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## Patterns of Soil and Tree Water Status and Leaf Functioning during Regulated Deficit Irrigation Scheduling in Peach

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**Abstract.** Seasonal patterns of soil water content and diurnal leaf water potential (LWP), stomatal conductance (g), and net CO<sub>2</sub> assimilation (A) were determined in a high-density peach [*Prunus persica* (L.) Batsch cv. Cal Red] subjected to regulated deficit irrigation scheduling. The regulated deficit irrigation treatment caused clear differences in soil water content and predawn LWP relative to control irrigation treatments. Treatment differences in midday LWP, g, and A were also significant, but not as distinct as differences in predawn LWP. Leaves on trees subject to the deficit irrigation treatment were photosynthetically more water-use-efficient during the latter part of the stress period than were the nonstressed trees. Midday LWP and g, on trees that received the regulated deficit irrigation treatment did not recover to control treatment values until more than 3 weeks after full irrigation was resumed at the beginning of stage III of fruit growth, because of water infiltration problems in the dry soil caused by the deficit irrigation. The regulated deficit irrigation treatment caused only a 8% reduction in trunk growth relative to the control, but resulted in a 40% savings in irrigation requirements.

Managing vegetative growth in high-density deciduous fruit orchards has become a subject of intense horticultural interest, particularly for crops with no acceptable dwarfing rootstocks. Chalmers et al. (1981) reported on an experiment conducted in a high-density peach orchard in which withholding irrigation water during specific times during the growing season was used to control vegetative growth without reducing yields. In a subsequent experiment, Mitchell and Chalmers (1982) obtained similar results and also emphasized the potential increases in irrigation efficiency that could be achieved with these irrigation strategies. In a subsequent paper with pear (*Pyrus communis* L.), Mitchell et al. (1984) called their strategy of using deficit irrigation during certain periods of the growing season to control vegetative growth Regulated Deficit Irrigation (RDI). The RDI strategy is based on the concept that vegetative growth can be limited by low plant water potentials during particular periods (primarily during stage II of fruit growth) while fruit growth remains unaffected. Another related concept is that shoot growth is integrally linked with root growth and thus restricting root growth will tend to restrict shoot growth (Chalmers et al., 1984). Root restriction was achieved in their experiments by three factors. Two factors discussed in their papers are root restriction by limiting water supply with trickle irrigation; the other is limiting soil volume by tree density (Chalmers et al., 1984). They asserted that, because peach tree roots from adjacent trees do not intermingle freely, planting trees close together in the row and using trickle irrigation can restrict root

growth effectively and limit shoot growth consequently because of a balance that is maintained between root and shoot growth in peaches (Proebsting, 1989; Richards, 1977). A factor not mentioned in Chalmers' papers is that the soil profiles on which these early experiments were conducted were very shallow, probably <0.5 m (Chalmers et al., 1983; D.J. Chalmers, personal communication). This shallow soil profile probably had a significant effect on root restriction and soil and plant water relations in these early experiments.

The RDI strategy proposed by Chalmers and co-workers in Australia has received much attention by other horticulturists because of its potential for limiting excessive vegetative growth and for increasing irrigation water use efficiency without decreasing tree yields. However, there is little experimental information about its effectiveness in other peach-growing regions where soil, climate, and irrigation conditions are different. No previous experiments have documented the effects of RDI treatments on soil and plant water status or leaf function. In 1988, we began a RDI study in a 4-year-old microsprinkler-irrigated, high-density peach orchard growing on a deep, fine sandy loam soil in California. Because of the deep soil in this orchard, we were particularly interested in the development of soil and plant water deficits and their effect on leaf function and vegetative growth during the course of an RDI treatment schedule in a single season.

### Material and Methods

**Experimental orchard.** The experiment was conducted during Spring and Summer 1988, in a 0.52-ha peach block located at the Univ. of California Kearney Agricultural Center, Parlier. The orchard soil is a Hanford sandy loam, with ≈400 mm of available water in a 3-m soil profile. The average annual rainfall is ≈250 mm, with virtually no precipitation during spring and summer. The average temperatures are 15C in April and 25C in August; the daily maxima are ≈40C. The relative humidity follows daily variations from 15% at solar noon to 98% early in the morning.

The peach cultivar used for the study was the late-maturing freestone 'Cal Red'. A total of 245 four-year-old trees on 'Nemaguard' rootstock were used in this study. Tree spacing was

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4.0 × 2.0 m and trees were pruned to a central leader system with no permanent scaffolds except the main leader. One-half of the plot was oriented north-south and the other east-west.

A localized microsprinkler irrigation system was installed in the plot. One 38-liter-h<sup>-1</sup> circular pattern microsprinkler per tree was located midway between trees in the row, wetting ≈60% of the total orchard soil surface. The system was controlled with a time clock and solenoid valves, and the water applied was recorded using water meters in each of the treatment/replication blocks. The plot was managed using commercial practices, including an herbicide strip in the tree rows and a mowed cover crop strip between rows. During the 4th week of April, the fruit were thinned to ≈150 per tree; the trees were summer-pruned in the last week of June. Fruit was harvested in three picks over a 10-day period (15–25 Aug.). During the 3 previous years, all trees were irrigated at 100% of estimated crop evapotranspiration (ET<sub>c</sub>).

**Design of experiment.** Two treatments were compared in this experiment: Control (C) and regulated deficit irrigation (RDI). C was irrigated under a full regime (139, 330, 472, and 270 mm of applied water during fruit growth stages I, II, III, and postharvest, respectively), managed according to modified Penman-determined reference crop water use (ET<sub>o</sub>) (Doorenbos and Pruitt, 1977) and estimated crop coefficients (K<sub>c</sub>) (Goldhamer, 1989). RDI was irrigated at 25% ET<sub>c</sub> during fruit growth stages I (Julian day 80 to 125, 23 mm of applied water), II (Julian day 125 to 180, 62 mm of applied water), and postharvest (Julian day 240 to 295, 64 mm of applied water), and 100% to 130% of ET<sub>c</sub> during Stage III (Julian day 180 to 240, 571 mm of applied water).

A randomized complete-block design with six replications was used in this experiment. Each block consisted of three adjacent tree rows with 10 trees in each row. The center eight of these 30 trees were used for experimental measurements; the others served as nonexperimental guard trees.

**General measurements.** Data from an automated weather station located 500 m from the plot were used to monitor weather information and estimate crop water use. The weather station is part of the California Irrigation Management Information System (CIMIS) (Snyder et al., 1985). Water meters were read weekly, and the difference between cumulative water applied and estimated water use was used to correct the next week's irrigation schedule.

Volumetric soil water content (θ<sub>v</sub>) was determined using a neutron probe (Campbell Hydroprobe Model 503, Campbell Scientific, Logan, Utah) that was calibrated for the site previously. One 3-m access tube was located in each block/treatment in the wetted area between a sprinkler and tree trunk. Soil moisture was determined weekly at 30-cm increments from 15 to 195 cm in the profile.

Trunk circumference measurements were made twice (June 1988 and March 1989) to evaluate if the different water supply had any effect on tree growth (Veihmeyer, 1975).

**Physiological measurements.** Physiological measurements of leaf function were made both seasonally and diurnally. Weekly midday (1:30–3:30 PM PST) measurements of leaf water potential (LWP) and stomatal conductance (g<sub>s</sub>) were made from 4 May to 23 Sept. (Julian days 125–267) on two exposed leaves from each of the six replications per treatment. Predawn LWP was determined weekly from 14 May to 23 Sept. (Julian days 135–267) on two dew-free leaves from each of three replications per treatment. Diurnal measurements of LWP, g<sub>s</sub>, and net CO<sub>2</sub> assimilation (A) (with readings every 2 to 3 h from sunrise to sunset) were made on six dates. However, data from only three dates (28 June, at the end of the RDI treatment; 21 July and 11 Aug., during the recovery phase) are presented in this paper because data collected on

additional dates did not contribute significantly new information. Diurnal measurements were made on six leaves from two of six replications per treatment.

Leaf water potential (LWP) was monitored using the pressure bomb technique (Scholander et al., 1965) following the recommendations of Turner et al. (1980). Readings were taken with a plant water status console (Model 3005, Soil Moisture Equipment Corp., Santa Barbara, Calif.). Stomatal conductance was measured with a steady-state porometer (Model LI-1600, LI-COR Corp., Lincoln, Neb.). Net CO<sub>2</sub> assimilation (A) was determined using a portable IRGA system (Model ADC LCA-2, The Analytical Development Co. Ltd., Hoddesdon, Herts, U.K.). Gas exchange calculations were made according to the equations given by von Caemmerer and Farquhar (1981).

## Results

**Applied irrigation water.** The control treatment (C) received a total of 1200 mm of irrigation water, and 720 mm was applied in the deficit treatment (RDI); thus, the RDI treatment received 40% less applied water.

**Soil water content.** There were clear treatment differences throughout the season in mean volumetric water content (θ<sub>v</sub>) of the soil profile between 15 and 195 cm (Fig. 1). Within 40 days from the beginning of the differential treatments, the RDI plots were significantly drier than the control; this difference increased until Julian day 180, when normal irrigation resumed. During the period from Julian day 180 to 240, when the RDI treatments received normal irrigation, there were large variations around the mean because the water did not rapidly penetrate to the lower soil layers. The soil water profiles at specific times during the season (Fig. 2) indicate that both treatments began the season with similar, uniform soil water profiles and that the soil profile in the RDI treatment dried from the top down until it was almost uniformly dry on Julian day 180, when normal irrigation schedules were resumed. Resumption of irrigation at 100% to 130% ET<sub>c</sub> primarily increased θ<sub>v</sub> in the upper soil layers, but had almost no effect on θ<sub>v</sub> below 1 m.

**Seasonal and diurnal patterns of plant responses.** Predawn LWPs were the clearest plant-based indicator of treatment effects, and they indicate that the RDI treatment did have significant negative effects on the plant water status (Fig. 3). Seasonal predawn LWP (Fig. 3A) differed between the two treatments in a pattern very similar to mean θ<sub>v</sub> (Fig. 1), and there was a clear

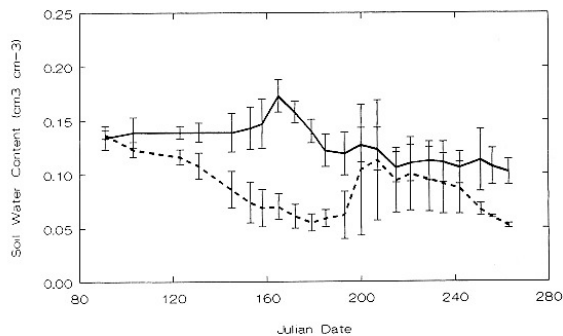


Fig. 1. Seasonal pattern of mean volumetric soil water content (θ<sub>v</sub>) from 15 to 195 cm soil depth in response to irrigation treatment. Solid line = control treatment; dashed line = regulated deficit irrigation treatment. Each point represents the mean of six replications ± SD.

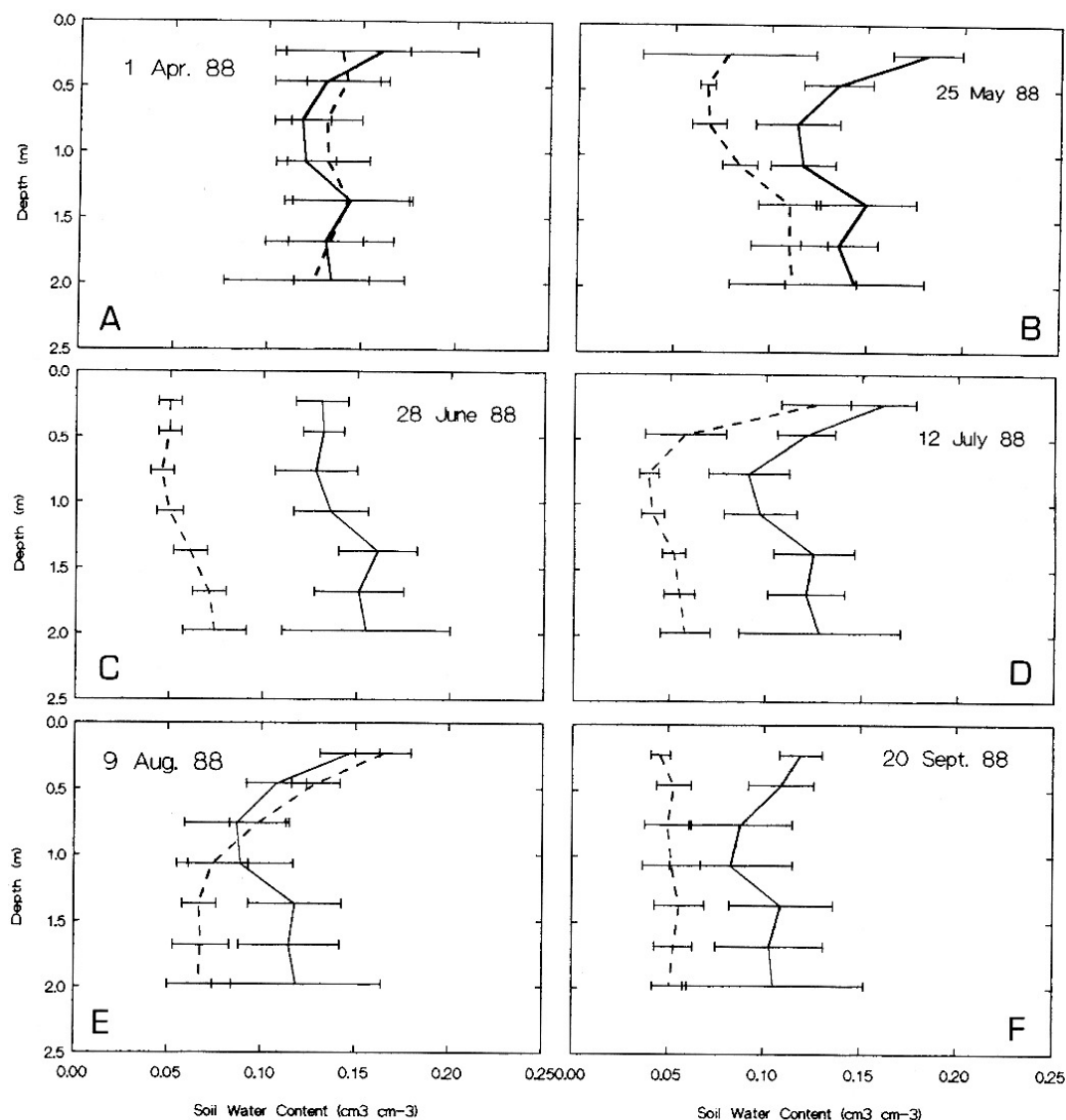


Fig. 2. Volumetric soil water content ( $\Theta_v$ ) profiles in response to irrigation treatment on (A) Julian day 92 (4 Apr.); (B) Julian day 146 (25 May 1988); (C) Julian day 178 (26 June 1988); (D) Julian day 194 (12 July 1988); (E) Julian day 222 (9 Aug. 1988); (F) Julian day 264 (20 Sept. 1988). Solid lines = control treatment; dashed lines = regulated deficit irrigation treatment (RDI). The RDI treatment received full irrigation from Julian day 180–240. Each point represents the mean of six replications  $\pm$  SD.

relationship between predawn LWP and mean  $\Theta_v$  during the course of this experiment (Fig. 4). Importantly, predawn LWP and mean  $\Theta_v$  of the RDI treatment did not recover to control values until 3 to 4 weeks after full irrigation was resumed during stage III of fruit growth (Julian days 180–240).

Midday LWP and  $g_s$  (Fig. 3 B and C) were also reduced in the RDI treatment relative to the control through most of the growing season. Even during the period of full irrigation (Julian days 180–240),  $g_s$  of the RDI treatment trees was usually lower than the control trees.

At the end of the initial deficit irrigation period (Julian day 180), there was a fairly consistent 0.5-MPa difference in LWP between

the control and RDI treatment throughout the entire day (Fig. 5). Leaf  $g_s$  and A of trees under RDI were significantly less than those of control trees in the afternoon, but less affected in the morning. Leaf  $g_s$  was clearly more affected by the decreases in LWP than was A. After >3 weeks of full irrigation (Julian day 203), afternoon LWP and  $g_s$  in the deficit treatment were still lower than the control; however, these differences had no apparent effect on A (Fig. 6). After >6 weeks of full irrigation (Julian day 225), there still were significant treatment effects on midday LWP and no consistent effects on  $g_s$  or A (Fig. 7).

**Vegetative growth.** Trunk growth over the study period was significantly less in the RDI compared the control treatment (Table 1).

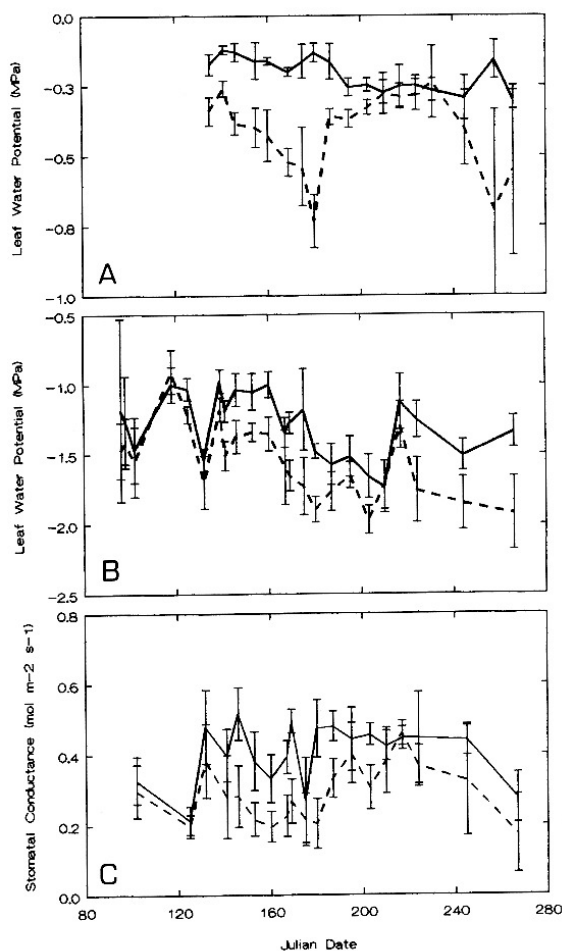


Fig. 3. Seasonal patterns of (A) predawn leaf water potential (LWP); (B) midday leaf water potential (LWP); (C) midday stomatal conductance ( $g_s$ ), in peach in response to irrigation treatment. Solid lines = control treatment; dashed lines = regulated controlled deficit irrigation treatment (RDI). The RDI treatment received full irrigation from Julian day 180–240. For (A) predawn leaf water potential each point represents the mean  $\pm$  sd of two leaves on each of three replications per treatment. For (B) midday leaf water potential and (C) midday stomatal conductance, each point is the mean for six exposed leaves measured on each of two replications per treatment.

However, the difference was only a 8% decrease in the RDI treatment relative to the control. In the field, there were no clear visible indications of decreased shoot growth in RDI trees compared to the control.

### Discussion

We detected significant differences in soil moisture content (Figs. 1 and 2) and predawn leaf water potentials (Fig. 3) between treatments within 40 days after the irrigation treatments began. The soil and leaf water status data obtained in this RDI study are difficult to relate to work by Chalmers et al. (1981) or other RDI studies (Mitchell and Chalmers, 1982; Mitchell et al., 1984; Li et al., 1989) because they have not reported on similar measure-

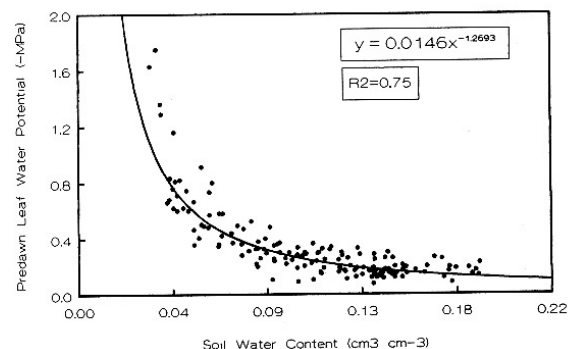


Fig. 4. Relationship between mean volumetric soil water content ( $\Theta_v$ ) and predawn peach leaf water potential (LWP). Each symbol represents data collected on the same plot within 2 days.

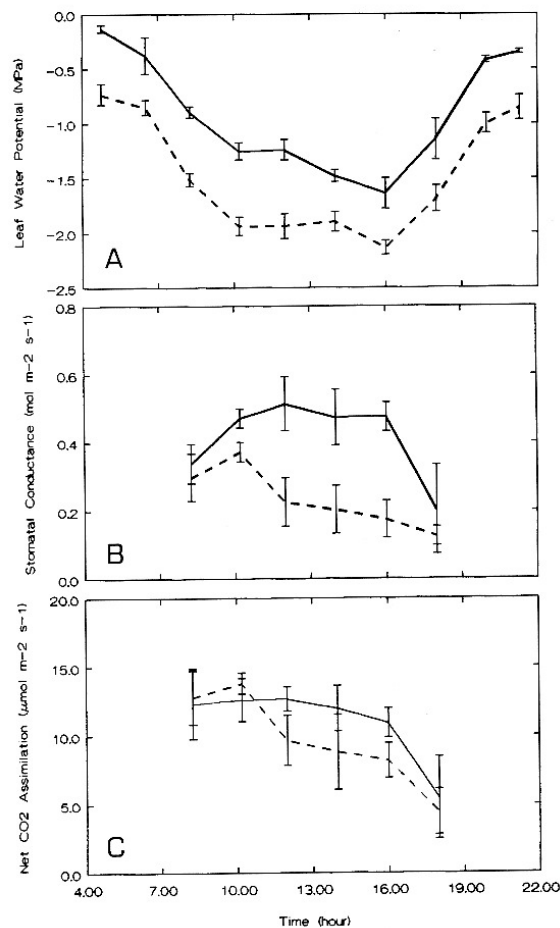


Fig. 5. Diurnal patterns of (A) leaf water potential (LWP); (B) stomatal conductance ( $g_s$ ); (C) net  $\text{CO}_2$  assimilation rate ( $A_n$ ), on Julian day 180 (28 June 1988). Solid lines = control treatment, dashed lines = regulated deficit irrigation treatment (RDI). Each point is the mean  $\pm$  sd of six exposed leaves measured on each of two replications per treatment.

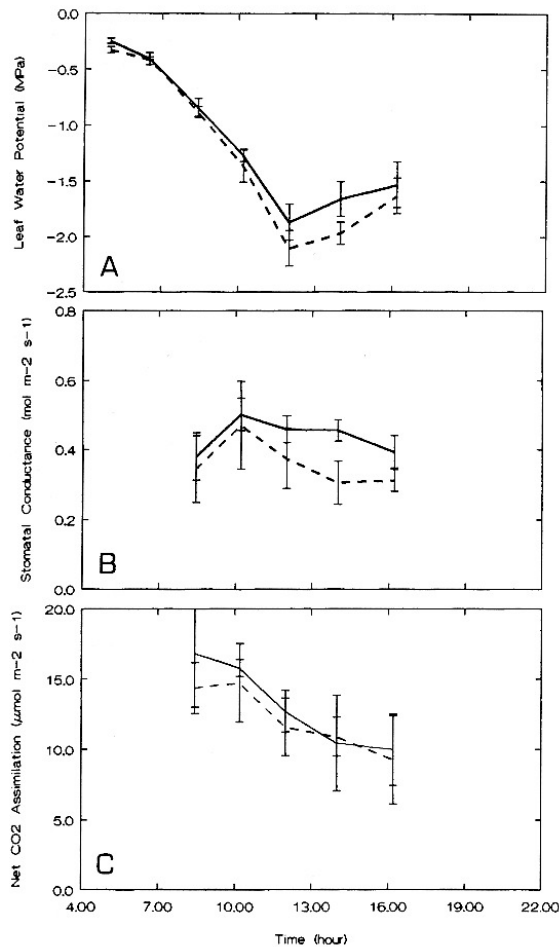


Fig. 6. Diurnal patterns of (A) leaf water potential (LWP); (B) stomatal conductance ( $g_s$ ); (C) net  $\text{CO}_2$  assimilation rate (A) of peach, on Julian day 203 (21 July 1988). Solid lines = control treatment, dashed lines = regulated deficit irrigation treatment (RDI). Each point is the mean  $\pm$  SD for six exposed leaves measured on each of two replications per treatment.

ments. However, in other water relations research, Chalmers et al. (1983) reported substantially lower LWP only 9 days after irrigation than were obtained in our study after 40 days of the RDI treatment.

Nevertheless, during stage II of fruit growth (Julian day 140–180), the soil moisture (Figs. 1 and 2) and predawn LWP (Fig. 3) measurements indicate that the trees under RDI were stressed significantly compared to the control trees. It is also clear that the limited water availability during this period caused significant decreases in daytime LWP,  $g_s$ , and A (Figs. 3 and 5), but the effect on these parameters was not as great as with predawn LWP (Fig. 3). These results are consistent with the idea that stomata function to reduce excessive water loss when evaporative demand is higher than water supply (Bradford and Hsiao, 1982). Similar stomatal behavior has been reported previously for peach under various experimental conditions (Acevedo et al., 1973; Garnier and Berger, 1985; Larson et al., 1988; Proebsting et al., 1989; Tan and Buttery, 1986; Xiloyannis et al., 1980). Presumably, there was no direct

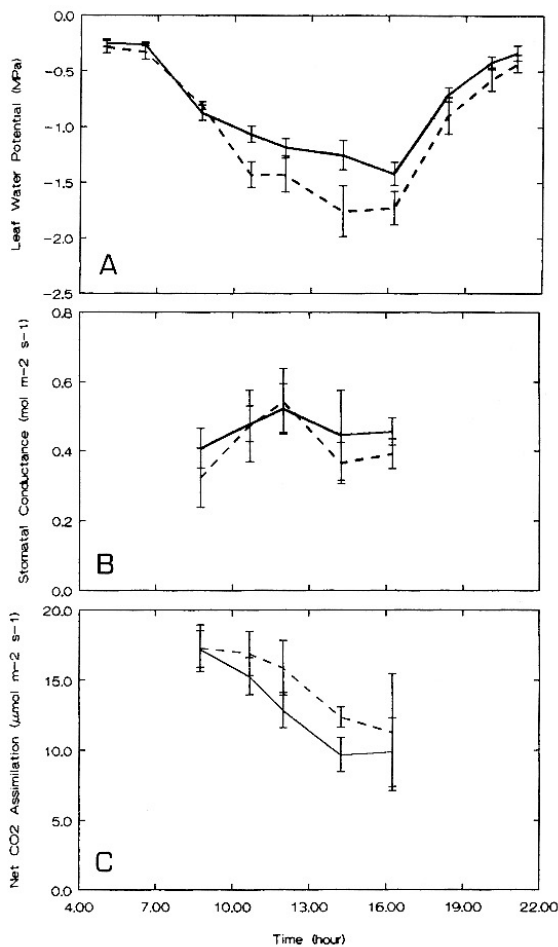


Fig. 7. Diurnal patterns of (A) leaf water potential (LWP); (B) stomatal conductance ( $g_s$ ); (C) net  $\text{CO}_2$  assimilation rate (A) of peach, on Julian day 225 (11 Aug. 1988). Solid lines = control treatment, dashed lines = regulated deficit irrigation treatment (RDI). Each point is the mean  $\pm$  SD for six exposed leaves on each of two replications per treatment.

stomatal effect on predawn LWP; this result apparently explains the very strong relationship between  $\bar{x}\Theta_v$  and predawn LWP during this study (Fig. 4). Similar results have been reported for peach by Xiloyannis et al. (1980); these data indicate that predawn LWP would be of value for indicating the relative effect of RDI treatments on soil and plant water status.

The fact that A of trees under RDI appeared to be less affected by plant water deficits than  $g_s$  of the same trees on Julian day 180 indicates that trees under RDI may have been more photosynthetically water-use-efficient than the control trees. To test this hypothesis, A values were plotted against  $g_s$  values obtained on the same leaves during the diurnal measurements on Julian day 180 (Fig. 8A). There was a general tendency for leaves from the RDI treatment to maintain higher A for a given  $g_s$  compared to the control leaves, particularly at high stomatal conductances, but the differences were not statistically significant. Because some of the variability in the A to  $g_s$  relationship (Fig. 8A) could be due to diurnal variations in temperature and humidity, the relationship

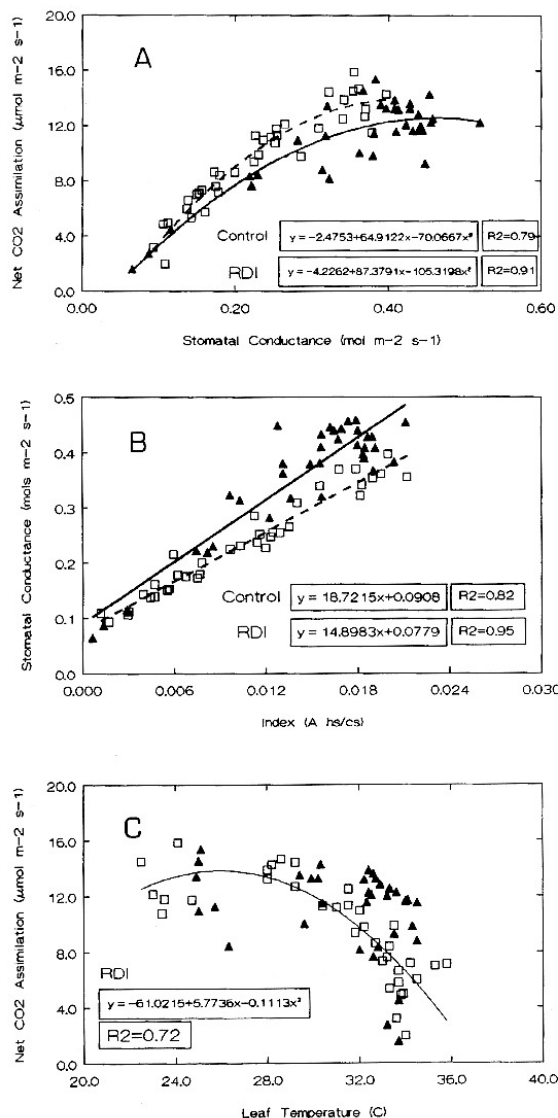


Fig. 8. Relationship between net CO<sub>2</sub> assimilation (A) and: (A) stomatal conductance (g<sub>s</sub>); (B) Ball Index; (C) leaf temperature in response to irrigation treatment on Julian day 180 (28 June 1988). Each symbol represents simultaneous data collected on the same peach leaf. Solid lines and solid triangles = control treatment; dashed lines and open squares = regulated deficit irrigation treatment (RDI). For part A, fitted lines were not statistically different at  $P \leq 0.05$ ; for part B, fitted lines were statistically different at  $P \leq 0.05$ , as indicated by Student's *t* test for comparison of regression statistics.

was re-evaluated using the "Ball Index" (Ball et al., 1987). This index has been designed for evaluating the relationship of  $g_s$  as it varies with A, relative humidity at the leaf surface (hs), and the inverse of the mole fraction of CO<sub>2</sub> at the leaf surface (Ca), such that  $g_s = k \times A \times (hs/Ca)$ . The slope *k* represents the sensitivity of  $g_s$  to A, CO<sub>2</sub> concentration, humidity and temperature. The slopes of the relationships resulting from this analysis were statistically different for the RDI and control leaves (Fig. 8B). The water-

Table 1. Influence of irrigation treatment on peach trunk growth.

Treatment	Trunk circumference (cm)		
	June 1988	Mar. 1989	New growth
Control	25.6	44.3	18.7
RDI	25.6	42.7	17.2 <sup>z</sup>

<sup>z</sup>Significantly different at  $P \leq 0.05$  with Student's *t* test.

stressed peach leaves in the RDI treatment were photosynthetically more water-use-efficient during this stress period; this response appeared to carry through until after some of the water stress was relieved and diurnal  $g_s$  of the treatments were the same (Fig. 7). Similar responses of peach to water stress have been reported by Reyes-Lopez (1985) and Harrison et al. (1989). This type of response is characteristic of plants that are exposed to a gradually increasing stress over a fairly long period. More-abrupt exposure to water stress generally decreases A to an equal or greater extent than  $g_s$  (Schulze, 1986). This difference may be important in relation to the RDI stress imposed in our study compared to the stress imposed during the RDI experiments in Australia (Chalmers et al., 1981; Mitchell and Chalmers, 1982) because of the more-rapid stress development in their shallow soil.

The general diurnal decline in A exhibited on the 3 days depicted in Figs. 5–7 are probably due to three factors: decreasing LWP, increasing VPD, and increasing leaf temperature. Plotting A vs. leaf temperature (Fig. 8C) indicated an abrupt decrease in A between 32 and 36°C. This steep decline in A above 36°C is greater than reported for other deciduous fruit crops (Lakso and Seeley, 1978), and is likely to be due to the combination of factors mentioned above and is not solely a temperature response.

The slow recovery of  $\bar{x}\Theta_v$  and  $\Theta_v$  in the lower depths of the soil profile (Figs. 1 and 2) when full irrigation was resumed during stage III of fruit growth (Julian day 180–230) was due apparently to low soil water infiltration rates. Low water infiltration rates are often due to high soil bulk densities and other soil properties in semi-arid environments (Haynes, 1981; Unger and Stewart, 1983). This is a common problem in much of the San Joaquin Valley, which is exacerbated by the usual mechanical management practices used in intensive agriculture. The irrigation and orchard floor management systems used in this experiment were chosen initially to try to minimize this problem and, as long as the soil was never allowed to become too dry, soil infiltration was not a significant problem. However, allowing the soil profile to dry out in the RDI treatment decreased soil infiltration rates so that, when normal irrigation schedules were resumed during stage III of fruit growth, the water ponded in the RDI plots and ran to other parts of the orchard. These soil infiltration problems could limit severely the feasibility of RDI practices in semi-arid environments where these problems exist, because it is critical to be able to resupply the trees with full irrigation requirements during stage III of fruit growth.

Our experiment shows that RDI can be used to impose moderate water stress on late-maturing peach cultivars during stages I and II of fruit growth in deep, fertile California soils. This moderate water stress was apparently severe enough to cause a small reduction in trunk diameter growth (Table 1). Although this reduction was statistically significant, it represented only an 8% reduction compared to the control—the horticultural significance of this reduction is questionable. There were no visible indications of significant extension shoot growth reductions. The minor vegetative growth effects are probably a consequence of the relatively long time that it took to achieve the moderate water stress in the RDI treatments on a deep soil.

The primary value of RDI scheduling may be in increasing



irrigation water use efficiency. Over the entire season, the RDI treatment required 40% less irrigation water than the control treatment. This would be a significant savings, particularly in a drought year, when irrigation water is scarce. These savings were achieved with only minor consequences on fruit size and yield (Girona, 1989).

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