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Production and water use in lettuces under variable water supply

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Abstract The effects of a variable water supply on the water use, growth and yield of two crisphead and one romaine (i.e., Cos) lettuce cultivar were examined in a field experiment using a line source sprinkler system that produced a range of water regimes that occur in growers fields. Four locations at increasing distances from the main line were monitored through the season (i.e., from thinning to harvest, 28–63 days after planting (DAP)). These locations at the end of the season corresponded to: (1) rewatering to field capacity (FC); (2) watering with a volume 13% below that required in the field capacity treatment ($0.87*FC$); (3) 30% below FC ($0.70*FC$); and (4) 55% below FC ($0.45*FC$). A linear production function for dry matter accumulation and fresh weight vs. crop evapotranspiration (ET_c) was determined for lettuce during this period, giving a water use efficiency for dry matter of $1.86 \text{ g m}^{-2} \text{ mm}^{-1}$ and for fresh weight of $48 \text{ g m}^{-2} \text{ mm}^{-1}$. For lettuce irrigated to field capacity, ET_c between thinning and harvest was 146 mm; maximum crop coefficients of 0.81–1.02 were obtained at maturity (55–63 DAP). For the three irrigation treatments receiving the largest water application, ET_c was higher in the Cos cultivar than in the two crisphead lettuce cultivars which had similar ET_c . Plant fresh weight was more sensitive than dry weight to reduction in water supply. In the FC treatment, root length density and soil water extraction were greatest in the top 0–45 cm, and de-

creased rapidly below 45 cm depth. Soil water extraction by roots increased at lower depths when irrigation was reduced. Instantaneous rates of leaf photosynthesis and leaf water potential showed no response to the irrigation treatments in this study, despite differences in biomass production. Evaporation was determined to be the major component of ET_c for 45 of the 63 days of the growing season. The large loss of water by evaporation during mid-season and the apparent insensitivity of lettuce to the volume of irrigation during this period may provide an opportunity for reducing irrigation applications.

Introduction

In all agricultural systems, low water use efficiency can occur when soil evaporation is high in relation to crop evapotranspiration, early growth rate is slow, water application does not correspond to crop demand, and when shallow roots are unable to utilize deep water in the profile. These problems are especially pronounced in intensive vegetable production systems, where large inputs of irrigation and nutrients are common (Stark et al. 1983; Doerge et al. 1991). Application of water in vegetable production often exceeds crop requirements, particularly in situations where the price of water is small in relation to the value of the crop. Many vegetable species are shallow-rooted and sensitive to mild water stress (Epstein and Grant 1973; Sammis 1980; Feigin et al. 1982). Breeding crops for deeper root systems, in principle, is a viable means to maximize water use, but it is a difficult and long-term process (Barnes 1983). Another possibility for improving water use is better management of water application. Both approaches require information on detailed seasonal changes in crop growth and on root distribution and root extraction of soil water that is not currently available for most vegetable crops.

In lettuce, where the harvested part of the plant is the photosynthetic leaf area, it is especially important to maintain optimal growth through the application of water and

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nitrogen. Little specific information currently exists for the irrigation of lettuce, which by area is the second largest vegetable crop in California. The Central Coast region, which produces most of the lettuce in California, has cool summers with coastal fog so that cool-season vegetables can be grown for most of the year. Groundwater overdraft, salt water intrusion, and nitrate contamination of groundwater in this region are problems related to water management (Snow et al. 1988). Irrigation is typically applied in this region on a routine basis without scheduling and it may be possible to decrease water application rates in lettuce without yield loss (Schulbach 1988; Jackson et al. 1994).

Crop responses to different rates of applied water have been used for many crops to determine irrigation strategies for optimal yield and maximum efficiency of water use (Black 1966; Bauder et al. 1975). The line source sprinkler system applies water uniformly along the length of an experimental area with a reduction in application rate with distance from the line of sprinklers (Hanks et al. 1976). Optimal irrigation scheduling requires accurate estimates of crop evapotranspiration (ET_c) (Doorenbos and Pruitt 1977) and accurate determination of ET_c without full ground cover requires that soil evaporation and crop transpiration be considered separately (Ritchie 1972). Regular irrigations are made during the first month of direct-seeded lettuce to ensure germination of the small seeds and the subsequent establishment of the slow-growing seedlings. Consequently, during this time evaporation from bare soil is likely to be considerable.

A line source system was used to examine the water use of lettuce under a variable water supply in the Central Coast region of California. A range of watering regimes was generated with the sprinkler line source system that was close to amounts typically used by growers in the area. Crisphead lettuce, the most common type, and a romaine (Cos) lettuce were examined. The objectives of this study were to: (1) establish the water production functions (i.e., the relationship between crop evapotranspiration (ET_c) and total dry matter and fresh weight) and water use efficiency (WUE) for the three lettuce cultivars; (2) determine the crop coefficients at four developmental stages; (3) assess the soil evaporation component of total ET_c ; and (4) describe profiles of root distribution and soil water extraction. To elucidate the mechanisms underlying the response of lettuce to a decreasing water supply, detailed seasonal changes in canopy development, dry matter accumulation, and soil water profiles were also frequently measured at four distances from the line source, and instantaneous rates of leaf photosynthesis and leaf water potential were compared among watering regimes.

Material and methods

Experimental site

The field experiment was conducted at the USDA-ARS station in Salinas, California (36° 37' N 121° 32' W). The climate of the Central Coast region of California is Mediterranean with mild winters

and cool, foggy rainless summers. Average daily maximum and minimum temperatures during the experimental period were, respectively, 22 °C and 11 °C. The soil at the experimental site is a Chualar sandy loam (Typic Argixeroll). Some characteristics of the upper 105 cm of soil are: 57% sand content, 33% silt content, 10% clay content, and 0.25 cm³ cm⁻³ and 0.08 cm³ cm⁻³ for the upper and lower limits of available water. These values, corresponding to volumetric water content after 0.01 and 1.5 MPa pressure was applied to wet soil, were obtained from a moisture retention curve determined with a pressure plate apparatus (DANR Analytical Laboratory, University of California).

Experimental design

The site was a 74×33 m field. A rye cover crop was grown on the site from January to late March 1994 to evenly deplete soil water and inorganic nitrogen from the soil profile. The cover crop was moved and removed from the field, and the stubble was incorporated into the soil 20 days before planting. Nitrogen fertilizer (ammonium nitrate, 60 kg N ha⁻¹) was incorporated with the plant material to accelerate its decomposition. Immediately before planting, 150 kg N ha⁻¹ of slow release fertilizer (sulfur coated urea, 39% N) was applied. Data on nitrate content in leaf fresh sap and in soil solution in soil water samplers (Soilmoisture Equipment Corp., Santa Barbara, CA) was monitored three times during the season and confirmed the homogeneity of soil nitrogen availability among irrigation treatments. The site was formed into 1 m raised beds, with bed tops 75 cm wide and furrows 25 cm across. A total of 32 beds were prepared where the outer five beds on both sides served as border rows, and there were 5 m borders on the lengthwise end of the plots (Fig. 1).

Three genotypes of lettuce (*Lactuca sativa* L.) were planted on 6 May 1994, including two crisphead lettuces ('Target' and 'Calmar') and a Cos (or romaine) lettuce ('Parris Island'), which are widely used in the area. Hereafter Target and Calmar will be used to refer to the crisphead lettuces and Cos will be used for the Parris Island cultivar. Target is a recently released 'Salinas'-type cultivar developed from germplasm of Calmar (EJ Ryder, pers. comm.). A fallow plot was included as the fourth cultivar treatment to allow a direct measure of soil evaporation (Cooper et al. 1983). Seeds were directly sown 3 cm apart in two rows per bed approximately 33 cm apart, and plants were thinned at 24 DAP to 30 cm between plants, which is a typical practice for these crops. The 5 m wide border zone surrounding the experimental area was sown to Target. Crop management followed conventional local farmers' practices as much as possible. For weed control, the herbicide "Kerb 50WP" (Pronamide) was applied before planting, and the plots were hand-hoed twice during the season. The final harvest of the plants was on 7 July, at 63 DAP.

Three sprinkler lines (10 m×10 m spacing) were installed to germinate the crop and were used twice, to apply a total of 27 mm, between planting and thinning (0 to 28 DAP). Thereafter, the crop was sprinkler-irrigated with an sprinkler line source (Hanks et al. 1976) in early morning (i.e., the period of lowest wind speeds) every 7–10 days. The line source irrigation system was along the middle furrow of the plot, giving 11 beds plus borders on either side (Fig. 1). The line source was 74 m long with sprinklers 5 m apart. A sprinkler head (Model 30, Rain Bird International, Inc., Glendore, CA) with two-nozzles (4.8 by 2.4 mm) was operated at 0.3 MPa of pressure. Irrigation rate at the line source was about 2.7 cm h⁻¹. Four irrigation treatments (total water applied of 136, 118, 95 and 61 mm) were provided by the decline in irrigation with distance from the line source. The irrigation frequency varied between 7 and 10 days. Just prior to every irrigation, the volumetric water content of the soil (0 to 105 cm) was determined; these values were used to calculate the volume of water required to bring the plots nearest the sprinkler line to field capacity (i.e., volumetric soil water content corresponding to -0.01 MPa). Applied water was measured by four rain gauges per irrigation treatment. The irrigation treatments were applied to 32, 41, 48 and 56 DAP. Calculations after the experiment showed that the percentages in relation to field capacity were: (1) rewatering to field

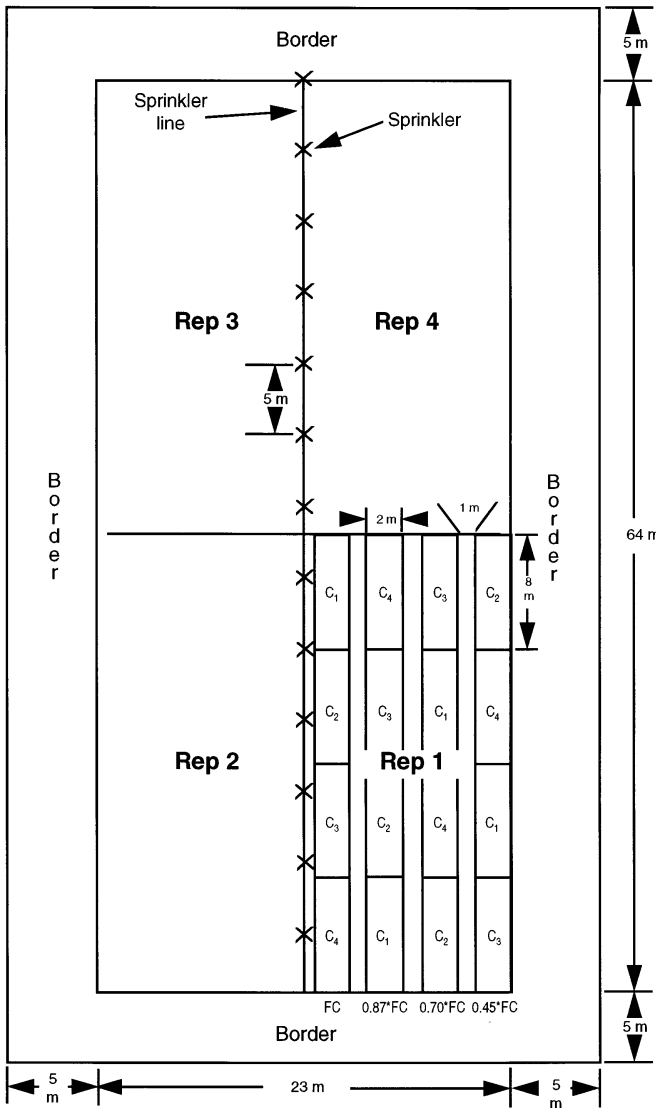


Fig. 1 Schematic diagram of the field site showing the line source sprinkler system. Irrigation treatments are labeled as FC, 0.87*FC, 0.70*FC and 0.45*FC. Cultivar treatments (C_1 – C_3) and a fallow treatment (C_4) are shown perpendicular to the irrigation treatments

capacity (FC); (2) watering with a volume 13% below that required in the field capacity treatment (0.87*FC); (3) watering 30% below FC (0.70*FC); and (4) 55% below FC (0.45*FC). Soil water status in each irrigation treatment was monitored with tensiometers set at 15 cm and 30 cm below the surface of the beds, mid-way between rows of plants. According to tensiometer readings one day after watering, the maximum soil water potentials at 24 h after irrigation in the rewatered plots were -0.01 MPa, -0.02 MPa, -0.04 MPa and -0.05 MPa, for the FC, 0.87*FC, 0.70*FC and 0.45*FC treatments, respectively. The minimum potentials before rewatering varied, but were generally in the range of -0.05 to -0.09 MPa.

The experiment used a modified split-plot design to examine the effect of the four irrigation rates on four cultivar treatments (Fig. 1). There were four replicated blocks each with four watering treatments. Within each block, numbering from the sprinkler line source, beds 1 and 2 were the FC treatment, beds 4 and 5 were the 0.87*FC treatment, beds 7 and 8 were the 0.70*FC treatment, and beds 10 and 11 were the 0.45*FC treatment. The beds in between were borders and were sown to the adjacent cultivar closest to the line source. The

plots were 8 m long and two beds wide (i.e., 2 m). The irrigation treatments within each block were divided into four cultivar treatments, along the length of the beds. Within each irrigation treatment of each block, cultivar treatments formed a randomized block design (Fig. 1). Analysis of variance followed the GLM procedures of SAS for split-plot design with fixed mainplot and random subplot factors (SAS institute 1985). Statistical comparisons between cultivars and cultivar \times irrigation interactions can be made but statistical analysis of irrigation effects are not strictly valid because of the lack of complete randomization (Hanks et al. 1980). Means were compared with a Least Squares Means procedure. Statistical comparisons were considered significant at $P < 0.05$. Due to the large number of comparisons, results of statistical tests are not all shown in the text, tables and figures.

Measurements

Crop evapotranspiration and reference evapotranspiration

Cumulative crop evapotranspiration (ET_c) was determined for the four irrigation treatments and the three cultivars using the water balance procedure (Haise and Hagan 1967). Soil water content was measured gravimetrically from soil cores (10 cm dia.) taken from the top 15 cm and at 30 cm intervals to a depth of 105 cm using a hydraulic corer (Giddings Machine Co., Fort Collins, CO). Each core was well-mixed, subsampled, and dried 48 h at 150°C . The sum of the differences in soil water content and applied irrigation water (rainfall never occurred during this part of the growing season) were calculated as ET_c for each 7–10 day period between irrigations, for the duration of 28–63 DAP, assuming negligible deep percolation and runoff. Bulk density was determined separately in beds and furrows at 10 cm intervals throughout the soil profile (0 to 50 cm) at the beginning of the experiment, by the core method (Blake and Hartge 1986). These bulk density values were used in all estimations of the volumetric soil water content.

To avoid runoff, the furrows were cultivated prior to each irrigation to increase surface roughness and water infiltration. Also, small soil dams were built prior to each irrigation in the furrows at equidistant intervals to further reduce the possibility of runoff during irrigation. The spatial pattern of water application were determined at each irrigation by collecting the sprinkler water in cans and measuring its volume. Catch cans were placed in the center of each individual plot.

Reference evapotranspiration (ET_o) was obtained from the nearby California Irrigation Management Information System (CIMIS) station (Snyder and Pruitt 1992) which calculates ET_o using a modified hourly Penman equation (Pruitt and Doorenbos 1977). The nearest CIMIS weather station (South Salinas), is situated approximately 5 km from the experimental site. Comparison of maximum and minimum temperature and relative humidity collected at the field site during this three-month period indicated that the ET_o of this station was representative of the conditions during the experiment. The experiment was conducted in late spring and early summer before the foggy period and after spring rains. Most days were fog- and cloud-free. Crop coefficients were calculated as the ratio between ET_c and ET_o (Doorenbos and Pruitt 1977). Four growth periods were chosen to determine crop coefficients: (1) rosette initiation (28–39 DAP); (2) rosette stage (40–46 DAP); (3) head formation (47–54 DAP); and (4) maturity (55–63 DAP).

Soil evaporation

Soil evaporation from fallow soil was measured during the period from sowing to thinning (0–28 DAP) prior to establishing the irrigation treatments. We assumed that during this period, plant transpiration was negligible due to the small size of lettuce seedlings. Low values of dry matter and ground cover at 28 DAP (Fig. 5 a and b) support this assumption. Two cycles of evaporation measurements were made while the soil dried from field capacity. During each cycle, daily evaporation was calculated as the difference in the gravi-

metric soil water content (0–15 cm) as determined on subsamples obtained from soil cores (15 cm deep and 10 cm dia.) taken every 24 h from the center of a given bed and furrow from the fallow plots. Each core was taken, in a line adjacent to the beds, approximately 20 cm away from where the previous core had been taken. The first cycle (4–12 DAP) commenced after a 27 mm irrigation (3 DAP) and 20 mm rainfall (1 and 2 DAP). The second cycle (13–22 DAP) started after one day of rain with 15 mm (12 DAP).

Soil evaporation from cropped soil (E) was estimated for the period when the irrigation treatments were applied (28–63 DAP) using the method of Cooper et al. (1983). Evaporation from fallow soil (E_f) was calculated from gravimetric changes in soil water content. The following equation estimated E:

$$E = E_f(1 - i)$$

where i is the proportion of photosynthetically active radiation (PAR) intercepted by the crop estimated from incoming and below canopy measures as described below.

Plant measurements

Shoot dry matter was determined five times during the experimental period (29, 39, 46, 54 and 63 DAP) by harvesting 10 heads at surface level per plot prior to each irrigation event. Dry matter determinations were made by weighing the plant material immediately after harvesting and taking a subsample for moisture determination. Dry weights were recorded after oven-drying plant samples at 70 °C for 48 h. At final harvest, assessment of crop commercial quality in Target was conducted by measuring on 10 heads: (1) yield or fresh weight (g per plant); (2) volume of the head determined by measuring the external diameter and assuming spherical heads; and (3) head density calculated as the ratio of head weight to volume. Canopy ground cover was estimated at 29, 35, 40, 47 and 66 DAP by measuring the proportion of the photosynthetically active radiation intercepted by the crop (PAR intercepted) with a 0.8 m long linear PAR sensor (AccuPAR, Decagon Devices Inc., Pullman, Washington). Measurements were made above and below the canopy for periods between 11.00 and 14.00 h. Total water use efficiency (WUE) was calculated as the ratio of the shoot dry matter or fresh weight accumulated for the period 28 to 63 DAP to water used for the same period.

Root measurements were confirmed to the irrigation treatment irrigated to field capacity (FC). Roots were sampled at final harvest (63 DAP) in the three cultivars. Three cores (10 cm diameter) were taken from each plot, one from the center of the bed, one directly over a plant to include the entire taproot, and one from the furrow. Cores taken from bed and plant were divided into 0–15, 15–45, 45–75, and 75–105 cm depth increments. Furrow cores were taken to the same depth as bed cores, but the 0–15 cm depth increment was considered absent. These three root sampling locations have been shown to cover the complete lateral distribution of lettuce grown in bed-furrow systems (Jackson and Stivers 1993). Subsamples of 200 g were removed for root washing with a Gillison's hydroneumatic root elutriator (Benzonia, MI; Smucker et al. 1982) and immediately stored in a solution containing 10% ethyl alcohol. Root length was determined on a Comair root scanner (Hawker de Haviland, Victoria, Australia) and dry weight was measured after drying at 70 °C. Root length and biomass were expressed separately for the three sampling positions through the soil profile as root length density (cm root cm⁻³ soil) and root biomass (g cm⁻³ soil). In the soil samples taken for root determinations, a well-mixed subsample was also taken to measure soil water content gravimetrically.

Measurements of gas exchange and leaf water potential were conducted at 62 DAP when the effect of the differential irrigation treatments were apparent. Readings were taken in the three cultivars and four irrigation treatments on fully-expanded leaves under clear sky in the middle of the day (11.00–13.00). The rate of net photosynthesis and stomatal conductance to water vapor was measured on four leaves per irrigation treatment and per cultivar using a portable closed photosynthesis system (LI-6000; LI-COR Inc., Lincoln, NE). A detailed description of the use of the instrument is given in Gallardo et al. (1996, submitted). After measurement of leaf gas exchange, a

distal portion of the leaf was enclosed in a plastic sheath, cut and the leaf water potential of the leaf section was measured using the pressure chamber method adapted for lettuce leaves (Gallardo et al. 1996, submitted).

Results

Total production and evapotranspiration (ET)

The total irrigation water applied during the experimental period (28 to 63 DAP) was very similar for the three cultivars for each irrigation treatment (Table 1 a). Cumulative evapotranspiration (ET_c) for the period when the watering treatments were applied (28 to 63 DAP) varied with distance from the line source. Values of ET_c for the three cultivars ranged from 153 mm for the FC treatment to 90 mm for the treatment 0.45*FC. ET_c was similar for the two irrigation treatments receiving the largest amounts of water and was considerably lower in the 0.70*FC and 0.45*FC treatments. For the three irrigation treatments receiving the largest water application, ET_c was higher in the Cos cultivar than in the two crisphead lettuce cultivars which had similar ET_c .

The Cos lettuce produced significantly more dry matter at the end of the experiment than the two crisphead cultivars (Table 1 b). There were significant differences between cultivars in fresh weight per plant; Cos had generally lower fresh weight than Calmar and Target, indicating a lower leaf water content in Cos compared to the crisphead lettuces. The decrease in water applied from FC to 0.87*FC generally did not affect final dry matter but slightly decreased the fresh weight (Table 1 b). For the three cultivars, a reduction in dry matter and fresh weight per plant occurred with the 0.70*FC treatment. A further reduction in both parameters for all cultivars occurred with the 0.45*FC treatment. The mean dry matter production and plant fresh weight for the 0.45*FC treatment for the three cultivars in relation to the FC treatment were 72% and 58%, respectively, indicating that the decreased water supply had a larger effect on the fresh weight than on the dry matter. The effect of the irrigation treatments on the volume and the density of the lettuce heads, which are parameters indicating lettuce quality, were determined at final harvest for Target. The head volume decreased linearly as irrigation decreased, with mean values ranging from 3387 cm³ head⁻¹ to 1443 cm³ head⁻¹, respectively, for treatments at FC and 0.45*FC. Head density increased as the irrigation decreased (0.28 g cm⁻³ at FC to 0.34 g cm⁻³ at 0.45*FC).

Shoot dry matter and fresh weight at harvest for the three cultivars increased linearly with cumulative ET_c for the experimental period (Fig. 2 a, b). There was a tendency for greater dry matter production in Cos for a given level of ET_c (Fig. 2 a), but there were no significant differences in the slopes of the regressions of dry matter vs. ET_c between cultivars. Mean WUE for dry matter across all irrigation treatments, however, was significantly higher for Cos (2.1 g m⁻² mm⁻¹) compared to Calmar (1.6 g m⁻² mm⁻¹). WUE for dry matter in Target (1.8 g m⁻² mm⁻¹) was not

Table 1 a Water applied and cumulative crop evapotranspiration (ET_c) for the experimental period (28 to 63 DAP) and b dry matter and fresh weight at maturity for the four irrigation treatments and the three cultivars. Values are means of four replications ± standard error

a Irrigation treatment	Distance to line source (m)	Water applied (mm)						Cumulative ET _c					
		Calmar		Target		Cos		Calmar		Target		Cos	
		mean ± se		mean ± se		mean ± se		mean ± se		mean ± se		mean ± se	
FC	1.0	137.4	6.6	134.5	5.6	137.0	6.2	143.5	2.8	141.6	8.3	153.0	7.4
0.87*FC	3.0	119.1	6.8	116.6	8.7	119.2	7.2	138.9	3.1	135.3	10.6	142.6	10.7
0.70*FC	5.5	93.1	10.8	95.5	8.7	95.2	12.1	123.4	9.3	115.6	4.8	138.8	5.8
0.45*FC	8.5	61.6	11.6	62.0	12.2	61.3	13.9	108.3	7.6	90.7	4.9	99.9	4.0

b Irrigation treatment	Distance to line source (m)	Dry matter (g m ⁻²)						Fresh weight (g plant ⁻¹)					
		Calmar		Target		Cos		Calmar		Target		Cos	
		mean ± se		mean ± se		mean ± se		mean ± se		mean ± se		mean ± se	
FC	1.0	262.5	42.5	243.4	49.5	341.5	28.1	1000.3	25.5	934.1	50.6	819.8	58.1
0.87*FC	3.0	225.0	34.3	264.5	33.2	344.7	29.4	945.4	24.4	828.6	50.6	809.8	56.1
0.70*FC	5.5	215.5	40.7	212.1	16.4	270.9	34.8	723.5	51.0	765.6	36.4	693.8	57.2
0.45*FC	8.5	175.8	12.1	193.9	17.4	236.7	28.6	606.4	32.5	494.3	40.8	505.9	60.0

Table 2 Daily reference evapotranspiration (ET_o), crop evapotranspiration (ET_c) and crop coefficients (K_c) for the four irrigation treatments and cultivars during the four periods of measurements. Each value is the mean of four replications

Irrigation treatment	Periods	ET _o (mm day ⁻¹)	Calmar		Target		Cos	
			ET _c (mm day ⁻¹)	K _c	ET _c (mm day ⁻¹)	K _c	ET _c (mm day ⁻¹)	K _c
FC	28–39 DAP	6.25	2.67	0.43	2.99	0.48	3.56	0.57
	40–46 DAP	6.32	4.93	0.78	4.37	0.69	4.29	0.68
	47–54 DAP	6.38	4.39	0.69	3.77	0.59	5.14	0.81
	55–63 DAP	5.60	4.95	0.88	5.32	0.95	4.74	0.85
0.87*FC	28–39 DAP	6.25	1.80	0.29	2.39	0.38	3.08	0.49
	40–46 DAP	6.32	3.22	0.51	4.19	0.66	2.89	0.46
	47–54 DAP	6.38	5.67	0.89	4.88	0.77	5.11	0.80
	55–63 DAP	5.60	5.69	1.02	4.52	0.81	5.32	0.95
0.70*FC	28–39 DAP	6.25	2.09	0.33	1.88	0.30	2.63	0.42
	40–46 DAP	6.32	3.51	0.56	3.59	0.57	4.72	0.75
	47–54 DAP	6.38	4.52	0.71	4.94	0.77	3.89	0.61
	55–63 DAP	5.60	4.40	0.79	3.36	0.60	4.92	0.88
0.45*FC	28–39 DAP	6.25	1.84	0.29	1.69	0.27	2.54	0.41
	40–46 DAP	6.32	3.03	0.48	3.00	0.48	1.83	0.29
	47–54 DAP	6.38	3.67	0.58	2.93	0.46	3.86	0.61
	55–63 DAP	5.60	4.21	0.75	3.08	0.55	3.14	0.56

statistically different from the other cultivars. Differences in biomass appear to be unrelated to N deficiency since the N content (dry matter basis) at harvest, in all treatments, was approximately 3.5%. During the season, the nitrate concentration of fresh petiole sap, from the lettuce plants, was periodically monitored; concentrations of nitrate were consistently above critical values for all the irrigation treatments (L. Jackson, pers. comm.).

Crop coefficients (K_c) were very similar between the three cultivars for a given irrigation treatment (Table 2).

Initial values ranged between 0.3–0.4 for the period 28–39 DAP (rosette initiation). The maximum values of K_c (0.81–1.02) were measured at the end of the season during the maturity period (55–63 DAP) in the two treatments receiving maximum irrigation (FC and 0.87*FC).

ET partitioning

Using the weighted mean of soil evaporation from beds (75%) and furrows (25%), mean evaporation rates from

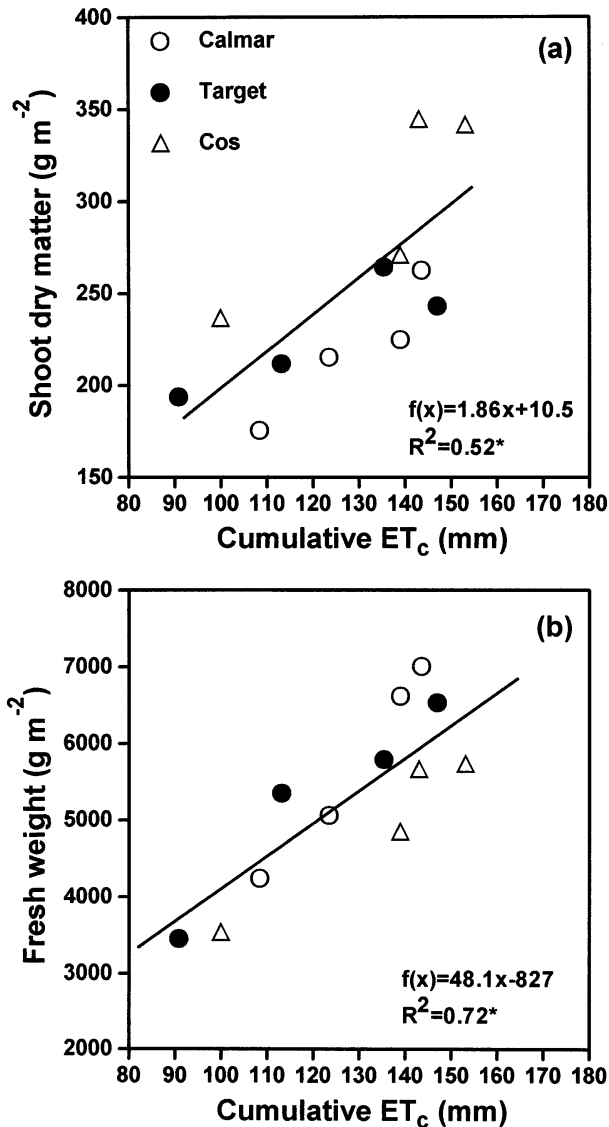


Fig. 2 a, b Cumulative evapotranspiration for the experimental period (28 to 63 DAP) in relation to final a shoot dry matter and b fresh weight. Data are means of four replicates and were collected from all irrigation treatments and cultivars. (* = significant at $P \leq 0.05$)

bare soil of 1.3 mm day^{-1} and 1.2 mm day^{-1} were measured in the first and second drying cycles, respectively, for the period from planting to thinning (0–28 DAP). Plant transpiration during this period was assumed to be negligible. Figure 3 a presents reference evapotranspiration (ET_0) and soil evaporation (E) from beds and furrows for the second irrigation cycle. A similar trend of E with time was found in the first cycle (data not shown). The evaporation rate from beds and furrows declined continuously with time and was significantly related to soil water content (Fig. 3 b). ET_0 in the second cycle fluctuated between 5.5 and 2.8 mm day^{-1} (Fig. 3 a). On the first day of measurement, E from the beds was 80% of ET_0 and afterwards, E decreased to minimum values of 10% of ET_0 (Fig. 3 a). During the first 5 days of the drying cycle, E was gener-

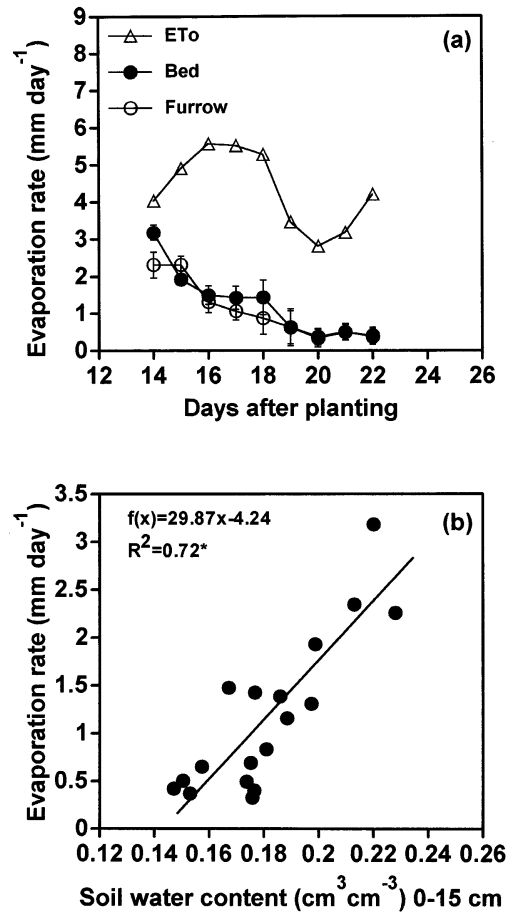


Fig. 3 a, b Evaporation during the second irrigation cycle (13 to 22 DAP). a Reference evapotranspiration (ET_0), and soil evaporation from beds and furrows. Bars indicate \pm the standard errors of evaporation measurements. b Evaporation rate as a function of soil water content in the top 15 cm of soil. Points are individual observations. (* = significant at $P \leq 0.05$)

ally higher from the beds compared to furrows; later, as the soil surface dried, the rate of E from the two surfaces was similar. The beds were more exposed to direct sunlight and to wind, and had lower bulk density in the 0–15 cm layer which may explain the lower E rates from the furrows.

The linear relationship between evaporation rate and volumetric soil water content (Fig. 3 b) indicates stage 2 evaporation (Ritchie 1972). The data from the second drying cycle were used to determine the α (slope of the linear regression of evaporation rate from an irrigated bare soils vs. squared root of days after irrigation) parameter for second stage evaporation used in the Ritchie (1972) model. A value of $\alpha = 3.78 \text{ mm/day}^{0.5}$ was obtained ($r^2 = 0.99$) which is in the range of values obtained by Ritchie (1972) for a loamy sand soil type. The estimated total soil E from planting to thinning (0–23 DAP) was 18.2 mm using the Ritchie (1972) model and 19.8 mm from soil moisture measurements.

Evaporation from the cropped soil and plant transpiration for each cultivar and irrigation treatment were deter-

Table 3 Cumulative soil evaporation (E) for the experimental period (28 to 63 DAP) and ratio of soil evaporation to crop evapotranspiration (ET_c) for the same period for the four irrigation treatments and the three cultivars. Values are means of four replications \pm standard error

Cultivar	Irrigation treatment											
	FC			0.87*FC			0.70*FC			0.45*FC		
	E (mm)		E/ ET_c	E (mm)		E/ ET_c	E (mm)		E/ ET_c	E (mm)		E/ ET_c
	mean \pm se			mean \pm se			mean \pm se			mean \pm se		
Calmar	68.7	6.3	0.48	61.2	4.4	0.44	49.9	4.1	0.40	30.1	2.3	0.28
Target	74.1	8.2	0.52	67.9	4.4	0.50	51.1	1.9	0.44	33.0	0.6	0.36
Cos	69.5	6.5	0.45	60.2	4.8	0.42	47.2	3.1	0.34	31.3	1.8	0.31

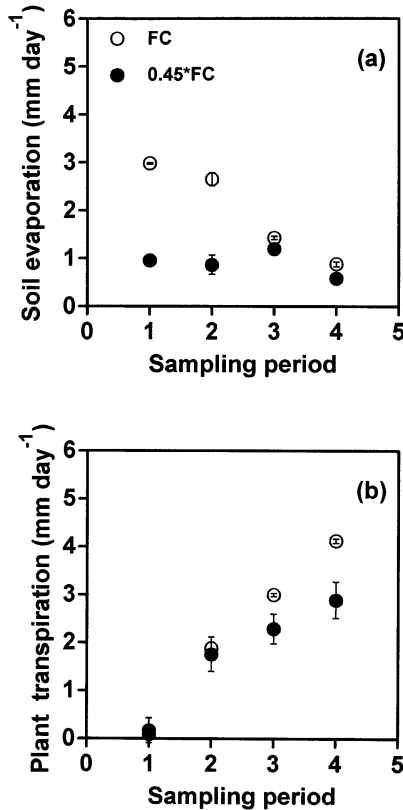


Fig. 4 a, b Seasonal changes in **a** soil evaporation and **b** plant transpiration rates for the treatments receiving maximum (FC) and minimum irrigation (0.45*FC). Data are means for the three cultivars. Measurements were conducted during four irrigation cycles: 1 (28–39 DAP), 2 (40–46 DAP), 3 (47–54 DAP) and 4 (5–63 DAP). Bars indicate \pm standard error ($n=4$)

mined between thinning and maturity according to Cooper et al. (1983). The contribution of E to total ET_c was similar between cultivars for a given irrigation treatment and decreased as the irrigation decreased (Table 3). Across cultivars, E/ET_c averaged 0.48, 0.45, 0.40 and 0.32 for FC, 0.87*FC, 0.70*FC and 0.45*FC treatments, respectively. Estimated mean daily soil E and plant transpiration for the three cultivars are presented in Fig. 4 a, b for the maximum and minimum irrigation treatments. Under maximum irri-

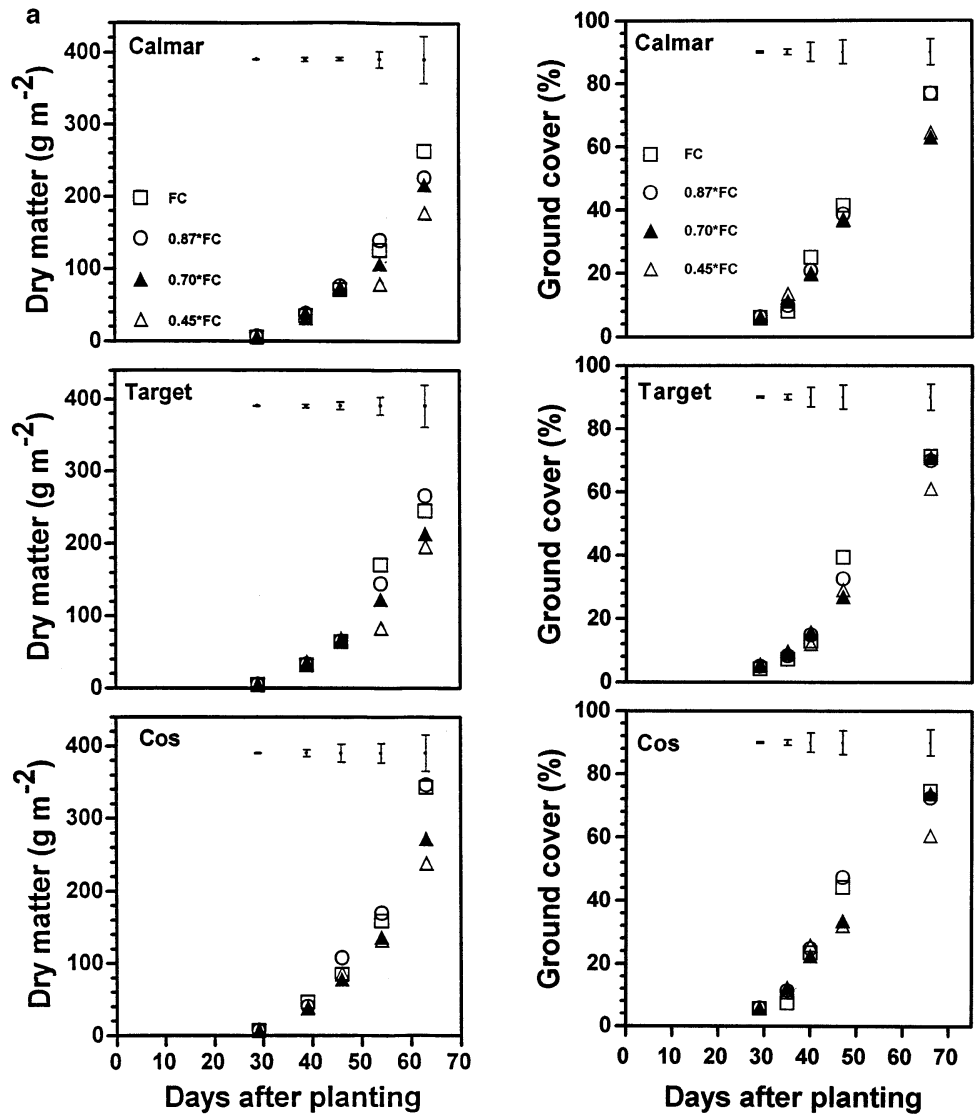
gation (FC), the E component of total ET_c decreased as the canopy developed (Fig. 4a). In the early part of the season, which corresponds to rosette initiation (28–39 DAP), soil E represented 98% of the total ET_c in the FC treatment. Soil E was 59% of the total ET_c in the rosette stage (40–46 DAP), 33% in the head formation period (47–54 DAP), and decreased considerably in the maturity period (55–63 DAP) to 18%. Compared to FC, soil E in 0.45*FC was considerably lower, particularly early in the season when the crop canopy was small and most water was lost as direct soil E (Fig. 4a). Differences in plant transpiration between the maximum and minimum irrigation treatments were apparent only in the last 3 weeks (47 to 63 DAP) of the cropping period (Fig. 4b).

Treatment effects on yield-determining parameters

Dry matter accumulated at a very low rate during the first 50 days of the growing season, and increased exponentially in the final three weeks (Fig. 5a). During the last 17 days, the plants attained 76% of total dry weight. The irrigation treatments did not produce differences in dry matter accumulation until 45 DAP (Fig. 5a); even so, the experimental design prevented statistical comparison of means. For the three cultivars, vegetative growth for the treatments 0.70*FC and 0.45*FC only declined, in relation to the FC treatment, during the last two measurement periods (54 DAP and 63 DAP). Under maximum irrigation the two crisphead lettuce had similar final dry matter (264 g m⁻²); Cos final dry matter was considerably higher (345 g m⁻²).

The seasonal development of ground cover was similar to that for dry matter accumulation (Fig. 5b). Very little ground cover was observed during the first 50 days of the season and a rapid increase in ground cover occurred in the last two weeks. Percentage ground cover at the end of the experiment reached maximum values of 75%. This indicates that lettuce plants attained full cover in the beds, considering that 25% of the area was bare furrows. For all cultivars, differences in ground cover between irrigation treatments were observed only at the last two sampling dates. However differences in ground cover between cultivars occurred at four of the five sampling dates. Cos and Calmar had consistently higher ground cover than Target.

Fig. 5a, b Time course for the three cultivars of **a** shoot dry matter accumulation and **b** percentage ground cover. Data (mean of four replicates) were collected from all irrigation treatments. Vertical bars indicate \pm the standard error of the mean



The differences in water supply at the end of the season did not affect the instantaneous measurement of leaf water potential, photosynthesis and stomatal conductance which were similar in all irrigation treatments (Fig. 6). For a given soil matric potential, stomatal conductance was higher in the cultivar Cos, which also had the greater seasonal ET_c and dry matter at harvest (Table 1).

Root distribution and soil water extraction

The distribution of the root system, determined for the irrigation treatment receiving maximum water (FC), was largely confined to the top 0–15 cm of soil. For the three cultivars, most of the root length at harvest was found in the 0–15 depth (Fig. 7). Few roots were found below 45 cm (root length density <2 cm cm⁻³). Furrow samples contained similar root length to bed samples. Generally there were no differences in root length density at 45–75 and

75–105 cm depth among cultivars for all three sampling zones. An exception was Calmar, which had a root length density at 75–105 cm depth in the furrows that was 2.5 and 3.7 times greater than the other two cultivars. Root length density directly beneath the plant samples containing the taproot was considerably higher than the mid-bed sample (taken at 16 cm from the plant) at 0–15 cm, and was slightly higher at 15–45 cm. In the top depth (0–15 cm), the Cos lettuce had a greater root length density than the other two cultivars. Due to the presence of large taproots, root biomass at final harvest was mainly in the top 0–15 cm (data not presented).

For all cultivars, ET_c exceeded the amount of water applied because of crop extraction of stored soil water (Fig. 8). The relationship between cumulative ET_c for the experimental period and water applied was curvilinear indicating that water extraction from soil reserves became more significant as the amount of irrigation water decreased. The range of water applied seems to be insuffi-

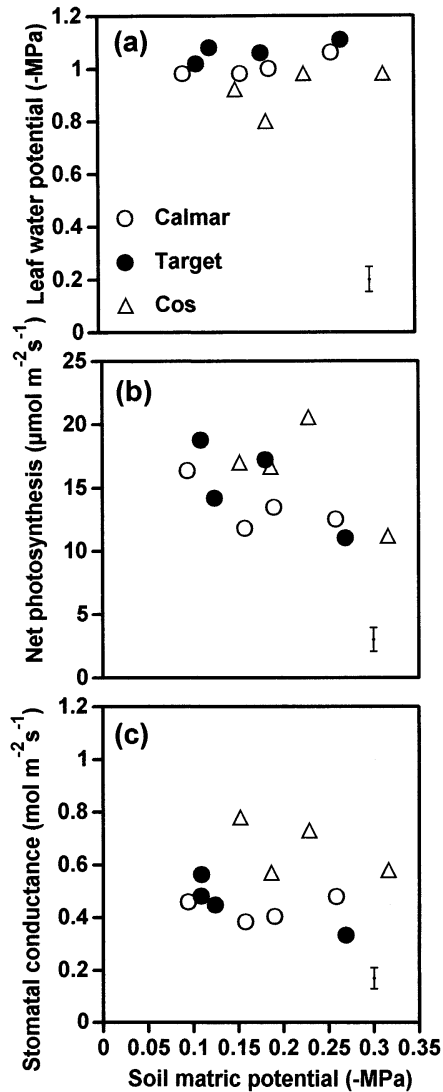


Fig. 6 a–c Relationship between average soil matric potential at 62 DAP for the 0–105 cm soil profile and **a** midday leaf water potential, **b** rate of net photosynthesis and **c** stomatal conductance. Values are means of four determinations. (Vertical bars indicate \pm pooled standard error)

cient to reach a plateau of maximum ET_c , but the curve of the relationship indicates that the treatment at FC was close to the maximum ET_c for lettuce. For any amount of applied water, ET_c was higher in Cos lettuce indicating differences between cultivars in the ability to extract soil water. As the applied water decreased, a higher water extraction was observed in Calmar than in Target. The stored soil water extracted by Target and Calmar during the season was respectively, 65 and 86% of that extracted by Cos.

Soil water extraction from deeper layers in the profile increased in the treatments receiving lower water inputs. Figure 9 presents profiles of soil water content in the center of the beds for the four irrigation treatments measured at the beginning (28 DAP) and at the end (63 DAP) of the experiment. Mean data for the three cultivars from the bed samples are presented. The zone of maximum depletion

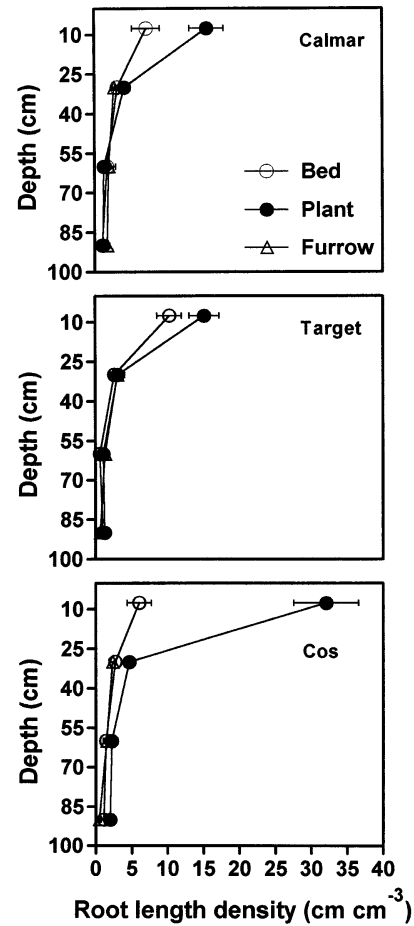


Fig. 7 Distribution of root length density in the soil profile for the three cultivars at the end of the experiment (63 DAP). Data were collected from the FC treatment from beds, furrows and directly underneath the plant. Values on the y axis represent the mid-point for each increment of depth. Bars indicate \pm the standard error (n=4)

and the total quantity that was depleted varied between irrigation treatments. At the highest rates of applied water (FC and $0.87*FC$), most of the water extraction occurred from the top 45 cm while for the treatments receiving the lowest irrigation ($0.70*FC$ and $0.45*FC$), soil water extraction occurred down to 105 cm. These results show increased water extraction from deeper layers as the water deficits increased, reflecting possible changes in root exploration of the soil profile.

Discussion

Detailed analysis of seasonal changes in crop canopy development and biomass production in relation to water use have shown that it is difficult to manage water application to match demand by the lettuce crop because of delayed biomass production and high soil evaporation during most of the growing season. Frequent estimations of the E/ET_c ratio have indicated that there may be periods when the

large loss of evaporation can be reduced, e.g., just after thinning when lettuce was apparently insensitive to the volume of applied irrigation water. Pattern of root distribution and water extraction have shown that the spatial aspects of water use also should be considered in managing irrigation. The shallow root system of lettuce is a major constraint on efficient water use, and may potentially benefit from genetic improvements.

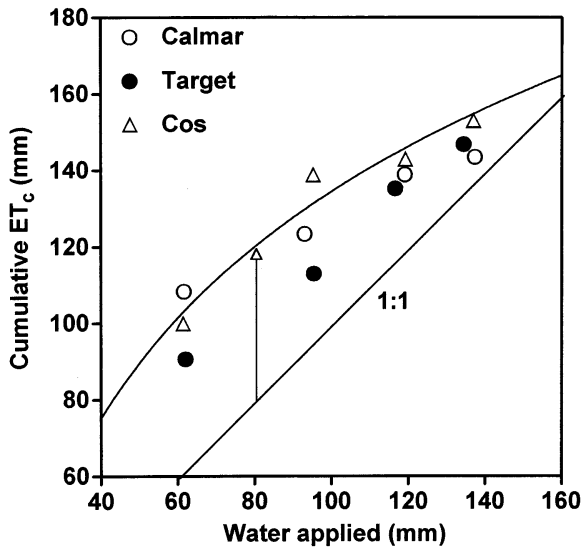


Fig. 8 Cumulative evapotranspiration for the experimental period (28–63 DAP) as a function of applied water for all lettuce cultivars. Each point is the mean of four replications

Lettuce dry matter and fresh weight were linearly related to total water use, which gave similar water use efficiency values for all irrigation treatments. The values of WUE for fresh and dry weight of lettuce obtained in this experiment were similar to those for lettuce in other field studies (Sale 1966; Shih and Radi 1984). The linearity of the production functions (ET_c vs. dry matter or ET_c vs. fresh weight) in this experiment is consistent with those of Sammis et al. (1988) and Sutton and Merit (1993) for lettuce grown under different conditions.

The ET_c for the period from thinning to harvest for lettuce ranged from 153 mm for the FC treatment to 90 mm for 0.45*FC treatment. Schulbach (1988, 1995) using a Bowen ratio energy balance system, estimated values of 100–190 mm for lettuce from planting to harvest at nearby sites in the Central Coast region. The ET_c of crops grown in this region is generally low because of the strong coastal influence on climatic conditions. Considerably higher values of ET_c were recorded in studies under higher ET_o conditions in southern California and New Mexico (Ayers and Branson 1973; Sammis 1980). The relative difference in fresh and dry weight between the highest and lowest irrigation treatments indicated that fresh weight was a more sensitive parameter under mild water stress conditions as observed by Bar-Yosef and Sagiv (1982) and Sutton and Merit (1993). The optimum soil water content for lettuce production has been assessed as the maintenance of field capacity (e.g., Salter and Goode 1967; Sammis et al. 1988; Sutton and Merit 1993), yet there are also reports that at soil water contents maintained slightly below field capacity (–0.03 to –0.08 MPa), yield was not affected (Dullforce and Garcia-Huidobro 1974; Sammis 1980). The results of this study indicate that lettuce growth is not limited by low water availability when soil is brought just to field capacity with intermittent irrigations that result in periodic decreases in soil water potential to –0.05 MPa at 0–30 cm depth.

The maximum values of K_c determined in this study (0.81–1.02) are similar to the value of 0.95 reported by Doorenbos and Pruitt (1977) for comparable climatic conditions and to values of 0.83–1.02 from the Imperial Valley in California for autumn grown lettuce (Letey and Vaux 1984). While our study was being conducted, daily measurements of ET_c from a lettuce crop of similar development were determined from a nearby lettuce crop with a Bowen ratio micrometeorological system (Schulbach, unpublished data). Summed daily estimates, for the same periods as in our study, gave very similar K_c values to those obtained with the soil water balance method in this experiment.

The technique of Cooper et al. (1983) was used to separate E and T. This technique has been both tested against micro-lysimeters (Allen 1990) and is commonly used (e.g., Gregory et al. 1992; Hamblin and Tennant 1987) in dry-land crops. The method assumes that evaporation from bare soil in fallow and cropped plots in the same. In our study, particularly when the crop was more advanced, as soil dried, fallow plots had slightly higher soil water content than cropped plots probably because root extraction of wa-

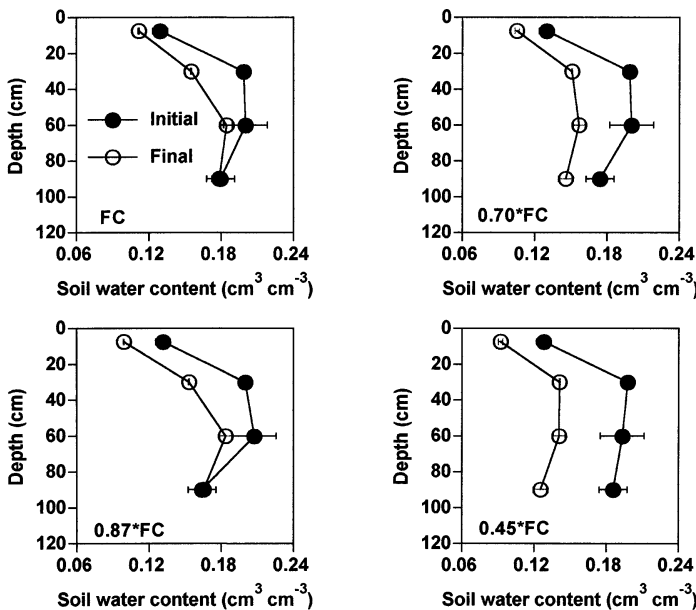


Fig. 9 Volumetric water content profiles at the beginning (29 DAP) and the end (63 DAP) of the experiment for the four irrigation treatments. Data are means for the four cultivars. Values on the y axis represent the mid-point for each increment of depth. Bars represent \pm the standard errors

ter decreased the surface soil water content. Consequently, E will be over-estimated, more so later in the growing period. However, in situations of frequent irrigation where soil drying is limited, the Cooper et al. (1983) method has been satisfactory in predicting E and the errors associated with the technique are likely to be smaller than under dry-land conditions (e.g., Allen 1990).

For the three lettuce cultivars, growth was initially very slow and in the last two and a half weeks, the plants attained 76% of their total dry weight, which is the characteristic pattern of lettuce growth (Lorenz and Minges 1942; Zink and Yamaguchi 1962, 1963). It was only at the last two sampling dates (54 and 63 DAP) that expansive growth, expressed by dry matter accumulation and ground cover, was affected by the irrigation treatments. These results suggest that the amount of water applied in the last three weeks, when most growth occurs, is particularly important for lettuce. Sale (1966) and Singh and Alderfer (1966) reported that lettuce growth was most sensitive to water supply during head formation, although insufficient water also slowed growth at earlier stages. Prior to 45 DAP, canopy ground cover was low (<20%) and most water applied was lost as soil evaporation. Reducing the water supply considerably reduced the soil evaporation component of ET_c during the entire season and lowered crop transpiration only in the latter part of the season. For the FC treatments, E was estimated to be the major part of ET_c for 45 of the 63 days of the experiment. The E/ET_c ratios between thinning and maturity decreased as the rate of irrigation decreased from 0.48 in the FC treatment to 0.31 in the 0.45*FC treatment. Seasonal E/ET_c ratios for other irrigated crops may vary from 0.20 in sorghum (Ritchie and Burnett 1971) to 0.56 in cotton (Al-Khafaf et al. 1978); crop morphology, irrigation technique, site characteristics and experimental methodology influences these values. Not only is biomass production of lettuce slow early in the season, but the overlapping leaves of lettuce contribute to slow coverage of the ground cover surface. In contrast, crops such as tomato cover the ground surface rapidly, so that E/ET_c ratios are lower through the season (Feres and Villalobos 1990). The bed-furrow configuration of lettuce fields also may play a role in the contribution of soil evaporation to total ET_c since surface soil in the furrows remains wet longer than in the beds, and furrows occupy a large proportion of the surface area in these cropping systems. Since a line source design was used, sprinkler irrigation was applied throughout the season. Most lettuce growers in the western USA use sprinkler irrigation for establishment and furrow irrigation from thinning to harvest (Whitaker et al. 1974; Ryder 1979; Jackson et al. 1994). The use of sprinklers throughout the season in this experiment would increase the soil surface area wetted by each irrigation, which would increase the soil E compared to furrow irrigation.

Measurement of leaf water potential and net photosynthesis on mature lettuce did not show differences between irrigation treatments. The values of net photosynthesis, stomatal conductance and leaf water potential were within the ranges determined on adequately watered plants grown

under controlled conditions (Wheeler et al. 1994; Gallardo et al. 1996, submitted). These results suggest that small differences in water supply lead to non-detectable differences in instantaneously measured physiological parameters. We suggest that small undetectable differences in instantaneous net photosynthesis and stomatal conductance persisted and accumulated over the growing season resulting in differences in final production. Similar results were reported by Sutton and Merit (1993). Greenhouse studies with lettuce (Gallardo et al. 1996, submitted) have shown that leaf water potential and rate of photosynthesis were reduced from -0.6 MPa and $20 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively, in a well watered treatment to -1.6 MPa and $2.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ under severe water deficits (soil water potentials below -3.7 MPa). Under commercial production, leaf water potential is unlikely to be sensitive to the expected moderate variations in soil water content and therefore cannot be recommended as a tool for irrigation scheduling (c.f., cotton, Grimes and Yamada 1982).

The Cos cultivar had a significantly higher ET_c and total dry matter production than the two crisphead cultivars. For a given soil matric potential, Cos maintained a higher stomatal conductance which could explain its higher ET_c . The contribution to ET_c from stored soil water differed between irrigation treatments and cultivars. As soil water deficits increased, extraction from soil reserves increased with Cos extracting more than the crisphead varieties. Cos had a greater density of roots in 0–15 cm soil which may explain its greater extraction of soil water. Some differences did occur between the two crisphead lettuces. Calmar, the older cultivar, had greater canopy development through the season, yet dry weight did not differ from Target, so that head density might have been lower. Calmar also produced significantly more roots in the lower depths of the soil profile in the furrows and extracted more soil water. However, Target does have higher WUE based on dry matter production and it is preferred commercially due to its high disease resistance.

In the three cultivars, most of the roots in the FC treatment were in the top 45 cm of soil. Studies of lettuce root development show maximum penetration to 60 cm with most of the roots in the upper 30 cm (Rowse 1974; Jackson and Stivers 1993). Profiles of soil water content at the beginning and at the end of the season, showed that as the irrigation water was reduced, plants extracted more water deeper in the soil, presumably due to root proliferation. Root proliferation by lettuce at depth in response to soil drying was observed by Rowse (1974) and Gallardo et al. (1996, submitted). The increased uptake of water from depth was insufficient to compensate for the reduced water supply and a reduction in growth occurred. Deeper and denser root systems may be more appropriate for maintaining crop yield under lower inputs and for decreasing nitrate losses to the environment, while shallow and small root systems may be sufficient under conditions of high water and nutrient availability (Greenwood and Draycott 1988; van Noorwijk and de Willigen 1987). Breeding for a deeper root system in cultivated lettuce using germplasm from deep-rooted wild lettuce to increase the water uptake

at depth had been suggested in earlier work (Jackson 1995; Gallardo et al. 1996, submitted).

In summary, detailed frequent sampling of soil water profile and lettuce biomass and canopy development provided information on temporal changes in crop responses to decreased moisture and measurements of root distribution and soil water extraction showed the spatial zonation of soil moisture. Crop coefficients and water production functions which are critical for determining optimal irrigation requirements in lettuce were generated, yet this approach also showed that in this slow-growing, shallow-rooted crop, opportunities exist for minimizing evaporative losses during the apparent insensitive periods in the growing season.

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