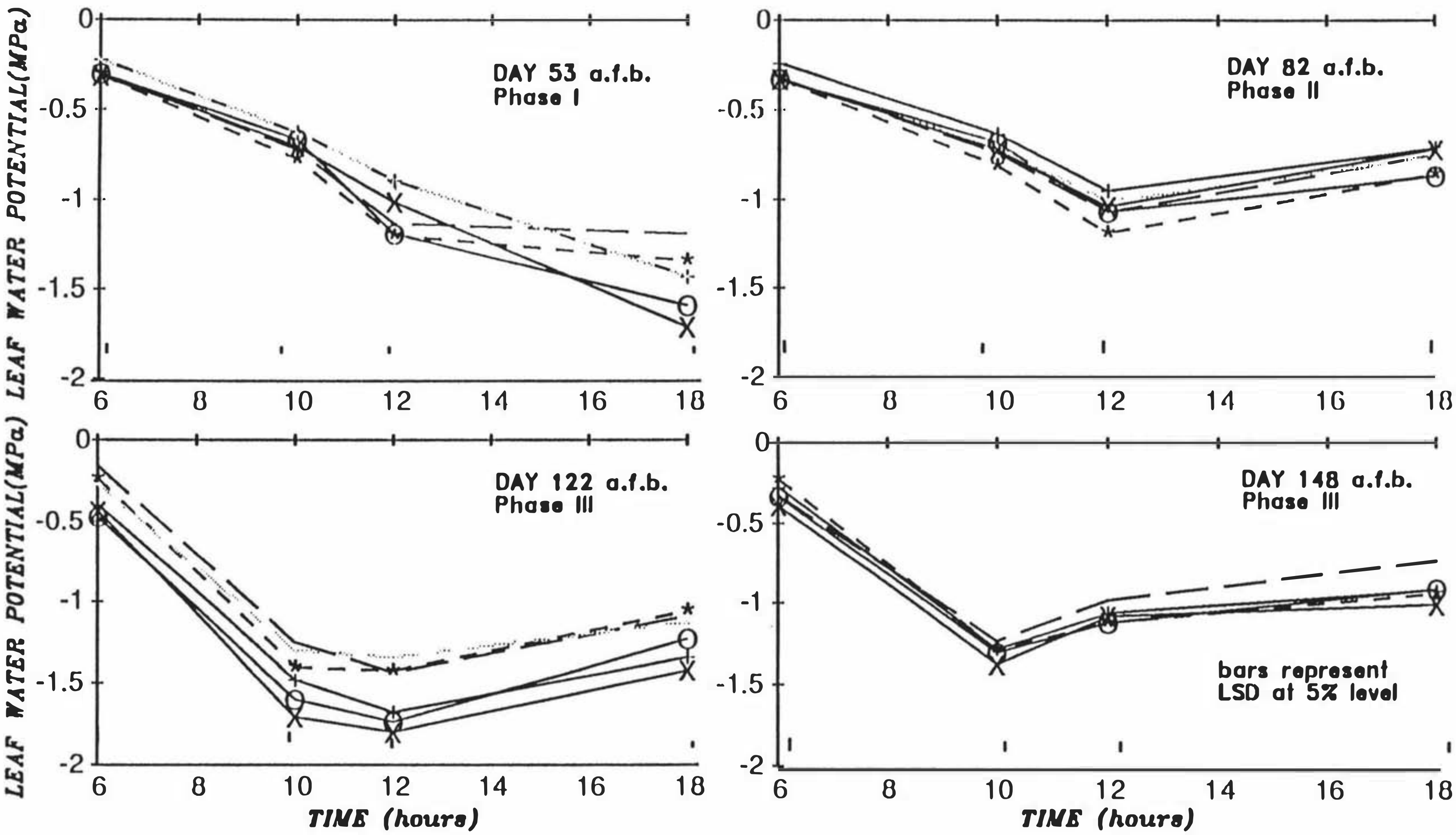

Figure 4.13. Diurnal pattern of leaf water potential (Ψ'_L) for all the treatments during days 53, 82, 123 and 148 after full bloom. Plastic X Full Irrig.(.*.); Plastic X RDI (O); Control X Full Irrig.(--); Control X RDI (+); Lucerne X Full Irrig.(-.-.); Lucerne X RDI (**X**).

4.4.6. *Effects of Treatments on Diurnal Pattern of Photosynthesis.*

For plastic and control treatments the daily maximum photosynthesis rate occurred at 10 am on day 53 a.f.b., while for the other treatments photosynthesis rate reached maximum values at midday (Figure 4.14). Midday values of photosynthesis for the former treatments, however, declined to values that were not significantly different from maximum of other treatments. All treatments declined to approximately same value at 4 pm. Plastic treatments, under which the total soil water storage by this time was higher, exhibited higher rate of photosynthesis for a longer period. Other treatments showed a more flattened diurnal pattern at this time. Not significant differences in diurnal pattern of photosynthesis were detected by day 82 a.f.b. Maximum values were obtained between 10 am and midday. On day 122 a.f.b. the highest maximum assimilation rate was obtained for the control X RDI. This was significantly different from other treatments. In contrast, the lucerne X RDI maximum for day 122 a.f.b. was the lowest among all the treatments and it was measured at 10 am. No significant differences were obtained in the maximum value of other treatments which occurred between 10 am to midday. The maximum rate of photosynthesis was recorded on control X RDI on day 148 a.f.b. Although this was not significantly higher than plastic X RDI at 10 am. Plastic X RDI, however, started to decline at midday while control X RDI reached the maximum at midday. High rates of photosynthesis during the stage of rapid fruit growth has been reported in peaches (Olsson, 1977.,Chalmers *et al.* 1983) and also on apple (Avery and Moore, 1978; Fujii and Kennedy,1985). In this study also, high rates of photosynthesis during rapid fruit growth appeared to be associated with crops that received RDI. Accordingly, the rate of fruit growth of these treatments was the highest.

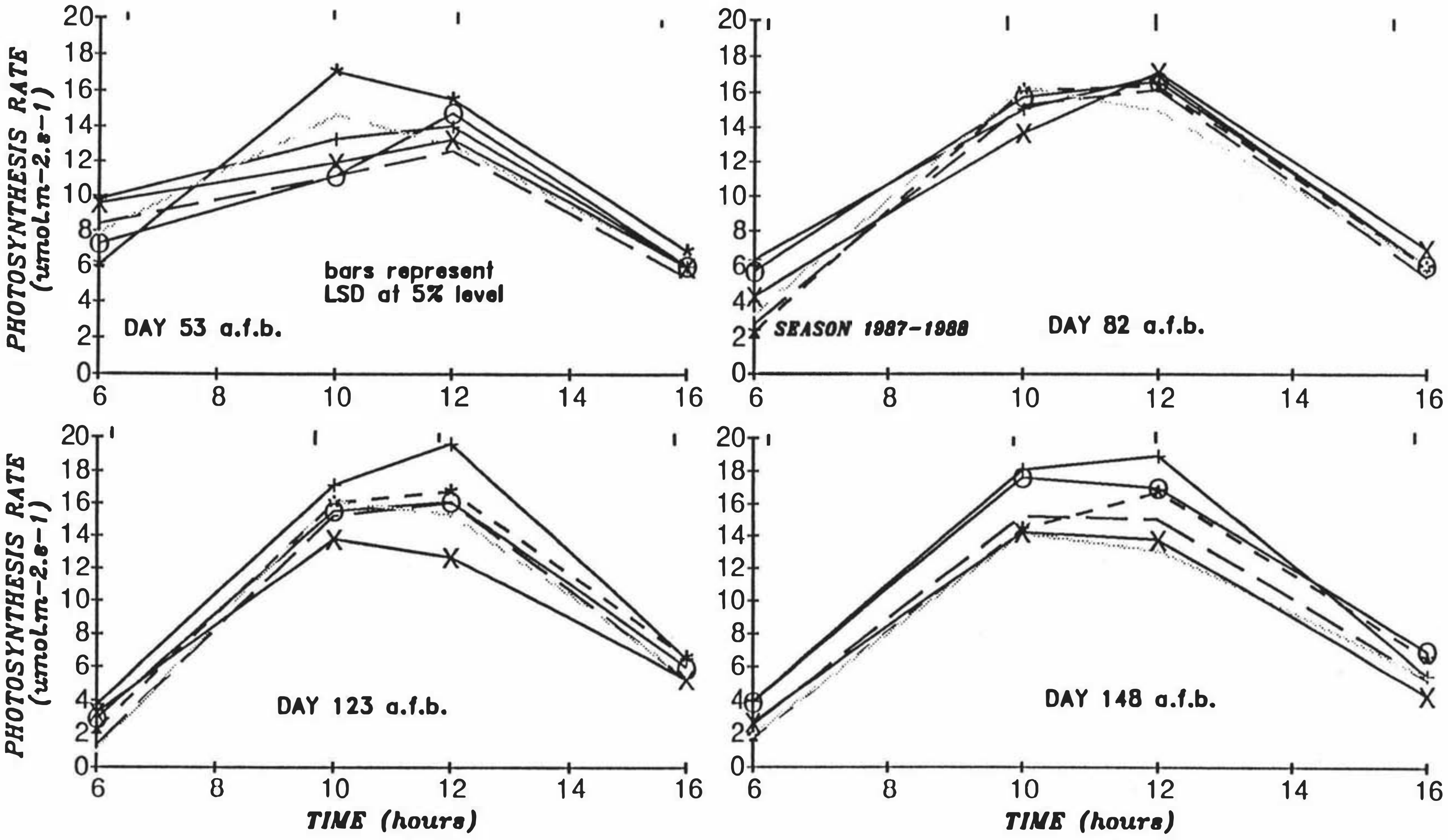

Figure 4.14. Diurnal pattern of photosynthesis rate for all treatments during days 53, 82, 123 and 148 after full bloom. Plastic X Full Irrig.(.*.); Plastic X RDI (O); Control X Full Irrig.(--); Control X RDI (+); Lucerne X Full Irrig.(-.-.); Lucerne X RDI (X).

4.4.7. *Effects of Treatments on Stomatal Conductance.*

An examination of the diurnal pattern of stomatal conductance on day 53 a.f.b. (Figure 4.15) shows a high peak of stomatal conductance at midday. The highest midday value was recorded in the control treatment, followed by lucerne. The lowest maximum was recorded in the plastic treatments. The high stomatal conductance obtained in treatments might be a response to increased soil moisture caused by rainfall events during preceding days. The diurnal pattern of stomatal conductance on day 82 a.f.b. changed to flattened curves. A small peak was obtained between 6 and 10 am, which was slightly higher in plastic X RDI. The highest stomatal conductance recorded at 10 am and midday was for control X RDI. On day 122 a.f.b. full irrigation treatments had higher stomatal conductance at dawn than RDI treatments. A decrease was obtained in all treatments by 10 am, but maximum values were reached at 14 hr under control and plastic X RDI which were significantly higher than other treatments. These results appeared to be correlated with the lowering in Ψ_L and the high photosynthesis rate recorded on same day (Figure 4.14). By day 148 a.f.b., when harvest was initiated, stomatal conductance was higher inmediately after dawn values than during the day.

4.4.8. *Effects of Treatments on Vegetative Growth.*

4.4.8.1. *Trunk Cross Sectional Area* (TCSA).

The analysis of variance showed no significant differences in TCSA due to soil management or to irrigation when the two variables were analysed separately. An analysis of variance considering these variables in interaction is shown in Table 4.11. The data showed that the plastic X full irrigation and control X RDI resulted in the smallest increase in TCSA. The other treatments were not significantly different. When the data were expressed as relative growth rate by which any possible effect of initial differences was eliminated, it was evident that not significant differences between treatments was obtained.

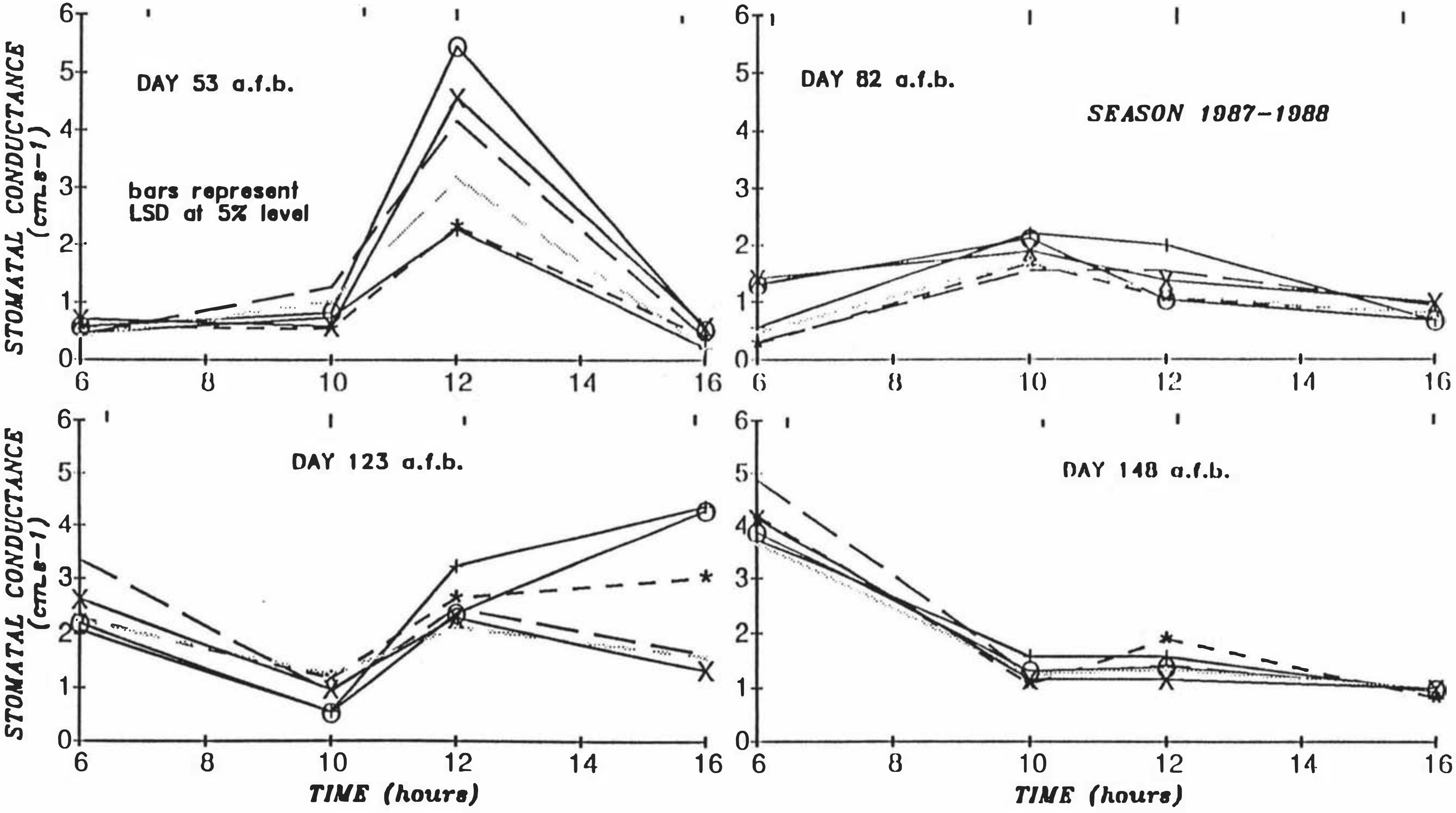

Figure 4.15. Diurnal pattern of leaf conductance for all treatments during days 53, 82, 123 and 148 after full bloom. Plastic X Full Irrig.(.*.); Plastic X RDI (O); Control X Full Irrig.(--); Control X RDI (+); Lucerne X Full Irrig.(-.-.); Lucerne X RDI (**X**).

This data indicated there was no effect of RDI on trunk growth during the first season.

Table 4.11. Absolute and relative trunk cross sectional area (TCSA) increase during season 1987-1988.

Treatment	Absolute Growth (cm^2)	Relative Growth $cm^2.cm^{-2}$
Plastic X Full Irrigation	10.71 b[z]	0.38 a[y]
Plastic X RDI	14.28 a	0.50 a
Control X Full Irrigation	12.69 a	0.43 a
Control X RDI	9.22 b	0.33 a
Lucerne X Full Irrigation	11.37 a	0.37 a
Lucerne X RDI	11.85 a	0.39 a

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

4.4.8.2. *Shoot Growth.*

The irrigation regimes in combination with the soil management caused considerable effect on shoot length. Figure 4.16 illustrates the accumulated shoot growth during the growing period. Under control and plastic X full irrigation, shoot growth was significantly higher than the remaining treatments. Lucerne X full irrigation had an accumulated growth closer to the RDI treatments than to the other full irrigation treatments. No significant difference was obtained between lucerne X full irrigation and control and plastic X RDI. Nevertheless, lucerne X RDI showed a significantly lower growth than other treatments except the plastic X RDI. Differences obtained at end of Phase I might be related to different levels of stored insoluble carbohydrates in shoots from previous season's growth (as explained in pears by Brun *et al.* 1985) pears) overlapping with the soil water deficit of present season.

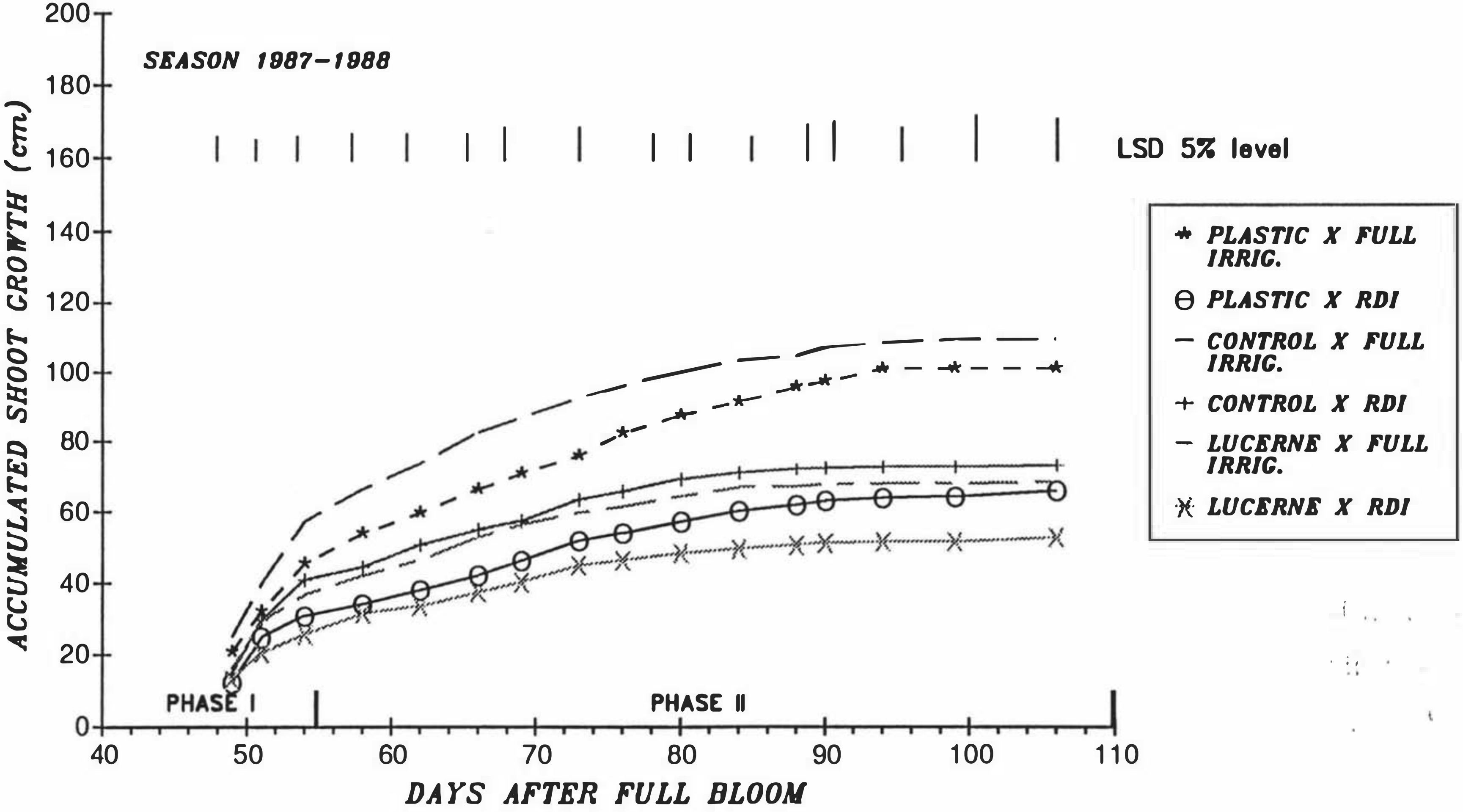

Figure 4.16. Accumulated shoot growth for all the treatments from day 48 to 106 after full bloom.

From day 78 a.f.b. shoot growth for lucerne X RDI became significantly lower than control RDI. From this time, a decline in rate of growth, which had ceased by day 80, was obtained under lucerne X RDI. Shoot growth of lucerne X full irrigation, and control and plastic X RDI ceased 5 days later. Control and plastic under full irrigation treatments continued their shoot elongation until day 94.

Results showed that RDI was effective in controlling vegetative growth early in the growing season. The fact that lucerne X full irrigation resulted in shoot growth closer to RDI treatments than to other full irrigation treatments indicates that lucerne X full irrigation had an effect on soil drying similar to RDI, and could therefore have possibilities for control of vegetative growth. Overall, results suggest that RDI treatments applied until day 84 a.f.b. were sufficient to slow down vegetative growth substantially.

As compared with data for pear trees receiving 0.23 EPS, reported by Mitchell *et al.* (1989), with the maximum levels of soil deficit of 88 and 97 mm obtained under control and plastic X RDI, supression in summer pruning of 22.8 and 24 % respectively would be expected. Whilst for the 104 mm cumulative soil water deficit obtained under lucerne X RDI, the equivalent suppression in summer pruning would have been 25.3%. Our results, however, revealed for the former treatments 33.4 and 39.8 % respectively and for the later 51.7 %. These figures are of the order of 10 to 15 % greater than expected under plastic and control X RDI, while double the expected suppression was obtained under lucerne X RDI. Two factors might be considered to be involved in the magnitude of the response. First, the maximum soil water deficit under the treatments was reached as early as day 55 a.f.b. and secondly, the trees were apples and only 3 years old. From the works of Hsiao (1973) and Lackso (1983, 1984) hypothesis and evidences indicate that cell elongation is highly sensitive to water deficit, and that moderate levels of water stress can inhibit the growth of immature tissue.

On the other hand, the data used by Mitchell *et al.* (1989) summarized work with peaches and pears (see later discussion).

4.4.9. *Effects of Treatments on Fruit Growth.*

4.4.9.1. *Phase I and II.*

In general, there were no significant differences between the rates of fruit growth during Phase I (Figure 4.17 and Table 4.12). Since the decline in soil water content during this Phase reflected differences between surface management treatments, the lack of a similar response in fruit growth suggests fruit growth was not affected by the soil water deficit during this Phase.

Table 4.12. Effect of treatments on fruit growth rate (cm^3·day^{-1}) during Phase I.

Treatment	Day 40-46 a.f.b.	Day 46-51 a.f.b.	Day 51-54 a.f.b.
Plastic X Full Irrig.	0.25 a[z]	0.46 a[y]	0.66 a
Plastic X RDI	0.23 a	0.39 a	0.60 a
Control X Full Irrig.	0.27 a	0.48 a	0.69 a
Control X RDI	0.26 a	0.42 a	0.64 a
Lucerne X Full Irrig.	0.26 a	0.48 a	0.66 a
Lucerne X RDI	0.23 a	0.42 a	0.57 a

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

Table 4.13 and Figure 4.17 showed that during Phase II, similar results to those of Phase I were obtained. While there were some data which indicated significant differences between treatments, only lucerne X RDI between day 96 to 100 a.f.b. was logically consistent.

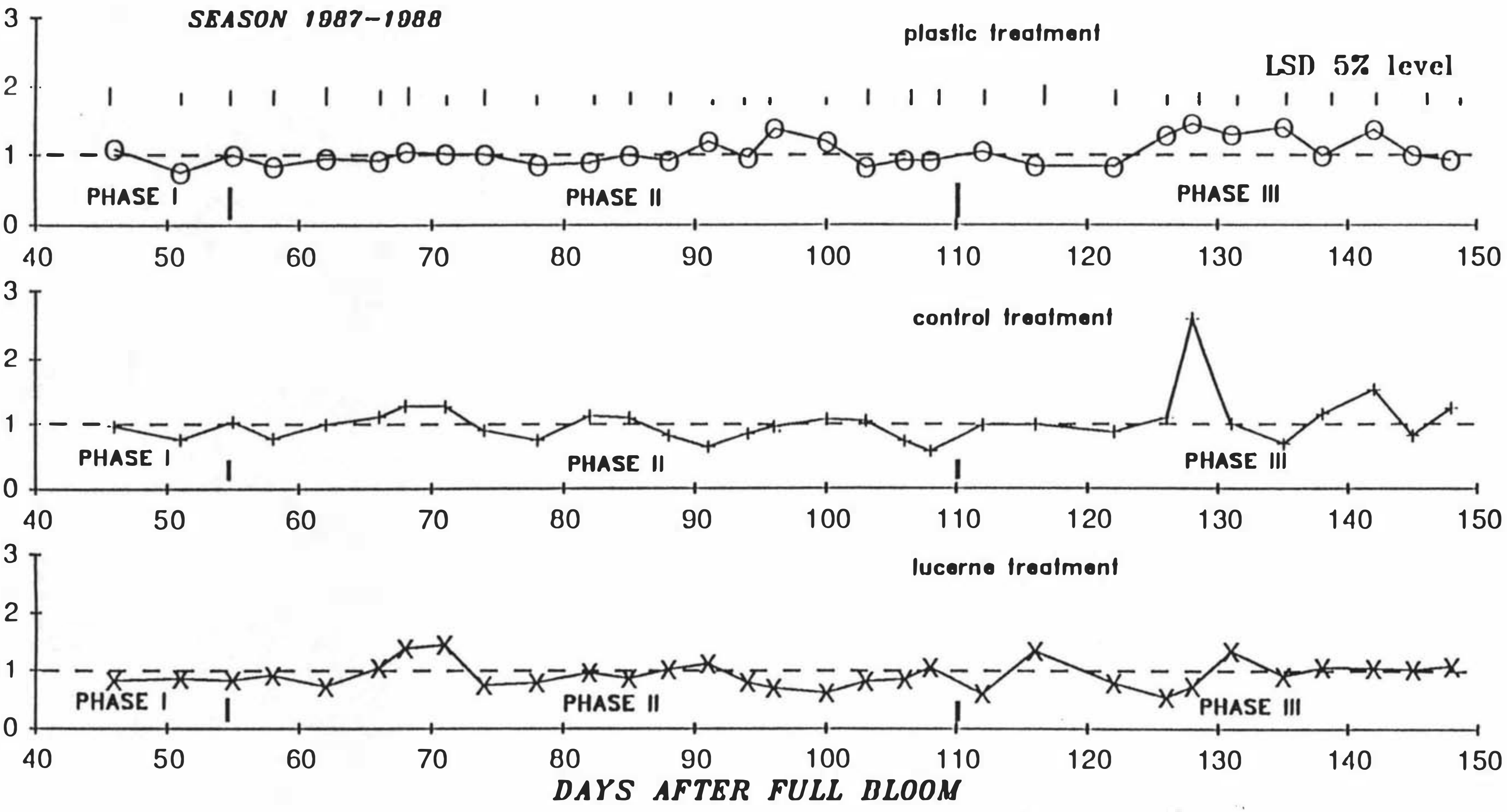

Figure 4.17. Ratio between fruit growth rate of RDI treatments to the respective full irrigation treatment.

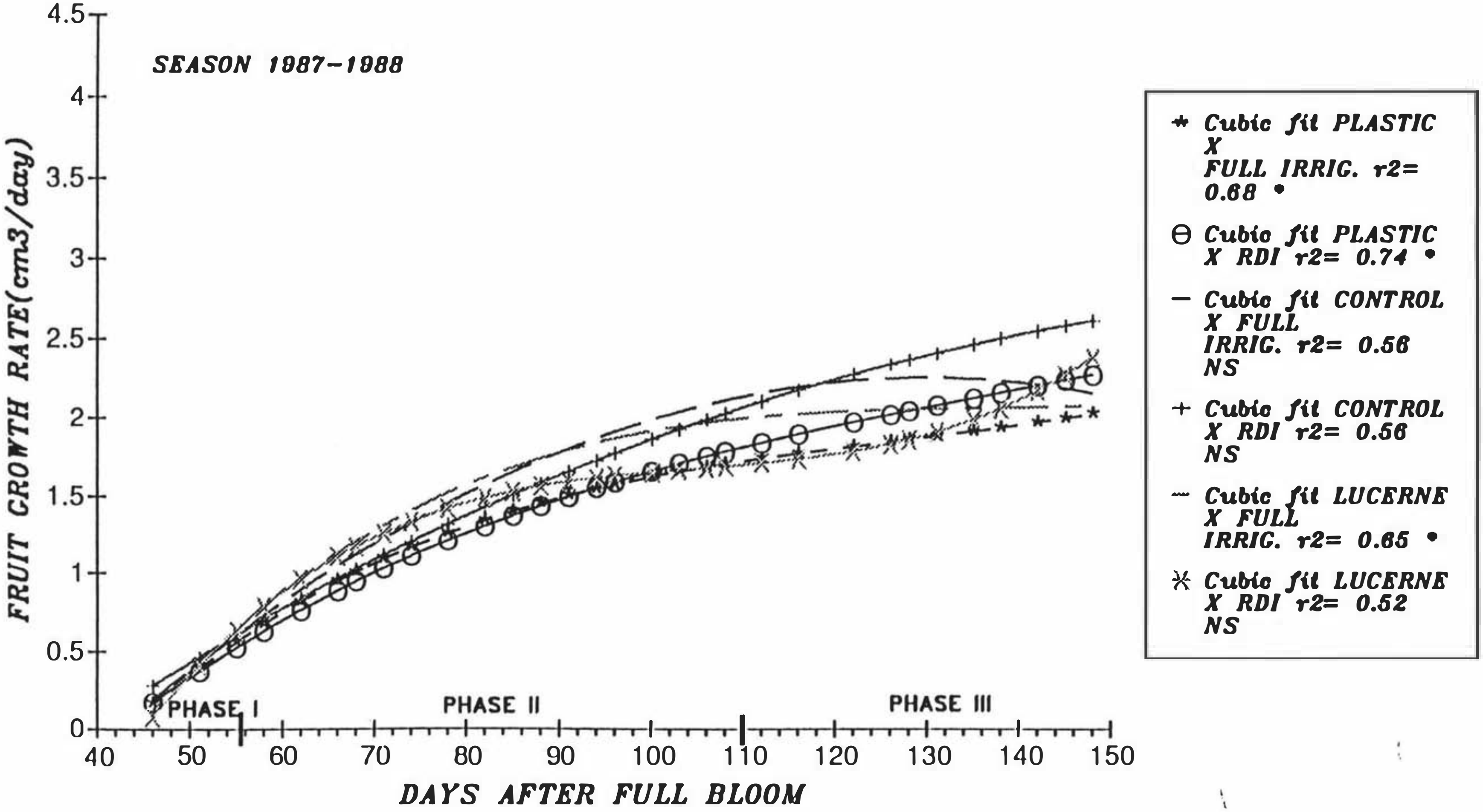

Figure 4.18. Cubic fit for fruit growth rate during growing season 1987-1988.

In general, there was no apparent suppression of fruit growth that could be clearly related to soil water deficit, particularly during the early part of Phase II.

Table 4.13. Effect of treatments on fruit growth rate ($cm^3 \cdot day^{-1}$) during selected periods of Phase II.

Treatment	Day 78-82 a.f.b.	Day 85-88 a.f.b.	Day 96-100 a.f.b.
Plastic X Full Irrig.	1.75 a[z]	1.74 a	1.32 c
Plastic X RDI	1.56 b	1.60 a	1.56 a
Control X Full Irrig.	1.72 a	2.07 a	1.65 a
Control X RDI	1.95 a	1.71 a	1.78 a
Lucerne X Full Irrig.	2.09 a	1.94 a	1.94 a
Lucerne X RDI	2.03 a	1.98 a	1.20 c

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different

4.4.9.2. *Phase III.*

From day 125-128 a.f.b. (Table 4.14) a marked increase in growth was observed in control X RDI fruit with respect to the full irrigation treatment and the other RDI treatments. Plastic X RDI also showed a higher rate than the full irrigation treatment, though this was not significant at 5% level. From day 128-131, the RDI treatments, except control, showed a higher growth rate than their respective full irrigation treatments. Differences were significantly, however, only for fruits from lucerne treatments. Figure 4.17 shows that during the period between day 138 to 142 a.f.b., plastic X RDI resulted in a higher fruit growth rate than the respective full irrigation.

Table 4.14. Effect of treatments on fruit growth rate (cm$^{3}\cdot$day^{-1}) during selected periods of Phase III.

Treatment	Day 125-128 a.f.b.	Day 128-131 a.f.b.	Day 138-142 a.f.b.
Plastic X Full Irrig.	1.47 b	1.93 c	2.12 b
Plastic X RDI	2.15 b	2.49 bc	2.91 a
Control X Full Irrig.	1.67 c	3.19 a	1.59 b
Control X RDI	4.38 a	3.23 a	2.47 a
Lucerne X Full Irrig.	1.95 b	2.67 b	2.17 a
Lucerne X RDI	1.44 bc	3.58 a	2.27 a

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

At the same time, control X RDI showed a more fluctuating response in fruit growth. Lucerne X RDI maintained a rate that was slightly higher, although not significantly different from its counterpart that received full irrigation.

It was evident from these results during Phase III, that fruits from the treatments that were subjected to RDI, except lucerne, showed a rapid increase in growth rate in relation to growth of full irrigation treatments, following the transition from RDI to full irrigation (Figure 4.18). This has been a persistent feature of other RDI studies in peaches and pears (Chalmers *et al.*1981,1983;

Mitchell and Chalmers, 1982) and in this study the data strongly indicated that apples respond similarly.

4.4.9.3. *Yield.*

Table 4.15 summarizes the effects of treatments on yield. Gross yield revealed no significant differences between treatments except for the lucerne X RDI, which was lower. Similar results were obtained expressing yield on a per tree basis. The yield expressed in terms of the unit tree size, however, revealed that control X RDI produced a significantly higher yield than other treatments, whereas lucerne X RDI showed the lowest yield.

Table 4.15. Effect of treatments on yield during the season 1987-1988.

Treatment	Gross Yield ($ton.ha^{-1}$)	Yield/unit (Kg/tree)	Yield Effc. ($Kg\cdot cm^{-2}$)
Plastic X Full Irrig.	49.92 ab[z]	39.94 ab[y]	1.32 c
Plastic X RDI	52.35 a	40.37 a	1.38 c
Control X Full Irrig.	50.47 a	41.37 a	1.46 b
Control X RDI	54.94 a	43.95 a	1.54 a
Lucerne X Full Irrig.	53.28 a	42.62 a	1.41 bc
Lucerne X RDI	45.41 b	36.33 b	1.18 d

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

Plastic X RDI and lucerne X full irrigation resulted in a similar yield efficiency. Since the effects of the latter treatments in controlling shoot growth was similar to RDI treatments, it could be considered as a viable alternative for this purpose. In general, these results reflect the effect of RDI that was observed on fruit growth rate, and are in agreement with other reports of the effect of RDI on fruit yield (Mitchell and Chalmers, 1982, 1983; Chalmers *et al.*1983; Mitchell *et al.* 1984).

4.4.9.4. ***Effects on Fruit Quality.***

4.4.9.4.1. ***Fruit Size.***

Results (Table 4.16) show that in the fruit size range from 170 to 180 g, RDI treatments produced a significant lower yield than the respective full irrigation treatments.

In the size class from 150 to 170 g, however, control RDI resulted in a significantly higher yield than all other treatments. Lucerne under RDI resulted in the lowest yield for this size class. In the classes, in the middle size range control X RDI was significantly different from the control X full irrigation only in the range from 120-130 g. Lucerne and plastic RDI resulted in the highest yield of fruits of the lowest class size, whereas control RDI resulted in the lowest yield in this category. Considering that gross yield was also suppressed, these results suggest that lucerne and possibly the plastic X RDI treatments were exposed to a water deficit during the stage of rapid fruit growth. This point will be discussed in more detail later.

Table 4.16. Effects of treatments on yield (kg/unit) by class size of the season 1987-1988.

Class Size (g)	170-180	150-170	130-150	120-130	110-120	100-110	<100
Plastic X Full Irrig.	2.57 a[z](15)	2.86 d[y](18)	4.95 b(35[x])	8.42 a(67)	8.65 a(75)	6.62 b(63)	8.84 a(88)
Plastic X RDI	0.31 c(2)	3.59 bc(22)	5.93 a(42)	6.18 c(49)	8.11 b(70)	5.85 c(56)	12.90 a(129)
Control X Full Irrig.	1.31 b(7)	3.86 b(24)	5.63 a(40)	7.42 b(59)	8.41 a(73)	6.16 b(59)	7.58 b(76)
Control X RDI	1.72 b(10)	6.66 a(42)	6.76 a(48)	9.37 a(75)	8.22 ab(71)	5.29 c(50)	5.93 b(60)
Lucerne X Full Irrig.	1.39 b(8)	3.33 c(21)	5.84 ab(42)	7.39 b(59)	9.80 a(85)	7.77 a(74)	7.14 b(71)
Lucerne X RDI	0.20 c(1)	1.84 c(12)	3.24 c(23)	4.63 d(37)	7.30 c(63)	6.71 b(64)	12.42 a(124)

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[z] Mean separation within columns by Duncan's multiple range test, 5% level.

[y] Means with same letter are not significantly different.

[x] Number of fruits in parenthesis.

4.4.9.4.2. *Flesh Firmness*

Pooled analysis of data by soil management, irrigation, harvest time and effect of storage, showed that the only effect on flesh firmness was the result of time at which measurement was carried out. Furthermore, multivariated analysis established that the treatment variables did not interact significantly. At time of harvest, (Table 4.17) fruits did not show significant differences in flesh firmness that consistently reflected effects of treatments. A significant decrease in firmness occurred in all the treatments after 10 weeks in cool store (Table 4.17). This decline was the highest in the control X full irrigation which were a significantly less firm than the other treatments. Whereas, control RDI showed the highest firmness after this period. This was significantly higher than other treatments. No significant differences were detected between other treatments.

4.4.9.4.3. *Total Soluble Solids.*

Time of harvest, effect of cool storage and irrigation resulted in highly significant effects on the total soluble solids (T.S.S.) in the fruit (Table 4.17). Percent of soluble solids was significantly higher under the lucerne and plastic X RDI treatments than the respective full irrigation treatments.

The highest and lowest means corresponded to plastic X RDI and full irrigation respectively. No significant differences were obtained between the control treatments, however, mean values were significantly higher than those obtained in plastic and lucerne X full irrigation.

Table 4.17. Effects of soil and irrigation management treatments on fruit quality.

	Fruit Firmness (Kg)		Soluble Solids (%)		Bruise Diameter (cm)
	At Harvest	10 Weeks -2°C	At Harvest	10 Weeks -2°C	10 Weeks -2°C
Plastic X Full Irrig.	6.21 c[z]	4.56 c[y]**	9.67 c	10.43 b^{NS}	2.25 b
Plastic X RDI	6.53 a	4.61 b**	11.30 a	11.27 a^{NS}	2.35 a
Control X Full Irrig.	6.48 b	4.30 d**	10.17 b	9.92 c^{NS}	2.28 b
Control X RDI	6.48 b	4.71 a**	10.38 b	11.02 a**	2.26 b
Lucerne X Full Irrig.	6.58 a	4.61 b**	9.90 c	10.93 ab**	2.27 b
Lucerne X RDI	5.97 c	4.62 b**	10.04 b	11.48 a**	2.23 b

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[z] Mean separation within columns by Duncan's multiple range test, 5% level.

[y] Means with same letter are not significantly different.

NS *, ** = non significant, significant at 5% (*) and significant at 1% (**) levels respectively.

After the cool storage period, T.S.S. increased significantly in RDI treatments with respect to their counterparts receiving full irrigation. The degree of change in T.S.S. during cool store was significantly higher under lucerne X RDI.

4.4.9.4.4. *Bruise Susceptibility*

The lack of information in bruise susceptibility at time of harvest prevented a comparison between times. Nonetheless, a comparison of effects of treatments after cool storage was carried out. By pooling the data according to irrigation, soil management and time of picking, multivariated analysis showed that the most important factor in determining the bruise susceptibility was the time of picking.

No significant effects were obtained due to irrigation or soil management. When the analysis took the irrigation and soil management interaction into consideration the highest and lowest mean were obtained in plastic X full irrigation and lucerne X RDI respectively (Table 4.17). These treatments were significantly different from other treatments. No significant differences were detected in other treatments. Since there are not previous studies relating bruise susceptibility with deficit irrigation on apples, the positive effects obtained in lucerne X RDI warrant further investigation.

4.4.10. *Discussion*

The experimental design and layout of neutron probe access tubes was established to obtain the information necessary to estimate the soil water balance under the different treatments. In the practice, however, this was not possible. One of the major limitations was the evaluation of soil water distribution. The wetting pattern under the drippers was reliable in the neutron probe access tubes closest to the drippers but these readings differed markedly with respect to the access tubes more distant from the trees during days when soil was dry (Section 4.4.4.1). This variability between the measurements in the different access tubes made it difficult to estimate water loss by drainage. Calculations were carried out to determine ΔW as one of the parameters required to estimate crop water use, however, with dry and wet areas of the soil a confounding effect of drainage and crop water use appeared in the results making interpretation difficult. Therefore, it appears that under trickle irrigation if a soil water balance using the neutron probe is intended, assessment of crop soil water use should be done in the root zone of the crop, and closer to water application points.

Both soil management techniques studied, effectively enhanced the soil water deficit in this environment but at different times. The lucerne treatment had a considerably greater impact on the soil water budget than that obtained using the plastic treatment, and the control. Since the control received rainfall and this was excluded from the plastic, the higher soil water storage under plastic by the end of Phase I, may have been due to the plastic retaining soil moisture. Bacon (1974) has already reported that black plastic mulching on apple trees prevented evaporation and retained soil moisture. Black plastic mulching also created a soil water deficit during Phase II, but this became effective later, and demonstrates that lucerne has a greater promise for control of water in the root zone of the crop early in the growing season.

Recognizable alterations in growth and possibly also assimilate partitioning resulted from the effect of RDI. During Phases I and II RDI strategy in combination with soil management effectively controlled vegetative growth. Vegetative growth, during similar phases, proved to be more sensitive to water deficit than fruit growth in peaches and pears (Chalmers *et al.* 1981; Mitchell and Chalmers, 1982, 1983; Chalmers *et al.*1983). In this work apple fruit growth was not affected by RDI during Phase I and II, while vegetative growth was strongly inhibited suggesting this crop responds in a similar way.

irrigation management. In this work, particularly with lucerne, soil management treatments were remarkably successful in lowering soil water in spring to the extent that one season can be used to judge the potential of these treatments. It appears that humid environments need not preclude the development of soil water deficits in spring particularly for apple which begin to grow relatively slowly and may be more sensitive to soil water deficits. These results supported findings by Powell (1976) and Lackso (1983, 1984) who showed high sensitivity to water deficits of shoot elongation in apple trees.

Thus, this treatment confirmed our hypothesis in the use of lucerne as under tree cover in orchard to reduce at early time the excess of water in the root zone of the crop, and generate the soil water deficit early in the season required to reduce the shoot growth.

Results of this study showed a clear cut in pattern of water extraction around day 84 a.f.b., which occurred in all the treatments. Coincidence in timing of the of the actual measurement of change in rate of water use, and the cessation of shoot elongation appeared to delineate a simultaneous alteration in growth events. The change in pattern of water extraction may have marked the transition from a stage of relatively low water use to one in which water demand increased. In other reports with apples (Assaf *et al.*1974. and Beukes and Weber, 1982) and peaches (Olsson, 1977 and Chalmers *et al.* 1983) increased water use has been observed to accompany an increase in fruit growth rate. A change to rapid fruit growth following stages of slow fruit growth was noted in these results initiating on day 84 a.f.b. Whether this timing could be used to schedule irrigation in this environment requires further study.

late.

Suppression of shoot growth was accompanied by an increase in the rate of fruit growth and yield efficiency of the control X RDI compared with the full irrigation treatment. Hence in this experiment it appeared that Royal Gala apple trees, in this humid environment, showed a response to RDI which was similar to the earlier studies in peaches and pears (Chalmers *et al.* 1981; Mitchell and Chalmers, 1982,1983., Mitchell *et al.* 1984). Diversion of photoassimilates from the suppressed vegetative growth towards the fruit in control treatment under RDI appeared is revealed in this study.

The replacement of RDI treatments by full irrigation initiated on day 110 a.f.b. increased the cumulative deficit in RDI treatments to same level of the respective treatments previously under full irrigation. Plastic and lucerne X RDI, however, by day 131 a.f.b. developed a greater water deficit than the same treatments previously under full irrigation. Simultaneously, the fruit growth rate in lucerne X RDI increased relatively sharply. This increased water demand in treatments that had been under RDI also suggests a greater photo assimilate demand in fruits of these treatments compared with those previously under full irrigation. The present results support the above conclusion and are in agreement with earlier studies (Chalmers *et al.* 1981, 1983, 1984, 1986).

Although control X RDI obtained positive effects on yield results were marginal. It is likely that the RDI period was extended to the rapid fruit growth. This stage appeared to begin around day 84 a.f.b. for season 1987-1988. The high rate of water use for lucerne treatments showed that this treatment drastically reduces the available soil water for the crop. This effect was deleterious on fruit growth during Phase III. As a result, final fruit size and yield were reduced, which is undesirable. Nevertheless, lucerne created a soil water deficit in the root zone of the crop earlier in the season, which was sufficient to control vegetative growth. Furthermore, an RDI response was manifested in the increased rate of fruit growth and crop water demand on day 131 a.f.b.. Results indicate that plastic RDI was subjected to a later but prolonged and greater deficit which also affected fruit growth.

Effects of RDI on fruit quality appeared to be related to a greater photosynthate concentration in the fruits which was reflected in a higher firmness and higher T.S.S. than in full irrigation treatments. Similar results have been reported for fruits growing under water deficit (Guelfat'Reich *et al.*1974., Assaf *et al.* 1975., Guelfat and Ben-Arie 1979., Proebsting *et al.* 1984., Irving and Drost, 1987). Nonetheless, the fact that RDI had positive effects not only on yield but also in fruit quality, deserves additional investigation.

Estimates of ET following Doorenbos and Pruitt (1977) correlation model appeared inadequate to evaluate ET crop in the environment of this experiment. According to this model K_L was too low as the season progressed in contrast with the data obtained. Results of this experiment showed that the deficit was unnecessarily prolonged when RDI effects on suppression of shoot growth already had been obtained. The situation of a soil water deficit occurring during stage of rapid fruit growth suggests that an irrigation schedule based on this estimation of E_{pan} was insufficient to satisfy crop water demand. It may be preferable to schedule irrigation based on a closer evaluation of the soil moisture and plant water status in this climate where estimation of ET by other means contains more potential sources for error.

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CHAPTER 5

SEASON 1988-1989

5.1. Introduction.

The management of soil water in a humid environment is difficult because of the regular occurrence of rainfall. The underlying assumption in the experiments carried out during the preceding season was that lucerne and plastic in combination with RDI might offer feasible alternatives to manipulate the soil water budget in this environment. Although both techniques were helpful in adapting RDI strategies, plastic became effective later than lucerne. Uncertainty associated with the possibility that plastic had been installed too late (in winter), when the soil might have accumulated considerable amounts of water, rendered the first seasons results inconclusive.

Despite the positive effects of integrated RDI and soil management techniques in controlling vegetative growth, a minor depression of yield by some treatment combinations was attributed partly to inadequacy of pan evaporation for estimating the crop water demand during rapid fruit growth. A closer assessment of plant water status and soil water content might be expected to predict water requirements more accurately at this stage.

Finally, information obtained during the previous season related to fruit quality showed great promise for RDI strategies, but further study was needed to confirm and develop these conclusions.

5.2. *Objectives.*

This experiment aimed to:

1) determine the effect of a lucerne sward and black polyethylene film established before winter, as a method for controlling soil water in spring.

2) evaluate the effectiveness of RDI strategies based on assessment of soil water content and plant water status.

3) determine the crop performance under the combination of soil management techniques and irrigation regimes.

4) confirm effects of RDI on fruit quality.

5.3. *Materials and Methods.*

5.3.1. *The Weather.*

The average rainfall during the growing season (Table 5.1) was 2.37 mm/day which resulted in a total of 354.9 mm, 42 mm less than the total during the previous season. From this total 246.6 mm fell during the first 109 days. Ten days were recorded with precipitation higher than 10 mm, with a maximum on 29 December of 38.9 mm. The longest period without rain occurred between day 70 to 83 a.f.b.(Figure 5.1). Another long period with low precipitation, however, occurred from day 124 to 150 a.f.b. during which rainfall averaged only 0.4 $mm.day^{-1}$. Total pan evaporation was 741.9 mm of which 535.0 mm were evaporated during the first 109 days of the growing season. Mean evaporation was 4.95 $mm.day^{-1}$. The maximum evaporation of 8.9 mm was recorded on day 110 a.f.b.

Table 5.1. Climatic data for Palmerston North during 1988-89 season.

Date	Total Days a.f.b.	Total Rainf. (mm)	No days Rainf > (10 mm)	Daily Average Class A Pan Evap. (mm)
6 Oct- 2 Nov	28	66.6	2.0	4.14
3 Nov-12 Nov	38	15.4	0.0	3.60
13 Nov-16 Nov	42	0.0	0.0	4.25
17 Nov-23 Nov	49	13.0	0.0	5.09
24 Nov-30 Nov	56	34.9	1.0	3.76
1 Dec- 7 Dec	63	4.9	0.0	4.14
8 Dec-12 Dec	68	0.0	0.0	5.72
13 Dec-17 Dec	73	1.1	0.0	7.26
18 Dec-24 Dec	80	3.8	0.0	6.10
25 Dec-29 Dec	85	39.7	1.0	5.90
30 Dec- 6 Jan	93	11.6	0.0	5.76
7 Jan-18 Jan	105	30.4	1.0	5.78
19 Jan-25 Jan	112	23.4	1.0	5.54
26 Jan- 7 Feb	125	101.0	4.0	4.91
8 Feb-14 Feb	132	3.2	0.0	4.89
15 Feb-19 Feb	137	0.0	0.0	5.66
20 Feb-28 Feb	146	4.1	0.0	6.22

Source: Grasslands Division, DSIR, Palmerston North.

5.3.2. *Irrigation Strategies.*

Irrigation strategies during 1988-1989 were the same as used in season 1987-1988, however, calculation of the amount of water to be applied was based on measurements of soil water using the neutron scattering method rather than E_{pan} data. A range of soil water extractions for this experiment was established between limits of soil water content obtained in the field. These limits are described as the drainage upper limit (DUL) and lower limit (LL) of available soil water (Ritchie, 1981 and Buss 1989), but some modifications were used to suit the purposes of this research.

Maximum values were established during winter by measurements of soil water content after heavy rain. Twelve access tubes randomly selected in the orchard were assessed daily until the water movement in the soil profile was negligible. The soil water content at this time, when it could be assumed drainage had ceased, represents the DUL. The minimum values of water content registered during the previous season in the lucerne X RDI treatment were taken as the LL. It was found that LL represented 31% of the W at DUL and (DUL-LL) was 162.5 mm of W. These limits are shown in Table 5.2.

Table 5.2. Drainage upper limit (DUL) and lower limit (LL) of volumetric soil water content $(\theta)^z$ in Massey orchard.

Depth	DUL	LL
0-300	33.47 +/- 0.68	7.98 +/- 0.17
300-400	31.81 +/- 1.25	8.48 +/- 0.36
400-500	22.33 +/- 1.32	8.11 +/- 0.25
500-600	21.50 +/- 1.24	6.64 +/- 0.74
600-700	18.05 +/- 0.78	5.92 +/- 0.63
700-800	12.42 +/-0.95	6.88 +/- 0.72
800-900	14.52 +/- 0.31	6.69 +/- 0.38
900-1000	14.93 +/- 0.95	6.72 +/ -0.31

[z] % volume/volume.

Soil water was replenished in full irrigation treatments when the soil water content reached approximately 50% of the above range in the top 600 mm of soil. Treatments under RDI received 25% of the amount of water given to full irrigation treatments. The irrigation schedule followed same separation of Phases used in season 1987-1988, as follows:

a) Phase I ended on day 64 a.f.b. (8 of December 1988).
b) Phase II was applied from day 65 a.f.b. (9 December 1988) until day 109 day a.f.b. (20 of January 1989).
c) Phase III began on day 110 a.f.b. (21 January 1990) and continued until end of the season. Data for Phase III was collected until the day of first harvest (day 146 a.f.b.).

5.3.3. *Estimation of Total Water Input.*

Total water input was estimated by adding the rainfall (to the treatments receiving it) and the amount of water (mm) needed to replenish the soil to the DUL (100%) or to 25% DUL according to the irrigation strategy of the treatment. An amount of 10% was subtracted from measured rainfall data to account for evaporation losses.

5.3.4. *Soils.*

Records of volumetric water content were obtained for half of the access tubes used in the previous season. This was done because six access tubes per plot was considered sufficient to evaluate the soil water dynamics of the treatments. On the other hand, measurement was carried out two or three times per week, depending of the incidence of rainfall.

Due to the regularity of precipitation, however, these measurements markedly fluctuated, and were of limited value for evaluating water use by the treatments. Thus, data is presented in weekly intervals.

Daily neutron probe measurements were carried out in plots considered to be the extremes of soil water content (lucerne X RDI and control X full irrigation). The purpose of these measurements was to estimate water use, and for timing of irrigation.

5.3.5. *Collection of Plant Data.*

5.3.5.1. *Shoot Growth.*

The length of four tagged twigs from the three middle trees in every plot, was measured twice a week from day 43 a.f.b. (17 Nov. 1988) until day 131 a.f.b. (13 Feb. 1989).

5.3.5.2. *Fruit Growth.*

Three fruits from each of the twigs already selected were also tagged giving a total of 12 fruits per plot which were measured twice weekly to assess fruit growth between day 28 a.f.b. (2 Nov.1988) until day of first harvest (28 Feb. 1989).

5.3.5.3. *Plant Water Status.*

5.3.5.3.1. *Leaf Water Potential* (Ψ_L).

Pre-dawn Ψ_{Lp} and midday Ψ_{Lm} were measured at one day intervals for 4 leaves of the two middle trees of every plot from day 48 a.f.b. (22 Nov. 1988) until day 143 a.f.b. (25 Feb. 1989).

5.3.5.3.2. *Stem Water Potential* (Ψ_s).

Pre-dawn (Ψ_{sp}) and midday (Ψ_{sm}) were assessed on two trees, one in the control X full irrigation treatment and the other one in lucerne under RDI. In situ stem hygrometers obtained from Dixon Instruments Co, Guelph, Canada. were controlled with a Wescor HR33T dew point microvoltmeter, Wescor Inc. Logan, Utah, US. Procedures described in the Stem Hygrometers Reference Manual (1987) were applied to correct for temperature differences between the sample and the chamber which might affect Ψ_s measurements.

5.4. *Results*.

5.4.1. *Weather Season 1988-1989*.

5.4.1.1. *Phase I*.

By the time the measurements started, 28 days a.f.b., a greater soil water deficit had developed than obtained during the analogous period of the former season, this was expected since pan evaporation was higher and rainfall lower than values recorded in season 1987-88 (Table 5.1 and Figure 5.1). A total of 66.6 mm of rain fell in the first 28 days of the growing season. Phase I was characterized by an irregular pattern of precipitation and accordingly irrigation was withheld until day 65 a.f.b. (9 Dec. 1988).

5.4.1.2. *Phase II*.

Phase II included a dry spell until day 85 a.f.b. after which a rainfall event of 35 mm occurred. Two additional dry intervals occurred from days 90 to 95 a.f.b. and from 97-109 a.f.b. Three rainfall peaks with precipitation higher than 10 mm disrupted these dry periods (Figure 5.1).

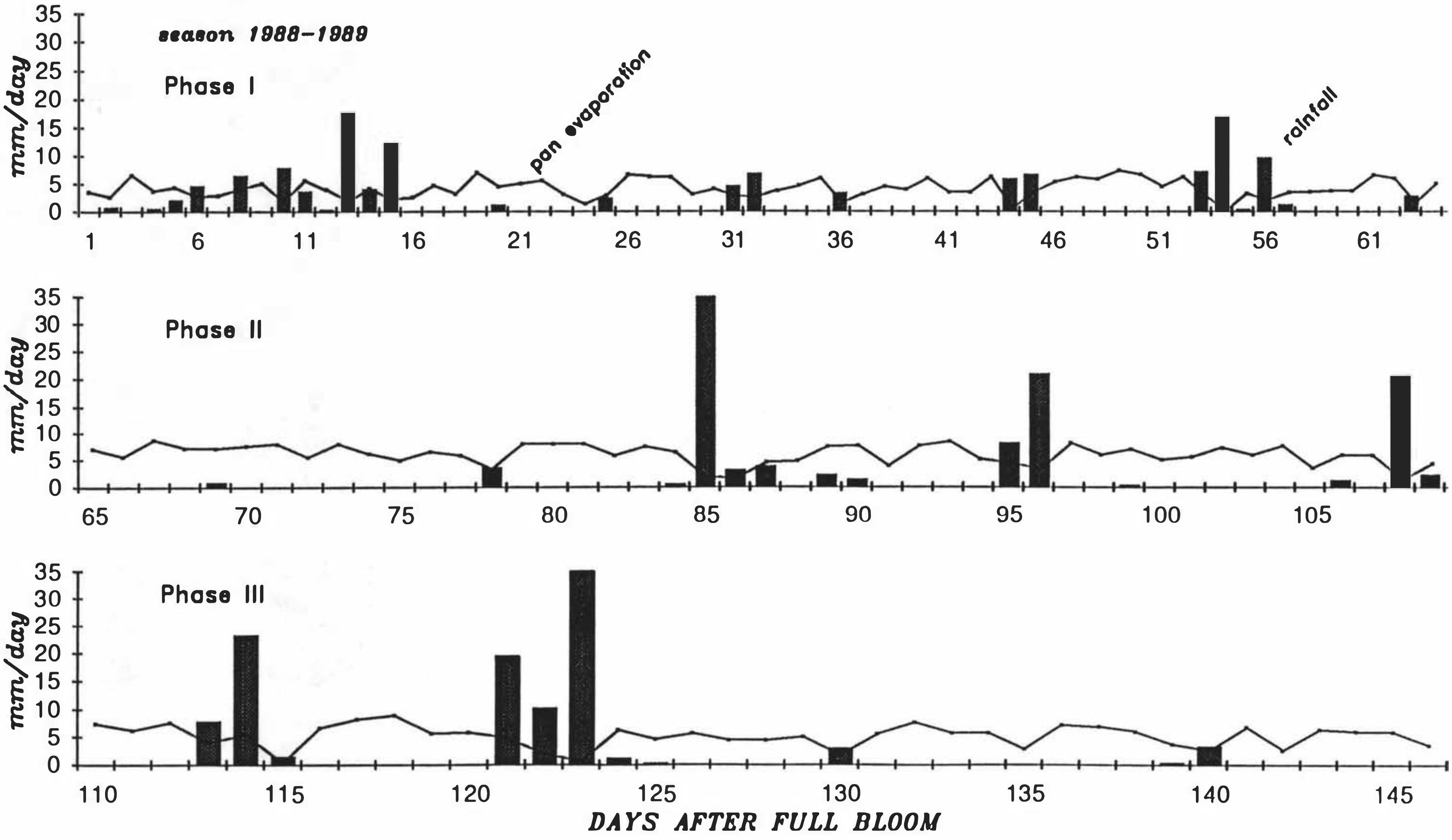

Figure 5.1. Daily water balance during growing season 1988-1989.

5.4.1.3. *Phase III.*

During Phase III there were two peaks of precipitation between days 113 to 115 and 120 to 125 a.f.b. (Figure 5.1) during when 23.4 mm 101 mm respectively, fell followed by a dry period until harvest (day 146 a.f.b.).

5.4.2. *Soil Moisture.*

5.4.2.1. *Volumetric Water Content.*

Table 5.3. Changes in soil water content (θ) during Phase I.

	θ (% V/V)					
	Plastic		Control		Lucerne	
Depth(mm)	Day 28[z]	Day 64	Day 28	Day 64	Day 28	Day 64
300	29.85a[y]	23.14a	30.44a	22.11a[x]	29.32a	21.28a
400	23.36b	17.64a	29.92a	17.26a	22.97b	16.84a
500	16.83b	12.51a	20.47a	12.94a	19.36a	12.48a
600	13.81a	10.73a	14.91a	9.58b	14.24a	9.12b
700	17.27a	12.80a	11.32b	8.31b	11.09b	7.22c
800	21.55a	16.42a	10.83b	8.60b	10.09b	6.33c
900	19.37a	15.19a	11.57b	9.25b	10.03c	6.59c
1000	15.17a	11.82a	14.10a	11.80a	11.86b	8.29b

[z] Days after full bloom.

y Mean separation between treatments by LSD, 5 % level.

[x] Means with same letter are not significantly different.

Initially, no significant differences in θ between treatments were obtained in the top 300 mm of soil (Table 5.3). However, significantly lower values were obtained under lucerne and control treatments in the layers from 600 and 1000 mm depth. Results suggest that plastic mulch was less effective than lucerne and control treatments in controlling soil water in the root zone of the crop at this stage. As Phase I progressed, the decline in θ was more pronounced under lucerne. The plastic mulch was less effective in reducing θ of all treatments during this Phase. Effects of lucerne and control were noticeable in the deeper layers beneath 600 mm in the soil profile. The results suggest a higher root activity for both treatments in these soil layers. A substantially lower change was obtained under plastic, which suggests that polyethylene film acted as a barrier retaining soil moisture and preventing evaporation. Since soil moisture appeared to be retained under plastic, surface root activity appears to have predominated.

An examination of range of θ values during this season revealed that maxima from 35 to 37 % V/V for the top 500 mm were obtained on day 125 a.f.b (data not shown). This event coincided with the highest peak of rainfall during the growing season. Minimum values for this layers were recorded on day 72 a.f.b. on lucerne X RDI treatment. Values ranged from 9 to 13 % V/V. The lowest values, however, in the lower layers were registered in the same treatment on day 81 a.f.b. Other RDI treatments resulted in higher values of θ. Results show that lucerne extracted water at a higher rate than the other treatments, and also that the crop in lucerne plots under RDI was exposed to a greater water deficit.

5.4.2.2. ***Effects of Treatments on Total Soil Water Storage.***

5.4.2.2.1. ***Phase I.***

The initial W (Table 5.4) on day 28 a.f.b. showed that soil water storage in all treatments was lower than data obtained on similar dates in the previous season. Although the plastic cover had excluded rainfall during winter no significant differences were obtained between lucerne and plastic treatments. Nonetheless, plastic was significantly drier than the control. Thus, it appeared that plastic had been no more effective than lucerne in controlling winter rainfall during this relatively drier spring.

Table.5.4.Changes in total soil water storage (W) during Phase I.

Treatment	W (mm)			
	Day 28 a.f.b.	Day 64 a.f.b.	ΔW	Water Use (mm)
Plastic X Full Irrig.	236.9 b^z	158.4 a^y	-78.5 c	78.50 c
Plastic X RDI	238.2 b	148.1 b	-90.1 b	90.10 c
Control X Full Irrig.	248.4 a	162.3 a	-86.1 bc	147.40 b
Control X RDI	248.5 a	158.7 a	-89.8 b	151.10 b
Lucerne X Full Irrig.	238.5 b	100.7 c	-137.8 a	199.10 a
Lucerne X RDI	232.3 c	103.7 c	-128.6 a	189.90 a

^{z} Mean separation within columns by LSD, 5% level.
^{y} Means with same letter are not significantly different.

The largest change in W and water use between days 28 and 64 a.f.b occurred under lucerne followed by the control and the plastic mulch. Lucerne was two times more effective than plastic in reducing the soil water storage during Phase I. Results were consistent with the previous season and appear to have established that plastic is less efficient than lucerne or the control in creating a soil water deficit in the root zone of the crop during Phase I in these particular conditions.

Results of soil water content under the herbicide strip revealed that the soil stored relatively high amounts of water during winter-spring, it also underwent a rapid depletion once the plant was actively growing.

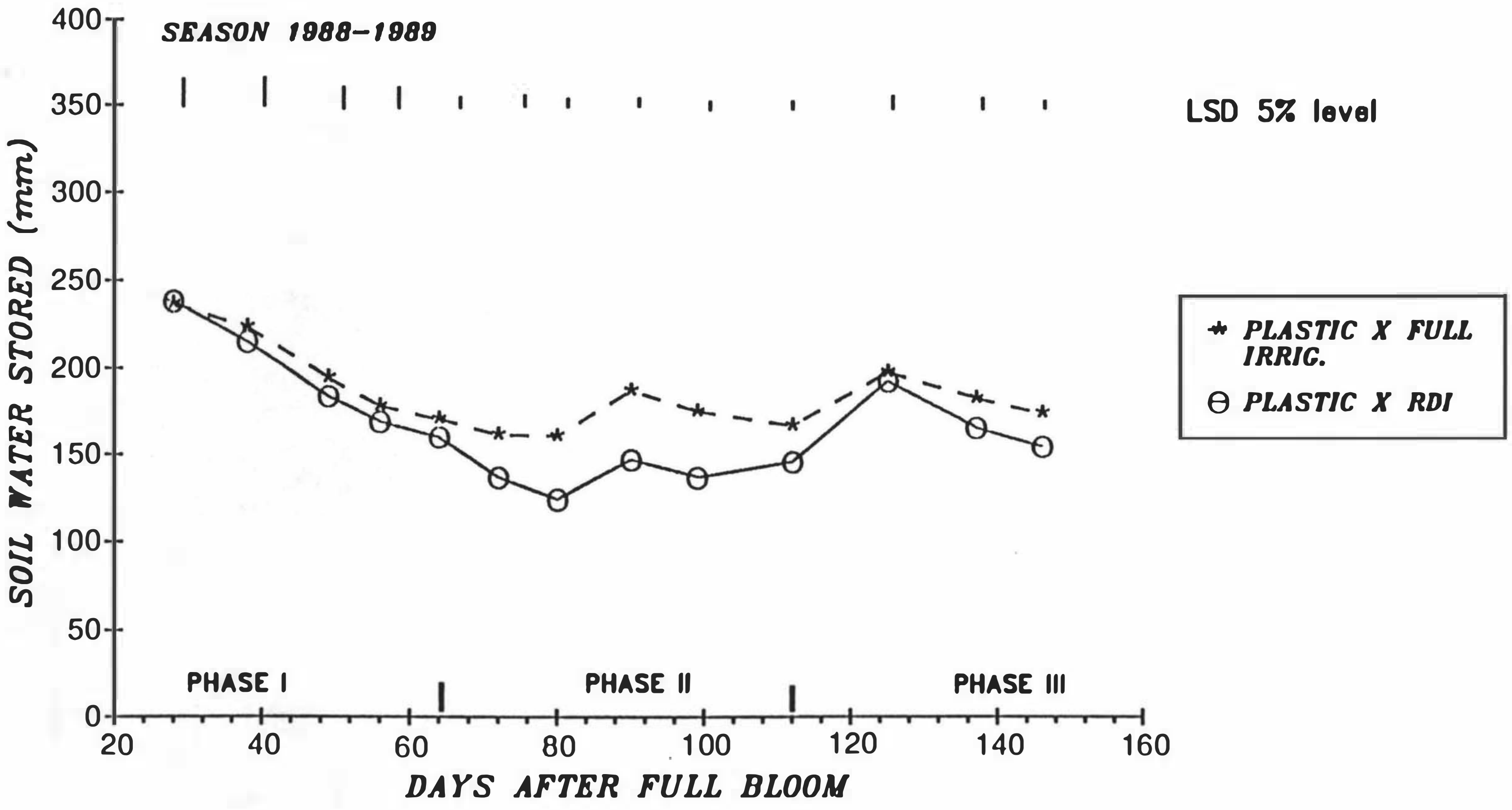

Figure 5.2. Seasonal pattern of soil water stored (W) under plastic treatments, estimated by the neutron probe.

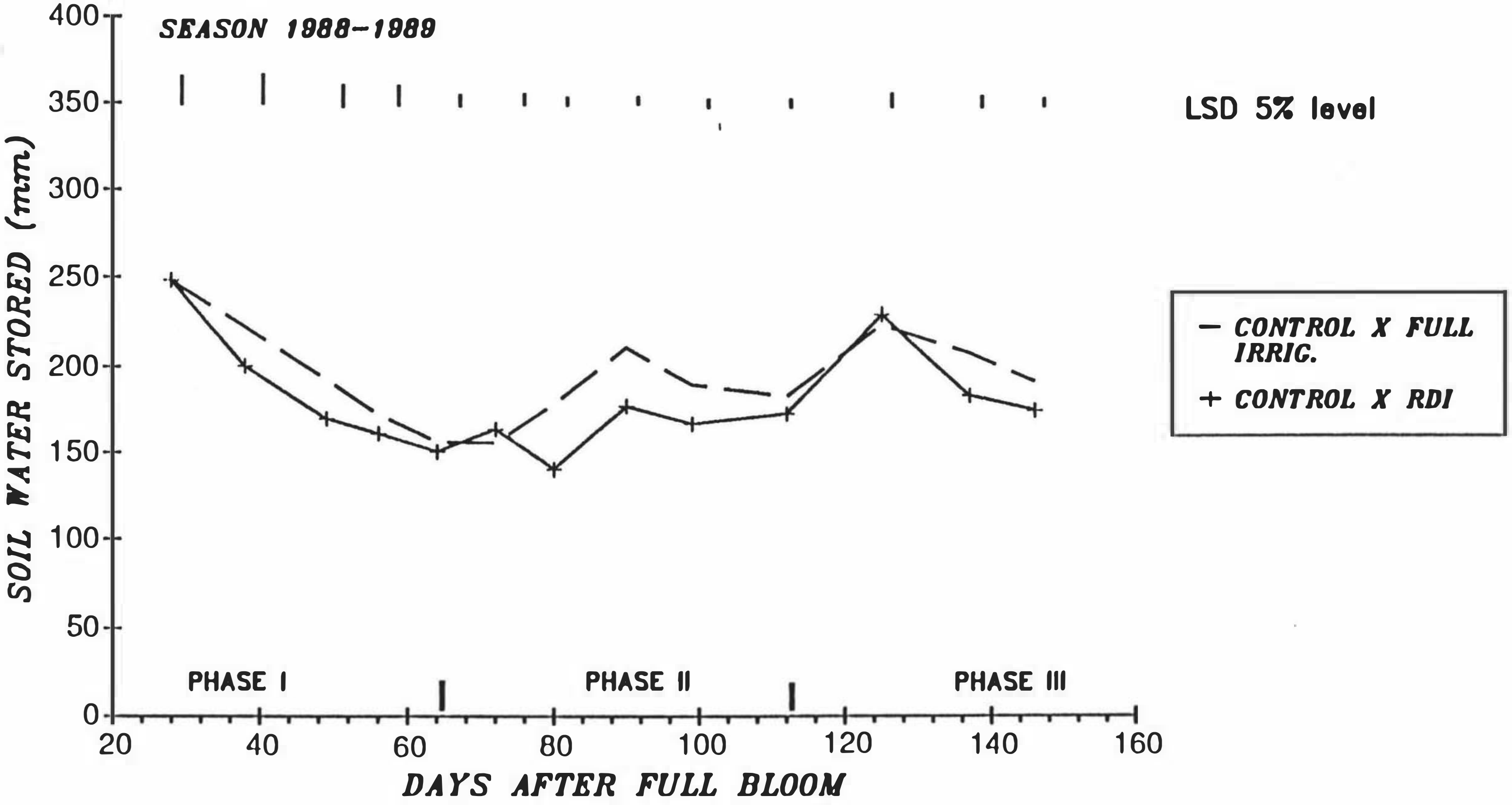

Figure 5.3. Seasonal pattern of soil water stored (W) under control treatments, estimated by the neutron probe.

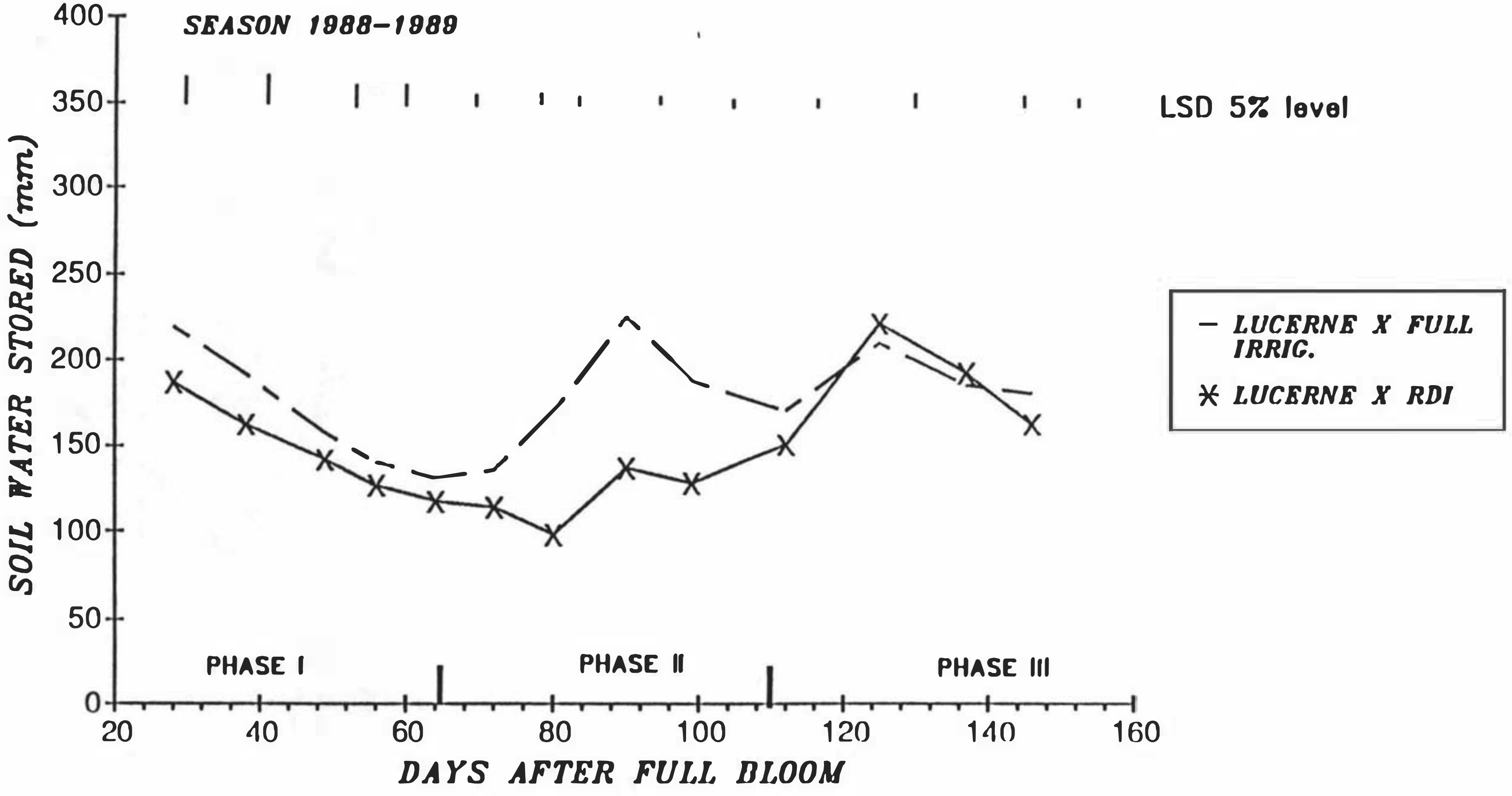

Figure 5.4. Seasonal pattern of soil water stored (W) under lucerne treatments, estimated by the neutron probe.

This reinforces one of the major underlying assumptions of this study, the need for an appropriated soil management to remove excess water at early stages of crop development in this soil and climate. On the other hand, it implies that careful irrigation management is required to recharge soil water in times of high demand by the crop.

5.4.2.2.2. *Phase II.*

Irrigation was initiated on day 65, but W continued decreasing under RDI treatments until day 80 a.f.b. (Figure 5.2, 5.3 and 5.4). The decrease was marked in plastic X RDI. Minimum values of W were reached in RDI treatments on day 80. However, from day 65 a.f.b. an increase in W was obtained in control and lucerne X full irrigation. Whereas, the plastic X full irrigation treatments showed a significantly lower increase than the other full irrigation treatments.

The value of W increased sharply from day 83 to 99 a.f.b. caused by high incidence of rainfall from day 83 to 90 a.f.b. A pronounced decrease in W occurred for all treatments from day 90 to 110 a.f.b. which may suggest a change in pattern of water extraction of the crop at this time.

By day 110 a.f.b. when irrigation treatments of Phase II were terminated, lucerne and plastic X RDI showed the lowest W (Figures 5.2, 5.3 and 5.4). No significant differences between these two treatments were obtained on this day. However, lucerne X RDI exhibited the lowest W throughout Phase I and II. From these results one can conclude that lucerne X RDI, although receiving rainfall, displayed a greater efficiency than plastic X RDI in drying the root zone of the crop.

5.4.2.2.3. *Phase III.*

From day 110 a.f.b. (Figures 5.2, 5.3 and 5.4) a general increase in W was obtained in all the treatments. Plastic treatments, however, exhibited a significantly lower increase than the other treatments. Between days 125 to 137 a.f.b. a pronounced W decrease occurred in all treatments. The decrease was more accentuated under control and lucerne X RDI treatments than in the full irrigation treatments. Initially this drop in W might have been due to drainage of water excess after rainfall peak occurred between days 120-125 a.f.b. Nevertheless, all treatments concomitantly showed a decrease in W until day 145 a.f.b. which was not as great under the full irrigation treatments. Considering that all treatments were receiving the same water input at this stage, results indicated a higher rate of water use in treatments that had received RDI. On the other hand, these data established that irrigation did not compensate for the higher crop water demand which has been shown to characterize the stage of rapid fruit growth (Chalmers and Van den Ende, 1975; Chalmers *et al.* 1981; Mitchell and Chalmers 1982, 1983).

- 5.4.2.3. *Accumulated Soil Water Deficit.*

5.4.2.3.1. *Phase I.*

The highest cumulative deficit during Phase I was obtained under lucerne treatments (Figures 5.5, 5.6 and 5.7). This was significantly different from control and plastic treatments, while no significant differences were obtained between the latter treatments (Table 5.5). Rate of water use during the Phase I was highest and lowest under lucerne and plastic respectively. Both treatments were significantly different from the control treatments. Results confirmed our previous conclusions with respect to phase I of season 1987-1988. Again lucerne showed capacity to extract water at a fast rate, which produced a soil water deficit earlier in the growing season of the crop than the other soil management treatments.

Table 5.5. Accumulated soil water deficit, ΔW (mm) over the planting square during Phase I.

Treatment	ΔW^z (mm) Day 54 a.f.b.	Rate Water Use (mm/day)
Plastic X Full Irrig.	-73.45 c^y	2.18 c^x
Plastic X RDI	-91.09 b	2.50 c
Control X Full Irrig.	-56.12 c	4.09 b
Control X RDI	-59.85 bc	4.19 b
Lucerne X Full Irrig.	-137.80 a	5.53 a
Lucerne X RDI	-123.62 a	5.28 a

[z] Difference in W with respect to first day of measurement.
[y] Mean separation within columns by LSD, 5 % level.
[x] Means with same letter are not significantly different.

5.4.2.3.2. *Phase II.*

Significant differences due to irrigation treatments during Phase II were present by day 72 a.f.b. It was apparent that the rate of water extraction of lucerne exceeded that of other treatments to the extent that lucerne X full irrigation attained a cumulative deficit not significantly different from plastic X RDI. The largest cumulative deficit for the control X full irrigation in Phase II, was obtained on day on 72 a.f.b. Thereafter, a general decrease in soil water deficit occurred from day 72 to 90 a.f.b. (Figures 5.5, 5.6 and 5.7). The smallest deficit was obtained under control and lucerne X full irrigation treatments by day 90 a.f.b. This increase in soil moisture also occurred under plastic X RDI and probably coincides with a period of very low ET in addition to rainfall.

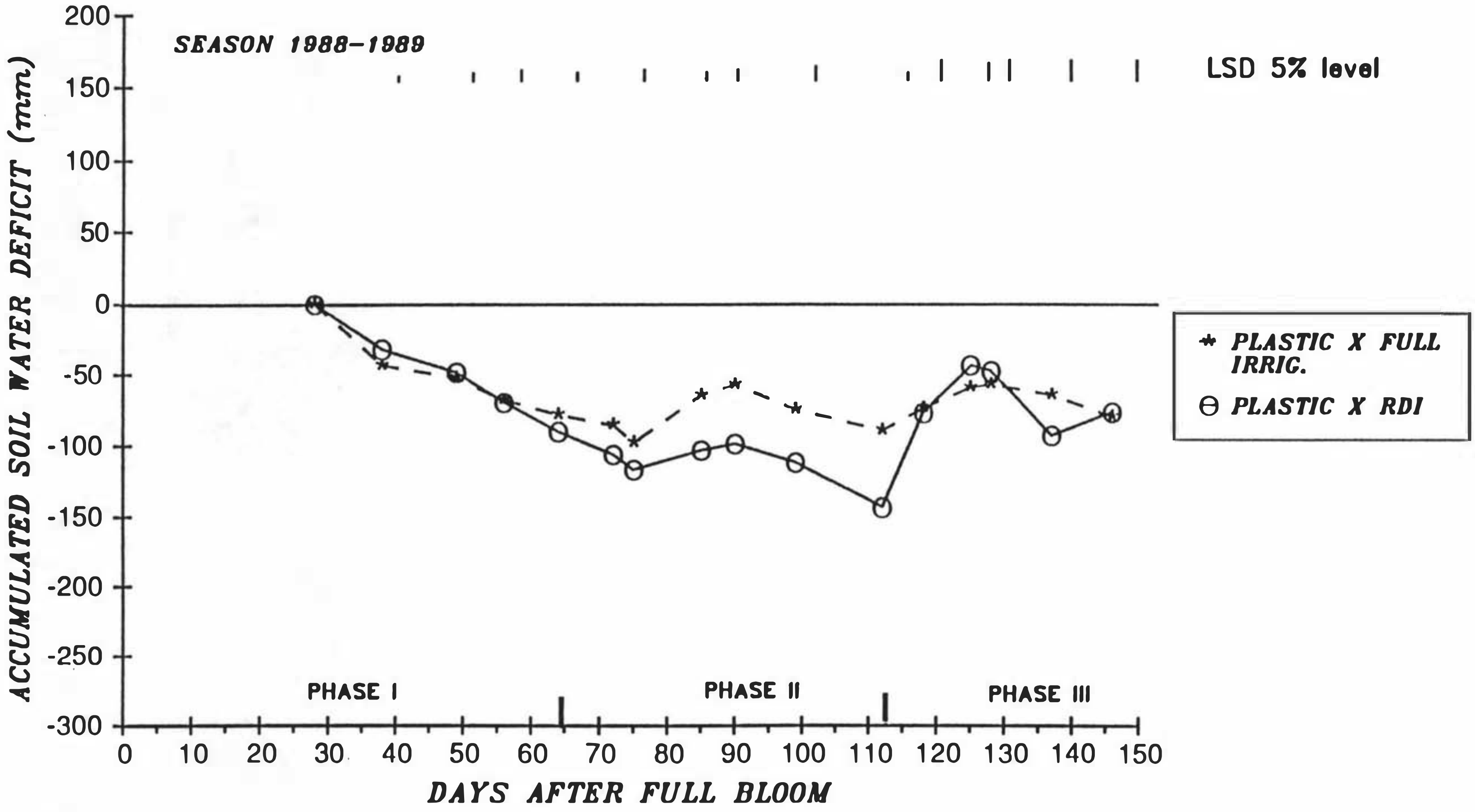

Figure 5.5. Cumulative soil water deficit obtained under plastic treatments during the growing season 1988-1989.

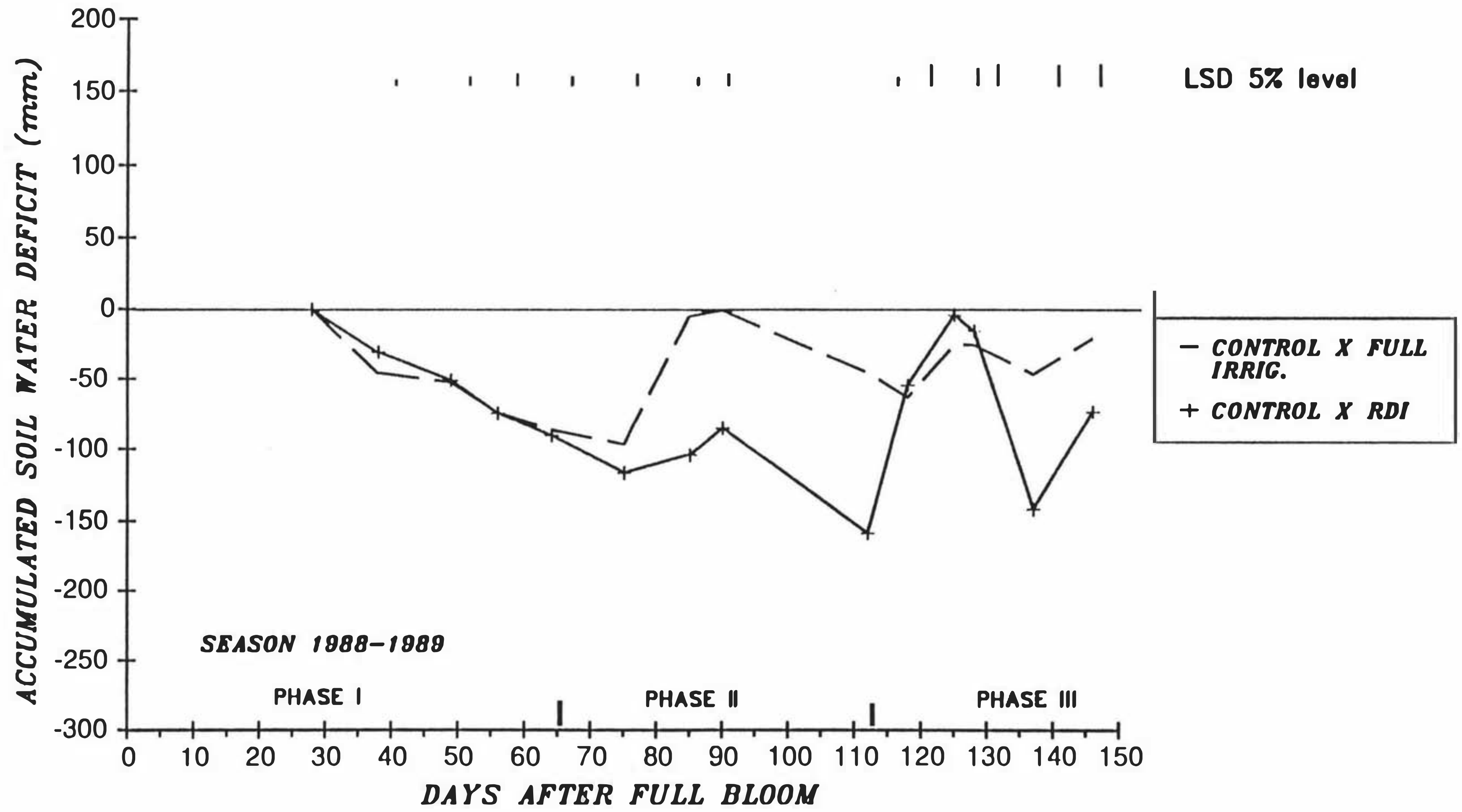

Figure 5.6. Cumulative soil water deficit obtained under control treatments during the growing season 1988-1989.

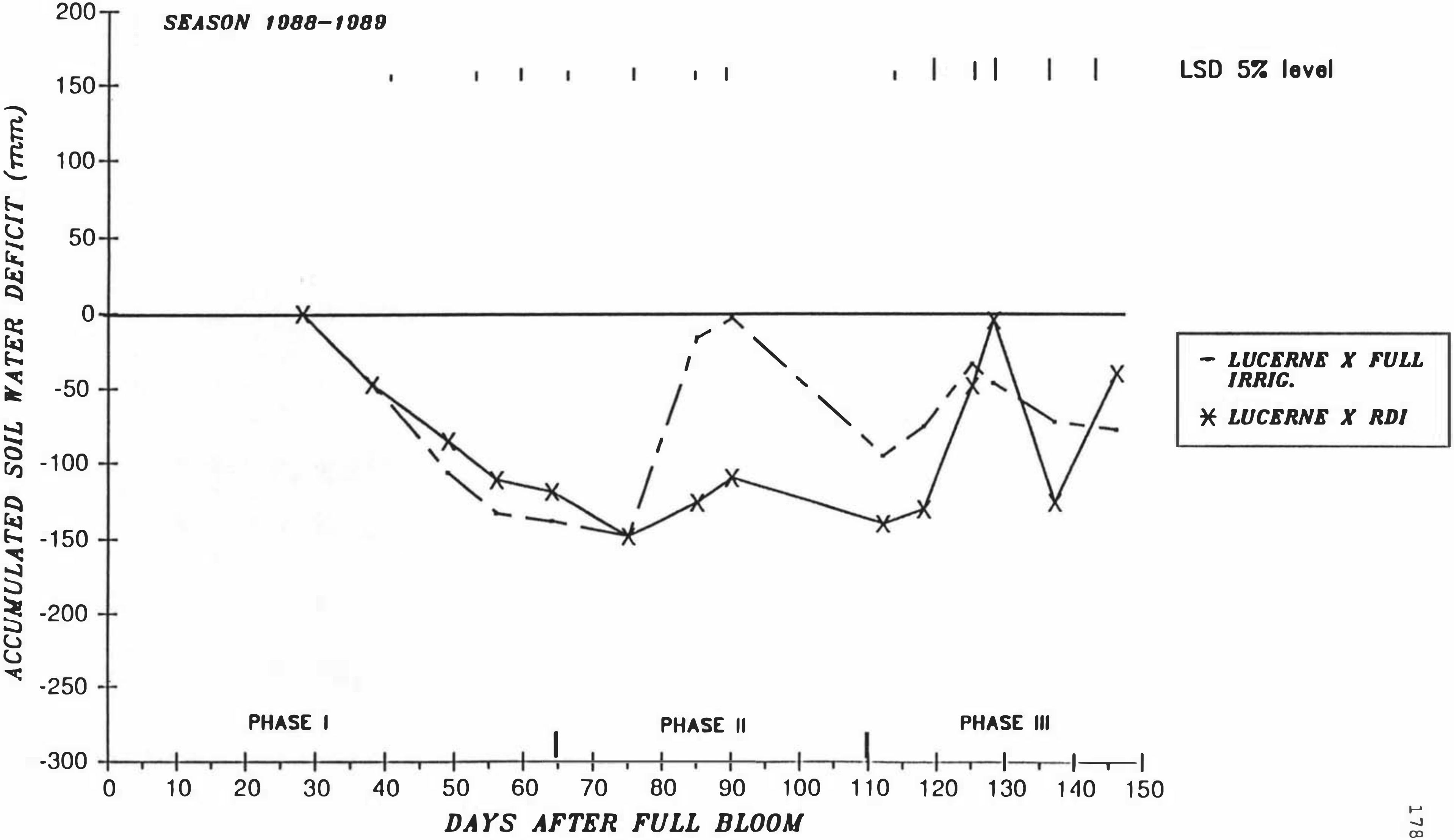

Figure 5.7. Cumulative soil water deficit obtained under lucerne treatments during the growing season 1988-1989.

At this time, incidence of rainfall between days 83 to 90 a.f.b. decreased soil water deficit of lucerne and control X full irrigation, however, significant differences between RDI and their respective full irrigation continued to be present. By day 110 a.f.b. lucerne X RDI resulted in the maximum soil water deficit although it was not significantly different from control and plastic X RDI. From days 90 to 110 a.f.b. an increase in accumulated soil water deficit in RDI treatments was obtained. A less accentuated increase in deficit was observed in full irrigation treatments. Thus, an apparent change in rate of water extraction for the crop was evident. Since the increase in soil water deficit was significantly greater in RDI treatments than that in full irrigation treatments, results suggest a higher water demand in these treatments. It might be that increased fruit growth rate was responsible for enhanced water demand. If this so it appears that full irrigation should have commenced around day 85 a.f.b. Whatever the cause this data shows soil water deficit increased at time when adverse effects upon fruit growth were also increasing. This makes it relevant to closely follow changes in W as a mean of preventing crop losses.

5.4.2.3.3. ***Phase III.***

Full irrigation replacement on RDI treatments commenced on day 110 a.f.b. which, with rainfall, decreased the soil water deficit in all treatments. Treatments that received RDI subsequently showed a higher water demand than the full irrigation treatments (Figures 5.5, 5.6 and 5.7). Despite the fact that irrigation was set to apply 5.3 mm per day and rainfall supplemented this from day 85 to 125 a.f.b. with a daily average of 5.1 mm, the accumulated deficit during Phase III still indicates that irrigation was insufficient to fully compensate for the crop water demand especially for RDI treatments. The data show that the irrigation rate during this period should have been higher, especially under lucerne and control.

The high water demand of treatments that received RDI indicates that levels of irrigation should assure soil water replenishment up to the DUL commences at an earlier date. For the season 1988-89 this date was established around day 85 a.f.b.

5.4.2.4. *Effects of Treatments on Pattern of Extraction with Depth.*

Table 5.6 shows the percentage of the total volume of water extracted from the upper layer of soil between 0 to 600 mm and the deeper layers from 600 to 1000 mm depth. During the period between day 68 to 80 a.f.b. plants in the lucerne X RDI treatment obtained about 50 % of the total volume of water from deeper layers. This proportion was lower to the control X RDI, which was significantly higher than under plastic. In contrast, surface root activity predominated in the remaining treatments. A change to greater extraction from upper layers was observed under the full irrigation treatments during the second period discussed here (days 85-105 a.f.b). The greatest change, however, occurred under lucerne X RDI, which extracted almost 100% from the upper layers during this period. Effects of increased soil water content due to high precipitation plus irrigation probably caused the change towards a preferential role of roots in the upper layers of soil. Considering, the effects of the soil and irrigation treatments on W, this change would be expected if no alteration in root distribution was induced by the irrigation treatments. This result also demonstrates that RDI treatments were exerting water stress in this experiment.

Only plastic X full irrigation and control X RDI maintained around 25 % of the extraction from deeper layers during Phase III. Surface root activity appeared to be favoured in other treatments indicating that the full irrigation treatments were adequately meeting crop water requirements during that period.

Table 5.6. Effects of treatments on the percent of water extracted from different depths in the root zone.

Treatment	Day 68-80 a.f.b.		Day 85-105 a.f.b.		Day 125-128 a.f.b.	
	0-600 mm[z]	600-1000 mm	0-600 mm	600-1000 mm	0-600 mm	600-1000 mm
Plastic X Full Irrig.	68.5 b[y]	31.6 bc[x]	69.7 c^{NS}	30.7 a^{NS}	74.9 b$_{*}$	25.1 a$_{*}$
Plastic X RDI	70.0 b[w]	29.9 c	81.7 b$_{**}$	18.4 b$_{**}$	86.5 a$_{*}$	13.5 c$_{*}$
Control X Full Irrig.	82.0 a	18.0 d	80.3 b^{NS}	19.7 b^{NS}	81.8 a^{NS}	18.2 b^{NS}
Control X RDI	60.8 c	39.2 b	66.3 c$_{*}$	33.7 a$_{*}$	73.9 b$_{*}$	26.2 a$_{*}$
Lucerne X Full Irrig.	78.7 a	21.3 cd	76.5 b^{NS}	23.5 b^{NS}	80.9 a^{NS}	19.2 b^{NS}
Lucerne X RDI	50.2 d	49.8 a	96.7 a$_{**}$	3.3 c$_{**}$	83.3 a$_{**}$	16.7 bc$_{**}$

[z] Depth.

[y] Percent of total volume.

[x] Mean separation within columns by Duncan's multiple range test, 5% level.

[w] Means with same letter are not significantly different.

NS * ** =non significant, significant at 5% (*) and 1% (**) levels respectively.

5.4.3. *Effect of Treatments on Seasonal Pattern of Leaf Water Potential.*

5.4.3.1. *Phase I.*

The highest values of Ψ_{Lp} in Phase I were recorded on day 48 a.f.b. for all treatments (Figures 5.8, 5.9 and 5.10). Effects of lucerne on soil water deficit already appeared to be reflected in these values. They were more clearly manifested in midday leaf water potential (Ψ_{Lm}), since lucerne treatment resulted in the minimum values on this day.

Minimum values of Ψ_{Lp} in this Phase were obtained on day 62 a.f.b. which were not significantly different between soil management treatments. Midday values for lucerne, however, were significantly lower than those of control and plastic. The control values of Ψ_{Lm} were significantly lower than those for plastic treatments suggesting a rapid plant response to the slower soil drying that took place under the latter treatment.

5.4.3.2. *Phase II.*

Measurement of soil water storage on day 72 a.f.b. showed a minimum value of 113 mm to one meter depth. The greatest cumulative deficit was also recorded on day 72 a.f.b. in the lucerne X RDI treatment (Figure 5.10), and this was reflected in the minimum value of Ψ_{Lp} obtained in this treatment. Lucerne X full irrigation, however, resulted in values that were not significantly higher than control X RDI (Table 5.7). On the other hand, on this date maximum values were obtained under plastic treatments and control X full irrigation with no significant differences between them. By day 72 a.f.b.(Table 5.7), Ψ_{Lm} of lucerne and plastic X RDI treatments only were significantly different to their respective full irrigation treatments.

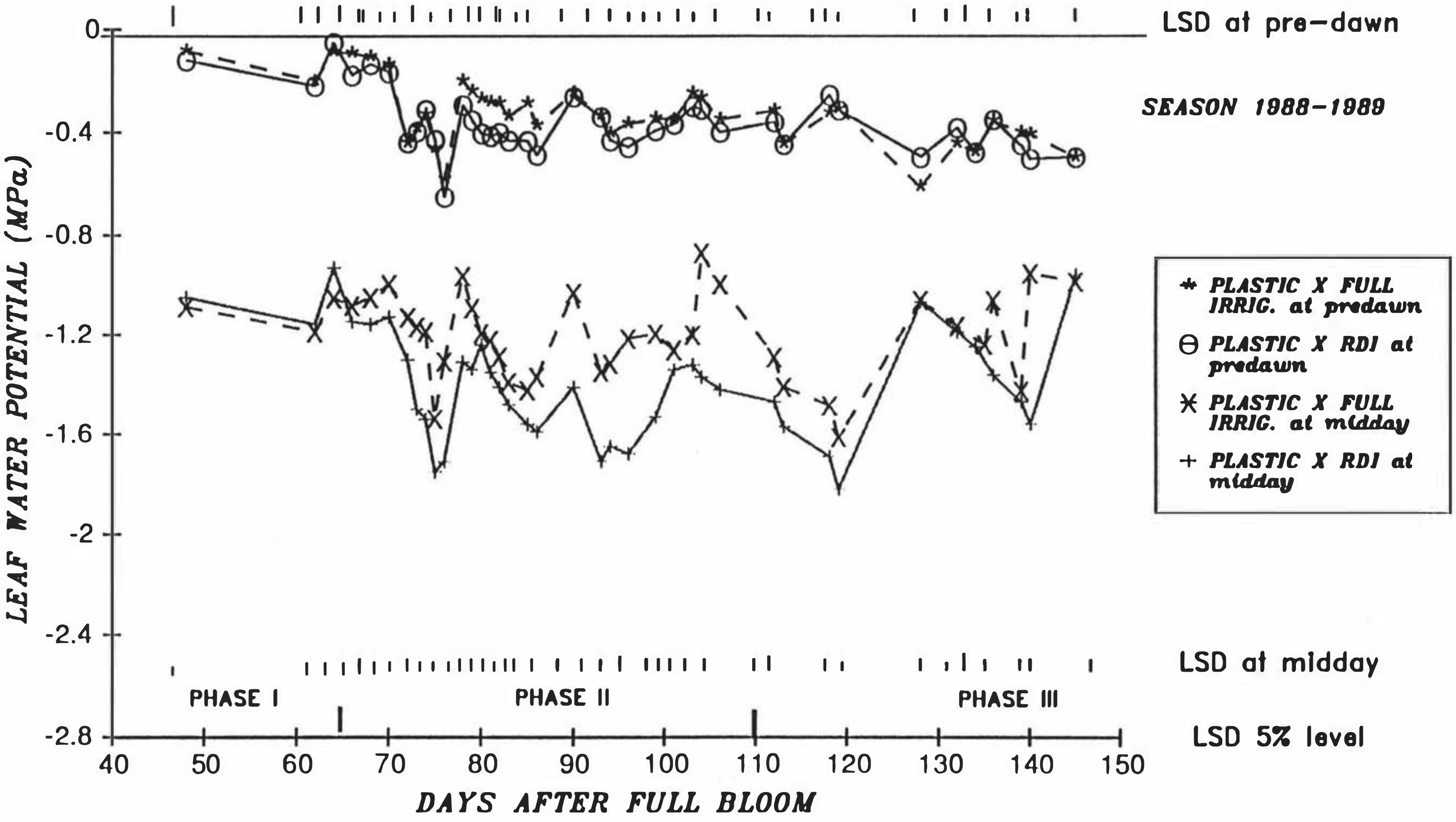

Figure 5.8. Seasonal pattern of predawn ($\Psi'_{l,p}$) and midday ($\Psi'_{l,m}$) leaf water potential for plastic treatments.

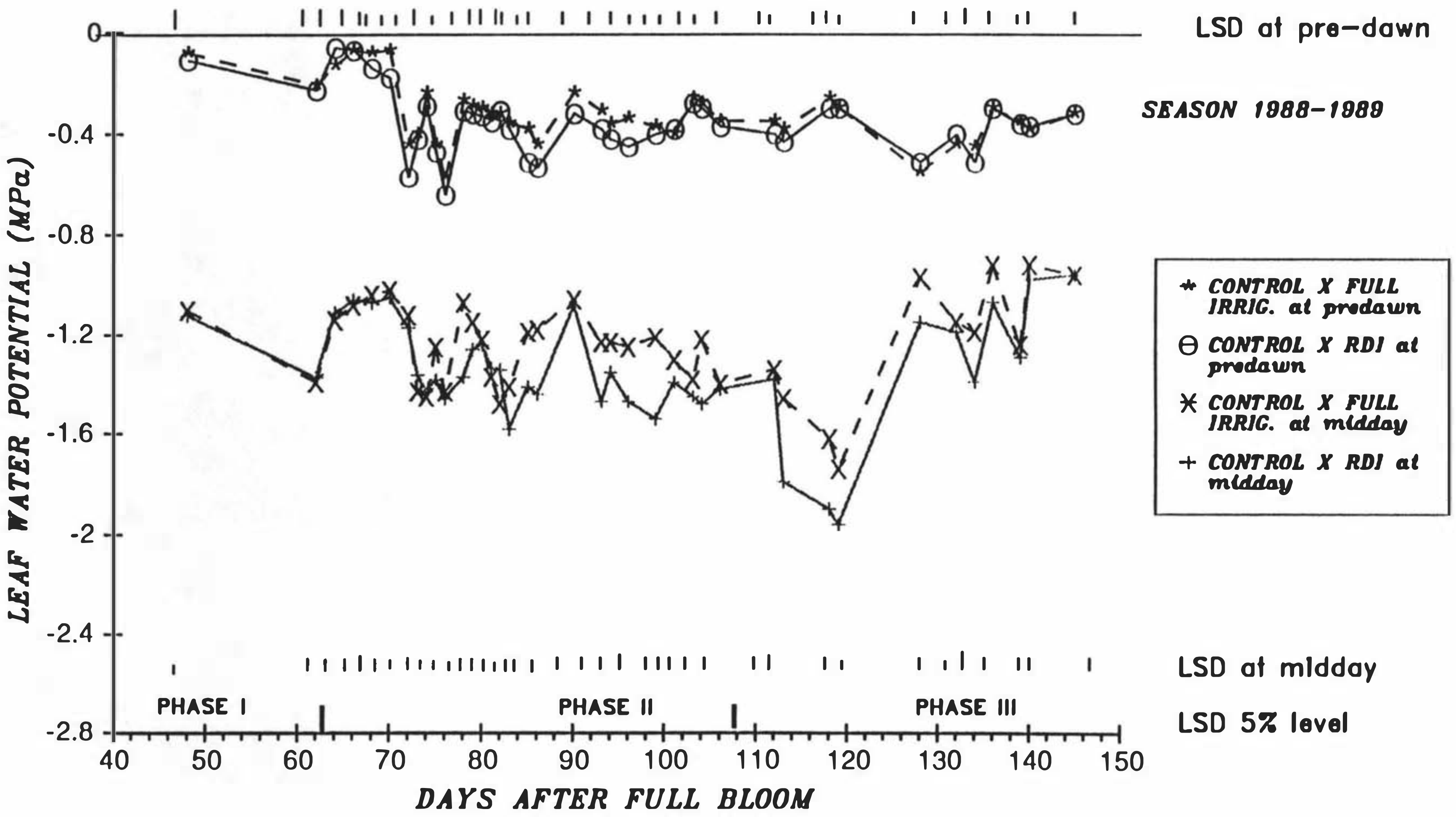

Figure 5.9. Seasonal pattern of predawn ($\Psi'_{l,p}$) and midday ($\Psi'_{l,m}$) leaf water potential for control treatments.

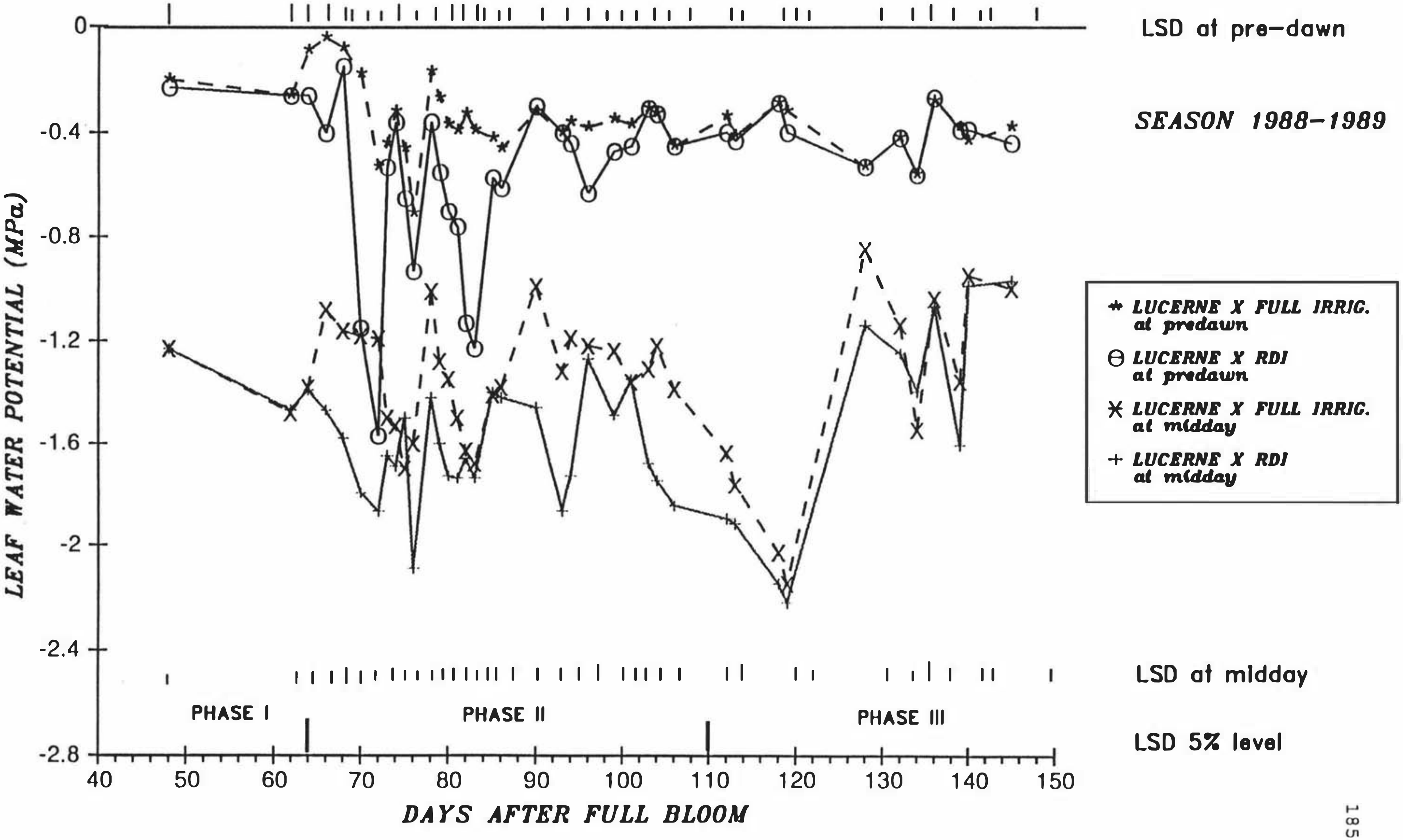

Figure 5.10. Seasonal pattern of predawn (Ψ'_{Lp}) and midday (Ψ'_{Lm}) leaf water potential for lucerne treatments.

Table 5.7. Effects of treatments on leaf water potential during Phase II.

Treatment	Day 72 a.f.b.		Day 83 a.f.b.		Day 106 a.f.b.	
	Ψ_{Lp} (Mpa)	Ψ_{Lm} (MPa)	Ψ_{Lp} (Mpa)	Ψ_{Lm} (MPa)	Ψ_{Lp} (Mpa)	Ψ_{Lm} (MPa)
Plastic X Full Irrig.	-0.44 c	-1.13 c^{z}	-0.34 e^{y}	-1.39 d	-0.35 cd	-1.00 c
Plastic X RDI	-0.44 c	-1.30 b	-0.41 b	-1.48 c	-0.40 ab	-1.42 b
Control X Full Irrig.	-0.44 c	-1.12 c	-0.36 de	-1.41 d	-0.35 cd	-1.40 b
Control X RDI	-0.57 b	-1.17 c	-0.38 cd	-1.48 c	-0.37 bc	-1.42 b
Lucerne X Full Irrig.	-0.53 b	-1.19 c	-0.39 c	-1.68 b	-0.34 d	-1.39 b
Lucerne X RDI	-1.57 a	-1.87 a	-1.23 a	-1.74 a	-0.45 a	-1.75 a

[z] Mean separation within columns by Duncan's multiple range test, 5% level.

[y] Means with same letter are not significantly different.

By examining the seasonal pattern of Ψ_{Lp} (Figures 5.8, 5.9 and 5.10) it can be seen that Ψ_{Lp} declined sharply between days 78 and 83 a.f.b. under lucerne X RDI and to a lesser degree in the remaining treatments. This decrease in Ψ_{Lp} resulted in a difference of 1 Mpa compared with the fully irrigated treatment. The plastic X RDI similarly had decreased to a significantly lower Ψ_{Lp} than the respective full irrigation treatment. There was no significant difference between the two control treatments. All treatments showed a decrease in midday values by day 83 a.f.b. (Table 5.7) following the same trend obtained in predawn data with the lower values recorded under lucerne X RDI and other RDI treatments. Plastic and control X RDI treatments, however, were not significantly different.

Following rainfall by day 106 a.f.b. lucerne X RDI Ψ_{Lp} had recovered to values which were closer to other treatments, although still significantly lower than all but plastic X RDI (Table 5.7). On same day (106 a.f.b.), Ψ_{Lm} increased in all the treatments except lucerne X RDI. Results of Ψ_{Lm} reflected treatment effect more markedly than Ψ_{Lp} which is consistent with studies of Ψ_{L} in peaches by Garnier and Berger (1987), indicating that influence of soil drying appeared more accentuated in midday than predawn values.

Overall data of Ψ_{Lp} for Phase II suggest that deficit treatments markedly affected lucerne Ψ_{Lp}, whereas in the control and plastic treatment, minor RDI effects only were obtained. The values of Ψ_{Lp} reached under lucerne X RDI, however, were considerably lower and more variable that those reported by Chalmers *et al.* (1983) for pears at similar times and treatments. This indicates that this treatment was more stressed at this time than the equivalent treatment in the above experiment, and establishes unequivocally that RDI treatments can be generated in spring in the Palmerston North climate with appropriate soil management and irrigation treatments. There was some evidence of RDI effects on the control and plastic treatment. Nevertheless, without additional management inputs RDI would not be likely to be fully effective in such climates.

5.4.3.3. *Phase III.*

Although all the treatments were receiving the same amount of irrigation, by day 119 a.f.b. Ψ_{Lp} of RDI treatments resulted in values that were significantly lower than their respective full irrigation treatments. A similar trend was also manifested on day 146 a.f.b. and overall. Results of Ψ_{Lp} for Phase III suggest that RDI soil water deficit remained greater than that for full irrigation treatments. These differences between treatments receiving the same irrigation or rainfall could be only explained by a dissimilar rate of water use in response to a different crop water demand. Fruit growth rates of these treatments at this time were indeed higher and provides further support for this conclusion.

Table 5.8. Midday leaf water potential (Ψ_{Lm}) during Phase III.

Treatment	Ψ_{Lm} (MPa)		
	Day 112 a.f.b.	Day 119 a.f.b.	Day 146 a.f.b.
Plastic X Full Irrig.	-1.29 c^z	-1.06 b^y	-0.99 ab
Plastic X RDI	-1.47 b	-1.82 a	-0.96 b
Control X Full Irrig.	-1.34 c	-1.74 a	-0.96 b
Control X RDI	-1.38 c	-1.96 a	-0.96 b
Lucerne X Full Irrig.	-1.54 b	-2.15 a	-1.00 a
Lucerne X RDI	-1.90 a	-2.22 a	-0.97 b

^{z} Mean separation within columns by LSD, 5 % level.
^{y} Means with same letter are not significantly different.

Results of Ψ_{Lm} showed a similar pattern. Despite the fact that all trees were receiving full irrigation from day 110 a.f.b., treatments recorded lower Ψ_{Lm} on day 112 a.f.b. (Table 5.8). Treatments that were under RDI exhibited lower values than the respective full irrigation treatments and the lowest value was obtained under lucerne X RDI, followed by lucerne X full irrigation (Figures 5.8, 5.9 and 5.10). Values of Ψ_{Lm} recorded in the latter treatment were significantly lower than those obtained under control treatments and also indicates the level of irrigation for lucerne treatment was underestimated. The minimum Ψ_{Lm} for the season for all the treatments, except plastic X full irrigation, was recorded on day 119 a.f.b. Excepting lucerne RDI on day 132 a.f.b. Minimum values of Ψ_{Lm} appeared uncorrelated with predawn data which reflected more closely the soil water deficit. Similar results have been reported in peaches as associated to higher crop water demand during periods of rapid fruit growth (Chalmers *et al.* 1983).

A general increase in Ψ_{Lm}, partly facilitated by rainfall had occurred by day 146 a.f.b. These results obtained during Phase III also suggest that trees were exhibiting an increased water demand which was not adequately compensated for the irrigation and rainfall until the last day of measurements. Although increased water demand might have been associated with the rapid fruit growth, it is clear that ET of all treatments was underestimated to some degree.

5.4.4. *Stem Water Potential* (Ψ_S).

Stem water potential appeared to follow closely the changes in Ψ_L (Figures 5.11 and 5.12). Minimum measured on day 80 a.f.b. at predawn (Figure 5.11) lucerne X RDI was lower than Ψ_{Lp} but differences might be due to the differential sensitivity in the instrument used to assess Ψ_S. The minima obtained on day 93 and 131 on lucerne were also measured in the control X full irrigation but lucerne showed the sharper decreases. The decline obtained on day 131 a.f.b. was less marked in midday values (Figure 5.12) in lucerne that had been under RDI than in control. However, significantly lower values were obtained at midday values. Results suggest that between days 76 to 80 a.f.b. a change in pattern of water use took placed that caused Ψ_S in both treatments to declined sharply.

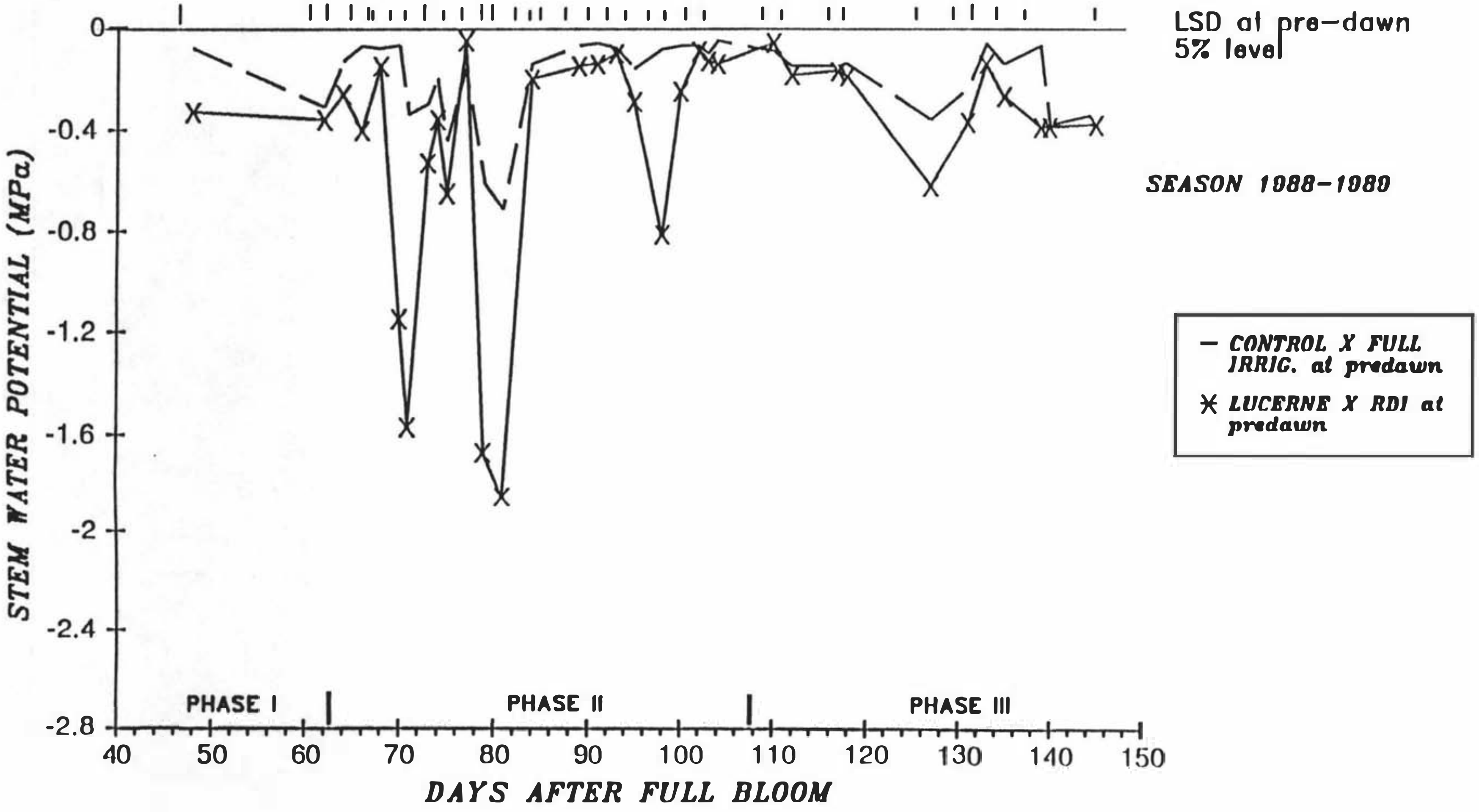

Figure 5.11. Seasonal pattern of predawn stem water potential (Ψ_s) of control X full irrigation and lucerne X RDI treatments.

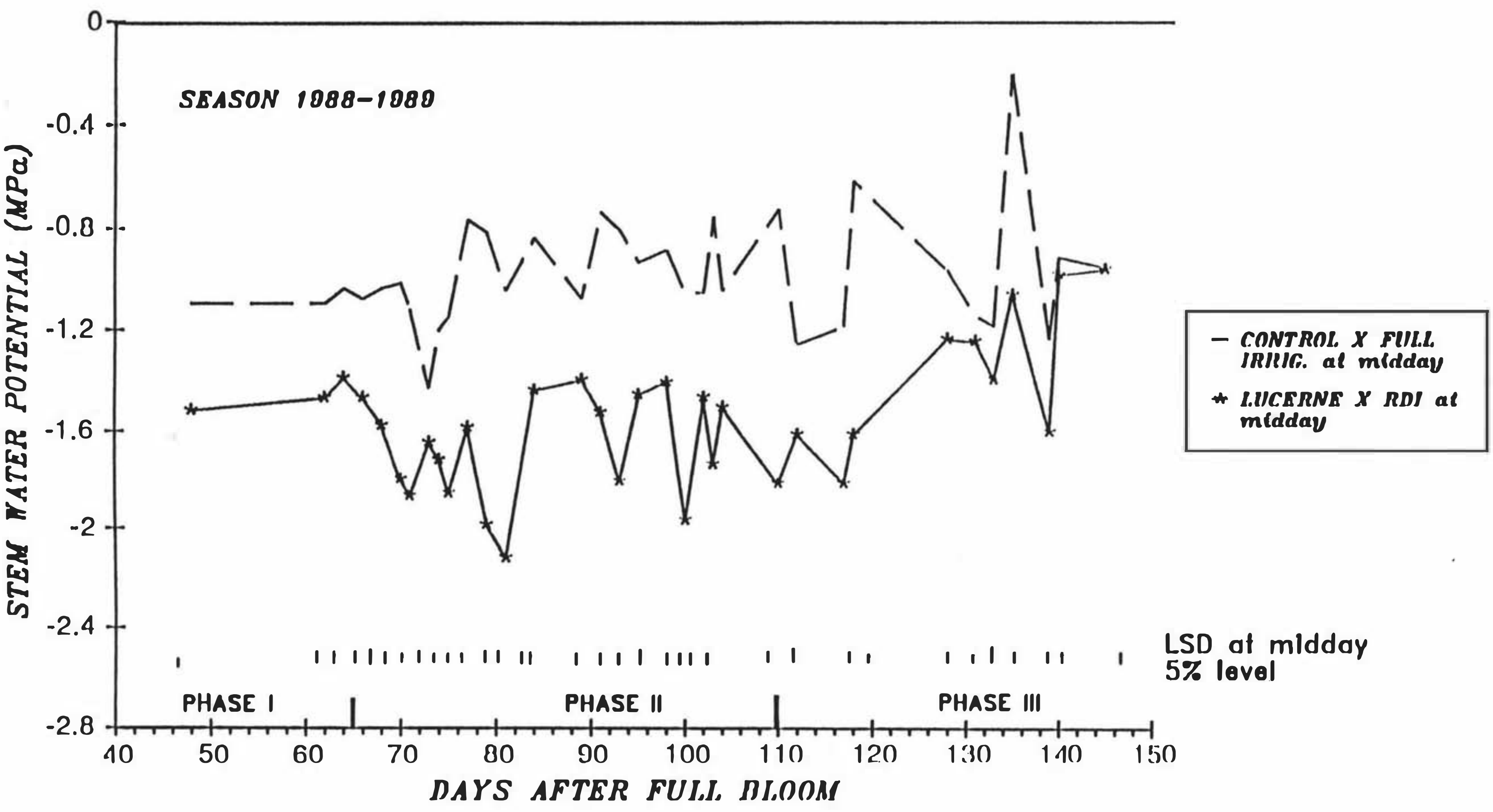

Figure 5.12. Seasonal pattern of midday stem water potential (Ψ_s) of control X full irrigation and lucerne X RDI treatments.

5.4.5. *Effects of Treatments on Vegetative Growth.*

5.4.5.1. *Trunk Cross Sectional Area*(TCSA).

Multiple analysis of variance for the overall effect of soil management and irrigation on absolute trunk growth resulted in no significant differences due to soil management. A highly significant effect was obtained due to irrigation. Effects of soil mangement were reflected in significant differences between plastic and lucerne X full irrigation. Full irrigation resulted in the highest trunk growth showing that RDI was effective in reducing vegetative growth during the season.

Table 5.9.Absolute and relative growth of trunk cross sectional area (TCSA) during season 1988-1989.

Treatment	Absolute Growth (cm^2)	Relative Growth $cm^2.cm^{-2}$
Plastic X Full Irrigation	17.11 a[z]	0.45 a[y]
Plastic X RDI	9.11 cd	0.21 c
Control X Full Irrigation	13.07 b	0.30 bc
Control X RDI	8.07 d	0.24 c
Lucerne X Full Irrigation	12.68 bc	0.34 ab
Lucerne X RDI	8.49 d	0.20 c

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

Since overall effects did not explain effects of interactions of soil management and irrigation, an analysis considering them resulted in data shown in Table 5.9. The highest absolute and relative growth was obtained under plastic X full irrigation treatment. This was significantly higher than all other treatments. Control and lucerne X full irrigation trunk growth were not significantly different.

Table 5.10.Total absolute and relative growth of trunk cross sectional area (TCSA) during the experiment.

Treament	Total Absolute Growth (cm^{-2})	Total Relative Growth $cm^{-2}.cm^{-2}$
Plastic X Full Irrigation	27.83 a[z]	0.98 a[y]
Plastic X RDI	23.39 a	0.82 a
Control X Full Irrigation	25.77 a	0.84 a
Control X RDI	17.29 b	0.65 b
Lucerne X Full Irrigation	24.05 a	0.84 a
Lucerne X RDI	20.34 b	0.67 b

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

Lucerne X full irrigation, hoewever, was not significantly different to plastic X RDI. No significant differences were obtained in the absolute and relative growth of TCSA of RDI treatments. The degree of RDI suppression of growth indicated the effectiveness of RDI strategies when combined with soil management in developing a soil water deficit in this environment.

As a result of treatments at the end of two growing seasons,(Table 5.10), the total absolute and relative growth of the TCSA of control and lucerne X RDI were significantly lower than other treatments. There was no significant differences between lucerne and control X RDI nor was among the remaining treatments. Plastic under RDI showed effect on trunk growth resembling that of full irrigation treatments. These results suggest that plastic X RDI was not effective in controlling trunk growth. Whilst effectiveness of lucerne and control X RDI was clearly manifested.

effective in controlling trunk growth. Whilst effectiveness of lucerne and control X RDI was clearly manifested.

5.4.5.2. *Shoot Length.*

Figure 5.13 shows the accumulated shoot growth for different treatments. Differences between treatments were evident during Phase I. which may be explained as an accumulated effect of previous season treatments. The control treatment X full irrigation became significantly different from plastic X full irrigation from day 54 until day 94 a.f.b. The shoot growth of these two treatment were significantly higher than the remaining treatments. In contrast, lucerne X RDI exhibited the lowest shoot elongation. From day 80 a.f.b. control X RDI and lucerne X RDI shoot growth declined. It ceased completely by day 88 a.f.b. The final shoot length attained by control X RDI, however, was not significantly different from lucerne X full irrigation and plastic X RDI but different from lucerne X RDI. An analogous response in shoot growth was observed in plastic X RDI and lucerne X full irrigation which converged to same final length. Shoot growth under these treatments ended by day 94 a.f.b., whilst growth of shoots under plastic and control X full irrigation stopped by day 99 a.f.b. (Summary of treatments effects on shoot lenght on both seasons is shown in Appendix 1).

5.4.6. *Effects of Treatments on Fruit Growth.*

5.4.6.1. *Phase I and Phase II.*

Analysis of fruit growth in terms of the ratio of the growth rates obtained under RDI to that obtained under full irrigation is shown in Figure 5.14. These results showed that soil water deficit and plant water deficit imposed by RDI and soil management treatments had no effect on fruit growth rate during the period preceding day 80 a.f.b. These data resembles previous findings by Chalmers *et al.* (1981, 1986) and Mitchell *et al.* (1984) in peaches and pears and show that apple fruit growth also have a growth that appears to be not very sensitive to water deficit. Indeed, during this period the present data include occasions when Ψ_{Lp} and Ψ_{Lm} fell to values considerably below those reported previously and further investigation of this phenomenon appears to be warranted. It is also evident (Figure 5.14) that RDI treatment resulted in a change in the pattern of fruit growth between days 80 to 87 a.f.b.

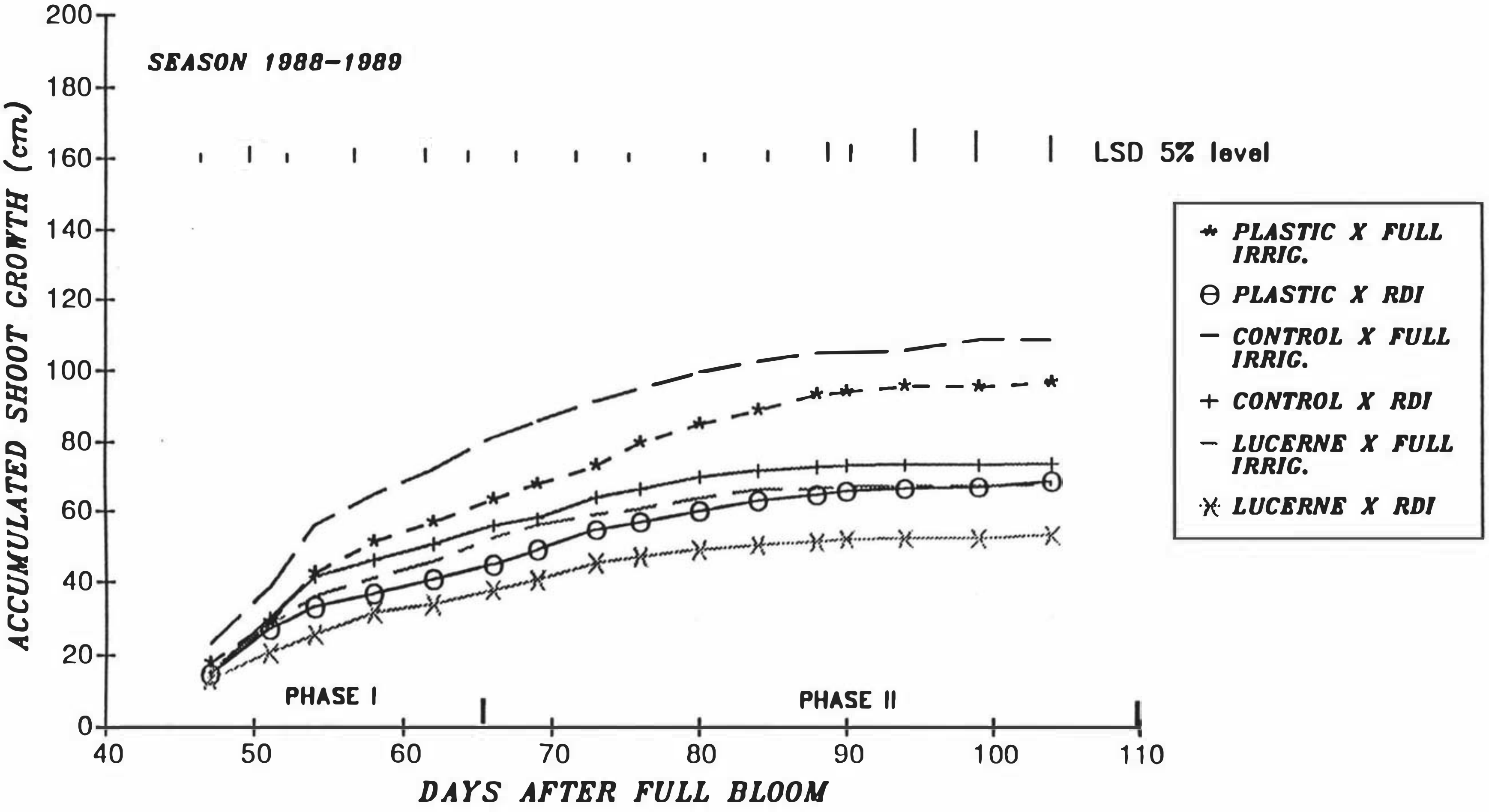

Figure 5.13. Accumulated shoot growth for all the treatments from day 47 to 104 after full bloom.

Fruit growth was suppressed under RDI compared to full irrigation treatments. This data corroborates the earlier conclusion that full irrigation replacement should have occurred around day 85 a.f.b. Suppression of fruit growth by RDI treatments was overcome by rainfall between days 85 to 93 a.f.b. after which the growth rate of RDI fruit exceeded that of the full irrigation treatments (Figure 5.14). A slight stimulation of fruit growth on day 90 a.f.b. and subsequent days of Phase II, was obtained under lucerne X RDI compared to the respective full irrigation treatment. This indicated a degree of fruit stimulation occurred under this treatment when it was relieved of its more severe water deficit.

5.4.6.2. *Phase III.*

Once full irrigation was replaced on RDI treatments, enhancement of fruit growth was obtained under plastic and control X RDI treatments. Rate of fruit growth exceeded that of full irrigation treatments until day 135 a.f.b. after which time it decreased to about same rate as full irrigation treatments (Figure 5.14). A minor effect but similar effect was also obtained in lucerne X RDI by day 131 a.f.b. Suppression of fruit growth was obtained under plastic and lucerne X RDI from day 137 a.f.b. until the first harvest (day 145 a.f.b.). These results confirmed that irrigation was insufficient to cope with crop water demand at times during Phase III. Moreover, a greater suppression of fruit growth resulted under lucerne X RDI, which indicate that crop water demand was higher under this treatment. Results indicate that a clear change in sensitivity to water deficit occurred from day 80 a.f.b. Despite the levels of cumulative soil water deficit and the low values of Ψ_L and Ψ_S reached before that time, RDI treatments did not result in fruit growth rates lower than those obtained under full irrigation. Treatments that received RDI responded to increased soil water in Phase III with a higher rate of fruit growth than of treatments receiving full irrigation. Although the degree of response was less marked at times lucerne X RDI also stimulated fruit growth.

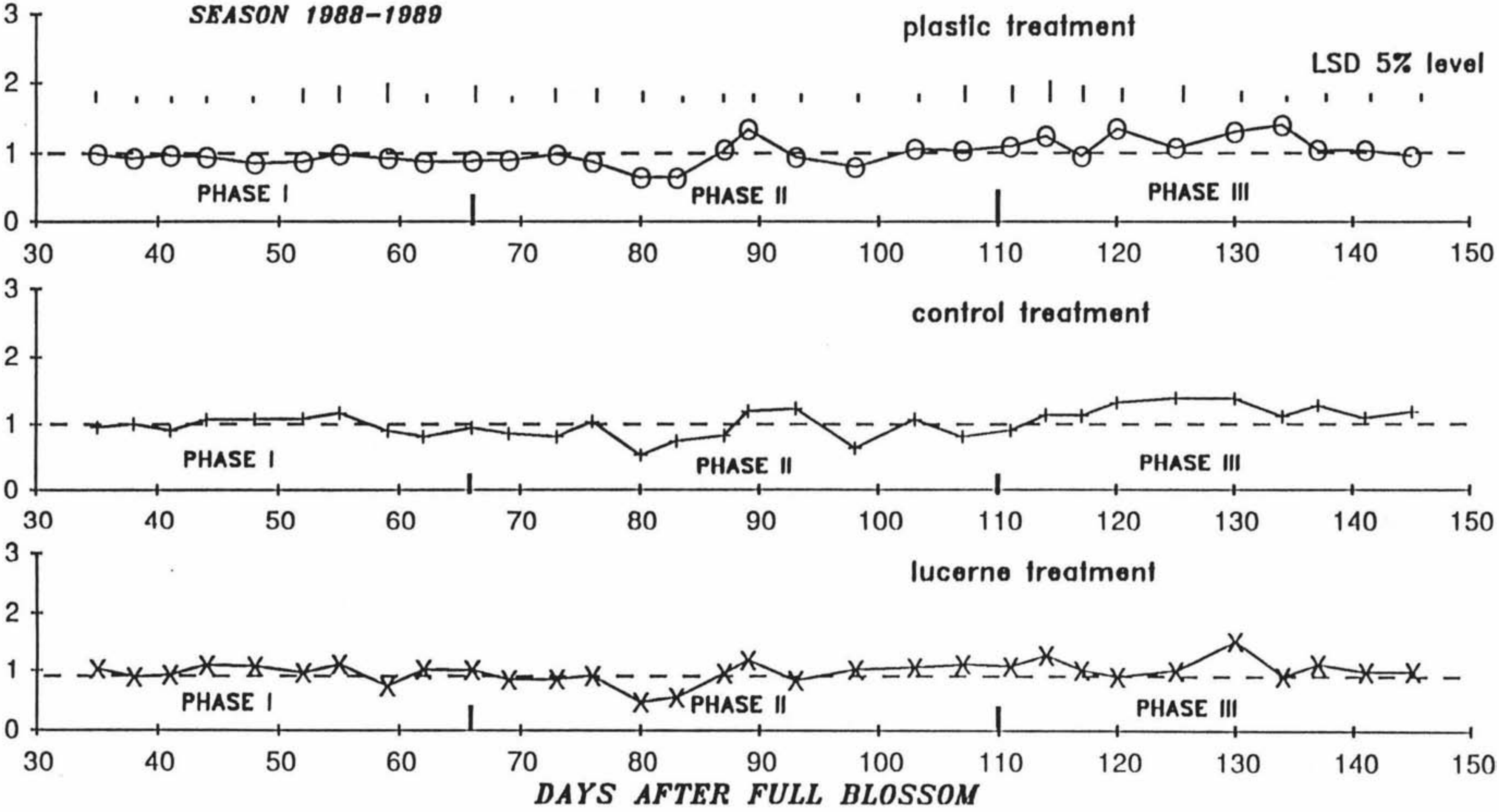

Figure 5.14. Ratio fruit growth rate of RDI treatments to the respective full irrigation treatments.

As judged by the marked degree of suppression of fruit growth by this treatment the highest crop water demand for this treatment occurred during Phase III. Obviously, ET for this treatment was underestimated.

Chalmers *et al.* (1983) proposed mechanisms of osmoregulation to explain the increased growth rate of fruits from RDI treatments. These authors explained that under conditions of soil water deficit fruits osmoregulate during the periods of low water potential thus maintaining the necessary turgor for cell enlargement. Through this process, soluble solids accumulate in the fruit against a gradient of negative water potential. Nevertheless, in this study the lowering in Ψ_{Lp} and Ψ_{Lm} was undesirable, since to elicit fruit growth response to RDI, an increase in Ψ_{L} is required. The present results are not exactly similar but comparably since RDI resulted also in higher Ψ_{Lp} and Ψ_{Lm} than in the previous work.

An examination of overall fruit growth in terms of volume increase (Figure 5.15) revealed no significant differences between treatments until day 90 a.f.b. From this time, the fruit size of control X full irrigation and lucerne X RDI was significantly lower than other treatments. From day 125 a.f.b. to harvest no significant differences between plastic and control X RDI treatments were obtained. The volume of these treatments, however, was significantly greater than other treatments.

5.4.6.3. ***Yield.***

An analysis of the effects of treatments on yield (Table 5.11) reveals that highest and lowest gross yield and tree per unit were obtained from control X RDI and lucerne X RDI treatments respectively. These results were significantly different from all other treatments.

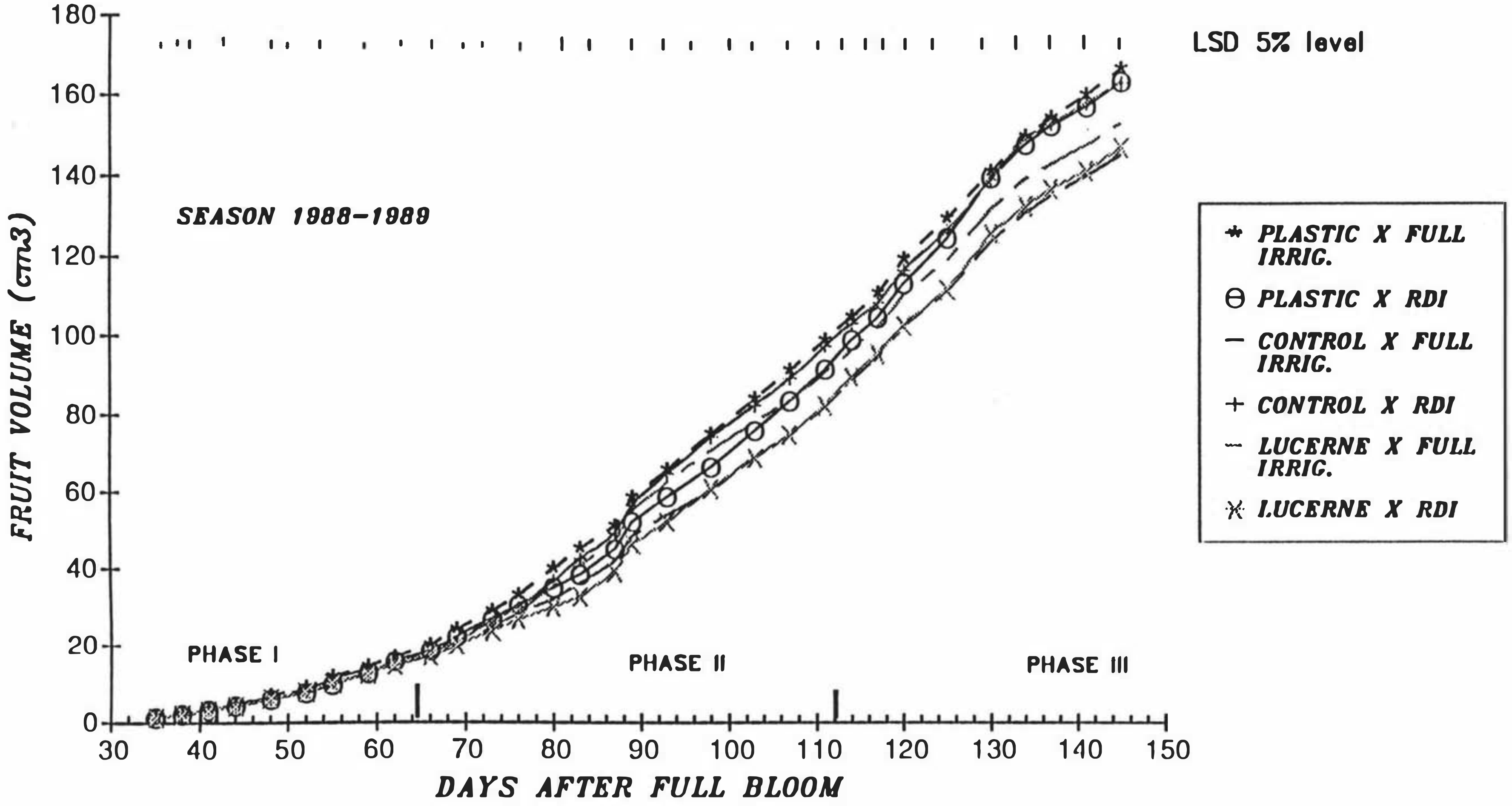

Figure 5.15. Change in fruit volume of Royal Gala apple trees as affected by treatments during the season 1988-1989.

Table 5.11. Effect of treatments on yield during the season 1988-1989.

Treatment	Gross Yield ($ton.ha^{-1}$)	Yield/unit (Kg/tree)	Yield Effc. ($Kg\cdot cm^{-2}$)
Plastic X Full Irrig.	70.66 bc[z]	56.23 bc[y]	1.31 c
Plastic X RDI	72.81 b	58.24 b	1.47 b
Control X Full Irrig.	72.36 b	57.89 b	1.39 c
Control X RDI	76.82 a	61.46 a	1.61 a
Lucerne X Full Irrig.	68.36 c	54.69 c	1.31 c
Lucerne X RDI	64.12 d	51.29 d	1.22 d

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

When yield was expressed in terms of the unit tree size, the highest yield efficiency was obtained under control X RDI. This was significantly higher than other treatments including plastic X RDI. Plastic X RDI, however, had a greater yield efficiency than comparable full irrigation treatment.

Comparing the yield for the two seasons (Table 5.12) it is evident that control and plastic X RDI showed positive effects on gross yield and yield per tree. Additionally, yield efficiency was also increased in both treatments. Lucerne X RDI produced the lowest yield which was lower than the full irrigation treatments. Excepting control X full irrigation, yield efficiency of full irrigation treatments decreased over the two years of the experiments whereas an increase occurred in RDI treatments. The results imply also that RDI treatments were substantially more efficient in water use than full irrigation treatments.

Table 5.12. Effect of treatments on yield during the experiment.

Treatment	Gross Yield (ton.ha^{-1})		Yield/ unit (Kg/ tree)		Yield Effc. (Kg·cm^{-2})	
	87/88	88/89	87/88	88/89	87/88	88/89
Plastic X Full Irrig.	53.64 b[z]	70.66 bc[y]	42.91 a	56.23 b	1.46 b	1.31 d
Plastic X RDI	53.59 b	72.81 b	42.87 a	58.24 b	1.38 c	1.47 b
Control X Full Irrig.	50.47 c	72.36 b	40.37 b	57.88 b	1.32 d	1.39 c
Control X RDI	54.93 a	76.82 a	43.95 a	61.45 a	1.54 a	1.61 a
Lucerne X Full Irrig.	53.32 b	68.36 c	42.66 a	54.69 c	1.41 bc	1.31 d
Lucerne X RDI	45.43 d	64.12 c	36.33 b	51.29 c	1.18 e	1.22 e

[z] Mean separation within columns by LSD, 5 % level.

[y] Means with same letter are not significantly different.

5.4.6.4. *Effects on Fruit Quality.*

5.4.6.4.1. *Fruit Size.*

The effects of soil and irrigation management treatments on fruit size varied inconsistently (Table 5.13). It is clear, however, that lucerne X full irrigation and lucerne X RDI reduced yield in the desirable size classes confirming the earlier conclusion that lucerne had adverse effects upon fruit growth. Of the other treatments only plastic X full irrigation showed superior fruit size. Examination of yield efficiency of this treatment (Table 5.11), however, reveals that it had a very low yield efficiency, comparable only with lucerne X full irrigation. This indicates that under cropping level rather than soil or irrigation treatment was the cause of superior fruit size in this treatment. It is notable that control X RDI which produced the highest yield per unit tree size of all treatments, had a superior fruit size to the fully irrigated control. This result is consistent with that reported by Mitchell *et al.* (1989) which showed after six seasons that RDI enhanced fruit size on similarly loaded pear trees.

5.4.6.4.2. *Flesh Firmness.*

A pooled analysis of firmness data showed that the most important factor affecting it was the time at which the measurement was carried out. Second in order of importance was the time of picking. Pooled analysis by soil management showed that fruits from lucerne treatments were significantly of firmer than those from control and plastic treatments. No significant differences were obtained in this analysis between plastic and control treatments. Overall analysis by irrigation showed that fruits from RDI treatments were significantly more firm than fruits from full irrigation treatments (Table 5.13).

At time of harvest the highest and lowest firmness was obtained from lucerne X RDI and plastic X full irrigation treatments respectively. Both data sets were significantly different from the other treatments.

Table 5.13. Effects of treatments on yield (kg/unit) by class size of the season 1988-1989.

Class Size (g)	170-180	150-170	130-150	120-130	110-120	100-110	<100
Plastic X Full Irrig.	2.50 a[z](14)	7.23 a[y](45)	10.41 a(74)[x]	13.78 b(110)	7.63c(66)	5.22c(50)	9.46c(95)
Plastic X RDI	0.54 b(3)	2.91 bc(18)	6.54 b(46)	15.23 b(121)	9.52a(83)	8.12b(77)	15.40b(154)
Control X Full Irrig.	0.34 d(4)	2.07 c(13)	4.36 c(31)	12.02 c(96)	9.52a(83)	8.79a(83)	20.79a(207)
Control X RDI	0.43 c(2)	3.37 b(21)	6.92 b(49)	17.55 a(140)	10.84a(94)	8.57a(82)	22.80a(228)
Lucerne X Full Irrig.	0.34 d(2)	1.67 cd(9)	4.34 c(31)	14.01 b(112)	8.26ab(72)	8.31a(79)	17.77a(178)
Lucerne X RDI	0.23 c(1)	1.05 d(7)	2.60 d(19)	11.35 c(91)	7.90bc(69)	8.49a(81)	19.67a(197)

[z] Mean separation within columns by Duncan's multiple range test, 5% level.

[y] Means with same letter are not significantly different.

[x] Number of fruits.

Table 5.14.Effects of soil and irrigation mnagement treatments on fruit quality season 1988-1989.

	Fruit Firmness (Kg)		Soluble Solids (%)		Bruise Diameter (cm)	
	At Harvest	10 Weeks -2°C	At Harvest	10 Weeks -2°C	At Harvest	10 Weeks -2°C
Plastic X Full Irrig.	6.65 bc[z]	4.88 b[y]**	11.69 c	12.00 c^{NS}	2.60 a	2.57 a^{NS}
Plastic X RDI	6.74 b	4.93 ab**	12.03 b	12.47 c *	2.52 b	2.54 b^{NS}
Control X Full Irrig.	6.76 b	4.87 b**	11.52 c	11.99 c^{NS}	2.52 b	2.64 a **
Control X RDI	6.72 b	4.98 a**	12.32 a	13.00 b*	2.43 c	2.56 b **
Lucerne X Full Irrig.	6.00 c	4.83 b**	11.90 b	13.03 b**	2.52 b	2.60 a **
Lucerne X RDI	7.21 a	4.97 a**	12.39 a	14.03 a**	2.50 b	2.50 c^{NS}

[z] Mean separation within columns by Duncan's multiple range test, 5% level.

[y] Means with same letter are not significantly different.

NS *, ** = non significant, significant at 5% (*) and significant at 1% (**) levels respectively.

Fruits from lucerne that was under full irrigation were also significantly firmer than the other treatments, whereas no significant differences were obtained between both control treatments and plastic X RDI. After 10 weeks in cool storage fruit firmness decreased significantly in all the treatments. Firmness of fruits from the RDI treatments, however, was significantly higher than the respective full irrigation treatments, though there were no significant differences between management systems. Furthermore, no significant differences between full irrigation treatments were obtained. Results suggest that fruits that were under full irrigation tend to become softer more rapidly than fruits from RDI treatments. Fruits of equal fruit size were used for this analysis therefore, one can conclude that treatment effects rather than fruit size *per se* was responsible for the reported results.

5.4.6.4.3. *Solids Soluble.*

Pooled analysis of variance by soil management and irrigation resulted in lucerne and RDI treatments showing higher solids soluble than control and plastic and other full irrigation treatments. An analysis taking in account the interaction of soil management and irrigation is shown in Table 5.13. At time of harvest fruits from the RDI treatments contained significantly higher levels of soluble solids than the respective full irrigation treatments. No significant differences were obtained between RDI treatments or between full irrigation treatments. However, fruits from lucerne X full irrigation were not significantly different from fruits from plastic under RDI treatment. Soluble solids content increased in all the fruits after 10 weeks of cool storage. A significantly greater increase was obtained in fruits from lucerne treatments. This effect was the highest for fruits that were under RDI. Not significant changes were obtained under plastic and control X full irrigation with respect to the values at harvest time. Nonetheless, fruits from RDI treatments showed a solid soluble content that was significantly higher than the respective full irrigation treatment.

Fruits from lucerne that were under RDI resulted in the highest soluble solid content after 10 weeks of cool storage. Results were significantly higher than fruits from control and plastic X RDI treatments. These results agreed with numerous reports in which high T.S.S. have been obtained in fruits from reduced irrigation treatments (Assaf *et al.* 1975., Guelfat and Ben-Arie. 1979., Proebsting *et al.*1984) and with those reported by Irving and Drost (1987) in Cox's Orange Pippin apples.

5.4.6.4.4. *Bruise Resistance.*

A multivariate analysis considering time of picking, time of measurement after harvest, soil management, and irrigation showed that main factor affecting the fruit bruise susceptibility was the time of picking (Data not shown). Pooled analysis of variance (Table 5.13), showed that plastic and control X RDI resulted in lower bruise susceptibility at harvest, than the respective full irrigation treatments. After 10 weeks of cool storage, fruit from RDI treatment were uniformly less susceptible to bruising than their fully irrigated counterparts. No consistent significant differences between soil management treatments were obtained from the pooled analysis. At time of harvest, the highest and lowest bruise susceptibility was obtained in fruits from plastic X full irrigation and from control that received RDI respectively.

After 10 weeks of cool storage no significant changes were detected in fruits from the RDI treatments, or from plastic X full irrigation. A significant increase in bruise susceptibility, however, occurred in fruits from control X RDI and control and lucerne treatments that previously had received full irrigation. Resulted suggested that quality of fruits when evaluated in terms of resistance to bruising was higher in fruits from RDI treatments.

5.5. *Discussion.*

Results from season 1988-1989, confirmed that RDI strategies can be applied in the humid environment of Palmerston North provided a suitable soil management technique is applied. Of the two techniques tested under this study a lucerne sward resulted a more effective system than black polyethylene film for creating a soil water deficit earlier during the growing season. Although the plastic was in place from early winter, it began to be effective when the crop was actively using water. From dawn and midday values of leaf water potential and evaluation of soil water, it was apparent that plastic acted to retain soil moisture in the root zone of the crop rather than prevent its accumulation. Similar effects of black plastic mulching on apple trees were reported by Bacon (1974) and Mage (1982) when used to maintain soil moisture.

Results of the present study contrast with reports by Jones *et al.*(1983) and Erf and Proctor (1989), in which positive effects on decreasing soil moisture content were obtained by the use of transparent polyethylene, under-canopy, tent covers. The method, however is clearly different, while the tent allows air circulation, encourages rain runoff, and maximizes reflectance with no marked effects on microclimate (Jones *et al.* 1983), the black plastic mulch directly covers the soil surface and prevents evaporation. Since, the albedo of the black mulch could be assumed to be practically null, it would be expected that temperature increase in the soil and atmosphere near the soil surface favouring evaporation. A concomitant water condensation would have occurred with the lowering of temperature during the night. This study did not evaluate microclimate under the black plastic mulch which could have supported these inferences. When the trees were actively growing, the crop transpiration decreased the soil water content more rapidly, thus a RDI effect, could be obtained with this soil management treatment, but only later in the season. The cumulative soil water deficit reached 116 mm by day 72 a.f.b. under black plastic mulch. The reduction in shoot elongation resulting from this treatment compared with the conventional soil management was 37%. According to Mitchell *et al.* (1989), with such an ET a 22% reduction in summer pruning is possible. To the extent that these results could be said to differ, they might be explained by the fact that my evaluation was not based on E_{pan} but on soil data which reflects the real deficit more exactly. Furthermore, these experiments were conducted on apple trees grafted onto semi-dwarfing rootstocks, which might be expected to be more sensitive to RDI.

On the other hand, soil water content was reduced rapidly and more efficiently under lucerne sward. Around day 72 a.f.b. minimum values of Ψ_L and Ψ_S water potential in midday and predawn values reflected effects of cumulative soil water deficit under this treatment which reached figures of 148 mm. This figure according to Mitchell *et al.* (1989) would reduce summer pruning in about 32%, whereas our results indicated a 46 % reduction of growth. The soil water deficit under the control reached values of 116 mm which is similar to data obtained under plastic mulch, whereas, the reduction in summer pruning was only 32%.

Since lucerne X full irrigation developed a soil water deficit during withholding period, equal to lucerne X RDI and reduced summer pruning in a 38 % it could offer a viable alternative for reducing tree vigour.

Effects of RDI in suppressing shoot elongation were obtained as early as day 76 a.f.b. under lucerne. Treatments were prolonged, however, until day 110 a.f.b. Obviously, this was unnecessary since the desired effects on reduced vegetative growth had been obtained. On the other hand, day 85 a.f.b. was found to be a more appropriate time to replace full irrigation to RDI treatments. It was apparent from results on fruit size that to extend RDI beyond the critical day had a marked effect on fruit growth and increased the number of fruits in the undesirable size classes.

Lucerne remain active throughout the growing season continuing to exert a marked effect on the soil water budget, and causing final fruit size and yield from these treatments to be more reduced. It is apparent that these problems may have been overcome for this treatment by increasing the water allocation to provide for the additional lucerne demand. These results show the importance of close assessment of the soil moisture content and plant water status to optimize orchard management.

The replacement of RDI for full irrigation elicited analogous responses in fruit growth to those obtained in peaches and pears (Chalmers *et al.* 1981; Mitchell and Chalmers,1982; Chalmers *et al.* 1983), but also indicates developing fruitlets may tolerate greater water deficits than recommendations by the preceding reports imply. Positive effects of RDI were manifested on yield per unit tree size. Also, the deficit resulting from a period of withholding irrigation and RDI indicated, by the minimum values of Ψ_L obtained here which were even lower than those data reported by Chalmers *et al.* (1983) in a dry environment that RDI did not affect fruit growth during the early stages (Figure 5.18). This confirms that stages of fruit growth vary in sensitivity to soil water deficits (Chalmers *et al.* 1981; Mitchell and Chalmers, 1982; Chalmers *et al.* 1983). Nevertheless this works shows the soil water deficit can be used to reduce tree vigour without adverse effects on yield. Furthermore, this works has established that RDI can be made more effective in humid environments when accompanied by an appropriate soil management strategy.

In additions to the positive effects of RDI on yield, fruit quality evaluated in terms of T.S.S., firmness and bruise resistance was also increased by RDI. High T.S.S. and firmness has been associated to fruits from plants that have been subjected to water deficit (Assaf *et al.* 1975; Guelfat and Ben-Arie, 1979; Proebsting *et al.*1984 and Irving and Drost, 1987). Nevertheless, some of these workers applied the water deficit throughout the growing season reason, and consequently obtained small fruit size. Measurements of quality were made on smaller fruit size and results explained in terms of low moisture content and small fruit size. In this study, T.S.S. compared fruits of the same size. The increase in T.S.S. thus obtained provides evidence that RDI increased the concentration of photo assimilates in fruits perhaps by an effect on osmoregulation. Considering that a highly significant increase in T.S.S. in fruits from RDI treatments was obtained after cool storage, results may indicate that initial starch content was also higher in these fruits at harvest time. Clearly, these effects of RDI on fruit quality postharvest open new and rewarding areas of research on the possible beneficial effects of RDI.

CHAPTER 6

GENERAL DISCUSSION

6.1. *Soil Management.*

The foregoing results obtained during two seasons with Royal Gala apple clearly demonstrated that Regulated Deficit Irrigation (RDI) can be adapted to a humid environment. The two soil management techniques studied facilitated the application of RDI under these conditions in different degrees.

Of the two soil management techniques used in this study, lucerne as under tree cover provided an excellent technique to impose a soil water deficit early in the growing season. Lucerne, however, was difficult to manage in this study and requires more research. Although the lucerne cultivar AS13R used in this study was selected to be winter active and supposedly more productive over late autumn and early spring, its activity, however, was high during summer. Thus, lucerne became a strong competitor for water to the crop at time when it was undesirable. The crop water requirement under lucerne treatment in both seasons was underestimated. Jensen (1968) suggested that in a two-stage agricultural crop such as the case of lucerne as an under tree cover in a deciduous orchard, the crop coefficient K_c may be as high as 1.2. It appears that the increase may be due to a smaller resistance to turbulent transfer of water vapour, resulting from increased aerodynamic roughness of the two level-crop. Thus, to overcome the increased ET as the season progresses a higher K_c factor should be used. In free draining conditions full irrigation might be planned to replace up to 200 % EPS to allow an adequate safety margin for the lucerne water requirements.

In contrast, black plastic mulch acted as a barrier preventing soil evaporation during the early stages of vegetative growth. Thus, high soil moisture in the root zone of the crop was maintained for a longer period allowed a considerable amount of vegetative growth. This amount was between 11 to 15% more than that obtained under lucerne X RDI. A similar amount of the growth was obtained by using RDI on a conventional herbicide strip soil management over the two experimental seasons. Considering its high cost and relative ineffectiveness, black plastic mulch would be inadvisable.

Conventional soil management using an herbicide strip, produced effects of RDI no different to those obtained under black plastic mulch. Consequently, while the conventional herbicide strip in conjunction with RDI strategies is less effective, under humid conditions, it can be applied with no additional cost and few risks. Considering vegetative vigour will still be reduced and fruit yield enhanced in most seasons, RDI can be justified as a standard irrigation management strategy for humid environment. On the other hand, should subsequent research confirm the effects on fruit quality in the way the present results indicate, RDI will have an important new role to play in orchard management.

6.2. *Irrigation Scheduling.*

Of the two methods used to estimate the crop water requirements and determine RDI strategies, the approach based on soil water monitoring and plant water status proved to be more adequate in this environment. Results indicated, however, that in both seasons irrigation needs of RDI treatments during Phase III were underestimated, especially under the lucerne treatments. It was apparent that a close assessment of soil water deficit expressed in terms of soil water potential could be useful for a rapid assessment of crop water needs. For this purpose devices such as electronic tensiometers may be helpful to growers in areas with similar difficulties. Measurements of plant water deficit if they are unaccompanied by soil water potential (although of exceptional value in early stages) may be misleading during rapid fruit growth. Low values of Ψ_{Lm} have been shown to be characteristic of periods of rapid fruit growth RDI (Chalmers *et al.* 1984). Similarly, in this study low Ψ_{Lm} values were obtained in days when soil water content was high. These values indicate that apple also has different levels of critical Ψ_{Lm} at different stages of growth. Decreases in predawn values were more consistently related to soil water deficit.

It was clear that crop water requirement varied during the growing season (Mitchell *et al.* 1986). The stimulating effect of RDI on photoassimilate demand and water needs together with the use of lucerne deserve special consideration. From the results obtained in this study, to estimate of total seasonal E_T for an RDI strategy including lucerne would require a crop potential evaporation with a different K_c depending on the stages of fruit development. Thus, during the RDI period (time t_0 to t_1):

$$ET = \int_{t_0}^{t_1} K_L E_0 d_t$$

where K_L can be the crop factor for lucerne, t_1 a critical time at which RDI must be interrupted (which coincides with the initiation of rapid fruit growth and which will be discussed later) and E_0 the initial potential evaporation would be reduced by a factor of 0.25 to obtain the RDI effects. Whereas, during rapid fruit growth stage (Phase III):

$$ET = \int_{t_1}^{t_2} K_L ER d_t$$

where K_L is equal to 1.2 (Jensen, 1968) and the total potential ER corresponding to the local meteorological conditions.

The time at which full irrigation is applied following RDI treatments appears to be critical to achieve positive effects of RDI on fruit growth and yield. In both seasons for Royal Gala apples this time appeared to be between days 80 and 85 a.f.b. Results obtained when soil water content was monitored further indicated that if this procedure is to be used. from this time on irrigation should be supplied at the amount and rate that raise soil moisture to the DUL.

6.3. *Sensitivity to Water Stress at Different Crop Stages.*

The differential sensitivity of apple tree to soil water deficit was clearly manifested by the pattern of Ψ_L and the rate of fruit and shoot growth. The minimum values of Ψ_{Lp} recorded during this study during Phase I and II. differentially affected shoot and fruit growth. While, shoot elongation was halted, by the soil water deficit, rate of fruit growth was clearly not suppressed in either season until the period between days 80 to 85 a.f.b. (Figures 4.16 and 5.13). Increased soil water deficit at the time when shoot was growing actively and cells were expanding rapidly could be expected to suppress vegetative growth. Cell expansion is driven by cell turgor which is directly related to plant Ψ. For this reason Hsiao (1973) hypothesized that cell elongation is most sensitive to water deficit. Although the exact physiological mechanism is still unknown, RDI appears also to suppress growth of roots, which leads to a response possibly mediated by root hormones causing a decrease in shoot elongation (Richards and Rowe, 1977; Richards, 1986). In these experiments, the effects of soil water deficit were also manifested in the decrease of Ψ_L which in extreme instances may have depressed photosynthesis. With the exception of the lucerne treatments, effects of depressed photoassimilate production, however, were confined to vegetative growth. The present results are therefore consistent with those of Lackso (1983) and Lackso *et al.* 1984), who showed that moderate water stress in apples can inhibit the growth of immature tissues, without affecting whole tree carbon assimilation by mature tissues.

The effects of RDI on reduction of summer pruning during season 1987-1988 were between 10 to 15% greater than those obtained by Mitchell *et al.* (1989) for the same levels of deficit. During the following season (1988-1989), the soil water deficit obtained was higher, but the reduction in summer pruning was in the same range as the obtained in the preceding season. Since the trees were only 3-yr old, a higher reduction in summer pruning indicates a greater sensitivity to water deficit of the younger trees. These results suggest that the regression obtained by Mitchell *et al.* (1989) may be applicable to apples in New Zealand, though some flexibility in the model is required to account for such factors as the age of the trees.

Effects of soil water deficit on shoot growth without negative effects on early fruit growth clearly divides fruit growth of apple into two stages which differ in their sensitivity to water deficit. The later stage of rapid fruit growth was shown to be highly sensitive to soil water deficit. During both seasons, days on which soil water deficits occurred, fruit growth was depressed. This effect was accentuated under lucerne treatments, which showed a higher water demand by the combined crop. On the other hand, the replacement of the RDI treatments with full irrigation resulted in a rapid increase in fruit growth which significantly exceeded the rate exhibited for treatments that had received full irrigation (Figures 4.17 and 5.14). These results appear to indicate that recognizable alterations in growth and, consequently assimilate partitioning occur during apple tree growth that are facilitated by RDI. A similar response has been consistently reported in RDI studies in pear, peaches and grapes (Chalmers *et al.* 1981, 1983, 1986; Mitchell *et al.* 1982, 1988 1989 and Goodwin and Jerie,1989). While it may be argued that a marked change in

Goodwin and Jerie,1989). While it may be argued that a marked change in developmental physiology could have caused this response, none of such changes was obvious. In these experiments, however, it is noteworthy that the response in fruit growth coincides with the cessation of vegetative growth. If, as Chalmers *et al.* (1983) has proposed, early fruit growth was more strongly affected by competition from vegetative growth than by mild water deficits, this would explain the present data. Fruit became sensitive to water deficits in these experiments only after competition from growing shoots was eliminated.

Results of this study appear to show, that by eliminating the competitive effect of vegetative growth the partitioning of assimilates towards fruits is increased. This is expressed in the phenological change to fruit growth with RDI treatments having higher fruit growth rate than their counterparts receiving full irrigation, and the increase in sensitivity to plant water deficits.

6.3. *Regulated Deficit Irrigation Effects on Fruit Quality.*

Effects of the diversion in photo assimilates towards fruit by RDI were reflected in the increased T.S.S. content of fruits from RDI treatments, which increased under cool storage. These data indicate that at the time of harvest, total carbohydrate content (soluble plus insoluble fractions), albeit not measured, was higher in fruits from RDI. In addition, fruits from RDI were of higher firmness and lower susceptibility to bruising.

The degree of bruising is a key determinant of apple fruit quality which strongly which strongly affects domestic international marketing. Progress with bruising in the apple industry has so far been confined to research and developments and equipment and methods. These data are one of the first clear indications that susceptibility of fruit to bruising can be modified by orchard management. If this can be confirmed it will be a major development in pomological research and give further impetus to more general use of RDI technology.

The magnitude of the deficit obtained under lucerne and the concomitant effect on reduction of summer pruning indicate that it might be invaluable to be used in conjunction with RDI strategies in soils of high water retentivity in humid climates.

A major limitation to high productivity in the humid tropics, is the vigorous vegetative growth of fruit trees which acts to the detriment of fruit yield. The opportunities for adapting RDI to a humid environment in New Zealand opened up by this research indicates possibilities for much wider use for RDI.

It is clear that much speculation that RDI may be of limited value in moister environments or on deeper soils is baseless. Furthermore, there are promising new possibilities which may lead to RDI becoming the standard irrigation practice for fruit tree crops throughout the world.

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Appendix 1A. Effects of treatments on shoot extension (season 1987-1988).

Treatment	Initial Length	End Phase I	Δ (cm)	End Phase II	Δ (cm)
Plastic X Full Irrig.	20.77 a[z]	45.5 b[x]		101.27 a	
Plastic X RDI	22.22 a	30.8 c	14.7	66.00 b	35.85
Control X Full Irrig.	24.89 a	57.4 a		109.67 a	
Control X RDI	24.22 a	41.1 b	16.4	73.11 b	36.56
Lucerne X Full Irrig.	20.08 a	36.9 bc		68.41 b	
Lucerne X RDI	18.66 a	25.6 c	11.2	52.97 c	15.44
LSD	12.08	11.5		11.90	

Appendix 1B. Effects of treatments on shoot extension (season 1988-1989).

Treatment	Initial Length	End Phase I	Δ (cm)	End Phase II	Δ (cm)
Plastic X Full Irrig.	17.77 a	63.3 b		96.27 b	
Plastic X RDI	14.72 a	44.8 c	18.5	68.50 c	27.70
Control X Full Irrig.	21.39 a	81.8 a		108.18 a	
Control X RDI	15.22 a	55.7 bc	26.1	73.61 c	34.55
Lucerne X Full Irrig.	15.22 a	52.2 c		67.11 c	
Lucerne X RDI	13.17 a	37.7 c	14.4	53.17 d	13.94
LSD	5.31	14.4		8.12	

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[z] Mean separation within columns by Duncan's multiple range test, 5% level.