Agricultural Water Management 202 (2018) 1–8

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Agroecosystem tradeoffs associated with conversion to subsurface drip irrigation in organic systems

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ARTICLE INFO

Keywords:
Aggregation
Carbon sequestration
Irrigation
Nutrient cycling
Organic agriculture
Irrigation water productivity

ABSTRACT

Subsurface drip (SSD) irrigation is becoming increasingly prevalent in drought-prone irrigated agroecosystems thanks to greater yields and irrigation water productivity (IWP) and decreased weed pressure. However, potential tradeoffs for soil health and biogeochemical cycles remain unclear, especially in organic systems that rely on soil ecosystem services and biological processes for productivity. Gains in IWP and weed control were evaluated with respect to shifts in soil biological and physicochemical parameters in an organic processing tomato (*Solanum lycopersicum* L.) agroecosystem. Yield, IWP, and spatial distribution of soil resources and microbial processes were measured in furrow and SSD irrigated organic processing tomato on long term organic fields. Higher IWP and lower weed density under SSD confirm known benefits, while altered distributions of inorganic N, salinity, microbial activity, and C/N cycling enzyme activities as a function of shifts in soil moisture highlight the far-reaching impacts of irrigation management on soil organic C (SOC) and N dynamics regulating resource availability. Decreased macroaggregate formation and greater unprotected C under SSD indicate that altered soil wetting patterns may reduce the C sequestration potential of irrigated land. Previously unknown tradeoffs should be integrated to develop irrigation strategies that maintain current and future sustainability and productivity of organic tomato agroecosystems.

1. Introduction

Multi-year drought conditions have incentivized growers to adopt more water-efficient alternatives to traditional furrow or flood irrigation in arid and semi-arid agroecosystems. Subsurface drip irrigation (SSD) can be managed to increase irrigation water productivity (IWP) (Li et al., 2016; Sadras, 2009) by delivering frequent, small volumes of irrigation water to subsurface soils containing maximum crop root length density, which increases yields, decreases evaporative losses (Ayars et al., 1999), and reduces weed density and water usage (Sutton et al., 2006). Use of SSD also decreases emissions of greenhouse gases such as N_2O (Aguilera et al., 2013; Ayars et al., 2015; Kallenbach et al., 2010; Zhang et al., 2016), highlighting the potential of drip irrigation as a climate-smart practice for both climate change adaptation and mitigation.

However, trade-offs often emerge between maximizing short-term production and ensuring sustainable long-term production, and unintended consequences of SSD for microbial processes and soil health remain to be explored. Soil biological and physicochemical parameters are closely linked to soil moisture (Austin et al., 2004) and are consequently predicted to respond to irrigation-system-dependent heterogeneity, including a more concentrated wetting zone and milder wet-dry cycles under drip irrigation. SSD delivers water and dissolved nutrients to a wetting bulb that affects a relatively small soil volume, while displacing salts only to its periphery. Whether the transition to drip irrigation incurs negative tradeoffs for soil health at the field scale, including microbial communities and associated processes remains unclear. Downstream impacts on mineralization dynamics and soil carbon sequestration potential are also uncertain.

Even in the short term, choice of irrigation system could have far-reaching impacts on soil resource availability and crop yields. Wet-dry cycles and interactions among water, nitrogen, and salinity can affect microbial community structure (Fierer et al., 2003; Holland et al., 2013) and biogeochemical cycling (Burger et al., 2005; Fierer and Schimel, 2002) but remain poorly studied in the context of drastic and widespread shifts in irrigation technology (Ayars et al., 2015).

Abbreviations: DAT, days after transplanting; DDI, double drip irrigation; SDI, single drip irrigation; SSD, subsurface drip irrigation; FI, furrow irrigation; BG, β-glucosidase; GWC, gravimetric water content; EC, electrical conductivity; FDA, fluorescein diacetate; NAG, *N*-acetyl-glucosaminidase; SOC, soil organic carbon; SOM, soil organic matter; IWP, irrigation water productivity

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https://doi.org/10.1016/j.agwat.2018.02.005
Received 12 June 2017; Received in revised form 29 January 2018; Accepted 5 February 2018

Microbial processes such as C and N cycling could be enhanced in the wetting zone of micro-irrigation systems, where soil moisture, root-derived carbon, and nutrients co-occur (Kuzyakov and Blagodatskaya, 2015; Smart et al., 2011).

An understanding of how drip irrigation affects temporal and spatial distribution of C and N cycling is especially critical in organically managed systems, which must meet crop nutrient requirements through mineralization of soil organic inputs (Pang and Letey, 2000). Mineralization of soil organic matter (e.g. cover crop residues, compost, or manures) must coincide with the timing of maximum N demand to avoid yield lags and penalties relative to systems receiving inorganic fertilizer, but little attention has been paid to potential differences in mineralization dynamics between SSD and furrow irrigated (FI) systems. Soil salinity can be an additional management concern, particularly in semi-arid or arid climates. Concentrations of salinity throughout the soil profile differ between SSD and FI systems (Berrada et al., 2006; Choudhary et al., 2010). Salts dissolved in irrigation water are transported from buried drip lines to the surface through mass flow in response to evapotranspiration, and can accumulate there as well as at the periphery of the wetting bulb (Hanson and Bendixen, 1995). Accumulation of salts in the root zone could limit yields if salts are not sufficiently leached and may exacerbate the negative effects of wet-dry cycles on soil microorganisms (Rath et al., 2017).

Given the fundamental role of microbial communities in soil aggregation and SOM formation (Six et al., 2004, 2006), potential tradeoffs could extend to long-term soil health and C sequestration. C sequestration is affected by physical protection through aggregation and mineral binding and biochemical stabilization through microbial activity (Kallenbach et al., 2016), both of which may be affected by variation in soil moisture. Repeated and severe wet-dry cycles under furrow irrigation could cause the breakdown of macroaggregates during the first few cycles and alter C distribution across aggregates (Denef et al., 2001) as compared to more consistently moist drip-irrigated soils. Alternatively, insufficient moisture outside the wetting zone in drip treatments could inhibit microbial activity and SOM cycling and therefore reduce aggregation. The relative importance of these mechanisms and the magnitude of irrigation-system-dependent effects will determine whether short-term productivity gains occur at the cost of reduced C sequestration and soil-building mechanisms regulating cropping system productivity in the longer term.

Processing tomato production in California is increasingly reliant on drip irrigation (Ayars et al., 2015), highlighting the need for more integrated assessment of benefits and potential tradeoffs and interacting soil and crop properties in irrigated agroecosystems. Soil health is key to the sustainability of irrigated tomato cropping systems in general and particularly crucial to organic production given its greater reliance on soil organic matter (Doran, 2002), highlighting the necessity of assessing impacts beyond the scale of a single growing season. The goal of this study was to evaluate the impact of conversion of an organic field to SSD using a systems approach, integrating diverse agronomic, soil, and microbiological parameters, and to test whether potential tradeoffs can be mitigated through SSD configuration. Installing two driplines spaced slightly apart could expand the lateral wetting zone compared to a single dripline and minimize the negative tradeoffs potentially resulting from localized soil moisture. Objectives included the assessment of shifts in i) irrigation-system-dependent spatiotemporal variation in resource availability, ii) resulting effects on mineralization dynamics and yields, and iii) preliminary indicators of impacts on soil health and C sequestration in an organic tomato production system. Yield, IWP, weed density, and multiple soil biological and physicochemical properties were compared between two subsurface drip irrigation configurations and furrow irrigation over two field seasons.

2. Materials and methods

2.1. Location and experimental design

The study took place over two years at the Russell Ranch Sustainable Agriculture Facility (http://asi.ucdavis.edu/rr) Century Experiment, managed by the University of California, Davis. Irrigation treatments were imposed in three replicated square 0.4 ha blocks of a corn-processing tomato-winter legume cover crop rotation managed organically since 1994 and amended with compost since 1999. In 2015, SSD was installed in 152.4 cm wide beds at 25 cm depth in two configurations: single drip irrigation (SDI), with one centered dripline, and double drip irrigation (DDI), with driplines at 25 cm right and 25 cm left of center where tomatoes were planted in a single row (Supplementary Fig. 1). Prior to SSD installation, all beds had been under FI. Each 0.4 ha block (48 beds total, running the length of the block) contained 6 SDI beds and 6 DDI beds randomized in four subplots of three beds each, with the remaining beds under FI. SDI and DDI beds received the same volume of irrigation water (5557 $m^3 ha^{-1}$ total in 2015 and 5752 $m^3 ha^{-1}$ in 2016) but delivered in half the time in DDI beds. Irrigation water applied was measured using a flow meter. In FI, alternate furrows were irrigated with no runoff leaving the field twice a week during the growing season, receiving a total of 6711 $m^3 ha^{-1}$ in 2015 and 8933 $m^3 ha^{-1}$ in 2016. Reference evapotranspiration (ET_0) was estimated with an in-field sensor (Tule Technologies Inc., CA, USA), and irrigation volume was determined for a six-day schedule based on manufacturer's recommendations for measured ET_0 readings. Sampling was performed during the processing tomato phase of the rotation and the sampled blocks changed from 2015 to 2016 in accordance with the rotation schedule. Prior to planting, a winter cover crop of mixed oat (*Avena sativa* L.), vetch (*Vicia villosa*) and bell bean (*Vicia faba* L.) was cut and incorporated. Composted chicken manure was applied at a rate of 8.1 $T ha^{-1}$ in 2015 and 4.0 $T ha^{-1}$ in 2016 based on results from pre-plant soil analysis by trenching (SSD) or spreading on top of bed and incorporating (FI). Processing tomatoes (variety Heinz 8504) were transplanted on April 21, 2015 and April 27, 2016. Beds were treated with sulfur and a *Bacillus thuringiensis* formulation to control pests at five weeks after transplanting.

2.2. Aboveground biomass, fruit yield and quality, and IWP

Plants and soil were sampled during the growing season at 41, 52, 65, 78, and 91 days after transplanting (DAT) in 2015 and at 35, 56, 77, and 98 DAT in 2016. At each sampling date, two plants were collected per block and irrigation treatment (n = 6). Fresh biomass was recorded, plant samples were dried at 60 °C for 72 h, and dry biomass was recorded. Crop yield was determined following a machine harvest of two 63.6 m strips per treatment per block and reported as fresh weight ($T ha^{-1}$) of red fruit. Hand harvests of two 2 m strips were performed to confirm machine harvest results and to obtain fresh biomass weights. Mature fruit concentrations of vitamin C, β-carotene, and total phenols were measured at the UC Davis Analytical Laboratory. IWP was calculated by dividing yield ($T ha^{-1}$) by the volume of water applied ($m^3 ha^{-1}$).

2.3. Soil sampling methods

At each sampling date, soil cores were taken from one randomly selected bed per irrigation treatment per block (n = 3). In FI and DDI beds, three cores were taken per bed at 0 cm, 30 cm, and 60 cm from the center of the bed. SDI cores were taken at 10 cm, 30 cm, and 60 cm from the center of the bed to avoid damaging the dripline (Supplementary Fig. 1). In SDI and DDI beds, two sets of cores were taken 54 cm apart to account for unknown distance from emitters, which are spaced every 36 cm along the dripline, and replicates were composited. Soil cores were taken to 60 cm deep in 20 cm increments using a 5 cm-diameter hand corer with removable plastic liner tubes (Giddings Machine Company, USA) (Supplementary Fig. 1). If a full core could not be taken, the percentage of a full core was recorded to calculate sampled soil volume. Cores were kept on ice in the field and stored at 4 °C until analysis.

2.4. Water, nitrate and ammonium, and salinity

Gravimetric water content (GWC), nitrate (NO_3^-), ammonium (NH_4^+), and electrical conductivity (EC) were measured on 27 samples per treatment and date (3 blocks x 3 distances x 3 depths, Supplementary Fig. 1). GWC was measured on ~30 g soil within 24 h of sampling. Soil was weighed and dried at 60 °C to constant weight; GWC was reported as g water per g dry soil (W.K. Kellogg Biological Station, 2017). Forty g of field moist soils were extracted with 100 ml 2 M KCl and extracts were stored at −20 °C until analysis. NO_3^- and NH_4^+ concentrations were measured colorimetrically (Doane and Horwath, 2003). Inorganic N concentrations per g dry soil were calculated by adjusting for GWC. EC was measured in a 1:1 soil:water slurry using a SevenEasy probe (Mettler Toledo, USA).

2.5. Weed density

Weeds belonging to nine dominant species (crabgrass [*Digitaria* spp.], jungle rice [*Echinochloa colona*], nutsedge [*Cyperus* spp.], purslane [*Portulaca oleracea*], pig weed [*Amaranthus* spp.], lamb's quarters [*Chenopodium album*], and bindweed [*Convolvulus* spp.]) were counted on a single date in ten 0.25 m^2 (7/8/2015) or 1 m^2 (7/25/2016) quadrats randomized in the bed per irrigation treatment per block. No other weed species were found.

2.6. Soil microbial activity and potential enzyme activities

Microbial activity (fluorescein diacetate hydrolysis, FDA) and activity of the enzymes β-glucosidase (BG) and N-acetyl-glucosaminidase (NAG) were measured on the same soil samples. Field-moist soil was stored at 4 °C and sieved to 2 mm prior to assays of microbial activity and potential enzyme activities. All assays were conducted on 1 g field-moist soil. Microbial activity was quantified colorimetrically based on hydrolysis of FDA as described by (Schumacher et al., 2015). Potential activities of C-cycling (BG) and C/N-cycling (NAG) enzymes were measured colorimetrically with the corresponding p-nitrophenyl (PNP)-linked substrates according to (Eivazi and Tabatabai, 1988) and (Parham and Deng, 2000).

2.7. Soil water-stable aggregate analysis and C content

Soil water-stable aggregation and carbon (C) content of different aggregate fractions were measured in SDI and FI treatments in 2015 on undisturbed cores from 0–10 cm and 10–20 cm depths. Three replicates were composited per irrigation treatment per block (n = 9). Large particles were removed through sieving moist soils (8 mm) and water-stable aggregates were separated by wet-sieving a 50 g subsample into four aggregate size fractions: 2000 μm (large macroaggregates), 250–2000 μm (small macroaggregates), 53–250 μm (microaggregates), and < 53 μm (silt and clay fraction) according to a protocol modified from Elliott (1986). Aggregate fractions remaining on each sieve were oven-dried at 60 °C and weighed. Mean weight diameter (MWD), a weighted-average index of aggregate stability, was calculated according to the following equation:

$$MWD = \sum_{i=1}^{4} P_i{*}S_i$$

where S_i is the average diameter (μm) for particles in that fraction and P_i is the weight percentage of the fraction in the whole soil (Van Bavel, 1950).

C content of aggregate samples was analyzed using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK) at the UC Davis Stable Isotope Facility.

2.8. Statistical analysis

Soil physicochemical and microbial properties were analyzed for each of the 9 distance-depth combinations. Negative FDA values were adjusted to 0 and negative GWC values and outlier values $> 0.35\ g\ g^{-1}$ were removed. Analyses were conducted using a linear mixed model (*lme()* function of the *nlme* package of R 3.2.2) with year, irrigation treatment, date, and the treatment:date interaction as fixed factors, block as a random factor, and an autocorrelation structure of order 1. Date was treated as a repeated measure using a conservative degree of freedom ANOVA in cases where the original ANOVA showed date or any of its interactions having a significant effect. If outcomes differed between the two analyses, the more conservative p value was reported. Significance levels were based on the Bonferroni correction to control the family-wise type I error rate, resulting in a comparison-wise α of $0.05/c$ for c comparisons. The treatment:date interaction could not be analyzed for NAG activity due to missing data. Block-level data (yield, IWP, C and aggregate fractions, and weeds) were analyzed using a linear model with irrigation treatment as a fixed factor in the R environment. Year was also included as a fixed factor when parameters were measured in both years. Data were transformed as needed to meet assumptions for analysis of variance. Post hoc Tukey tests were conducted using a Bonferroni-adjusted family-wise error rate of 5%.

3. Results

3.1. Yield, nutritional quality, and IWP

Processing tomato yields were not statistically different among irrigation treatments in either year (p = 0.0511), and the Year effect was not significant (p = 0.090, Fig. 1a). Likewise, fruit quality was not affected by irrigation treatment, as antioxidant content and total phenols did not differ (Table 1). As expected, SSD irrigation allowed significant gains in irrigation water productivity (IWP) compared to furrow in both years with no significant yield decreases despite 17% (2015) and 36% (2016) less irrigation water applied in SSD compared to FI (Fig. 1b). The Year effect was significant, with higher IWP observed in 2015 than 2016.

3.2. Soil resource availability and salinity

Spatial distribution of water (GWC), inorganic N (NO_3^- and NH_4^+), and salinity (EC) varied among treatments and sampling time had no significant effect (Table 2, Fig. 2). GWC was significantly higher in FI compared to SDI and DDI in the center of the 20–40 cm depth and throughout the 40–60 cm depth (Fig. 2). Despite differences in lateral spacing of driplines, the shape of the wetting zone did not differ significantly between DDI and SDI such that soil moisture was not significantly different at any location across sampling dates.

The spatial distribution of nitrogen resources significantly varied with irrigation technology in center of the bed at 40–60 cm depth (Fig. 2). NO_3—N (adjusted for soil water content) was higher in SSD treatments, which were not significantly different from one another, compared to FI. NH_4^+ concentration was affected by irrigation treatment only around the drip line in the center of the 20–40 cm depth, but post hoc tests did not differentiate among treatments (Table 2, Supplementary Fig. 2). The Year effect was significant for nitrate at locations 3, 5, 6, and 9, and for ammonium at location 4 (Supplementary Fig. 1).

Salinity concentrations varied with irrigation treatment at the

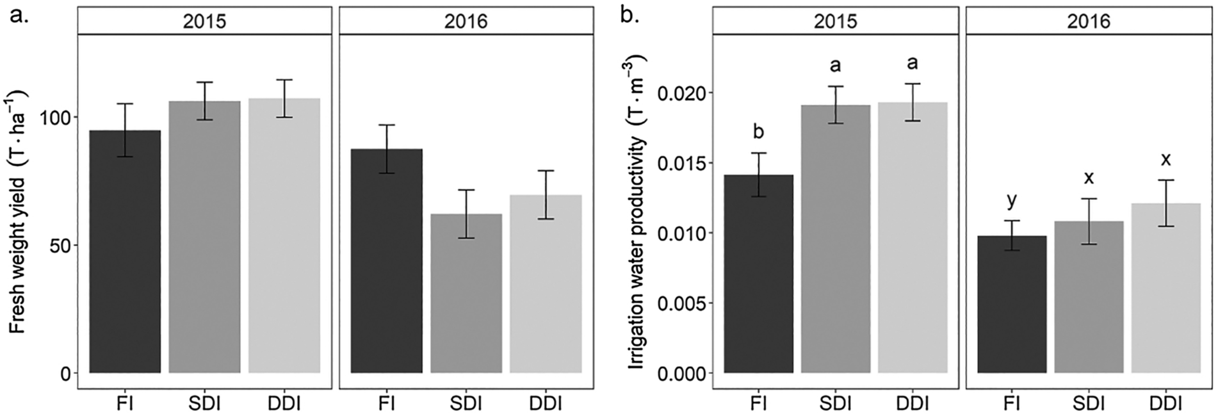

Fig. 1. Impact of irrigation on organic tomato yield and irrigation water productivity (IWP). A) Fresh weight yields were not significantly affected by irrigation treatment or year. B) Water savings associated with SSD led to higher IWP in SDI and DDI in both years. SDI = single drip irrigation; DDI = double drip irrigation; FI = furrow irrigation. Letters indicate statistical differences between means at p = 0.05 within each year and error bars indicate standard error.

shoulder of the bed and the center of the 40–60 cm depth. SSD treatments had higher EC at these locations than FI, but values remained relatively low.

3.3. *Weed suppression*

SSD treatments were highly effective at suppressing weeds, with fewer than 0.15 weeds m^{-2} in both years. Weed density was higher in FI than drip-irrigated treatments by a factor of 30 in 2015 and 100 in 2016, but did not differ between SDI and DDI (Fig. 3). Nutsedge and purslane were the dominant weed species. The Year effect was not significant (p = 0.11).

Table 1
Antioxidant and phenolic content of tomato fruits in 2016.

	Treatment		
	SDI	DDI	FI
Vitamin C (ppm)	6084.00 ± 46.66	6267.50 ± 213.86	6549.67 ± 522.04
β-carotene (ppm)	53.82 ± 4.35	64.69 ± 4.35	61.97 ± 4.62
Total phenols (mg GAE - g^{-1})	6.18 ± 0.16	6.24 ± 0.16	6.06 ± 0.18

No parameters were significantly affected by treatment. SDI = single drip irrigation; DDI = double drip irrigation; FI = furrow irrigation. Values are least squares means ± standard error.

Table 2
ANOVA table showing significant treatment effects and interactions for soil resource availability and salinity.

	Location^{+}	1		2		3		4		5		6		7		8		9	
		df		*df*		*df*		*df*		*df*		*df*		*df*		*df*		*df*	
GWC	Year	1	NS	1	*	1	NS	1	NS	1	*	1	NS	1	NS	1	NS	1	NS
	Treatment	2	NS	2	NS	2	NS	2	**	2	**	2	NS	2	**	2	**	2	**
	Date	4	NS	1	NS	4	NS	4	NS	4	NS	4	NS	1	NS	4	NS	1	NS
	Treatment:Date	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS
NO_3^-	Year	1	NS	1	NS	1	**	1	NS	1	**	1	**	1	NS	1	NS	1	**
	Treatment	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	**	2	**	2	NS
	Date	4	NS	4	NS	4	NS	4	NS	4	NS	1	NS	1	NS	1	NS	4	NS
	Treatment:Date	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS
NH_4^+	Year	1	NS	1	NS	1	NS	1	NS	1	NS	1	NS	1	*	1	NS	1	NS
	Treatment	2	NS	2	NS	2	NS	2	*	2	NS	2	NS	2	NS	2	NS	2	NS
	Date	4	NS	4	NS	1	NS	4	NS	1	NS	4	NS	4	NS	1	NS	4	NS
	Treatment:Date	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS	8	NS
EC	Treatment	2	NS	2	NS	2	**	2	NS	2	NS	2	NS	2	**	2	NS	2	NS
	Date	3	NS	3	NS	1	NS	3	NS	1	NS	3	NS	1	*	1	*	1	NS
	Treatment:Date	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS
FDA	Treatment	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS
	Date	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS
	Treatment:Date	2	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS
BG	Treatment	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	*
	Date	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS
	Treatment:Date	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS	6	NS
NAG	Treatment	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS
	Date	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS	3	NS
	Treatment:Date	6	N/A	6	N/A	6	N/A	6	N/A	6	N/A	6	N/A	6	N/A	6	N/A	6	N/A

* Indicates $p < 0.0055$ (α using the Bonferroni correction for 9 comparisons).
** Indicates $p < 0.001$: indicates interaction.
$^{+}$ For sampling locations, please refer to Supplementary Fig. 1.

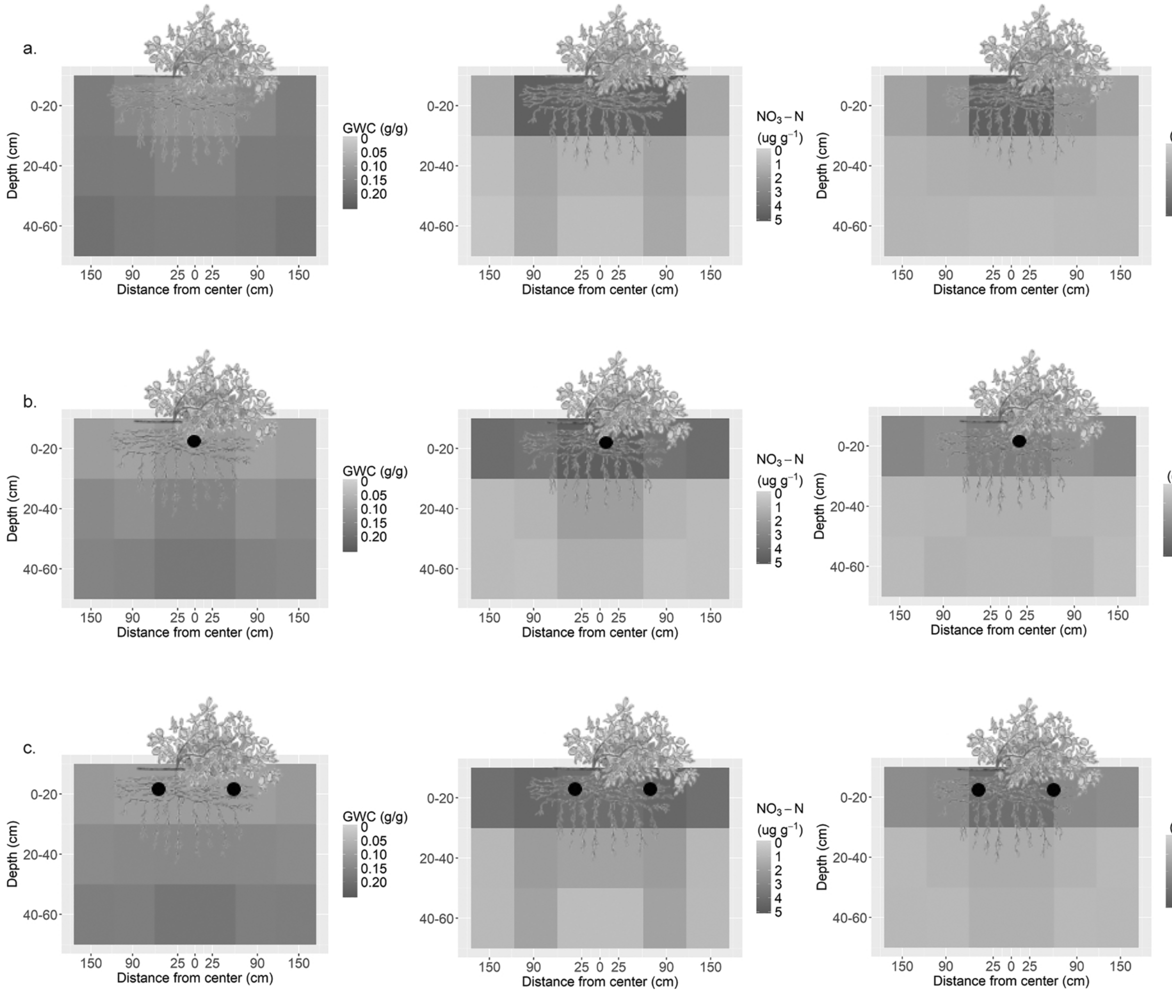

Fig. 2. Impact of irrigation technology on salinity and spatial distribution and availability of soil resources averaged across all sampling dates. Patterns of soil moisture (GWC, left), nitrate (NO3–N, center), and salinity (EC, right) differed among a) FI, b) SDI, and c) DDI treatments. FI rows had higher moisture in the center of the 20-40 cm depth and throughout the 40-60 cm depth and wetting patterns did not differ between SDI and DDI. Nitrate was lower in FI in the center of the 40–60 cm depth and salinity was higher at the shoulder of the bed and center of the 40–60 cm depth in SSD treatments. SDI = single drip irrigation; DDI = double drip irrigation; FI = furrow irrigation.

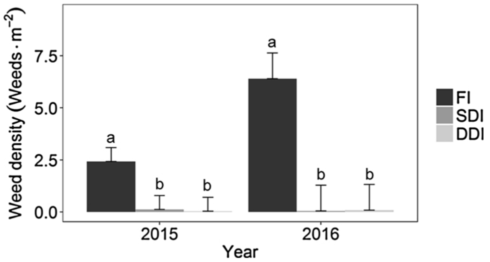

Fig. 3. Weed pressure as affected by irrigation. Weed density was much higher in FI in both years, as reduced surface wetting under SSD prevents weed seeds from germinating. Furrow-irrigated rows had more than 20 times as many weeds per m2 than drip-irrigated rows in 2015, and nearly 100 times as many in 2016. SSD = subsurface drip irrigation; SDI = single drip irrigation; DDI = double drip irrigation; FI = furrow irrigation. Letters indicate statistical differences between means at p = 0.05.

3.4. Microbial activity and nutrient cycling

We characterized how shifts in soil moisture influence total microbial activity (FDA hydrolysis) and activity of the enzymes BG and NAG across the bed in 2016. Lateral patterns of FDA, BG, and NAG activity tended to vary with irrigation treatment, although differences were not significant at the 0–20 cm depth (Fig. 4). Total microbial activity (FDA) was higher in the center of the bed in SSD treatments and decreased towards the furrows (Fig. 4a). A contrasting pattern was observed in FI beds in which FDA was lower in the middle of the bed than at intermediate distances, although activity was still lowest at the shoulder of the bed (Fig. 4a). BG activity was relatively evenly distributed in SSD beds, but FI beds showed a sharp gradient in activity with a peak in the center of the bed and low activity near the furrow (Fig. 4b). NAG activity was spatially heterogeneous but the pattern was similar across treatments (Fig. 4c).

3.5. Soil aggregation and C sequestration

Soil aggregation status and the distribution of C within aggregate classes differed between FI and SDI (Fig. 5a, b). Soil MWD was 55% greater in furrow-irrigated treatments at the 0–10 cm depth, but did not differ between treatments at the 10–20 cm depth. A significant increase in MWD with depth was seen across treatments ($p = 0.022$). MWD was 83% higher at the 10–20 cm depth than the 0–10 cm depth in SDI and 25% higher at the 10–20 cm depth in FI (Fig. 5a). Soil C was distributed differently across aggregate classes in FI and SDI at the 0–10 cm depth (Fig. 5b). At this depth, 38% of soil C was contained in macroaggregates in FI as compared to only 17% in SDI. The percentage of C in microaggregates was similar between treatments, but 53% of soil C was found in the silt and clay fraction in SDI as compared to 29% in FI.

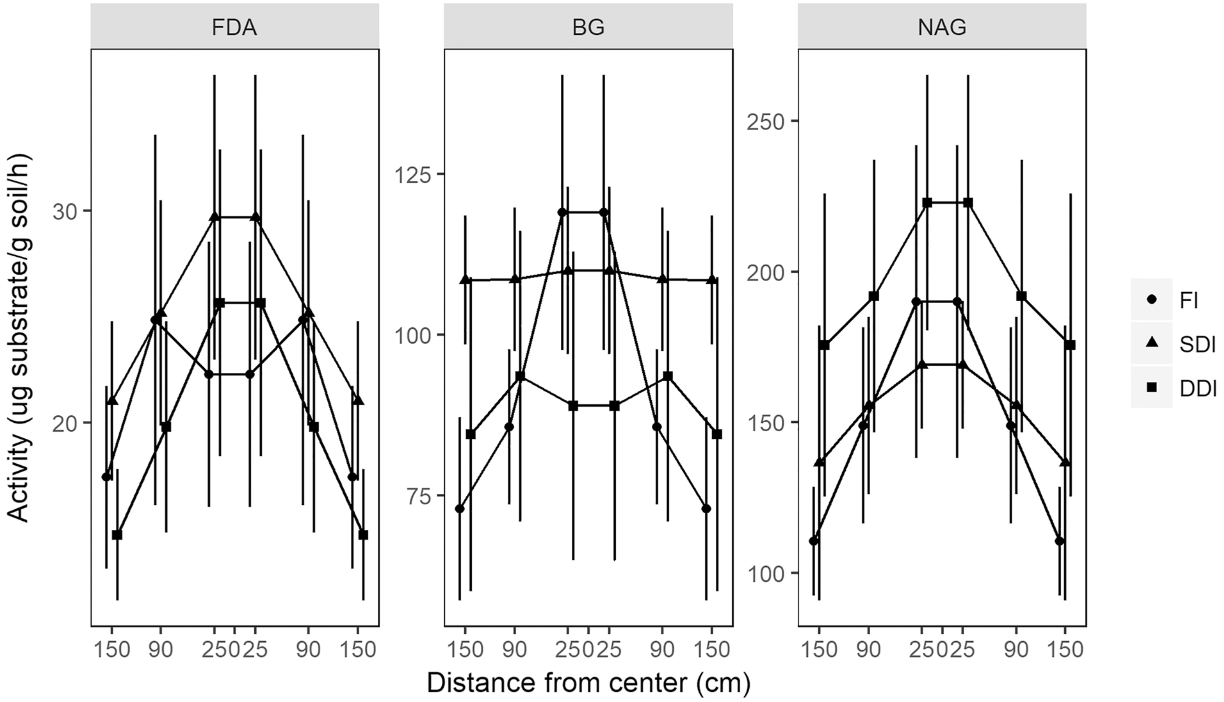

Fig. 4. Microbial activity and potential enzyme activities at 0-20 cm depth across all dates in 2016. Microbial activity (FDA hydrolysis assay) showed distinctly different patterns under SSD and FI, with higher activity in the center of the bed under SSD. A hotspot of C-cycling enzyme activity was observed in the center of the bed in FI, whereas potential enzyme activity was more uniform under SSD. Irrigation treatments had different effects on BG and NAG activity. SSD = subsurface drip irrigation; SDI = single drip irrigation; DDI = double drip irrigation; FI = furrow irrigation. Error bars represent standard error.

4. Discussion

We characterized irrigation-system-dependent variation in soil moisture and N distribution, microbial processes, impacts on accumulation of salts, and indicators of long-term effects on soil aggregation and C sequestration. Assessing how agroecosystem functions may be affected by conversion to SSD is especially relevant for organic systems, which face a unique set of challenges for weed management and crop nutrition. We confirmed well-known benefits of SSD for water conservation and weed suppression but also provided preliminary evidence of tradeoffs with potential impacts on long-term system functions (Fig. 6).

First, our results show a trend towards yield lags in the second year following conversion to SSD, which is consistent with anecdotal observation from organic growers in California and is perceived as a major impediment to adoption. Though not statistically significant ($p = 0.0511$), this trend highlights the difficulty of maintaining integrated fertility management strategies in SSD systems and the need for more research addressing how to effectively meet dynamic crop nutrient demands in these systems.

As expected, the distribution of soil resources was affected by

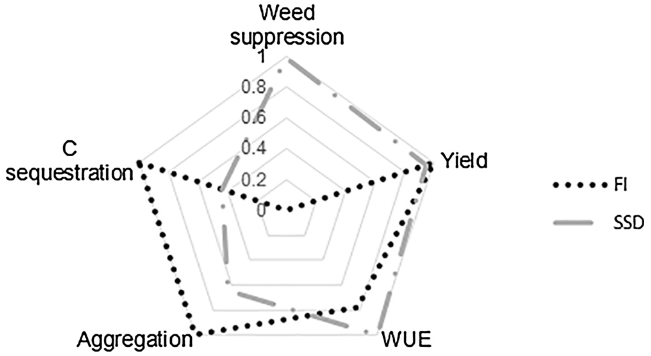

Fig. 6. Synergies and potential tradeoffs associated with irrigation treatments. SSD improved WUE and weed suppression, but did not increase yields. However, furrow irrigation improved soil aggregation and the proportion of C was protected by macroaggregates, suggesting that conversion to SSD could incur long-term penalties in terms of soil health and C cycling. Values indicate the ratio of the treatment of interest relative to the highest-performing treatment, except for "Weed suppression," which was calculated as [1 - (weeds in SSD/weeds in FI)]. "C sequestration" represents the percentage of carbon contained in macroaggregates and "Aggregation" represents mean weight diameter (MWD).

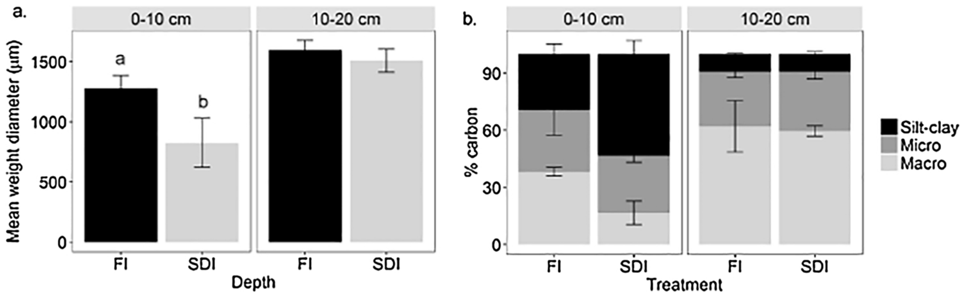

Fig. 5. Soil aggregation and C distribution. A) Mean weight diameter, an index of soil aggregate size, was higher in the 0–10 cm depth in FI than SDI rows. B) More carbon was found in the silt-clay fraction and less in macroaggregates in SDI than in FI. SDI = single drip irrigation; FI = furrow irrigation.

irrigation treatment, but linkages with yields and productivity remain unclear given our poor understanding of root distribution as affected by irrigation management (Schmidt and Gaudin, 2017). Tomato root development appears to be surprisingly sparse and independent of N concentrations under furrow irrigation (Jackson and Bloom, 1990), but highly responsive to the location of fertigation lines under SSD (Zotarelli et al., 2009). Variation in dominant nitrogen species would likely affect yields only if substantial differences between irrigation treatments occur in the depletion zone around roots. In the future, direct comparisons of root distribution under different irrigation treatments at different phenological stages would help clarify how shifts in resource heterogeneity may affect crop productivity.

The distributions of water, nitrate, and salinity differed among irrigation treatments, with most of the significant differences occurring in the center of the bed at the 40–60 cm depth (Table 2, Supplementary Fig. 1). Higher GWC, lower nitrate (but not ammonium), and lower salinity at this location may indicate displacement of mobile species by excess irrigation water in the FI treatment. Salinity concentrations, although slightly higher in SSD treatments, remained relatively low. The maximum soil EC values measured were well below the threshold value of 2.5 $\mathrm{dS\,m^{-1}}$ at which tomato yields are negatively impacted by salinity (Cahn, 2017).

Patterns of microbial and enzyme activity, which are critical drivers of productivity in organic systems, were highly heterogeneous and not easily explained by a single abiotic factor (Fig. 4). Microbial activity and potential activity of BG tended to be higher at the shoulder of the bed in SDI and DDI. Activity patterns could potentially correspond to temporal variation in the biochemical structure of C compounds as mineralization occurs, as C-cycling enzyme activity increases when complex organic compounds predominate (Allison and Vitousek, 2005). This hypothesis would indicate a greater prevalence of complex SOM under SSD, perhaps because less intense wet-dry cycles favor microbial processing and condensation reactions over wetting-induced mineralization. Further analysis of SOM structural composition and mineralization dynamics could clarify the potential implications of a transition to SSD for C-cycling enzymes.

Treatment effects on aggregate size and C distribution suggest that irrigation management decisions have long-term ramifications for soil structure and C sequestration. FI had larger soil aggregates in the upper 10 cm of the soil, a greater proportion of C in macroaggregates, and a lower proportion of C in the unprotected silt and clay fraction than SDI or DDI. SOC near the surface may thus be less vulnerable to mineralization under furrow irrigation despite more frequent wet-dry cycles. An initial decrease in macroaggregate fraction followed by stabilization has been observed with repeated wet-dry cycles (Denef et al., 2001), consistent with the maintenance of macroaggregates in FI. The proportion of C contained in microaggregates was consistent across irrigation treatments, indicating that SOC stored in this highly protected fraction (Six et al., 2002) is independent of management over the timeframe observed here. A decline in macroaggregates under SSD could nonetheless reduce the rate of microaggregate formation, decreasing the system's ability to store SOC. In turn, these shifts in soil aggregation may alter water dynamics in agroecosystems and the potential for groundwater recharge by maintaining sufficient porosity to allow infiltration and percolation of winter precipitation and protect SOM, which improves water retention (Dorado et al., 2003; Franzluebbers, 2002). While the reduced wetting volume of SSD increases short term IWP as measured by crop per unit of irrigation water applied, overall system water use efficiency must take into account alterations in microbial activity and processes that affect soil structure, SOC, and regulation by agroecosystem-scale plant-soil-water relations.

Yields were not significantly different between DDI and SDI treatments in either year. Closer lateral spacing of driplines increases the uniformity of soil moisture when the maximum horizontal infiltration distance is limited (e.g. to 30 cm, (Zhou et al., 2017)), but this did not appear to affect rhizosphere processes contributing to yield. Whether soil moisture is indeed more evenly distributed in the rhizosphere under DDI should be assessed using advanced imaging techniques. Neutron radiography or tomography have been effectively utilized for direct visualization of water distribution at a higher spatial resolution in studies under controlled conditions (e.g. Carminati et al., 2010; Moradi et al., 2011), and future extension of these technologies to the field environment would greatly aid understanding of rhizosphere processes. Although a detailed economic analysis is beyond the scope presented here, a slight and non-significant yield increase under DDI would likely not compensate for the increased investment and maintenance costs of doubling the length of dripline.

5. Conclusions

The present study took place in the two years following SSD installation in an organic management system. Effects of irrigation treatment were apparent not only on short-term metrics such as IWP and weed density but also on soil biological and physicochemical parameters connected to biogeochemical cycling. Such shifts in agroecosystem properties in only two years highlight the potential for dramatic effects over an extended timeframe and at a large spatial scale, given the rapidly increasing surface area under SSD. Current discussion of SSD implementation, strongly influenced by the ongoing drought in California, has focused primarily on increased IWP, but findings of the present study call for a broader perspective that includes long-term implications for different nutrient management systems. Unexpected tradeoffs should be incorporated into the discourse to avoid sacrificing future soil health and soil health-building processes for present yield benefits.

Conflicts of interest

None.

Acknowledgments

The authors would like to acknowledge support from the Agricultural Sustainability Institute and funding from the National Science Foundation GRFP grant to CP (institutional grant number 1650042, P Mohapatra), and by the USDA National Institute of Food and Agriculture Agricultural Experiment Station Hatch Projects to AG [project CA-D-PLS-2332-352H] and KS [Project CA-2122-H]. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the National Institute of Food and Agriculture (NIFA) or the United States Department of Agriculture (USDA). The authors thank Israel Herrera and the staff at the Russell Ranch Sustainable Agriculture Facility, as well as the interns and graduate students in the Nansen, Gornish, and Gaudin labs for their valuable assistance with field and laboratory work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agwat.2018.02.005.

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