Yield and Leaf Quality of Processing Spinach under Deficit Irrigation

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Abstract. Restrictions placed on water usage for farmers have prompted the development of irrigation management projects aiming at water savings of economically important crops. The objective of this work was to determine yield, water use efficiency, and leaf quality responses to deficit irrigation rates of processing spinach (Spinacea oleracea L.) cultivars. Three irrigation treatments were imposed with a center pivot system, 100%, 75%, and 50% crop evapotranspiration rates (ETc). Commercial cultivars used were ‘DMC 09’, ‘ASR 157’, and ‘ACX 3665’. Leaf quality was significantly affected by deficit irrigation rate and cultivar. Leaf yellowness was highest at 50% ETc, and was more evident for ‘ACX 3665’. The percent excess stem (>10 cm) was higher at 100% ETc. This response was greater in ‘ACX 3665’ than in ‘ASR 157’ and ‘DMC 09’. Marketable yields were significantly higher for ‘ASR 157’ at either 100% or 75% ETc rates, compared to ‘DMC 09’ and ‘ACX 3665’. High water use efficiency was also measured at 75% ETc for ‘ASR 157’. Minimum canopy temperature differences were detected among the irrigation treatments. This work demonstrated that it is possible to reach a 25% water savings in one season, without reducing yields when using vigorous cultivars.

Irrigation is critical for high quality and crop yield especially in semi-arid farmland areas of South Texas. The Edwards Aquifer is the primary underground water source for this region, supplying water to 1.7 million citizens in the San Antonio–Austin corridor and surrounding counties, as well as agricultural industries. In 1993, the Texas legislature passed restrictions on irrigation that limited farmers’ water usage to 610 mm·year–1. Therefore, a need has arisen to develop deficit irrigation strategies that consistently deliver high quality products with sustainable yields. Spinach is one crop of great economic impact in the geographic areas west of San Antonio, known as the Wintergarden of South Texas. It represents about 3,300 hectares of farmland in southwest Texas (Texas Agr. Stat., 2002) and contributes to about 29.4% of the total U.S. processed spinach market, with a $41.5 million economic impact (Pena, 2004). Spinach is also recognized as a highly nutritious vegetable, containing significant amounts of vitamin A and C, calcium, and iron.

Several studies were conducted on water stress affecting leaf physiology, plant growth and yield of spinach. One of them showed that water stress plays a definite role in spinach metabolism (Zrenner and Stitt, 1991). Another study by Tone and Uchiyama (1989) revealed that oxalic acid is present in higher concentrations in water-stressed spinach. Oxalic acid poses potential health risks when present in large amounts (Libert and Franceschi, 1987). Nishihara et al. (2001) reported that spinach plant height increased when irrigated at high and intermediate frequencies compared to low frequencies, and that intermediate frequency produced earlier growth and greater harvested leafarea, leaf fresh and dry weight. In a previous study in Texas, leaf chlorosis in a processing spinach cultivar was higher at high compared to low irrigation rates (Leskovar and Black, 1994). A study performed in semi-arid regions of Botswana revealed that spinach irrigated according to a cumulative pan evaporation (CPE) series (11, 22, 33, 44, and 55 mm) produced the highest marketable yield at 11 mm CPE (Imtiyaz et al., 1999). The impact of limited irrigation and its interaction with cultivars on leaf quality and yield is largely unknown.

The aim of this 2-year study in spinach was to determine the relationships between yield and water efficiency with irrigation rates, as well as to examine changes in leaf quality in response to deficit irrigation. We expect that the information from this work will help producers in water restricted areas to adjust to current and future water limitations, while maintaining profitability through maximization of yield and water use efficiency.

Materials and Methods

Plant material. Three commercial processing smooth leaf cultivars of spinach were used: ‘DMC 09’ (Del Monte Foods, Crystal City, Texas), ‘ASR 157’ (Seminis, Donna, Texas), and ‘ACX 3665’ (Alf Christiansen Seed Co., Mt. Vernon, Wash.). Seeds from each cultivar were planted at the Texas Agr. Expt. Station in Uvalde (29°1’N, 99°5’W) on a silty clay loam (fine-silty, mixed, hyperthermic Aridic Calciustoll) soil. The experiment was conducted over two seasons in the fall. During the first season, seeds were planted on 23 Oct. 2001 in a field previously planted with cotton and then left fallow. In the second season, seeds were planted on 12 Nov. 2002 in a field previously planted with corn and then left fallow. Seedbeds were 15 cm high and spaced 1.0 m apart in a circle. Each bed was composed of four lines (two on each side) in 2001, with seeds separated 6.4 cm apart (planter set to a plant density of 617,284 seeds/ha). Seeds planted in 2002 were grown in beds with two lines (one on each side) at the same plant density as in 2001, with 3.2 cm between the seeds on each line. The herbicide S-metolachlor at 1.24 kg·ha−1·a.i. (Dual II Magnum, Novartis Crop Protection) was sprayed over the surface at planting and incorporated with 20 mm of sprinkler irrigation.

Irrigation treatments and culture. The spinach crop was irrigated by a center pivot system with low energy precision application (LEPA) nozzles (Senninger, Orlando, Fla.) at 100%, 75%, and 50% of crop evapotranspiration rates (ETc). Total rainfall during the 2-year study was 33 and 40 mm in 2001–02 and 2002–03 seasons, respectively. ETc values were obtained based on climatic parameters applied to the Penman-Monteith equation and adjusted by crop coefficients (Kc) based on canopy development. Climate models, such as the one used in our experiments, appear to better quantify soil water deficit (Li et al., 2003). During the 2001–02 season, all plots in the field were irrigated with 38 mm of water at planting on 23 Oct. 2002., followed by 25 and 13 mm after emergence, for a total of 76 mm. Thereafter, plots were irrigated differentially from 29 Dec. to 22 Jan. with 24 mm of rainfall. The total irrigation amount applied was 86, 41, and 15 mm for the 100%, 75%, and 50% ETc rates, respectively. Cumulative water received (postplant + rainfall + irrigation) amounted to 195, 150, and 124 mm for the 100%, 75%, and 50% ETc rates, respectively. All plots in the 2002–03 season received 19 mm at planting on 12 Nov. 2002, followed by 19 mm after emergence. Differential irrigations represented a total of 94, 71, and 49 mm for the 100%, 75%, and 50% ETc rates, and adjusted according to rainfall. Total water accumulated in the 2002–03 season (postplant + rainfall + irrigation) was 172 mm for 100% ETc, 149 mm for the 75% ETc and 127 mm for the 50% ETc. Water use efficiency (WUE) was calculated by dividing total marketable leaf yield by total water applied plus rainfall received during the growing season.

A preplant fertilizer of 78N–14P–12Zn kg ha−1 was applied broadcast followed by an application of 7N—7P—15K ha−1 at planting in both years of the study. Copper hydroxide, a protective fungicide, was applied to the spinach plants twice followed by azoxystrofin.
trobin (Quadris, Novartis Crop Protection) in both seasons. The insecticide Permethrin was applied once in both seasons to control spotted cucumber beetle (Diabrotica undecimpunctata howardi Barber). White rust (Albugo occidentalis G.W. Wils) the major fungal disease affecting spinach in southern Texas, was monitored throughout plant development.

Leaf measurements. To determine the percent of leaf area infected with white rust disease, 24 leaves per treatment–replication (96 total leaf per treatment) were destructively sampled at three row cross section positions in the row (0°, 45°, and 90° angles). Spinach plants were harvested on 5 Feb. 2002 and 15 Feb. 2003. Harvesting was performed using a commercial Pixail Big Jack spinach harvester (Oxbio Industries, Clear Lake, Wis.) according to Del Monte canning company procedures. Plants were cut at about 5 cm above the soil surface on plots that consisted of 4 rows of 9 m length. After harvest, a random leaf sample of about 1.4 to 2.3 kg/replication in 2002, and 2.3 to 3.6 kg/replication in 2003 was collected for grading according to the Del Monte standards (R. Dabney, Del Monte Corp., Crystal City, Texas). For each sample the weight of weeds, roots, foreign material, yellow leaves, and excess stem (includes leaf petioles) >10 cm were recorded and percent culls determined. To obtain net marketable yields, field plot weights were adjusted based on the percent of yellow leaves and percent stem weight.

Canopy temperatures for all experimental plots were obtained at the end of the growth period in 2003 using a set of infrared thermometers (Exergen, Infrared transducers (IRT) c01T80F/27C, Brampton, Ontario). Thirty infrared thermometers were mounted at about 4.5 m spacing along the pivot length to record canopy temperatures. The IRTs measured the infrared band between 8 to 14 µm and had a height to view angle ratio of 1:1. A micrologger (CR 23X; Cambell Scientific Inc., Logan, Utah) recorded canopy temperatures from the IRTs every 10 s, and averaged temperature values every 60 s.

Statistical design. The experiment was conducted using a split-plot experimental design with four replications. Irrigation rates were the main plots and cultivars the subplots. A four-row spinach subplot was used to cut a single 25-m path from each of the experimental units. Leaf yellowness, percentage of leaf stem, yield, water use efficiency and canopy temperature were subjected to analysis of variance (ANOVA) by PROC GLM (SAS Institute, Inc., Cary, N.C.). Significant interactions were partitioned by irrigation rates and cultivars, and means ± SE were graphed for each variable.

Results and Discussion

Leaf quality. White rust disease severity was minimal (<0.3% leaf area) and there were not significantly differences among treatments (data not shown). White rust disease is known to be associated with high moisture conditions (Leskovar and Black, 1994). In this experiment our intent was to prevent the development of this disease to isolate the irrigation treatment effect on leaf quality and yield.

Overall, deficit irrigation at 50% ETc inhibited stem growth (a desirable response for leaf quality in the canning industry) in most cultivars for both seasons (Fig. 1A and B). Conversely 100% ETc promoted stem development as compared to 50% ETc in ‘ACX 3665’ and ‘DMC 09’ in both seasons. The percentage of excess stem was largest for ‘ACX 3665’ at 100% ETc in both years (Fig. 1A and B), and for ‘ASR 157’ in the first season. Conversely high irrigation rates promoted stem development in ‘ACX 3665’ and ‘DMC 16’ only in the 2001–02 season. The percentage of excess stem was largest for ‘ACX 3665’ at 100% ETc in both years (Fig. 1A and B), and for ‘ASR 157’ in the first season. Among the three cultivars, the standard variety grown in the region ‘DMC 09’ exhibited the smallest stem growth weight as compared to ‘ASR 157’ and ‘ACX 3665’. Nishihara et al. (2001) studied the effects of frequency of irrigation (based on soil based measurements using electronic tensiometers placed at 10 to 20 cm, 20 to 30 cm and 30 to 40 cm of the root zone) on growth of spinach in sandy soils under greenhouse conditions. They reported an increase in plant height and leaf area at moderate frequency, which was equivalent to medium irrigation rate compared to high or low (stress) frequency.

The percent of yellow leaves increased significantly for each variety at 50% ETc as compared to 75% and 100% ETc during the first season (Fig. 1C). Comparing cultivars, ‘ACX 3665’ irrigated at 50% ETc had the greatest percent of yellow leaves in the 2001–02 season (Fig. 1C). In the 2002–03 season the percent of yellow leaves did not increase to the same extent with deficit irrigation, but was significantly higher for the cultivar DMC 09 at both 50% and 75% ETc compared to 100% ETc (Fig. 1D). In a previous study by Nishihara et al. (2001), chlorophyll content was significantly reduced in spinach leaves subjected to low irrigation rates between 60 and 70 d after seeding. The lower degree of yellowness measured in the second season of our study could also be associated with a cooler and shorter season (averaged 11.3 °C) compared to 2001–02 season (13.9 °C). The cultivar ‘ASR 157’ appeared less sensitive to chlorosis based on measurements during the second season. Flat leaf genotypes, like ‘ASR 157’, have been bred with a lighter green color appearance and have less green-yellow contrast as compared to genotypes like ‘DMC 09’, which have darker green color and therefore more contrast when chlorosis occurs. Zrenner and Stitt (1991) found that starch degradation was present in spinach leaves as a result of water stress, which is possibly a contributor to the increased levels of sucrose in the same leaves. Chlorosis in spinach may also result as a response to flooding conditions. Leskovar and Black (1994) measured an increase in leaf chlorosis with irrigation in excess of 50 mm for plots that received a total rainfall of 370 mm. They hypothesized that the increase in
leaf chlorosis was probably due to flooding causing a hypoxic root environment, triggering ethylene, a flooding-induced stress hormone (Kawase, 1976).

**Yield and water efficiency.** Marketable yield was calculated by the difference between the harvested yield and percent culls (yellow leaves, excess stem, seed stalk, and weeds). The experiments in 2001–02 and 2002–03 had the same plant density but different planting configurations (four lines per bed with 6.4 cm in-row spacing in the first season and two lines per bed with 3.2 cm in-row spacing for the second season); therefore, our intent was not to compare statistically yield across seasons.

For 2001–02 season, none of the cultivars produced well at 100% and 75% ETc. The highest marketable yield resulted from ‘ASR 157’ at 100% and 75% ETc. Yield of ‘DMC 09’ and ‘ACX 3665’ progressively declined with deficit irrigation (Fig. 2A). In 2002–03 season deficit irrigation at 50% ETc decreased yield of two cultivars, while ‘ACX 3665’ had the highest yield at 100% ETc (Fig. 2B). ‘DMC 09’ generally produced well at 50% ETc. The highest marketable yield resulted from ‘ASR 157’ at 100% and 75% ETc for ‘ASR 157’. Remote sensing through the use of infrared thermometers (IRTs) mounted on a center pivot irrigation system can monitor plant temperature which can then be correlated to water stress in the crops being irrigated by the pivot (Maas et al., 1999; Michels et al., 1999). Furthermore, irrigation can be controlled by maintaining optimal canopy temperature using the IRTs (Wanjura et al., 1992). Studies to establish possible correlations of canopy temperature with transient water stress levels at various plant populations are needed.

In the 2001–02 experiment, ‘ASR 157’ revealed the highest water use efficiency (conversion of biomass produced per centimeter of water received) of the three cultivars, reaching 3470 kg·cm–1 (equivalent to 86 g·L–1 fresh weight) at 75% ETc (Fig. 2C). ‘DMC 09’ had similar levels of water use efficiency at each irrigation rate while ‘ACX 3665’ had slightly higher water use efficiencies as irrigation rate increased. Similar trends were measured in the second year (Fig. 2D). Water use efficiency was highest for ‘ASR 157’, and lowest for ‘DMC 09’ and ‘ACX 3665’ at 50% ETc (Fig. 2D). Highest WUE (18 g·L–1 fresh weight) was also reported for the most water deficit treatment in spinach grown in a greenhouse for 70 d (Nishihara et al., 2001).

**Canopy temperature.** Leaf canopy measurements taken at the end of the growing season in the 2002–03 season revealed minimal canopy temperature differences among treatments. Even though lower canopy temperatures were measured for ‘ASR 157’ at 75% ETc (26.7 °C ± SE 0.9) compared to ‘ACX 3665’ (28.2 °C ± SE 0.7), overall there were not statistical differences among cultivars or irrigation. The relationship between water stress and increased canopy temperature is well known (Isdo et al., 1982; Grimes et al., 1987). Our 1-year canopy temperature data correlate well with the lack of significance yield differences between 100% and 75% ETc for ‘ASR 157’. Remote sensing at the end of the growing season in 2001–02 indicated that cultivar plays a significant role in quality and yield while the 2002–03 results showed that both variety and irrigation rate affected yield (Fig. 2A). The experiments in 2001–02 and 2002–03 had the same plant density but different planting configurations (four lines per bed with 6.4 cm in-row spacing in the first season and two lines per bed with 3.2 cm in-row spacing for the second season); therefore, our intent was not to compare statistically yield across seasons.

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**Literature Cited**

Grimes, D.W., H. Yamada, and S.W. Hughes. 1987. Climate-normalized cotton leaf water potentials for irrigation scheduling. Agr. Water Mgt. 12:293–304.

Maas, S.J., G.J. Fitzgerald, W.R. DeTar, and P.J. Pinter Jr. 1999. Detection of water stress in cotton using multispectral remote sensing. Proc. Beltwide-Cotton Conf. 1:584–585.

Michels, G.J. Jr., G. Piccinini, C.M. Rush, and D.A. Fritts. 1999. Using infrared transducers to sense cotton leaf water potentials for irrigation based on threshold canopy temperature. Environ. Expt. Bot. 34:363–370.

Nishihara, E., M. Inoue, K. Kondo, K. Takahashi, and N. Kawase. 1976. Ethylene accumulation in flooded plants. Physiol. Plant. 36:236–241.

Leskovar, D.I. and M.C. Black. 1994. White rust infection and leaf chlorosis in relation to crop development in spinach. Environ. Expt. Bot. 34:363–370.

Li, Y., Y. Cohen, R. Wallach, S. Cohen, and M. Fuchs. 2003. On quantifying soil water deficit of a partially wetted root zone by the response of canopy or leaf conductance. Agr. Water Mgt. 65:213–38.

Libert, B. and V.R. Franceschini. 1987. Oxalate in crop plants. J. Agr. Food Chem. 35:926–938.

Manase. 1999. Response of six vegetable crops to irrigation schedules. Agr. Water Mgt. 45:331–342.

Tone, S. and Y. Uchiyama. 1989. Effects of cultivar on the osmotic concentration of spinach. J. Jpn. Soc. Hort. Sci. 58:329–333.