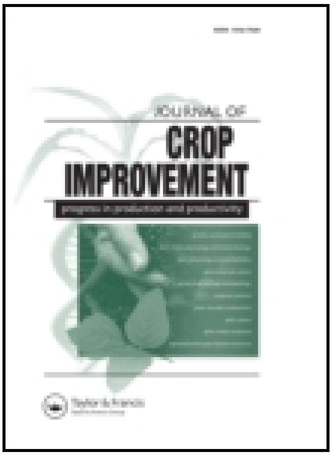

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Subsurface Drip and Overhead Irrigation Effects on Conservation-tilled Cotton in the San Joaquin Valley

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*Conservation cropping systems are being developed for cotton (*Gossypium *spp.) traditionally grown on raised beds with several soil-disturbing tillage passes in the San Joaquin Valley (SJV) of California, USA. Overhead (OH) irrigation and subsurface drip irrigation (SSDI) systems are water-conserving techniques being tested with reduced tillage in the SJV. However, crop growth, yield, microclimate, and pest population dynamics in these systems have not been documented. A field study was conducted in 2011 and 2012 at Five Points, Calif., to evaluate the difference between the two irrigation systems. Cotton cv. Phytogen 725 RF was no-till planted into wheat residue. In both years, the soil surfaces in the OH plots were 1° to 2°C cooler and 5% to 15% wetter than the SSDI plots. These differences had no effect on crop growth, development, yield, or quality, but weed densities and biomass were lower in the SSDI than in the OH in both years. However, the SSDI plots had more spider mites (*Tetranychus *sp.) than the OH plots in 2011. The study showed that cotton could be successfully grown with conservation tillage, high residue systems, with either OH or SSDI systems in the SJV.*

KEYWORDS *cropping systems, microclimate, spider mites, sustainable agriculture, weed densities*

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INTRODUCTION

Cotton (*Gossypium* spp.) is commonly grown on conventionally tilled, raised beds with furrow, flood, or sprinkler irrigation systems in the San Joaquin Valley (SJV) of California. Conventionally tilled systems, in general, require 16 tractor operations for tillage and other crop management practices, such as preparing beds, planting, and harvesting (Mitchell et al. 2012a). In recent years, concerns about high-input costs, air-quality regulations, and long-term soil quality have motivated some researchers and growers in the SJV to explore the feasibility of growing cotton with high-residue reduced tillage systems to reduce the number of these operations (Mitchell et al. 2012a).

Studies have demonstrated that the number of tractor passes during a growing season can be reduced by 50% with the use of reduced tillage systems compared with the conventional tillage systems (Mitchell et al. 2012b). However, obstacles to the adoption of conservation tillage (CT) include plant residues obstructing the movement of water down the furrows, crop establishment, and pink bollworm (*Pectinophora gossypiella*) regulations that require plow down of crop residues in California (Mitchell et al. 2012a). Some of these impediments may be overcome by innovations in tillage equipment and irrigation systems.

The introduction of these tillage systems requires a new approach to irrigation systems as well. Innovative, water-use efficient irrigation systems are already being developed in the SJV to address future water shortage scenarios. One such system is subsurface drip irrigation (SSDI), which has several economic and environmental benefits (Sammis 1980; Phene et al. 1992). Examples of these benefits include the ability to improve irrigation efficiency by reducing evaporation and deep percolation and reducing pesticide and fertilizer-laden runoff compared with furrow irrigation (McHugh et al. 2008). Additionally, Shrestha et al. (2007) reported reduced weed density and emergence in tomato beds by as much as 90% in SSDI plots compared with furrow-irrigated plots.

When SSDI is used, farmers tend to be limited to rotations of crops that can be accommodated by similar placement and spacing of the buried tape. The SSDI also typically requires controlled traffic, permanent bed tillage management equipment for incorporating crop residues and preparing the soil for subsequent crops (Mitchell et al. 2012a). However, the tape used in SSDI systems can last several years if there is no subsurface tillage. For example, Dougherty et al. (2009) reported that the drip tape could last for 10 years, whereas Lamm et al. (2010) have cited several cases where the drip tape had lasted for more than 20 years. Thus, SSDI could be combined with CT, provided that crop rotations are designed strategically and that rotation sequences and architecture of crops does not necessitate the removal of drip tape. An additional benefit of merging SSDI with CT could be weed control, as Clements et al. (1996) reported that in a no-till system 90% of the weed seed bank tended to rest in the top 0-5 cm of soil. Therefore, weed germination could be greatly reduced with SSDI because the weed seeds would not receive enough moisture at the soil surface to germinate and emerge. This hypothesis was supported by findings of Shrestha et al. (2007), as mentioned earlier. Another form of irrigation not widely used in the SJV is mechanized overhead (OH) systems, which include linear move systems and center pivots. Overhead irrigation systems can work well with CT operations because impediment of water movement by crop residues is not an issue with OH irrigation as with furrow irrigation. Whitaker et al. (2008) compared SSDI and OH in cotton and found both systems tended to have similar yields and water-use efficiency (WUE). Crop quality and maturity were similar between the two systems. Colaizzi et al. (2004) reported increased WUE of SSDI compared with OH systems at low water application rates but not at the 75% or 100% water application rates. Ritchie et al. (2009) reported that cotton grown with SSDI retained more bolls at the bottom and less at the top, resulting in an earlier maturing crop. Burke (2003) found that center pivot sprinklers reduced boll retention when irrigation occurred during the time of day when the cotton petals were open and pollen was dehiscing. Guinn (1982) reported that OH systems could affect boll set and shape as the sprinklers could disrupt pollination. However, none of these studies was conducted in CT systems and did not look at microclimatic differences.

It is possible that different irrigation systems would cause differences in microclimates, which can have implications for crop growth, development, yield, and pest population dynamics. For example, Colaizzi et al. (2010) reported that SSDI maintained higher soil temperatures than OH system. A study showed that soil temperature affected cotton germination, root development, flower and boll set, and fiber production (Gipson 1986). Another study showed that lower soil temperatures (as a result of irrigation) decreased cotton root growth in comparison with that in higher temperatures in non-irrigated conditions (Burke and Upchurch 1995). There is limited research comparing the effects of OH and SSDI on pests in cotton, although some research has indicated that more mites (*Tetranychus* sp.) and their eggs are found in lower-moderate soil moisture, and higher temperatures in strawberries (White and Liburd 2005). Also, lygus (*Lygus hesperus*) has been shown to be more abundant in cotton with moist soil (Leigh et al. 1974). Therefore, the objective of this study was to compare differences in crop growth and development, surface soil temperature and moisture, and pest population dynamics of OH and SSDI, CT cotton, and their ultimate effect on crop yield and quality.

MATERIALS AND METHODS

Experimental Design and Treatments

A two-year (2011 and 2012) field study was conducted at the University of California (UC) West Side Research and Extension Center, Five Points, CA (36°20′14″N; 120°6′58″W). The soil type was a Panoche clay loam (fine-loamy, mixed, superactive, thermic Typic Haplocambids) with 0%–2% slope. Total monthly precipitation and mean monthly temperature for this location were collected from a local California Irrigation Management Information System (CIMIS) weather station and are presented in Figure 1. The experimental design was a randomized complete block with four replications. Treatment comparisons included two irrigation systems, SSDI and OH. The OH irrigation was a Valley lateral move system (Valmont Industries, Valley, NE) with eight 45.7-m-wide spans. The area under each span of the OH system was considered a treatment plot. Thus, each treatment plot was 45.7-m wide and 91.4-m long. The OH system was fitted with spinner type nozzles

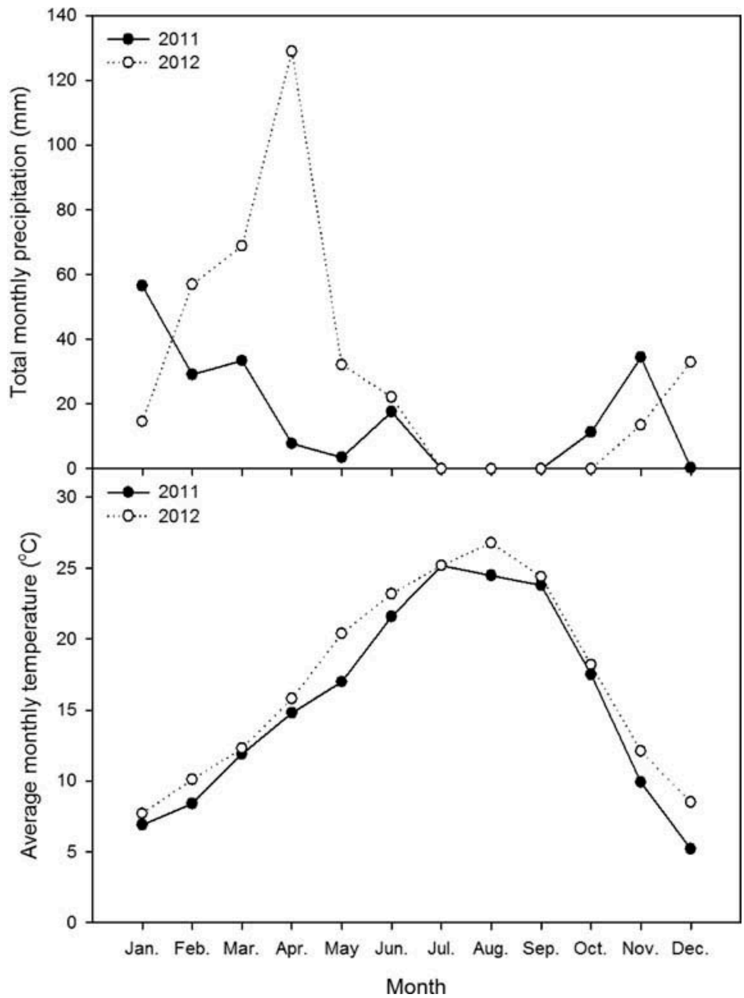

FIGURE 1 Average monthly temperatures and total precipitation in 2011 and 2012 at the West Side Research and Extension Center, Five Points, California.

that spin 360 degrees (outer nozzles had a 180-degree center-facing range to prevent overlap with the SSDI). Nozzles were spaced 1.52 m apart and were 0.91 m off the ground. In alternate spans of the OH system, the nozzles were turned off and 2.25 cm diameter Netafim Streamline 875 0135F drip tape (Netafim USA, Fresno, CA) was installed 30 cm deep in the soil and 76 cm apart on 11 May 2011. In each row, the emitters were spaced every 35 cm. In both years of the study, the previous crop was silage wheat (*Triticum aestivum* L.). The drip tape was maintained in the plots for the 2012 study.

Acala cotton var. Phytogen 725 RF was strip-till planted with a six-row Orthman 1-tRIPr strip-tillage implement (Orthman Co., Lexington NE) in 76-cm-wide rows in the wheat residue in each plot on 13 May 2011 at a rate of 24,048 seeds ha^{-1}. The crop in all the plots was initially irrigated (up to 3 weeks after planting) with the OH system in both years of the study to ensure germination and seedling emergence. This was in keeping with the typical grower practice of using sprinkler irrigation to germinate their crop before switching to SSDI. The plots were strip-tilled in 2011 to negate the difference in soil movement that occurred when the drip tape was installed in some of the plots.

Irrigation events were scheduled weekly based on accumulated daily evapotranspiration (ETo) data from the CIMIS station located 100 m from the study site and crop coefficient (Kc) values based on percent canopy cover and previously published estimates developed in the SJV (Hake et al. 1996). Total water applications were verified through flow meters and kept as similar as possible in the OH and SSDI plots. In 2011, a total of 6.29 Ml $ha^{-1}$and 6.22 Ml $ha^{-1}$of water was applied in the OH and SSDI plots, respectively. Fertilizer nitrogen (N) was applied in all plots of the irrigation system at 61.3, 49.0, and 29.4 kg ha^{-1}, respectively, on 1 July, 7 July, and 21 July. Glyphosate was applied at 0.82 L acid equivalent (a.e.) $ha^{-1}$and 0.96 L a.e. ha^{-1} on 25 May and 23 June, respectively. The plots were hand weeded on 22 June and 6 July to remove glyphosate-resistant volunteer corn that emerged from a previous planting (2009) at the study site. Imidacloprid was applied at 0.06 L active ingredient (a.i.) ha^{-1}on 11 July to control aphids (*Aphis gossypii*). Flonicamid was applied at 0.10 L a.i. ha^{-1} on 25 July and 11 August to control aphids. Imidacloprid was applied at 0.15 L a.i. ha^{-1} on 1 August to control lygus (*Lygus hesperus*). This was combined with 0.840 L ha^{-1} of mepiquat chloride. Spiromesifen was applied on 2 September at 0.26 L a.i. ha^{-1} to control mites. A defoliant, tribufos, was applied at 2.1 L ha^{-1} in combination with 2.8 L ha^{-1} of boll opener ethephon to all the plots on 3 October. On 13 October, the cotton was defoliated with 2.8 L ha^{-1} sodium chlorate and 0.44 L a.i. ha^{-1} paraquat dichloride. Cotton in each plot was machine harvested on 28 October. One 2.7 kg sample was taken from each plot and sent to the USDA cotton quality laboratory, Shafter, Calif., for high volume instrument (HVI) analysis of quality. Characteristics measured in the samples included uniformity, micronaire, fiber length, fiber strength, color, and trash content. After harvest, the cotton was taken to UC Shafter Cotton Field Station to be ginned and weighed to determine lint yield. When harvest was completed, the cotton plants were pulled up from the ground and shredded in the field to comply with cotton plow down requirements for control of pink bollworm, a pest that can overwinter in cotton residue that is left in the field. Wheat was no-till planted in all the plots on 16 November and the crop was then green-chopped on 19 April 2012.

The experiment was repeated in 2012. A total of 8.15 Ml ha^{-1} and 9.07 Ml ha^{-1} of water was applied in each OH and SSDI plot, respectively. A pre-plant application of paraquat dichloride at 1.35 L a.i. ha^{-1} was made on 20 April to control existing vegetation. The cotton was no-till planted with a John Deere 1730 six-row no-till planter (John Deere, Moline, IL) on 9 May. Immediately after planting, all the plots were irrigated for 36 hours with the OH system for seed germination and emergence and 15.6 kg ha^{-1} N and 23.0 kg ha^{-1} P were applied on 7 May. Further split applications of fertilizers included: 58.8 kg ha^{-1} N on 4 June in the SSDI treatment and 8 June in the OH treatment; 34.3 kg ha^{-1} N in all the plots on 13 June; 29.4 kg ha^{-1} N in the SSDI and 24.5 kg ha^{-1} N in the OH plots on 20 June; 29.4 kg ha^{-1} N in the OH and 24.5 kg ha^{-1} N in the SSDI plots on 30 June and 1 July, respectively; 19.6 kg ha^{-1} N in both plots on 15 July, and 49.0 kg ha^{-1} N to all plots on 3 August. The fertilizer was applied through the OH or the SSDI system depending on the plot. Glyphosate was broadcast applied at 1.09 L a.e. ha^{-1} on 7 June. Weeds that emerged after glyphosate application were hand hoed on 19 June and 27 July. Flonicamid at 0.105 L a.i. ha^{-1} and 0.05 L a.i. ha^{-1} of acetamiprid were combined with 0.02 L a.i. ha^{-1} abamectin and applied on 2 August to control aphids, lygus, and mites. Cotton was defoliated with 0.067 L a.i. ha^{-1} thidiazuron plus diuron, 1.55 mL a.i. ha^{-1}ethephon and a spreader on 5 October. Paraquat dichloride was applied at 0.337 L a.i. ha^{-1} with 0.210 L ha^{-1}pyraflufen ethyl and a spreader on 18 October.

Six rows of cotton on either side of each treatment plot were maintained as a buffer while taking various data. Also, the wheel tracks of the OH irrigation system also created approximately 2 m of buffer space between plots. Plant population was estimated by counting the number of plants in a 5.3 m row length at two random spots in every plot. These samplings were done on 22 June 2011 and 8 June 2012. Weekly measurements of chlorophyll content, light interception, soil moisture, soil temperature, plant mapping, lygus populations, and petiole nitrate (NO_3) content were taken starting 6 July 2011 and 29 May 2012.

Chlorophyll content of the cotton plants was estimated with a Minolta SPAD-502 meter (Spectrum Technologies Inc, Plainfield, IL). A leaf at the top, middle, and bottom of the canopy was randomly selected on five plants in a plot, following a W-shape sampling pattern; the readings were then averaged on a per plant basis. Canopy light interception was estimated with a ceptometer (AccuPar LP-80, Decagon Devices Inc, Pullman, WA). Readings were taken above and below the canopy at five random spots in each plot in a W-shaped sampling pattern between 1100 and 1300 hours. Percent light interception was calculated as:

$$(\text{PAR above canopy} - \text{PAR below canopy}) / (\text{PAR above canopy}) \times 100$$

Soil water content was measured with a time domain reflectometer (TDR) (Hydrosense, Campbell Scientific, Logan, UT). Measurements were taken at five random spots in each plot in a W-shaped sampling pattern. The probe was placed 15 cm deep five times within the crop row and between the crop rows at each sampling spot. This depth was chosen because one of the primary objectives of the study was to compare weed population dynamics in the treatments. Because most of the weed species emerge from the top few centimeters of the soil, a depth of 15 cm was chosen. The unit of measurement taken with the TDR was the period of the square wave output from the probe, in milliseconds. This was then converted to gravimetric water content by first taking readings in several locations in wet and dry fields and running a correlation between them and the gravimetric water content that was determined from weighing wet, and then dried soil samples. The TDR is a highly accurate and automatable method for determination of water content (Jones et al. 2002). Soil temperature was measured in the same spots by inserting the probe of a soil thermometer 15 cm deep in the soil.

Plant mapping to determine the maturity of the crop was done according to the UC Statewide Integrated Pest Management guidelines (UCIPM 2005). Five average sized plants per plot were selected. For each plant, the height, and number of vegetative and reproductive branches were recorded. First position square and fruit retention on the upper and lower branches were also monitored, as well as nodes above white flower (NAWF). Cotton flowers are only white for the first day or two that they are open; therefore a white flower indicates the most recently matured node. Fewer NAWF indicate a more mature plant.

Nitrogen status of the plants was estimated by petiole samples. Petioles were taken from 10 random plants in each plot. These petioles were collected from the fourth fully expanded leaf from the top of the plant. Soon after sampling, the petioles were transported to the laboratory, rinsed with deionized water, air dried for a few hours, then dried in a forced air oven at 70°C for 72 h. The dried samples were ground through a Wiley mill equipped with a 1 mm mesh and 0.10 g of the ground petioles were then combined with 25 ml of 2% acetic acid, shaken for 15 min, and then filtered. The samples were then diluted with DI water and analyzed for NO_3 content with a Seal AQ2 Automated Discrete Analyzer (Seal Analytical, Mequon, WI). Leaf area of the cotton plants was estimated twice during the growing season on

13 July and 18 August 2011 and on 16 July and 15 August 2012. Five random plants in each plot were clipped at the surface of the soil, inserted in plastic bags, placed in an ice chest, and transported to the laboratory. The leaves on each plant were separated, counted, and the total leaf area on each plant was estimated using a LI-3000 (LI-COR, Lincoln, NE) desktop leaf area meter. After measuring the leaf area, the leaves and stems were placed in paper bags and dried in a forced air oven at 70°C for 72 hours and the dry weight was recorded.

Lygus populations in the plots were estimated with a sweep net every week, 25 sweeps per plot. Mite populations were monitored weekly by visual assessments. A destructive sample of 15 leaves per plot was taken on 31 August 2011 and 1 August 2012, when number of mites was increasing. Weed density by species was estimated by randomly tossing a 0.25 m^2 quadrat four times within a plot in the beginning, middle, and end of the growing season in both years. The corresponding sampling dates were 22 June, 10 August, and 4 November 2011, and 5 June 19 June, 18 July, and 27 July 2012. Weed biomass was estimated by taking four samples per plot on 4 November 2011, 19 June 2012, and 27 July 2012. All the plants within a 0.25 m^2 area were clipped at the soil surface, placed in paper bags, and dried in a forced-air oven at 70°C for 72 hours and the dry weight was recorded.

Data Analysis

Data were analyzed using SAS v. 9.2 (SAS Institute Inc., Cary, NC). Testing for normality and homogeneity of variance checked assumptions of ANOVA. Data that failed to meet the assumptions were log-transformed before running the ANOVA. The GLM procedures were used at a significance level of 0.05 to examine differences between the years, treatments, and interactions between years and treatments. Replications and years were considered random effects and irrigation treatments as fixed effect. When there was no interaction between year and treatment, the data from the two years were combined and analyzed; otherwise each year was analyzed separately. The ANOVA values for cotton growth parameters are presented in Table 1.

RESULTS AND DISCUSSION

Stand Establishment

Cotton stand establishment did not differ between the two systems in either year of the study. There were an average of 9 and 10 plants m^{-1} row in the SSDI and the OH plots in both years of the study. However, these data do not truly reflect the stand establishment capability of the SSDI system, as all the plots in the study were pre-irrigated with the OH system, as

TABLE 1 Analysis of variance (ANOVA) table for various parameters of cotton

Variable/Source of variation	Degrees of freedom	Mean squares	F value	*P*-value
No. of leaves plant^{-1}				
Replications	3	8978.67	3.69	0.0558
Year	1	3721.00	1.53	0.2477
Treatment	1	4692.25	1.93	0.1985
Year X Treatment	1	2.25	0.01	0.9764
Total leaf area plant^{-1}				
Replications	3	19115397.90	3.20	0.0763
Year	1	4103835.25	0.69	0.4283
Treatment	1	3531721.51	0.59	0.4613
Year X Treatment	1	83398.22	0.01	0.9085
Total aboveground biomass plant^{-1}				
Replications	3	19238.37	3.41	0.0664
Year	1	218065.65	38.69	0.0002
Treatment	1	2.03	0.01	0.9853
Year X Treatment	1	1634.18	0.29	0.6033
Cotton lint yield				
Replications	3	98500.64	7.42	0.0083
Year	1	313779.20	23.65	0.0009
Treatment	1	383.80	0.03	0.8687
Year X Treatment	1	30336.42	2.29	0.1648

mentioned earlier, to create a moist soil surface. Nevertheless, these data do indicate successful crop establishment in high residue strip-till (2011) and no-till (2012) plots.

Microclimate (Surface Soil Temperature And Moisture)

The soil temperature (15 cm depth) in the OH system was lower than in the SSDI system by 1° to 2°C during most of the growing season (Figure 2). Soil temperature is an important factor for growth of cotton. Oosterhuis (2001) suggested that soil temperature at seeding depth should be above 18°C for optimum cotton growth and development. The soil temperature at this depth for most of the growing season in our study ranged from 22° to 24°C in 2011 and 18° to 26°C in 2012. Therefore, the soil temperature was optimum for cotton growth and development in both the OH and SSDI systems in both years of the study. Soil water content in the top 15 cm of the soil profile was consistently greater ($P < 0.05$) in the OH than in the SSDI plots, both within and between the rows (Tables 2 and 3). This was logical because in the OH plots, the water was penetrating the soil from above, whereas in the SSDI plots, the water was being pulled up from a depth of 30 cm by the roots. Also, the drip lines were located directly below the cotton rows in the SSDI plots, whereas in the OH plots, the entire plot, including the inter-row spaces, was being irrigated, thus, resulting in more surface moisture between the rows than in the SSDI plots.

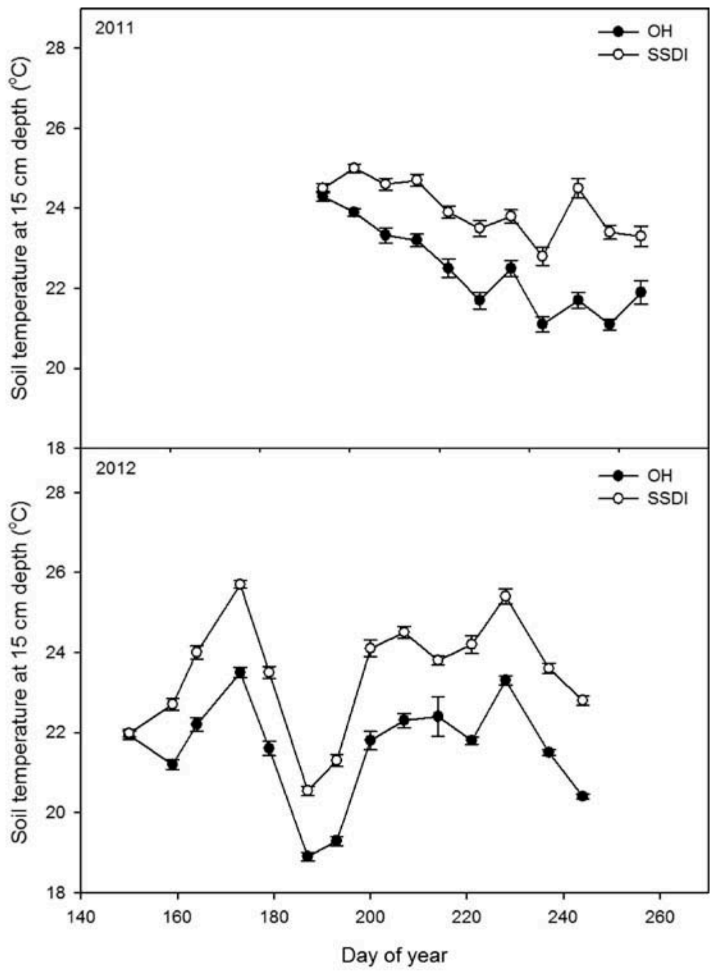

FIGURE 2 Soil temperature at 15 cm depth in the overhead (OH) and subsurface drip (SSDI) irrigated cotton plots in 2011 and 2012 at the West Side Research and Extension Center, Five Points, California.

Crop Growth and Development

Light interception was similar between the OH and SSDI systems in both years of the study, indicating that the crop developed at the same rate in both the treatments (Figure 3). Leaf area and shoot biomass of the cotton plants were similar between the two irrigation systems. On the July sampling dates, the cotton had an average of 34 and 32 leaves plant^{-1} in the OH and SSDI plots, respectively. The total leaf area of the cotton plants was also similar with an average of 1148 and 1077 cm^2 plant^{-1} in the OH and the SSDI system, respectively. The results were similar in the August sampling date with an average of 261 leaves plant^{-1} in the OH and 227 leaves plant^{-1} in the SSDI and total average leaf area of 10239 cm^2 plant^{-1} in the OH and

TABLE 2 Gravimetric soil water content at 15 cm depth, between and within the rows of the overhead (OH), and subsurface drip (SSDI) irrigated cotton in 2011 at the West Side Research and Extension Center, Five Points, California

	Gravimetric soil water content between rows			Gravimetric soil water content within rows		
	OH	SSDI	*P*-value	OH	SSDI	*P*-value
Date	% water content					
5 July	16.05	14.27	0.0653	24.28	20.05	0.0913
13 July	15.07	14.54	0.6695	15.82	18.44	0.1685
20 July	14.18	11.20	0.0011	16.53	10.01	< 0.0001
27 July	13.46	10.01	0.0029	17.96	7.21	< 0.0001
3 August	15.10	10.34	0.0004	21.00	7.33	< 0.0001
10 August	12.12	8.55	< 0.0001	13.11	6.58	< 0.0001
17 August	17.25	9.53	< 0.0001	24.90	10.13	< 0.0001
24 August	13.08	8.19	< 0.0001	18.53	7.51	< 0.0001
31 August	11.79	6.02	< 0.0001	15.28	6.97	< 0.0001
8 September	17.63	8.13	< 0.0001	19.12	8.13	< 0.0001
15 September	11.17	7.09	< 0.0001	15.94	7.15	< 0.0001
28 September	10.72	7.89	< 0.0001	10.63	5.57	< 0.0001

P-values within a row are for mean gravimetric soil water content comparisons between the treatments at each sampling date between and within the rows.

9299 cm^2 $plant^{-1}$ in the SSDI systems. The total aboveground biomass of the cotton plants was also similar between the two systems, with an average of 302 and 281 g $plant^{-1}$ in the OH and SSDI systems. These similarities in crop growth parameters provide further indication that the canopy developed at the same rate in both systems. It can also be implied that differences in surface soil temperature and moisture had no effect on these crop growth parameters. Nelson (1967) found that stem biomass and leaf area of cotton were affected when root temperatures differed by 6° to 12°C. Because the difference between the OH and SSDI systems in our study was only 1° to 2°C, soil temperature was probably not sufficiently different to influence crop growth. Most studies comparing OH and SSDI systems have only assessed final yield and growth parameters of cotton (e.g., Nuti et al. 2006; Whitaker et al. 2008); therefore, it cannot be ascertained how the findings of this study compare with other studies for these measured parameters. Although Whitaker et al. (2008) compared WUE of the two irrigation systems, we did not measure WUE in our study. Also, most of these studies have been under conventional tillage systems as opposed to CT systems, as in this study.

Final height of the cotton plants was similar between the two irrigation systems in 2011 (Table 4). However, in 2012, the cotton plants were taller ($P < 0.05$) in the OH than in the SSDI plots. This could be because of slightly warmer temperatures between July and September in 2012 compared with 2011 (Figure 1). Although plant height was monitored throughout the

TABLE 3 Gravimetric soil water content at 15 cm depth, between and within the rows of cotton in 2012 at the West Side Research and Extension Center, Five Points, California

	Gravimetric soil water content between rows			Gravimetric soil water content within rows		
	OH	SSDI	*P*-value	OH	SSDI	*P*-value
Date	% water content					
29 May	12.35	11.70	0.4226	16.30	16.05	0.8068
7 June	14.20	9.50	< 0.0001	18.55	12.65	< 0.0001
12 June	32.90	24.90	0.0001	33.25	30.70	0.3854
21 June	23.45	20.30	0.4986	28.90	24.40	0.3553
27 June	26.35	25.50	0.7197	31.35	24.35	0.0012
5 July	22.65	16.25	< 0.0001	29.90	17.45	< 0.0001
11 July	22.95	13.35	< 0.0001	26.60	13.75	< 0.0001
18 July	26.60	16.25	< 0.0001	27.25	13.85	< 0.0001
25 July	25.20	20.40	0.0181	28.20	13.60	< 0.0001
1 August	17.95	11.95	< 0.0001	17.85	12.60	< 0.0001
8 August	19.95	11.75	< 0.0001	22.25	11.60	< 0.0001
15 August	18.95	13.20	0.0005	23.60	13.40	< 0.0001
24 August	16.05	13.70	0.0201	19.30	13.05	< 0.0001
31 August	21.50	13.60	< 0.0001	24.85	11.85	< 0.0001

P-values within a row are for mean gravimetric soil water content comparisons between the treatments at each sampling date between and within the rows.

growing season, only late-season data are presented (Table 4) as no differences in plant height were observed between the irrigation systems early in the season. On the last two sampling dates, the cotton plants in the OH plots were on average 106.5 cm and 113 cm tall compared with 98.4 and 103.9 cm in the SSDI plots. This finding is consistent with that of Whitaker et al. (2008), who also reported that the final plant height was greater in the OH than in the SSDI plants in their study.

Studies have also found that irrigation type can affect boll dynamics in cotton plants. For example, Ritchie et al. (2009) reported that cotton irrigated with OH had fewer bolls at the bottom of the plant, compensated by more at the top, compared with the SSDI system, where there were more bolls at the bottom of the plant and less at the top at the end of the season. Such differences were also found in our study, but the findings were inconsistent between the two years (Table 4). The reason for this inconsistency is not known and could be due to temperature differences between the two years in the later part of the growing season or parameters not measured in this study. Although plant mapping was done throughout the growing season, only late-season data are presented (Table 4) as no differences in any of the parameters were observed between the irrigation systems early in the season. In 2011, the number of bolls at the top was similar between the cotton plants grown with OH or SSDI system, but the number of bolls in the bottom was greater ($P < 0.05$) in the SSDI than in those in the OH system.

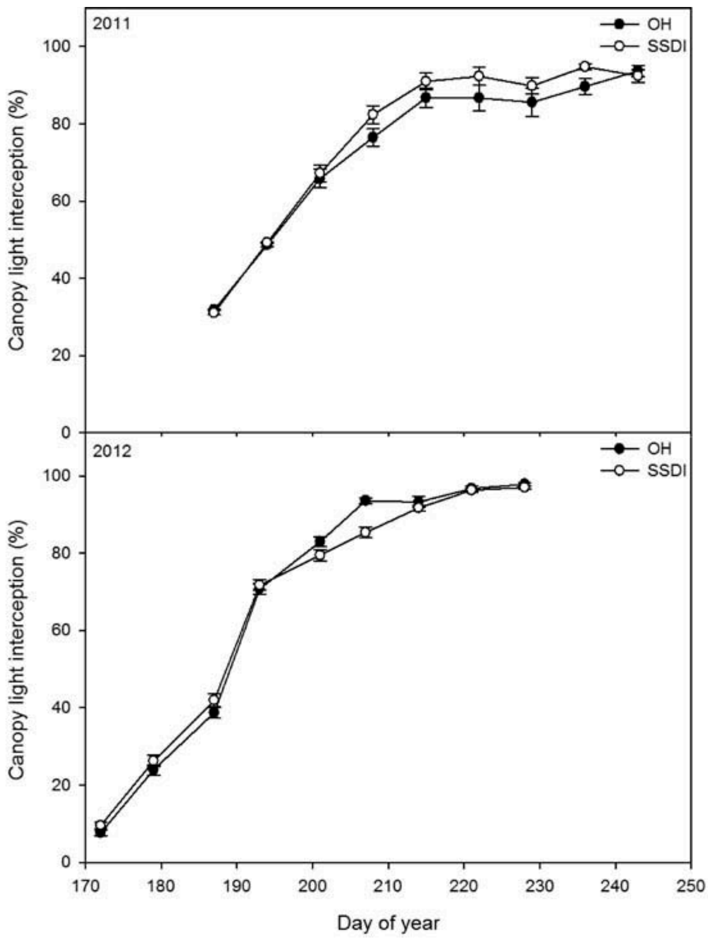

FIGURE 3 Canopy light interception in the overhead (OH) and subsurface drip (SSDI) irrigated cotton plots in 2011 and 2012 at the West Side Research and Extension Center, Five Points, California.

There was an average of 37% retention of the five lowest positions in the OH system compared with 59% retention in the SSDI system on the last sampling date. However, these findings were reversed in 2012 as the cotton plants in the OH plots had more bolls ($P < 0.05$) on the top than those in the SSDI plots, whereas the number of bolls on the bottom were similar between the two irrigation systems. Again, the reason for this inconsistency between the two years is not known and could be due to differences in temperature between the two years from July to September or parameters not measured in this study. The OH plots had an average 69% retention in the top five positions on the last sampling date, compared with 53% in the SSDI. The differences in boll numbers on the plant were only evident at final plant mapping.

TABLE 4 Late-season plant mapping on cotton irrigated with either OH or SSDI, in 2011 and 2012 at the UC West Side Research and Extension Center, Five Points, California

			No. of nodes		% Boll Retention		
Date	Treatment	Height (cm)	Vegetative	Fruiting	Top 5	Bottom 5	NAWF
2011							
3 Aug.	OH	85.8	6.0	10.6	100	69	7.1
	SSDI	93.9	6.1	11.6	99	75	8.1
	P-value	0.0114	0.9843	0.0100	0.3242	0.3815	0.790
10 Aug.	OH	93.4	6.4	12.1	96	50	6.5
	SSDI	94.2	6.4	12.2	97	60	7.8
	P-value	0.8351	1.000	0.9450	0.7606	0.2440	0.0747
17 Aug.	OH	93.4	6.5	12.0	78	33	4.1
	SSDI	99.8	6.1	12.1	89	35	4.0
	P-value	0.2349	0.4513	0.8899	0.1360	0.8199	0.8360
24 Aug.	OH	106.1	6.3	13.4	84	37	2.6
	SSDI	103.8	6.1	13.7	79	59	2.4
	P-value	0.4441	0.6022	0.5628	0.3623	0.0042	0.5335
2012							
1 Aug.	OH	90.6	6.6	11.4	94	69	7.6
	SSDI	88.2	6.9	11.5	96	62	6.0
	P-value	0.3986	0.2538	0.8142	0.8168	0.1682	0.0042
8 Aug.	OH	102.5	6.9	12.8	98	73	5.5
	SSDI	100.8	7.2	12.9	95	61	5.2
	P-value	0.6486	0.1397	0.9661	0.3195	0.0418	0.8140
15 Aug.	OH	106.5	6.3	14.1	88	55	4.7
	SSDI	98.4	6.7	12.6	77	61	3.0
	P-value	0.0220	0.1268	0.0005	0.0157	0.2622	0.1062
24 Aug.	OH	113.0	7.0	15.4	69	57	3.6
	SSDI	103.9	6.9	14.0	53	57	2.0
	P-value	0.0117	0.7836	0.0038	0.0024	1.000	< 0.0001

(NAWF) Nodes above white flower.

In 2011, the two irrigation systems had similar NAWF. However, in 2012, the plants in the OH system had on average of one more ($P < 0.05$) NAWF than plants in the SSDI system. This difference was evident from mid-season. Whitaker et al. (2008) also reported that at the end of the season, plants in the OH matured more slowly than in the SSDI system, with taller plants and more NAWF. However, the authors did not make any conclusions on the dynamics leading to these differences. Similarly, it can only be speculated that such differences may have been an outcome of water management differences (aboveground and belowground water applications and residual soil moisture levels) in the two systems in our study.

Leaf chlorophyll levels, as estimated by SPAD, were lower in the cotton plants in the SSDI than in the OH system for most part of the growing season in 2011 (Table 5). Visual observations showed that the cotton leaves were much darker green in the OH than in the SSDI plots. This difference was not seen consistently in 2012 (Table 5). The difference seen in the chlorophyll content could not be adequately explained, and

TABLE 5 Chlorophyll (SPAD) readings of cotton leaves in the OH and SSDI plots in 2011 and 2012 at the UC West Side Research and Extension Center, Five Points, California

	2011				2012		
	OH	SSDI			OH	SSDI	
Date	SPAD Units		*P*-value	Date	SPAD Units		*P*-value
13 July	48.9	48.5	0.8065	12 June	41.7	47.8	0.0005
20 July	53.9	50.4	0.0028	21 June	52.0	49.1	0.0654
27 July	56.2	50.1	< 0.0001	27 June	51.1	49.9	0.1305
3 August	52.6	49.4	0.0026	5 July	52.4	52.7	0.7751
10 August	51.0	47.3	0.0085	11 July	52.1	54.2	0.0679
17 August	54.6	49.9	0.0002	18 July	52.1	49.8	0.0121
24 August	49.9	44.8	< 0.0001	25 July	51.0	49.4	0.0943
31 August	48.9	41.3	< 0.0001	1 August	52.4	49.4	0.0070
15 September	55.2	45.8	< 0.0001	8 August	51.4	47.5	0.0016
28 September	50.4*a*	40.0*b*	< 0.0001	15 August	51.6	50.5	0.4202
				24 August	46.5	46.8	0.8846
				31 August	45.5	42.3	0.0576

P-values within a row are for mean SPAD unit comparisons between the treatments at each sampling date.

TABLE 6 Petiole nitrate (NO_3) levels of the cotton plants in the OH and SSDI plots in 2011 and 2012 at the UC West Side Research and Extension Center, Five Points, California

	2011				2012		
	OH	SSDI			OH	SSDI	
Date	NO_3 (mg Nl^{-1})		*P*-value	Date	NO_3 (mg Nl^{-1})		*P*-value
3 August	4538.0	3020.0	0.5283	5 July	7283.0	6446.0	0.4768
10 August	1188.8	574.2	0.3202	11 July	5904.4	3128.3	0.0110
17 August	1193.0	2086.0	0.7038	20 July	2727.0	3123.0	0.7580
24 August	609.6	253.6	0.0126	27 July	2844.7	1532.1	0.0490
31 August	912.6	596.3	0.2709	1 August	2098.8	980.2	0.1356
8 September	743.6	283.6	0.2157	10 August	1840.0	1232.6	0.3564
15 September	238.5	145.2	0.8598	15 August	1015.3	887.6	0.8786
				24 August	350.7	1538.9	0.1670

P-values within a row are for mean nitrate concentration comparisons between the treatments at each sampling date.

its cause remains unknown. One explanation could be greater soil NO_3 concentrations in the OH plots; however, soil analysis was not undertaken to substantiate this possibility. In 2011, the petiole NO_3 levels differed between the two irrigation systems on one of the sampling dates, and in 2012, the levels differed only on two sampling dates (Table 6). It can be speculated that surface soil moisture, temperature, and their combined effect on root development may have had some influence on NO_3 uptake dynamics. Nevertheless, these differences did not affect crop growth and development.

Pest Population Dynamics: Lygus, Mites, and Weeds

Lygus populations were not affected ($P > 0.05$) by the irrigation systems in either year of the study (data not shown). On average, the lygus population was 5 and 2 per 25 sweeps in the OH and SSDI plots, respectively, in 2011 and less than 1 lygus per 25 sweeps in 2012 in both the irrigation systems. This differed from the study conducted by Leigh et al. (1974), which showed lygus populations increasing in plots with moister soil, such as were found in the OH plots. Studies have also reported that air temperature can influence the egg (Cooper and Spurgeon 2013) and reproductive (Spurgeon and Cooper 2012) development of *Lygus* sp., and hence the population dynamics, but these studies did not consider soil temperature per se. Differences in canopy temperature between the two irrigation systems were not measured in this study, but it can be speculated that the difference in canopy temperature between the two irrigation systems may not have been sufficiently different to create a difference in lygus populations.

Spider mite populations were affected ($P < 0.05$) by the irrigation systems in 2011. The average number of spider mites was 37 leaf^{-1} in the SSDI, whereas it was > 1 mite leaf^{-1} in the OH system. This was probably because the cotton leaves were drier and dustier in the SSDI system than the leaves in the OH system, which were washed weekly with overhead irrigation. It has been reported that dusty conditions can increase spider mite populations in cotton (Demirel and Cabuk 2008). However, this difference in population was not observed in 2012 probably because the crop was sprayed for mites as soon as they were observed. Had the sprays been delayed, similar results as in 2011 may have been obtained.

Weed densities in June were similar between the two irrigation systems in both years ($P = 0.1275$ and 0.6781 in 2011 and 2012, respectively) of the study (Figure 4a). Weed species found in 2011 included shepherd's purse (*Capsella bursa-pastoris*), annual sowthistle, common lambsquarters, black nightshade (*Solanumnigrum*), pigweeds (*Amaranthus*sp.), and volunteer corn (*Zea mays*). Hairy fleabane (*Conyza bonariensis*), prostrate spurge (*Euphorbia maculata*), field bindweed (*Convolvulus arvensis*), and volunteer wheat (*Triticum aestivum*) were also found. Weed species found in 2012 included common lambsquarters and field bindweed, common purslane (*Portulacaoleraceae*), hairy fleabane, and velvetleaf (*Abutilon theophrastii*). There were no differences in the density of these individual weed species between the OH and the SSDI treatment in either year of the study. Average weed densities ranged from 15 to 27 plants m^{-2} in the OH and 25 to 30 plants m^{-2} in the SSDI plots at this sampling time in 2011 and 2012. This was likely because all plots were treated similarly with glyphosate one month after cotton planting. The results may have been different if the SSDI plots were not irrigated with the OH system during seedling emergence stage, as mentioned earlier.

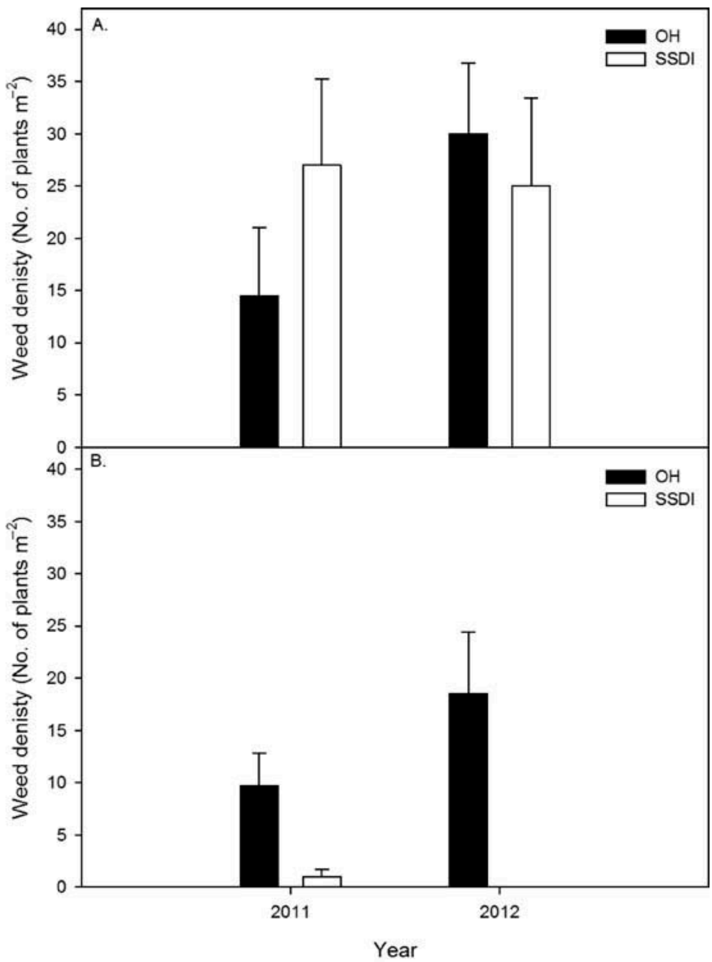

FIGURE 4 (A) Early season and (B) late season weed densities in the overhead (OH) and subsurface drip (SSDI) irrigated cotton plots in 2011 and 2012, at the UC West Side Research and Extension Center, Five Points, California.

Although weed densities were similar in the OH and SSDI plots at the early (June) sampling date, in 2012 the biomass of the weeds was more than two times greater ($P < 0.0001$) in the OH than in the SSDI plots (83.6 vs. 37.7 g m^{-2} in the OH and SSDI plots, respectively). This suggested that although soil water content may have been similar for weed seed germination in both systems, more water was available for growth of the weeds in the OH compared with the SSDI plots later in the season. The surface soil water data (Tables 2, 3) supports this speculation. During the time of weed seed germination (in the first two weeks of data collection in 2011, and the first week of data collection in 2012), there were no significant differences in soil moisture between the two systems. In 2011, the weeds were too small to be sampled for weed biomass measurements at this sampling date.

Weed densities towards the later part of the season (10 August 2011 and 27 July 2012) were affected ($P = 0.05$ and 0.0011 in 2011 and 2012, respectively) by the irrigation systems. In both years of the study, there were almost no weeds in the SSDI plots, whereas the densities were as high as 19 plants m^{-1} in the OH plots (Figure 4b). Weed species present at this sampling date in both years of the study included annual sowthistle, shepherd's purse, common lambsquarters, volunteer wheat, and field bindweed and all of these species were present in greater numbers in the OH compared with the SSDI plots. Therefore, as reported by Shrestha et al. (2007), lack of soil moisture in the SSDI plots prevented weed seed germination and seedling emergence mid- to late-season in the cotton plots. Additionally, in our study, the wheat residue mulch may have prevented weed seedling emergence, especially in the SSDI plots. In the OH plots, some weeds were still seen to emerge through the wheat mulch because of availability of soil water within and between the crop rows.

End of season weed biomass reflected the weed density data, as in both years of the study weed biomass was greater ($P < 0.0001$ in both years) in the OH than in the SSDI plots. In 2011, the weed biomass in the OH plots was 1 gm^{-2}, whereas there were no weeds in the SSDI plots to assess biomass. In 2012, the weed biomass in the OH plots was 29.4 gm^{-2}, and similar to 2011, there were no weeds in the SSDI plots to assess biomass.

Crop Yield and Quality

Despite differences in the microclimate, SPAD, petiole NO_3, weeds, mite populations, and some plant mapping parameters in the two irrigation systems, there were no differences ($P > 0.05$) in the cotton yield in either year of the study. The average cotton yields in 2011 in the SSDI and OH plots were 1365.9 and 1288.6 kg ha^{-1}, respectively, whereas in 2012 yields were 1557.9 kg ha^{-1} and 1666.8 kg ha^{-1} in the SSDI and OH plots. However, the average cotton lint yield was greater in 2012 than in 2011 (1327.4 kg ha^{-1} and 1607.5 kg ha^{-1} in 2011 and 2012, respectively). The yield results reflected the similarities in crop growth and development over the growing season in the two systems. Also, as discussed earlier, the differences in yield between the two years could be related to the differences in temperature between July and September in the two years. This is contrary to the findings of Nuti et al. (2006) and Ritchie et al. (2009), who reported that SSDI had greater yields than OH. Again, these latter studies were conducted with conventional tillage and not CT, as our study. In 2011, the cotton quality was similar for most of the parameters except length, whereas the OH was greater ($P < 0.05$) with an average of 3.02 cm compared with 2.92 cm in the SSDI system. Micronaire, fiber strength, color, trash, and uniformity of the cotton was similar between the two irrigation systems. In 2012 there was no difference in fiber strength, color, trash, length, or uniformity, but micronaire was greater ($P < 0.05$) in SSDI (4.3 mic units versus 4.075 mic units in the OH).

CONCLUSION

This study demonstrated that both OH and SSDI were well suited for CT cotton in the SJV. Some microclimatic (surface soil temperature and moisture) differences occurred between the OH and SSDI systems, with the plots in the OH system being cooler and wetter than the SSDI plots for most of the growing season, but these differences did not affect crop growth, development, and yield. Microclimatic differences affected weed densities and biomass as more moisture in the surface soil profile increased weed densities and biomass in the OH compared with the SSDI plots. However, the effect of these differences in weed parameters was not evident in the crop growth, development, or yield. In one year of the study, the pattern of irrigation affected mite populations. The OH systems may eliminate the need for miticide applications. The OH and SSDI systems, in general, did not affect crop growth and development. However, differences in plant mapping, SPAD, and petiole NO_3 levels were found in different sampling dates. The SPAD and petiole NO_3 levels were generally higher in the OH than in the SSDI system, but these parameters did not affect crop yield. Both irrigation systems were able to produce yields comparable with the industry average (1300 to 1600 kg ha^{-1}) of conventional cotton under CT. Therefore, economics, WUE, and management issues may have a bigger role to play in deciding between SSDI and OH systems in CT cotton. This is the first study of its kind to show the successful establishment and comparison of cotton planted no-till in OH and SSDI systems in the SJV.

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