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Assessments of Humic Substances Application and Deficit Irrigation in Triploid Watermelon

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***Abstract*. Soil organic matter degradation and water limitation caused by intense farming activities are some of the major threats affecting agricultural production. Accordingly, the concepts of sustainable agricultural systems with optimized irrigation and improved soil quality can be adapted to address these issues. During this 2-year field study, two management factors—humic substances (HS) as organic inputs (HS vs. control) and deficit irrigation as the irrigation method (50% vs. 100% based on evapotranspiration)—were evaluated based on triploid watermelon (*Citrullus lanatus* cv. Fascination) yield and soil property changes. HS application increased watermelon early yield by 38.6% and total yield by 11.8% compared with the control; the early yield mainly increased under deficit irrigation. Compared with full irrigation, deficit irrigation increased water use efficiency (WUE) without significantly affecting total yield. In addition, HS application significantly increased the soil organic carbon (SOC) content, which was found to be positively correlated with crop WUE. These results indicate that soil organic inputs with HS and deficit irrigation are valuable strategies to establish sustainable systems for watermelon production, which will not only increase yield and WUE but also significantly improve soil quality and save irrigation water.**

Increasing crop production and mitigating abiotic stresses are major challenges under extreme climatic environments and intense farming activities. Increased yield can be achieved through either agricultural expansion or intensification and optimized practices with high-yielding varieties (Tilman et al., 2011). Several abiotic stresses can be alleviated through appropriate management strategies. For example, deficit irrigation is a well-established method used to save water while maintaining crop yield, whereas organic amendments can be applied to reverse soil nutrient runoff and deficiency and improve soil fertility and aggregate stability, which can positively affect crop yield (Diacono and Montemurro, 2010; Qin et al., 2019). Therefore, sustainable agricultural systems that include the combination of optimized irrigation and organic input could be applied in the production of horticultural crops to address the pressing social, economic, and environmental issues of water shortage and soil quality degradation.

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Watermelon, which is considered a high-value crop, was grown on 43,670 ha in the United States, resulting in the production of 1.84 million metric tons with a farm gate value of approximately $600 million and an average price of $328/t (FAO, 2017). At least 1800 m^3/ha (180 mm) or 250 mm water (optimized) is required for growing watermelon from seedling establishment to final harvest, with the WUE fluctuating greatly due to differences in climatic conditions of the producing regions and water management practices (Leskovar et al., 2016; Li et al., 2018). Crop management strategies such as drip irrigation, plastic mulching, and deficit irrigation can decrease soil evaporation, runoff, and plant transpiration, which, combined, can increase watermelon WUE and water conservation (Yang et al., 2017). In addition to these practices, organic input, which includes the application of organic materials (compost, humic substances, biochar, etc.), cover crop residues, and reduced soil disturbance (conservation tillage), is an additional strategy that increases soil water retention and can potentially improve plant WUE. Minasny and McBratney (2018) reported that a 1% mass increase in SOC, on average, can increase water content at saturation, field capacity, and available water capacity by 2.95, 1.61, and 1.16 mm H_2O per 100 mm soil, respectively. In addition, our recent study of peppers showed that when plants are grown in soils amended with HS, leaves lost less moisture while maintaining the photosynthetic rate under water stress conditions (Qin and Leskovar, 2018). As organic inputs, HS are the decomposition products from plant and animal residues that can be classified as humic acid, fulvic acid, and humin based on their solubility in water under different pH conditions (MacCarthy et al., 1990). HS have striking effects on plant root growth and stress mitigation (e.g., salinity and drought) due to hormonal and antioxidant activities (Canellas et al., 2015). They have become promising organic amendments for improving plant growth and plant–soil water balance; furthermore, they have been attractive for their application in several horticultural crops such as pepper, tomato, and lettuce (Rose et al., 2014). However, little is known regarding their efficacy in watermelon production, which was the main target of this experimental work. Therefore, a 2-year study was conducted to evaluate the effects of field soil amended with lignite-derived solid HS on watermelon yield, quality, WUE, and soil property changes under a deficit irrigation schedule. WUE can be measured at the crop level (yield-to-water use ratio), plant level (biomass-to-water loss ratio), and leaf level (CO_2 assimilation-to-transpiration ratio) (Medrano et al., 2015). Because yield and water usage were the main focus of the study, WUE was measured at the crop level. Integrating HS soil amendments with deficit irrigation could provide growers an optional practice for managing watermelon growth in water-limited regions and organic matter–degraded soils.

Materials and Methods

Growth environment, soil, and irrigation treatments. Field studies were conducted at the Texas A&M AgriLife Research and Extension Center in Uvalde, TX (lat. 29.21°N, long. 99.79°W) in 2017 and 2018. The study sites had different cultivation histories: the field used in 2017 was previously cropped with peppers, and the field used in 2018 was maintained with perennial grasses for 5 years and left fallow in 2017. The basic surface soil (0–20 cm) properties are shown in Table 1. Lignite-derived solid HS (Novihum Co., Dresden, Germany) with a pH of 7.7, composition of 65.8% C, 3.5% N, and 56.7% humic acid, 0.7% fulvic acid, and 24.1%

Table 1. Basic soil properties (0–20 cm) at the study sites in Uvalde, TX.

Variable	Unit	2017	2018
Sand	%	28	31
Silt	%	25	28
Clay	%	47	41
pH		8.3	8
EC	dS/m	0.55	0.29
NO_3-N	mg/kg	25.3	20.4
P	mg/kg	78	47
K	g/kg	1.1	0.8
Ca	g/kg	12.6	11.4
Mg	mg/kg	348	206
S	mg/kg	19.1	19.1
Na	mg/kg	23	4.1
SOC	%	1.24	2.05

SOC = organic carbon.

humin were used as organic amendments by mixing with the surface soil (0–20 cm) at the rate of 5 t·ha^{-1} at both study sites before planting. Nitrogen compensation was applied in control plots by using urea fertilizer to ensure that the only difference between HS-amended plots and the control was the presence of organic matter. After setting up the drip tape (10–15 cm depth in the middle of the row) and black plastic mulch, 6-week-old triploid (*Citrullus lanatus* cv. Fascination) and diploid watermelon (cv. Estrella, used as pollinator) transplants were arranged following a 4:1 ratio planting configuration and established in a 12 m × 90 m (1080 m^2) area that contained 6 rows spaced 2 m apart with a 0.9-m distance between plants.

Watermelon is more sensitive to water stress during flowering and fruit stages than during the vegetative period (Erdem and Yuksel, 2003). Therefore, two different irrigation treatments were initiated at 25 d after transplanting (early flowering stage): deficit irrigated based on 50% evapotranspiration (ET) and fully irrigated based on 100% ET. The required irrigation was determined following the potential ET (ET_0) and crop coefficient of watermelon ($K_{c\ initial}$ = 0.4, $K_{c\ mid}$ = 1.00, and $K_{c\ end}$ = 0.75) (Allen et al., 1998). The drip tape flow rate, rainfall, and plastic mulch were also considered when calculating the irrigation rate applied. Temperature, irrigation scheduling, and precipitation during the 2-year studies are shown in Fig. 1. Seasonal mean temperature, total amount of irrigation received for 50% ET and 100% ET, and rainfall for 2017 were 25.7 °C, 168 mm, 262 mm, and 167 mm, respectively; for 2018, these values were 26.3 °C, 169 mm, 255 mm, and 70 mm, respectively. For each irrigation treatment, soil moisture sensors (EC5; Decagon Devices, Pullman, WA) were installed at the center of the rows and close to plants at 15 and 30 cm soil depth to assess the dynamic daily moisture variation (Fig. 2).

Within each year, the planting area was organized following a randomized complete block design (RCBD) with 4 blocks and gaps between blocks; each block had a 12 m × 20 m (240 m^2) area and was divided into 4 units by splitting in half on both sides (3 rows with a 6-m width and 10-m length). Each unit randomly received treatment from the 2 × 2 factorial design with soil amendments (control and HS by mixing soil with urea and solid HS) and irrigation rates (50% and 100% ET by precisely splitting and arranging each irrigation line).

Plant and soil measurements. Triploid watermelons were harvested three times (indicated by arrows in Fig. 1) and marketable yield was sorted by fruit size at each harvest time. WUE at the crop level was then calculated by dividing the total fruit yield by the total amount of water irrigated during the growing season. For each harvest, fruit quality from each treatment in each block was determined based on three sampled fruits. The soluble solid content (SSC) was measured using a digital refractometer (PR-32α; ATAGO, Tokyo, Japan), and fruit firmness was measured using a digital force gauge (DFS II; Ametek, Newark, DE). At the end of the experimental period in each year, a 5-cm-diameter soil auger was used to collect soil cores within 0–20 cm depth. Soil samples were then shipped to the Soil, Water, and Forage Testing Laboratory (Texas A&M

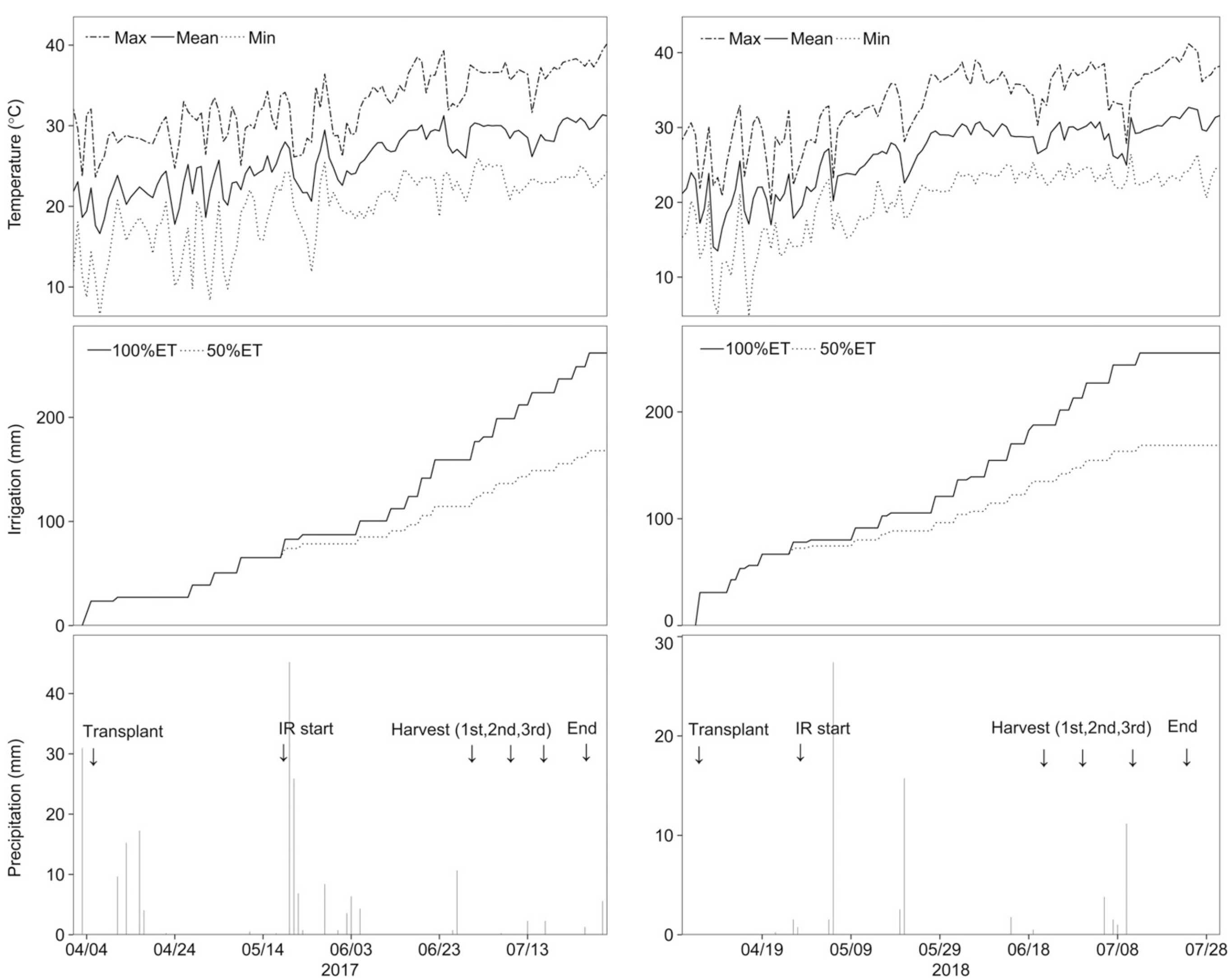

Fig. 1. Temperature, irrigation, precipitation, and harvest scheduling during the 2017 and 2018 growing seasons.

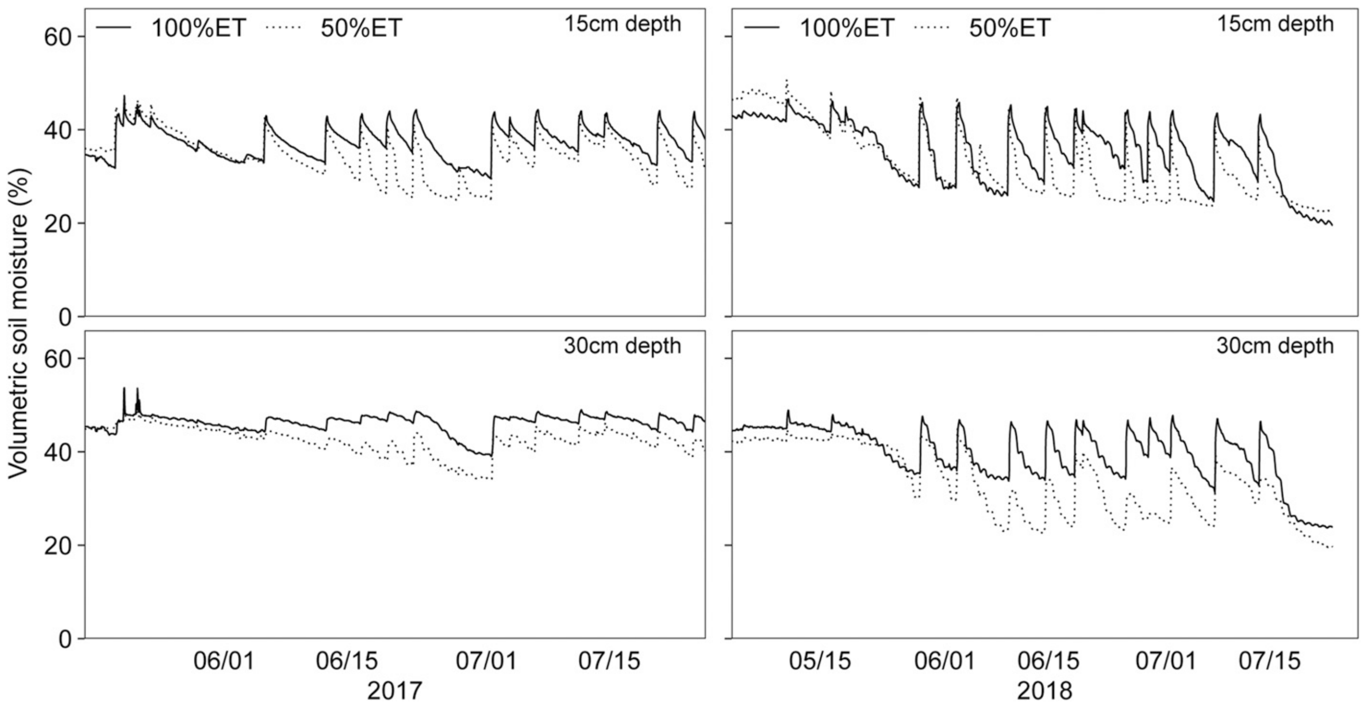

Fig. 2. Volumetric soil moisture (%) sensor data at 15 and 30 cm depth after imposing the irrigation treatments during the 2017 and 2018 seasons.

Table 2. Analysis of variance and means for comparisons of marketable yield sorted by harvest (H) time and weight (W) distribution (the sum of individual fruit ≤5, 5–7, 7–9, ≥9 kg) as affected by soil amendment (SA), deficit irrigation (IR), and year (Y).

		First H	Second H	Third H	Total H	W5	W5–7	W7–9	W9
Source	Treatment	t·ha^{-1}							
SA	C	8.32	21.16	14.89	44.37	8.51	16.23	11.78	7.84
	HS	11.53	22.72	15.35	49.60	9.57	17.17	14.89	7.97
IR	50% ET	9.23	20.33	15.44	44.99	10.35	15.64	11.27	7.73
	100% ET	10.68	23.50	14.83	49.02	7.84	17.73	15.37	8.07
Y	2017	10.29	20.88	22.22 a[z]	53.39 a	12.22 a	23.05 a	13.81	4.32 b
	2018	9.64	23.12	7.56 b	40.33 b	5.68 b	9.97 b	12.94	11.73 a
P value	SA	0.093	0.546	0.852	0.178	0.455	0.703	0.187	0.950
	IR	0.401	0.221	0.809	0.277	0.091	0.389	0.079	0.857
	Y	0.660	0.424	< 0.001	0.002	0.001	<0.001	0.631	<0.001
	SA×IR	0.541	0.936	0.442	0.887	0.916	0.744	0.464	0.356
	SA×Y	0.273	0.158	0.441	0.311	0.706	0.634	0.280	0.123
	IR×Y	0.528	0.022	0.475	0.081	0.975	0.267	0.075	0.922
	SA×IR×Y	0.133	0.807	0.247	0.865	0.771	0.756	0.579	0.355

[z]Different letters within columns from the same factor indicate significant differences at α = 0.05 according to the least significant difference test.

AgriLife Extension Service, College Station, TX) for chemical analysis following the procedures described by Klute (1986). Soil pH and electrical conductivity (EC) were measured in a soil:water (1:2) extract; nitrate–nitrogen (NO_3-N) was extracted using 1 M KCl solution and determined by reduction of nitrate (NO_3-N) to nitrite (NO_2-N) using a cadmium column followed by spectrophotometric measurement. Soil P, K, Ca, Mg, Na, and S were extracted using the Mehlich III extractant and then determined by inductively coupled plasma mass spectrometry (ICP-MS), and soil organic carbon was determined using a combustion procedure.

Statistical analysis. A two-way randomized complete block design with soil amendments (control and HS) and irrigation rates (50% and 100% ET) was used in the study. Data for plant yield, quality, and soil traits were analyzed by an analysis of variance; the means of year and treatment effects were separated by the least significant difference at α = 0.05 using R (R Core Team, 2019).

Results

Yield responses. Soil amendments with HS application, deficit irrigation, and year had different effects on yield and size distribution of triploid watermelon, but there were no significant three-way interactions among these factors (Table 2). The HS-treated soil had 38.6% higher early yield than the control ($P < 0.1$), and the early yield increase mainly occurred under deficit irrigation (60.7% increase with 50% ET and 24.9% with 100% ET). Although the HS stimulating effects gradually diminished as harvests progressed, total marketable yield still increased by 11.8%, mostly due to a higher yield (26.4% increase) of the large 7- to 9-kg fruits. Deficit irrigation using 50% ET slightly decreased early yield (13.6%) and total yield (8.2%) compared with well-watered treatment. It also increased the yield of small fruits (32.0%; $P < 0.1$) but decreased the yield of large ones (26.7%; $P < 0.1$). Year 2018 had a significantly lower yield during late harvest (66.0%; $P < 0.001$) and total yield (24.5%; $P < 0.01$) than 2017, with the most reduction in the yield of smaller fruits (53% to 56%; $P < 0.01$) but promotion of larger ones (171.5%; $P < 0.001$). Responses to irrigation rates varied between years for the second harvest ($P < 0.05$) and total yield ($P < 0.1$). In 2017, compared with the high irrigation rate, deficit irrigation decreased the total yield (47.8 vs. 59.0 t·ha^{-1}), mostly because of the reduction in the second harvest (16.2 vs. 25.5 t·ha^{-1}); in

Table 3. Analysis of variance and means for comparisons of fruit quality traits, crop water use efficiency (WUE), and end-season soil chemical properties as affected by soil amendment (SA), deficit irrigation (IR), and year (Y).

Source	Treatment	SSC (°Brix)	Firmness (N)	WUE ($kg \cdot ha^{-1} \cdot mm^{-1}$)	pH	EC ($dS \cdot m^{-1}$)	NO_3-N ($mg \cdot kg^{-1}$)	P ($mg \cdot kg^{-1}$)	K ($g \cdot kg^{-1}$)	SOC (%)
SA	C	11.45	16.46	212.73	8.04	0.47	46.13	70.16	0.75	1.53 b
	HS	11.36	16.46	240.13	8.05	0.44	32.52	84.98	0.77	1.73 a
IR	50% ET	11.45	16.62	267.13 a	8.03	0.48	52.31	82.44	0.77	1.67
	100% ET	11.36	16.31	189.13 b	8.06	0.43	26.73	73.47	0.75	1.59
Y	2017	11.69 a[z]	17.03 a	254.80 a	8.22 a	0.35 b	7.88 b	105.93 a	0.71 b	1.45 b
	2018	11.10 b	15.85 b	197.08 b	7.86 b	0.56 a	72.41 a	47.81 b	0.81 a	1.82 a
P value	SA	0.580	0.994	0.127	0.856	0.704	0.310	0.232	0.572	0.007
	IR	0.545	0.405	<0.001	0.259	0.480	0.059	0.489	0.602	0.304
	Y	0.001	0.004	0.004	<0.001	0.002	<0.001	<0.001	0.004	<0.001
	SA×IR	0.013	0.147	0.882	0.130	0.592	0.436	0.484	0.123	0.332
	SA×Y	0.458	0.734	0.286	0.117	0.189	0.090	0.202	0.170	0.068
	IR×Y	0.014	0.640	0.341	0.529	0.028	0.066	0.217	0.034	0.346
	SA×IR×Y	0.194	0.094	0.936	0.264	0.157	0.694	0.441	0.045	0.251

[z]Different letters within columns from the same factor indicate significant differences at $\alpha = 0.05$ according to the least significant difference test.
SSC = soluble solid content; EC = electrical conductivity; SOC = soil organic carbon.

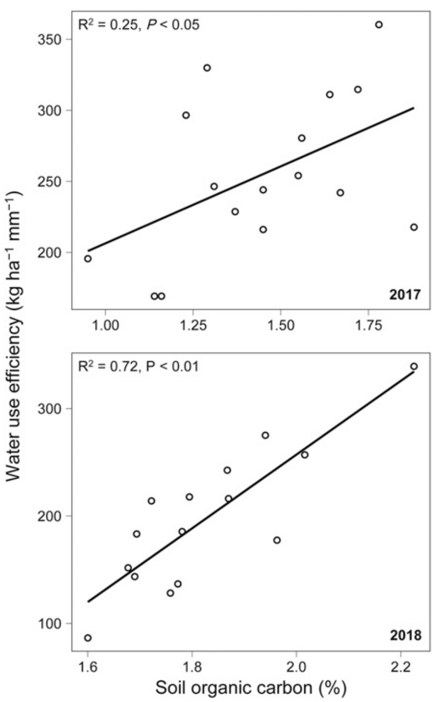

Fig. 3. Linear regression plotted for crop water use efficiency against soil organic carbon content during the 2017 and 2018 seasons.

2018, 50% ET resulted in a similar second harvest and total yield compared with 100% ET irrigation.

Quality responses. In terms of fruit quality (Table 3), watermelon harvested in 2018 had significantly lower firmness than that harvested in 2017 ($P < 0.01$). Irrigation rates had significant effects on SSC among soil amendment treatments and the two years ($P < 0.05$): in the HS-amended plot, 50% ET increased watermelon SSC more than 100% ET irrigation (11.60 vs. 11.12 °Brix); however, the control had opposite results (11.25 vs. 11.60 °Brix). Regarding years, 50% ET increased SSC more than 100% ET in 2017 (11.92 vs. 11.46 °Brix); however, the opposite results occurred in 2018 (10.92 vs. 11.25 °Brix). In addition, deficit irrigation slightly increased watermelon fruit firmness more than the well-watered treatment, especially in 2017 (17.3 vs. 16.8 N; $P < 0.1$).

Crop WUE and soil property responses. Crop WUE was significantly higher under deficit irrigation and in year 2017. The HS application slightly increased crop WUE ($P = 0.127$) and significantly increased soil organic carbon (SOC) ($P < 0.01$) contents (Table 3). By plotting these two variables (WUE and SOC), we found significantly positive correlations ($P < 0.05$) (Fig. 3) in both years. The HS application slightly increased soil P and K retention, especially in well-watered conditions in 2018, but the effects on the NO_3-N content were inconsistent (increased in 2017 but decreased in 2018). Furthermore, the increase in SOC due to HS application was higher in 2017 (from 1.29% to 1.60%) than in 2018 (from 1.79% to 1.85%). The 50% ET had significantly higher WUE than the 100% ET irrigation. Irrigation rates also affected the soil nutrient status, especially the deficit-irrigated plot, which retained more NO_3-N than the fully irrigated plot ($P = 0.059$). In 2018, the field with less soil disturbance had significantly lower pH and P, but it contained remarkably higher EC, N, K, and SOC compared with the field in 2017.

Discussion

Soil and crop management practices that alter plant water and nutrient availability could affect the processes of crop evapotranspiration and WUE, which can influence the yield and fruit quality by changing the internal nutrient and water balance (Hatfield, 2011). During watermelon production, severe water stress decreased the plant leaf relative water content, cell membrane stability, whole plant dry biomass, and fruit yield (Abdelkhalik et al., 2019); however, moderate water stress under drip irrigation and plastic mulch practices could maintain marketable yield by inducing a higher plant root length density (Xie et al., 2006). Bang et al. (2004) found that deficit irrigation was associated with lower watermelon total yield but higher small fruit yield, SSC, and firmness; these results were in agreement with our results. Although watermelon is sensitive to water stress, a 25% to 50% reduction in the irrigation amount only led to an 8% to 15% reduction in the marketable yield (Kirnak et al., 2009; Leskovar et al., 2016), but it resulted in higher WUE. Using drip irrigation, the water deficit achieved by the ET-based method could be easily adopted in arid or semi-arid areas. Additionally, side effects triggered by deficit irrigation could also benefit watermelon quality; for example, plant defense responses under water stress increase the biosynthesis and accumulation of secondary metabolites such as ascorbate, carotenoids, and polyamines (Kyriacou et al., 2018).

Incorporating organic matter within a crop growth system either as leaf spray or soil mix is a complementary strategy to improve crop growth and WUE. By inducing antioxidant enzyme activities, HS could assist plants in stomata functioning, thereby closing stomata more efficiently under drought stress, which results in plant water conservation (Aguiar et al., 2016). For instance, HS application (56% humic acid, 30% fulvic acid, 6% potassium) was found to increase potato vegetative growth, yield, and WUE (Alenazi et al., 2016). Although the use of HS in watermelon growth has been less often reported, other organic amendments with compost and manure application for watermelon showed increases in soil P, K, Ca, Mg, Zn, Mn, Fe, Cu, and organic matter (Ozores-Hampton et al., 2005). In our study, soil amended with HS also had a numerical increase in the retention of P and micronutrients (Zn, Mn, and Cu; data not shown). This response may be related to the HS capacity to lower soil pH and increase cation exchange capacity (CEC) by providing negatively charged sites on their surfaces (Liang et al., 2006), which can electrostatically attract positively charged ions. At the end of the growing season, SOC was significantly increased due to the HS application, which was consistent with our previous results of a pepper field study (Qin et al., 2019). In addition, total watermelon marketable yield was numerically higher in HS-treated soil; the improvement in early harvest will especially benefit growers because earlier fruits typically result in higher market profits (Galinato and Miles, 2013). As an estimate, considering an average watermelon yield of 45 $t \cdot ha^{-1}$ and price of \$330/t, the total yield increase could translate into a profit of $1750/ha (FAO, 2017).

However, except for the outstanding effects on the improvement in SOC, the overall lack of significant effects of HS application observed during our study could be explained by two reasons. The first is the form of HS: many previous studies used liquid HS products (mainly the extraction of humic acids) that had quick and profound effects on plant growth (Rose et al., 2014), but their lasting effects were usually short. The solid HS we used might have less intense effects, but they could last longer, thus benefiting the soil environment for both plants and microbes (Olivares et al., 2017). The second is the raw material used to produce HS: lignite-derived HS are composed of highly oxidized sulfur-containing molecules and aromatic and aliphatic groups, which can give the products more hydrophobic protection than other raw materials (e.g., peat, sludge, leonardite) and allow them to become more stable in terms of their existence (lifespan) in the soil solutions (Francioso et al., 2001; Zherebker et al., 2016). This property could also explain the insignificant results.

Our study showed seasonal responses in yield and soil properties. In 2018, watermelon yield, WUE, soil pH, and P retention were lower, but soil EC, N, and K were higher compared with 2017. The yield decrease in 2018 could be due to colder temperatures during the transplanting period, which slowed early vegetative growth. With almost the same irrigation amount, WUE was also decreased in 2018 compared with 2017. Soil N and K contents in 2017 and 2018 had similar unamended soil levels (before experiments), but 2018 had higher retention, possibly due to lower rainfall (Fig. 1) and runoff. In addition to climatic factors, cultivation history also has an important role in plant growth and crop yield. The field used in 2018 was not mechanically disturbed for more than 5 years and had higher SOC than the field in 2017. In our case, HS application only had significant effects on SOC in 2017, but not in 2018.

Higher crop WUE can be achieved by obtaining higher SOC; this might be due to the changes in soil hydraulic properties triggered by SOC because increased SOC results in stabilized soil aggregation due to its binding effects and consequent improved water-holding capacity related to the increase in macro-porosity (Tisdall and Oades, 1982). Soil aggregation requires the oxidation of residue compounds into organic agents from soil microbes, whereas water shortage could minimize the microbial activity and impair the process (Benjamin et al., 2008) as well as reduce C retention in the soil environment (Wang et al., 2010). Therefore, the application of deficit irrigation along with organic input could reverse the negative effects induced by water stress. Additionally, organic input and tillage could also be considered to protect soil from erosion by improving infiltration and incorporating aggregate-stabilizing compounds, which could reduce soil evaporation and conserve soil moisture to increase crop WUE. However, it is important to note that excessive tillage could decrease infiltration due to the direct effects of soil compaction on hydraulic conductivity (Benjamin et al., 2008; Hatfield, 2011).

The adaptation of sustainable management practices with organic input and deficit irrigation was evaluated experimentally in a triploid watermelon field in 2017 and 2018. The results showed the following: 1) as organic inputs, HS application increased the watermelon early yield and had significantly positive effects on soil organic carbon accumulation; 2) as a management strategy to save water resources, deficit irrigation imposed based on 50% ET did not significantly reduce marketable yield compared with fully irrigated plots but did improve crop WUE and slightly increased fruit quality; and 3) WUE was found to be positively correlated with SOC, which indicated that the effective use of solid HS and deficit irrigation would bring more beneficial results for plant growth and soil quality changes, especially in water-limited and organic matter–degraded regions.

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