Response of Seed Carrot to Various Water Regimes. I. Vegetative Growth and Plant Water Relations

R.B. Hutmacher¹
Water Management Research Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Fresno, CA 93727

J.J. Steiner²
National Forage Seed Production Research Center, U.S. Department of Agriculture, Agricultural Research Service, 3450 SW Campus Way, Oregon State University, Corvallis, OR 97331

J.E. Ayars³
Water Management Research Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Fresno, CA 93727

A.B. Mantel³
Institute of Soils and Water, Volcani Center, Bet Dagan, Israel

S.S. Vail³
Water Management Research Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Fresno, CA 93727

Additional index words. Daucus carota var. sativa, seed crops, soil water deficit, water stress, deficit irrigation

Abstract. The influence of irrigation frequency and the severity and rate of development of soil water deficits on the vegetative growth and water status of carrots (Daucus carota L. var. sativa DC.) grown for seed were investigated in a fine sandy loam soil. Beginning with the period of rapid development of primary umbels, various irrigation frequencies (daily vs. intervals corresponding to 30 mm of accumulated crop evapotranspiration (ET)) were investigated at irrigation rates ranging from 40% to 120% of estimated ETC. The magnitude and rate of development of soil water deficits markedly influenced carrot responses to developing water deficits. Stomatal conductance and leaf water potential (LWP) measurements exhibited some potential for use in irrigation scheduling and were the most sensitive and consistent indicators of plant water status. Under low-frequency continuous-deficit irrigation, a combination of moderate reductions in stomatal conductance and major reductions in peak leaf area and late-season maintenance of viable leaf area occurred. These responses were effective water-conserving mechanisms, allowing growth at a reduced rate and continued development of viable seed. In contrast, rapid development of soil water deficits resulted in nearly complete stomatal closure, cessation of growth, and rapid reductions in leaf area.

Regions for successful production of carrot seed are generally restricted to those with negligible summer rainfall to provide acceptable drying conditions for the seed before harvest. For this reason, most carrot seed production is in areas where irrigation is required (Salter and Goode, 1967).

The duration of the growing season and the optimal plant morphology for yield differ markedly between carrots grown for seed vs. those grown for roots. Carrots grown for roots are managed for rapid root growth during a relatively short growing season. In contrast, seed production requires a long growing season, with seed typically matured on the plant and harvested dry. These production-related differences between root vs. seed production necessitate differences in crop management. In addition, two production systems exist for carrot seed production: one based on planting seed in the summer, followed by seed harvest the next summer (seed-to-seed production); the other based on transplanting carrot roots (stecklings) in midwinter with seed harvest the following summer (root-to-seed production).

Despite the high value of the crop and the potential of improving seed production through water management practices, little definitive information is available regarding either specific physiological responses of carrots to soil water status or general horticultural responses to water management. Most carrot seed is produced under furrow irrigation in areas with medium to coarse-textured soils with moderate to low soil water holding capacities (Salter and Goode, 1967). MacGillivray and Clemente (1949) suggested that in a sandy loam soil filled to field capacity to a depth of 180 cm, 200 to 300 mm of additional irrigation should be adequate for carrot seed production in a soil holding 40 mm of water per 30 cm of depth. They did not attempt to determine specific plant responses to applied water, and seed yield response was highly variable across the years in that study. In general, their data suggested that seed yields increased with increases in irrigation.

Abbreviations: ET, crop evapotranspiration; DOY, day of year; K, crop coefficient; LWP, leaf water potential; RWC, leaf relative water content; VPD, air vapor pressure deficit.
In an evaluation of carrot seed-to-seed production, Hawthorn (1951, 1952) evaluated the interactions between soil water content, N, and plant spacing, and identified a trend toward higher seed yields at medium to low soil water levels when compared with those grown under nearly constant high soil water availability. Other information sources (Food and Agriculture Organization, 1961; Hawthorn and Pollard, 1954) indicated that maintenance of relatively low available soil water during bolting and umbel development is required to achieve favorable combinations of high seed yields and quality. However, the duration and timing of soil water deficits required to maximize seed yield and quality were not specified.

In reviewing the literature on carrot irrigation studies, Salter and Goode (1967) found no consistent evidence indicating growth stage sensitivity to water deficits in carrots grown for seed production. Various measurements potentially useful as plant water status indicators have been widely used in other crops (Kramer, 1983). However, we found no studies detailing specific plant responses to water deficits (expressed as LWP, stomatal conductance, RWC, or canopy temperature) on carrots grown for seed.

The objectives of this study were to: 1) identify the sensitivity of vegetative growth of carrots grown for seed to irrigation frequency and quantity; and 2) assess the potential of leaf conductance, RWC, canopy minus air temperature difference, and LWP measurements as indicators of carrot plant water status, particularly with respect to their potential use in irrigation scheduling.

The influence of irrigation management practices and resulting plant water deficits on carrot seed production and seed quality characteristics are reported in a second paper (Steiner et al., 1990).

Materials and Methods

Experiments were conducted in 1985 in Fresno, Calif., on a deep Hanford fine ‘sandy loam soil (Typic Xerorthents) that has a total available water capacity of ≈175 to 190 mm in the top 2 m of the soil. This type of soil is typical of those existing in many carrot, seed production areas (Hawthorn and Pollard, 1954; Salter and Goode, 1967). ‘Nantes’ carrot stecklings, produced from seed planted in Aug. 1984, were transplanted on 16 Jan. at a spacing of 0.1 to 0.12 m on beds 1 m wide. Plot size was five beds wide x 15 m long. Metham was applied 4 weeks before planting at 323 liters-ha⁻¹ for both pathogen and early season weed control. Trifluralin was applied at 0.51 liter-ha⁻¹ and incorporated into the upper 10 cm of soil before transplanting, and Linuron was applied ≈3 weeks after transplanting at 0.45 kg a.i./ha for weed control. Soil samples were collected to a depth of 2 m before planting and analyzed for total soil N, P, and K. Based on these analyses, 32 kg N/ha was applied as ammonium nitrate as a sidedress at first bolting.

During crop establishment and early vegetative growth, 138 mm of water was applied by sprinklers. In addition, 88 mm of rainfall was measured from planting through 18 Apr. Differential drip irrigation treatments were initiated beginning on 19 Apr. (DOY 109) and were terminated 5 July (DOY 186). The drip system consisted of drip line laterals placed on the center of each bed, with in-line, turbulent-flow emitters spaced every 50 cm, each discharging 2 liter-h⁻¹. Water applications were measured using water meters. ETc was calculated using grass-reference evapotranspiration data in combination with an estimated Kc. Grass-reference evapotranspiration was determined by an integrated Penman approach (Howell et al., 1984) using data from a weather station at the site. The Kc used for the vegetative and early reproductive growth stages was estimated based on carrot water use data compiled by Erie et al. (1982) for carrots grown for root production. An initial Kc value at transplanting was assumed to be 0.2, increasing to 1.0 by 4 May. After 4 May, the Kc was assumed to remain at 1.0 until irrigation was terminated.

In the first of two design layouts, six irrigation frequency and water application rate treatments were established in a randomized complete-block design with four replicates. In the second layout (adjacent to the first), three treatments were arranged in a randomized block design with four replicates to evaluate several irrigation termination dates. The variances for measurements in treatments from both designs were found to be equal; therefore, the results were tested in a single analysis of variance.

Beginning on 19 Apr., treatment 100-L was irrigated at 100% ET after 30 mm of accumulated ETC. Four additional low-frequency treatments were irrigated at the same frequency, but at rates equal to 40%, 60%, 80%, and 120% of accumulated ET, and were designated as treatments 40-L, 60-L, 80-L, and 120-L, respectively. The frequency of irrigation averaged every 3 to 5 days. Treatment 100-D was irrigated daily at 100% of the previous day’s ETC.

Initially, all 3 treatments in the second design layout were drip-irrigated at the same frequency and rate as the 100-L treatment, but irrigation was terminated either 22 May (DOY 142), 5 June (DOY 156), or 27 June (DOY 178). These termination dates corresponded to 7, 5, and 2 weeks before harvest and were designated as 100-L-7W, 100-L-5W, and 100-L-2W, respectively.

To monitor plant vegetative and reproductive development, five plants were sampled from each plot for treatments 100-D, 40-L, 60-L, 80-L, 100-L, and 120-L at 14-day intervals, beginning 6 May and ending 2 July. Treatments 100-L-7W, 100-L-5W, and 100-L-2W were sampled only on 20 May, 7 June, 21 June, and 3 July. Each sample was divided into leaf, stem, and floral components. Plant population measurements were used to express total dry weight and leaf area measurements on a ground area basis. Leaf area was estimated using leaf area: dry weight ratios.

Leaf growth rates were monitored on fully illuminated immature leaves ( >0.09 m beginning length, located within 0.35 m of the tip of secondary branches), with the length measured from the petiole base to the tip of the terminal leaflet. In each treatment, measurements were made on four leaves on each of six separate plants in three replicate plots on 4 May, 27 May, and 11 June.

Soil water content was monitored at 30-cm increments through the soil profile using neutron attenuation techniques, with one 2.1-m access tube within the planted row within each plot. LWPs were measured using a pressure chamber. Leaves were placed in polyethylene bags, excised, and the flattened petioles were inserted into pressure chamber gaskets normally used for grass leaves. Total leaf conductance of water vapor was determined with a steady-state diffusion porometer (LI-COR Model 1600, LI-COR, Lincoln, Neb.) using both abaxial and adaxial measurements. RWCs were determined according to the methods described by Hewlett and Kramer (1963). All measurements were made on the most recent, fully expanded leaves within five nodes below the primary umbel or within four nodes below umbels on secondary branches, with all leaves receiving a minimum of 1500 μmol-s⁻¹·m⁻² photosynthetic photon flux density (PPFD) in the 400- to 700-nm waveband.

Crop canopy temperatures were measured using an infrared thermometer (Everest Interscience model 110; Tustin, Calif.) held at an angle 30° below horizontal, with canopy temperatures expressed as the mean of readings made in the NW, NE, SE,
and SW compass directions. Air wet- and dry-bulb temperatures were measured using an aspirated psychrometer held 0.5 m above the crop canopy. Nonstressed baselines for the difference between canopy temperature \( T_c \) and air temperature \( T_a \) vs. VPD were determined before and during the umbel development growth stages using measurements made within 1 day following irrigation in the 120-L treatment plots. A baseline for the “fully stressed” condition was determined on plants sprayed with 75 µM concentrations of abscisic acid (used to achieve short-term stomatal closure) \( \approx 20 \) to 30 min before infrared thermometry measurements.

Unless stated otherwise, all response differences are reported at \( P \leq 0.05 \). Data were analyzed by SAS General Linear Model Procedures (SAS Institute, 1985). Single-degree-of-freedom contrasts were used to determine irrigation treatment effects on growth responses. Repeated measures analysis was used to determine single-degree-of-freedom contrasts across measurement dates for relative water content data.

### Results and Discussion

**Effects of irrigation treatments on soil water status.** Average soil profile (0 to 2.1 m depth) stored water was similar in all treatments following transplanting or the initiation of the differential irrigation treatments on DOY 109 (data not shown). At transplanting, the upper 1.5 to 1.7 m of the soil profile had soil water contents close to field capacity (= 0.15 to 0.17 m of plant available water between – 0.03 and – 1.5 MPa soil matric potential within the upper 2.1 m of the profile). Below 1.5 to 1.7 m, the soil water content averaged <60% of the quantity held at field capacity. On DOY 109, soil profile stored water in all treatments had increased slightly since DOY 15 but still was not different across treatments (Table 1). Plant responses in this experiment, therefore, resulted principally from differential irrigation treatments initiated midseason (DOY 109) rather than from pre-existing differences in available soil water.

Total soil profile stored water changed during each irrigation cycle in treatments irrigated at the lower frequency (treatments 40-L, 60-L, 80-L, 100-L, 100-D, and 120-L treatments, respectively (Table 3). Rapidly reducing soil water the plants would use if available, as evidenced by the decrease in soil profile stored water in treatments 100-L and 100-D vs. the small increase in soil profile stored water observed between DOY 108 and 186 in the 120-L plots.

**Plant growth responses to irrigation treatments.** The major vegetative responses of seed carrots to deficit irrigation were reductions in plant dry matter components and plant height (Table 2), and in leaf area and increases in specific leaf weight (Table 3). Reductions in water application amounts below 100% ET resulted in production of fewer and smaller leaves, reductions in leaf area during the latter portion of the season (Table 3), and reduced branching (Steiner et al., 1990). During the period from DOY 140 to 168, the leaf area index declined 59%, 56%, 35%, 20%, 9%, and 3% in the 40-L, 60-L, 80-L, 100-L, 100-D, and 120-L treatments, respectively (Table 3). Rapidly developing water deficits in the irrigation termination treatments resulted in even more rapid losses in leaf area. During the same period, the leaf area index in treatments 100-L-7W and 100-L-5W declined by 76% and 52%, respectively.

Diurnal changes in leaf length were used to determine water deficit effects on leaf expansive growth. Measurement dates (Table 4) were 1 day before irrigation in the low-frequency treatments; therefore, the data represent leaf growth rate re-

### Table 1. Applied water, rainfall, change in stored soil water, and estimated ET, for seed carrot irrigation treatments in Fresno, Calif., in 1985.

| Irrigation schedule’ | Sprinkler (DOY 15 to 108) | Drip (DOY 108 to 186) | Total (DOY 15 to 186) | Change in soil profile (0 to 2.1 m depth) stored water (mm) | ET \( C_{x,w} \), \( C_{x,w} \) (mm) |
|----------------------|--------------------------|-----------------------|-----------------------|------------------------------------------------|--------------------------|
| 40-L                 | 138                      | 206                   | 344                   | +15 – 99                                        | 211 ± 12                  |
| 60-L                 | 138                      | 309                   | 447                   | +11 – 96                                        | 215 ± 4                   |
| 80-L                 | 138                      | 413                   | 551                   | +17 – 110                                       | 209 ± 8                   |
| 100-L                | 138                      | 517                   | 655                   | +13 – 69                                        | 213 ± 13                  |
| 120-L                | 138                      | 620                   | 758                   | +9 +17                                          | 217 ± 19                  |
| 100-D                | 138                      | 517                   | 655                   | +19 – 77                                        | 207 ± 6                   |
| 100-L-7W             | 138                      | 157                   | 295                   | +12 – 88                                        | 214 ± 10                  |
| 100-L-5W             | 138                      | 243                   | 381                   | +20 – 106                                       | 206 ± 5                   |
| 100-L-2W             | 138                      | 396                   | 534                   | +10 – 79                                        | 216 ± 11                  |

‘Numerals = percent of accumulated ET; \( L = \) low-frequency irrigation; \( D = \) daily irrigation; \( W = \) irrigation terminated given weeks before harvest of seed.

Rainfall between days 15 and 186 was 88 mm for all treatments.

Estimated ET, determined as the sum of applied water plus rainfall plus soil water depletion, all for dates between DOY 15 and 186.

Values are means ± SE (n = 4).
Fig. 1. Soil profile stored water (in millimeters of total water in the upper 2.1 m of the soil profile) in treatments 100-D, 60-L, 120-L, and 100-L-7W for seed carrot as a function of DOY. Arrows indicate the dates of irrigation in low-frequency (L) treatments. Irrigation treatments were: 100-D = daily irrigation to supply 100% of ET; 60-L, 120-L = 60% and 120% ET, respectively, after 30 mm of accumulated ET; and 100-L-7W = 100% ET application after 30 mm of accumulated ET until irrigation termination on DOY 142.

Plant water relations. Treatment differences in leaf conductance were consistently more pronounced in the afternoon hours when compared with the morning hours. Lower leaf conductance prevailed in deficit-irrigated treatments when compared with the 100% ET, treatments (Fig. 2). With progressive soil water deficits developing during a period of 4 days following irrigation of the low-frequency treatments, afternoon conductance levels declined by > 30% in treatment 60-L as compared to <1.5% in treatment 120-L plants (Fig. 2). Leaf conductance levels following irrigation (DOY 146) showed essentially complete recovery. However, as the season progressed and vegetative growth slowed, plants from deficit-irrigated treatments showed a gradual decline in postirrigation conductance levels. There are several potential explanations for these variations in conductance. In deficit-irrigated plants, reductions in conductance were highly correlated (r² = 0.77) with progressive reductions in total soil profile water content during the season. In treatments 100-D, 100-L, and 120-L, higher soil water availability was maintained throughout the season, and conductance levels were not highly correlated with variations in stored soil water (r² = 0.51). In these treatments, conductance values were negatively correlated with VPD across measurement dates (r² = 0.68), suggesting a stomatal response to VPD. Environmental influences such as these must be considered when using conductance measurements to quantify plant water status.

The rapidly developing severe water deficits imposed by terminating irrigation 7, 5, and 2 weeks before harvest in treatments 100-L-7W, 100-L-5W, and 100-L-2W, respectively, resulted in 65% to 80% reductions in leaf conductance in treatments 100-L-7W (Fig. 3) and 100-L-5W (data not shown) within 7 to 10 days after irrigation termination. Large losses in functional leaf area were also observed in these plants (Table 3) as compared to any other treatment during this same period. This rapidly developing water deficit resulted in limited productivity, with continued growth and development essentially terminated due to both reduced gas exchange capabilities and loss of photosynthetic leaf area. As with numerous other crop species (Turner, 1979), the rate of development and severity of

Table 2. Carrot plant growth measurements as a function of irrigation treatments and day of year at Fresno, Calif., in 1985.

| Irrigation schedule | Plant ht (cm) | Dry wt (mg·ha⁻¹) | Leaf | Stem | Total |
|---------------------|--------------|------------------|------|------|-------|
|                     | DOY          | DOY              | DOY  | DOY  | DOY   |
|                     | 168 183      | 126 168 183      | 168 183 168 183 | 168 183 168 183 |
| 40-L                | 111 114      | 168 168          | 4.1  | 7.4  | 5.4   |
| 60-L                | 120 121      | 126 168          | 1.8  | 6.8  | 7.9   |
| 80-L                | 129 134      | 168 168          | 3.3  | 6.8  | 5.6   |
| 100-L               | 122 134      | 168 168          | 2.9  | 6.8  | 5.5   |
| 200-L               | 134 140      | 168 168          | 3.3  | 6.8  | 5.6   |
| 100-L-7W            | 131 138      | 168 168          | 3.3  | 6.8  | 5.6   |
| 100-L-5W            | 119 120      | 168 168          | 3.3  | 6.8  | 5.6   |
| 100-L-2W            | 124 126      | 168 168          | 3.3  | 6.8  | 5.6   |
| Contrasts           |              |                  |      |      |       |
| 40-L vs. 80-L, 100-L| * ** NS       | * ** NS          | **   | **   | **    |
| 60-L vs. 80-L, 100-L| NS ** NS     | NS ** NS         | **   | **   | **    |
| 80-L vs. 100-L      | NS NS        | NS NS            | NS   | NS   | NS    |
| 100-L-7W vs. 100-L  | NS ** NS     | NS ** NS         | **   | **   | **    |
| 100-L-5W vs. 100-L  | NS NS        | NS NS            | *    | NS   | NS    |

*Dashed line = no data collected for specific treatments.

NS. **. *** Non-significant or significant at P = 0.05 or 0.01, respectively.
Table 3. Mean leaf area index and mean specific leaf weights of carrot plants as a function of irrigation treatments and DOY at Fresno, Calif., in 1985. Only living leaf area was included in determining leaf area index values.

| Irrigation schedule | Leaf area index (m²·m⁻²) | Specific leaf wt. (mg dry wt/cm²) |
|---------------------|--------------------------|----------------------------------|
| DOY 125             | 0.4 ± 0.1                | 0.2 ± 0.1                         |
| 60-L                | 0.4 ± 0.1                | 0.2 ± 0.1                         |
| 80-L                | 0.3 ± 0.1                | 0.2 ± 0.1                         |
| 100-L               | 0.2 ± 0.1                | 0.2 ± 0.1                         |
| 100-L-7W            | 0.2 ± 0.1                | 0.2 ± 0.1                         |
| DOY 150             | 0.4 ± 0.1                | 0.2 ± 0.1                         |
| 60-L                | 0.4 ± 0.1                | 0.2 ± 0.1                         |
| 80-L                | 0.3 ± 0.1                | 0.2 ± 0.1                         |
| 100-L               | 0.2 ± 0.1                | 0.2 ± 0.1                         |
| 100-L-7W            | 0.2 ± 0.1                | 0.2 ± 0.1                         |

Contrasts
- 40-L vs. 80-L, 100-L NS NS NS NS NS NS
- 60-L vs. 80-L, 100-L NS NS NS NS NS NS
- 80-L vs. 100-L NS NS NS NS NS NS
- 100-L-7W vs. 100-L NS NS NS NS NS NS
- 100-L-5W vs. 100-L-7W NS NS NS NS NS NS

* Dashed line = no data collected for specific treatments.
* Essentially no living leaf area remained on plants in any replication of this treatment.

Table 4. Average leaf length expansion rates as a function of time of day and total 24-hr expansive growth for plants in seed carrot irrigation treatments on 3 days at Fresno, Calif., in 1985. All data shown are for dates that were 1 day before irrigation in the low-frequency (L) treatments, thereby representing close to the maximum water deficit experienced during the irrigation cycles.

| Hour of day | Total rate of expansion in leaf length (mm·h⁻¹) | Total leaf growth in 24 hr (mm) |
|-------------|-----------------------------------------------|-------------------------------|
| DOY 125     | 0600-1100 1100-1500 1500-2000 2000-0600       | 5.1 ± 0.3                     |
| 40-L        | 0.4 ± 0.1                                       | 0.2 ± 0.1                     |
| 60-L        | 0.6 ± 0.1                                       | 0.3 ± 0.1                     |
| 80-L        | 0.5 ± 0.4                                       | 0.3 ± 0.3                     |
| 100-L       | 0.5 ± 0.3                                       | 0.3 ± 0.4                     |
| 100-D       | 0.5 ± 0.3                                       | 0.3 ± 0.4                     |
| 100-L-7W    | 0.6 ± 0.3                                       | 0.4 ± 0.3                     |
| DOY 155     | 0600-1100 1100-1500 1500-2000 2000-0600       | 5.1 ± 0.3                     |
| 40-L        | 0.4 ± 0.3                                       | 0.2 ± 0.3                     |
| 60-L        | 0.3 ± 0.3                                       | 0.2 ± 0.3                     |
| 80-L        | 0.3 ± 0.3                                       | 0.2 ± 0.3                     |
| 100-L       | 0.3 ± 0.4                                       | 0.2 ± 0.4                     |
| 100-D       | 0.3 ± 0.4                                       | 0.2 ± 0.4                     |
| 100-L-7W    | 0.4 ± 0.3                                       | 0.3 ± 0.4                     |
| DOY 165     | 0600-1100 1100-1500 1500-2000 2000-0600       | 5.1 ± 0.3                     |
| 40-L        | 0.3 ± 0.3                                       | 0.2 ± 0.3                     |
| 60-L        | 0.3 ± 0.3                                       | 0.2 ± 0.3                     |
| 80-L        | 0.3 ± 0.3                                       | 0.2 ± 0.3                     |
| 100-L       | 0.3 ± 0.3                                       | 0.2 ± 0.3                     |

Values shown are mean ± SE (n = 6).
* Irrigation was terminated for treatment 100-L-7W on DOY 142.

Inadequate data were collected to assess the degree of change in plant hydraulic resistance and/or variations in environmental conditions than with large changes in soil water content. Inadequate data were collected to assess the degree of change in plant hydraulic resistance. Within-season variation in LWP in treatment 120-L was significantly correlated with relative indicators of daily evaporative demand such as reference ET (r = 0.68) and midaftemoon VP D (r = 0.79). As with interpretations of leaf conductance measurements, LWP values are an environmentally dependent index of plant water status.

In other treatments, where soil water contents declined both during irrigation cycles and progressively throughout the season, LWP changes reflected plant responses to both soil water deficits and changes in aerial environmental conditions. The magnitude of treatment differences in LWP was influenced by the rate of development and severity of soil and plant water deficits. Even though total applied water and season total soil water depletion were similar in treatments 40-L and 100-L-7W.
Fig. 2. Leaf conductance responses to irrigation treatments (A) 100-D, (B) 120-L, and (C) 60-L for seed carrots. The dates 141, 143, 144, and 146 correspond to 1, 3, and 4 days after an irrigation, and 1 day after the subsequent irrigation, respectively, in the low-frequency (L) treatments. Treatment 100-D plants received daily irrigation. Data points and error bars indicate the mean ± SE (n = 18). Irrigation treatments are described in caution for Fig. 1.

Fig. 3. Midafternoon (1400 to 1600 hr) postirrigation leaf conductance responses to irrigation treatments 40-L, 100-L, 120-L, 100-D, and 100-L-7W for seed carrots. Mean leaf conductance values represented were collected within 24 to 36 hr following irrigation in the 100-L and 40-L treatments, representing peak leaf conductance recovery within each irrigation cycle. Data points and error bars indicate the mean ± SE for each date shown (n = 18). Irrigation treatments were: 40-L, 100-L = application of 40% and 100% of ETc, respectively, after 30 mm of accumulated ETC. Treatments 120-L and 100-D are described in caption for Fig. 1.

(Table 1), LWP declined to a greater extent and more rapidly in the irrigation termination treatment 100-L-7W (Fig. 5). During irrigation cycles in low-frequency irrigation treatments, gravimetric soil water content measurements in the upper 1.2 m of the soil profile indicated significant reductions in root zone water content between irrigations (data not shown). Between DOY 166 and 169 (1 day after irrigation in the low-frequency irrigated treatments, and 4 days following irrigation, respectively), total soil profile stored water declined by an average of 22, 16, and 13 mm in treatments 100-D, 80-L, 60-L, and 40-L, respectively. In all low-frequency treatments, irrigation applications on DOY 171 increased soil profile stored water nearly to levels measured immediately after irrigation on DOY 165. Lower LWP developed between DOY 166 and 169, and LWP recovered after plants received the next irrigation on DOY 171 (Fig. 6). Vapor pressure deficits were similar across the 3 days, indicating that LWP differences were not associated simply with VPD differences. Similar patterns showing a relationship between LWP and changing soil water content were measured during numerous other irrigation cycles. If the potential influence of changing environmental conditions is considered in interpreting the results, LWP measurements appeared to have greater potential than other evaluated plant water status measurements for use in irrigation scheduling.

Table 5. RWC of the most recent fully expanded leaves on branches bearing secondary umbels as a function of time of day and number of days since the most recent irrigation (for four irrigation schedules during one irrigation cycle) at Fresno, Calif., in 1985. Relative evaporative conditions for the measurement dates are indicated by VPD.

| Irrigation schedule | Days since previous irrigation | Hour of day | RWC (%) | VPD–mean for 1400-1700 |
|---------------------|-------------------------------|-------------|---------|------------------------|
| 100-D               | 161                           | 0600-1000   | 1400    |
|                     | 163                           | 1300-1600   | 1400    |
|                     | 164                           | 1600-2000   | 1400    |
| 100-L               | 161                           | 0600-1000   | 1400    |
|                     | 163                           | 1300-1600   | 1400    |
|                     | 164                           | 1600-2000   | 1400    |
| 40-L                | 161                           | 0600-1000   | 1400    |
|                     | 163                           | 1300-1600   | 1400    |
|                     | 164                           | 1600-2000   | 1400    |
| 100-L-5W            | 156                           | 0600-1000   | 1400    |
|                     | 161                           | 1300-1600   | 1400    |
|                     | 168                           | 1600-2000   | 1400    |

Means within column and treatment followed by an asterisk differed from values on DOY 161 in treatments 100-D, 100-L, and 40-L and from values on DOY 156 in treatment 100-L-5W by repeated measures multivariate analysis, $P = 0.05$ (n = 16).

'DIrrigation applications to treatment 100-L-5W were equivalent to 100% ETc before DOY 156. After DOY 156, no further irrigation was applied to plants in this treatment.
Fig. 4. Baselines for nonstressed conditions for the canopy temperature (T<sub>c</sub>) minus air temperature (T<sub>a</sub>) vs. VPD relationship for seed carrot plants in treatment 120-L within 1 day after irrigation: during vegetative development prior to extension of primary umbels into the upper canopy (DOY 74 through 98), and during the umbel development (reproductive) period (DOY 118 through 170). Treatment 120-L is described in caption for Fig. 1.

Fig. 5. Midafternoon (1300 to 1600 HR) LWP responses of seed carrot to irrigation treatments 100-D, 120-L, 40-L, 100-L-7W, and 100-L. Arrows indicate irrigation dates for the low-frequency (L) irrigation treatments. Data points and error bars indicate the mean ± SE for each date shown (n = 15). Irrigation treatments are described in captions for Figs. 1 and 3.

In plants exposed to early termination of irrigation and rapidly developing soil water deficits (i.e., treatment 100-L-7W), tissues dehydrated rapidly, resulting in severe reductions in LWP, eventual stomatal closure, and a rapid loss of leaf area needed for producing photosynthate. If this type of water deficit is imposed too early in the umbel development period, the plant cannot respond favorably in terms of maintained abilities for gas exchange, growth, and seed maturation (Steiner et al., 1990). Under slowly developing water deficits such as in the 40-L and 60-L treatments, carrot plants apparently can restrict excessive tissue dehydration and adjust to limited water availability through a combination of both moderate reductions in stomatal conductance and major reductions in leaf area. These responses to slowly developing water deficits are effective as water-conserving mechanisms but still maintain some opportunity for gas exchange, maintenance of the plant, and eventual seed maturation.

Literature Cited

Éric, L. J., O.F. French, D.A. Bucks, and K. Harris. 1982. Consumptive use of water by major crops in the southwestern United States. U.S. Dept. of Agr., Conservation Res. Rpt. no. 29.