Tillage and Cover Cropping Affect Crop Yields and Soil Carbon in the San Joaquin Valley, California

Jeffrey P. Mitchell,* Anil Shrestha, William R. Horwath, Randal J. Southard, Nicholaus Madden, Jessica Veenstra, and Daniel S. Munk

ABSTRACT

Rising costs and air quality regulations have created interest in California's San Joaquin Valley (SJV) in production systems that reduce tillage operations and soil disturbance. From 1999 to 2009, we evaluated conventional (CT) and reduced tillage (RT) systems for a cotton (*Gossypium hirsutum* L.)/tomato (*Solanum lycopersicon* Mill.) rotation with (CC) and without (NO) cover crops in a Panoche clay loam soil (fine-loamy, mixed, superactive, thermic Typic Haplocambid) in Five Points, CA, in terms of yield, soil C, and the NRCS soil conditioning index (SCI). The RT reduced tractor operations by 50% for tomato and 40% for cotton. Cover cropping produced 38.7 t ha^{-1} of biomass. Tomato yields were 9.5% higher in RT vs. CT systems and 5.7% higher in NO vs. CC systems. The CT cotton yields were 10.0% higher than RT yields and 4.8% higher in NO systems, but yield patterns were not consistent from 2005 to 2009. Soil C content was uniform (0–30-cm depth) in 1999 (19.72 t ha^{-1}) and increased in all systems in 2007 (t ha^{-1}): RTCC 29.11, CTCC 26.36, RTNO, 24.09, and CTNO 22.65. Soil C content of RT and CT systems did not differ, but was greater in CC than in NO systems. In the 0- to 15-cm depth, RT increased soil C, indicating stratification, and also increased C in the occluded light and mineral fractions. The SCI was positive for RT treatments, predicting a soil C increase, and negative for CT systems, predicting a soil C decline, but measured soil C content increased in all systems. Results show that RT maintains or increases yields relative to CT, and CC stores more soil C than NO.

Conservation tillage practices such as no-tillage, strip-tillage, and mulch-tillage are currently used on <2% of annual crop hectarage in the Mediterranean climate of California's SJV (Mitchell et al., 2007). Traditional tillage systems in this region, that consistently includes six of the nation's top 10 agricultural production counties (USDA NASS, 2011), have been used since the introduction of irrigation beginning in the late 1930s. These systems enable the predictable production of rotations of crops such as cotton, wheat (*Triticum aestivum* L.), safflower (*Carthamus tinctorius* L.), and sugar beet (*Beta vulgaris* L.), as well as vegetables, such as tomato, melon (*Cucumis melo* L.), onion (*Allium* spp.), lettuce (*Lactuca sativa* L.), and garlic (*A. sativum* L.). Cropland in the SJV generally has little or no slope and thus concerns about soil erosion have not been a major driver for RT practices as in other regions. In recent years, however, increased diesel fuel prices and interest in reducing labor needs and dust emissions in SJV crop production systems have provided incentives for RT options.

A variety of "minimum-tillage" approaches that consolidate tillage functions and reduce the total number of tillage passes across a field are now being used (Mitchell et al., 2009). These minimum-pass systems rely on combining tillage passes and do not necessarily reduce the overall volume of soil that is disturbed (Reicosky and Allmaras, 2003; Mitchell et al., 2004). Sustained RT practices such as no-tillage (Derpsch et al., 2010) or zone tillage systems (Luna et al., 2012; Shi et al., 2011) and their abilities to increase soil C sequestration over time have been reported (Franzluebbers and Follett, 2005; Martens et al., 2005). However, there has been no system developed in the SJV to evaluate the capability of the more classic forms of RT management to reduce production costs or to increase soil C sequestration. Although successful RT systems have been implemented elsewhere for a number of the crops commonly produced in the SJV (Wiatrak et al., 2006; Siri-Prieto et al., 2007; Sainju et al., 2005), these RT systems have been employed in rainfed production regions. The arid SJV receives about 180 mm of rainfall annually and contemporary cropping systems are completely dependent on irrigation. Management of these systems can be complicated by surface plant residues that tend to accumulate in RT fields to higher levels than in CT fields.

In 1999, we began research in Five Points, CA, to evaluate RT tomato and cotton systems with and without winter cover crops

J.P. Mitchell, Dep. of Plant Sciences, Univ. of California-Davis, One Shields Ave., Davis, CA 95616; A. Shrestha, Dep. of Plant Science, California State Univ.-Fresno, 2415 E. San Ramon Ave. M/S AS 72, Fresno, CA 93740-8033; W.R. Horwath and R.J. Southard, Dep. of Land, Air and Water Resources, One Shields Ave., Davis, CA 95616; N.M. Madden, Office of International Programs, One Shields Ave., Davis, CA 95616; J. Veenstra, Flagler College, 74 King St., Saint Augustine, FL; D.S. Munk, Univ. of California Cooperative Extension Fresno County, 550 E. Shaw Ave., Fresno, CA 93710. Received 7 Aug. 2014. Accepted 13 Oct. 2014. *Corresponding author (jpmitchell@ucdavis.edu).

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Abbreviations: CC, winter cover crop; CDFA, California Department of Food and Agriculture; CT, conventional tillage; NO, no winter cover crop; NRCS, Natural Resource Conservation Service; PBW, pink bollworm; RT, reduced tillage; SCI, soil conditioning index; SJV, San Joaquin Valley; SOM, soil organic matter; STIR, soil tillage intensity rating.

in terms of productivity, costs, and soil C. Following the first 4 yr of this study, no increases were measured in total soil C content in the surface 0 to 30 cm of soil, however a redistribution of both C and N from deeper soil into the top 15 cm of soil under RT compared with CT was measured (Veenstra et al., 2006). Similar to other long-term studies with cover crops (Horwath et al., 2002), a significant increase in soil C and N contents was measured in the 0- to 30-cm layer (Veenstra et al., 2006) in the cover-cropped systems. When averaged over the 2001 to 2003 period (at which point the RT systems had become "established"), tomato yields in the RT system without a cover crop were 13 to 18 t ha^{-1} (16–18%) higher than in the other treatments (Mitchell et al., 2009). In cotton, the CTNO yields during this period were the highest of all treatments and were 309 kg ha^{-1} (13%) higher than the RTNO system. As this study proceeded beyond 4 yr, we became more familiar with and were increasingly able to implement RT practices consistently. Our objective in the work reported here was to compare how these tillage and cover cropping systems performed after 10 yr of the study in terms of crop yields and soil C sequestration.

MATERIALS AND METHODS

A field comparison of conservation and standard tillage cotton and tomato rotations with and without winter cover crops was established in the fall of 1999 and continued through 2009 at the University of California West Side Research and Extension Center in Five Points, CA. A 20-ha field in a map unit of Panoche clay loam (Arroues, 2006) was used for the study. A uniform barley (*Hordeum vulgare* L.) crop was grown over the entire field before beginning the treatments. Prior crop management included a variety of crops, including cotton, wheat for forage, garbanzo bean (*Cicer arietinum* L.), garlic, and sugar beet, all of which were conventionally managed, without cover crops. Soil particle size analysis indicated a distinct texture gradient from clay loam (32% clay, 33% silt, 35% sand) at the south end to sandy clay loam (23% clay, 23% silt, 54% sand) at the north end (Baker et al., 2005), and this information was used in blocking treatments along the gradient in the experimental design. The field was divided into two halves; a tomato–cotton rotation was used in one half, and a cotton–tomato rotation was pursued in the other half to allow tomato and cotton plantings and experiments to occur within each year. Management treatments of conventional tillage without cover crop (CTNO), conventional tillage with cover crop (CTCC), reduced tillage without cover crop (RTNO), and reduced tillage with cover crop (RTCC) were replicated four times in a randomized complete block design in a factorial manner on each half of the field. As customary throughout the SJV, raised beds were used for both tomato and cotton production systems. Treatment plots consisted of six beds, each measuring 9.1 by 82.3 m. Six-bed buffer areas separated tillage treatments to enable the different tractor operations that were used in each system. A cover crop mix of Juan triticale (*Triticosecale* Wittm.), Merced ryegrain (*Secale cereale* L.), and common vetch (*Vicia sativa* L.) was planted at a rate of 89.2 kg ha^{-1} (30% triticale, 30% ryegrain, and 40% vetch by weight) in late October in the CTCC and RTCC plots and irrigated once in 1999 with 10 cm of water to establish the crop. In each of the subsequent years, the cover crops were planted in advance of winter rains, however, no irrigation was applied due to concerns about the cost and availability of additional water that would be needed to grow a cover crop. The cover crops were chopped in mid-March of the following years using a Buffalo Rolling Stalk Chopper (Buffalo Equipment, Columbus, NE). In the CTCC system, the chopped cover crop was disked into the soil to a depth of about 20 cm, and 1.52 m-wide beds were formed before tomato transplanting or cotton seeding. The chopped cover crop in the RTCC system was sprayed with a 2% solution of glyphosate [N-(phosphonomethyl)glycine] after chopping and left on the surface as a mulch.

Conventional intercrop tillage practices that break down and establish new beds following harvest were used in the CT systems (Tables 1 and 2). The RT systems were managed from the general principle of trying to reduce primary intercrop tillage to the greatest extent possible. Controlled traffic farming, or zone production practices that restrict tractor traffic to certain furrows were used in the RT systems, and planting beds were not moved or destroyed in these systems during the entire study period.

In the tomato-planted half of the field, a common commercial variety in the SJV, 8892, was transplanted in the center of beds at an in-row spacing of 30.5 cm and a final population of 21,581 plants ha^{-1} during the first week of April in each year using a modified three-row commercial transplanter fitted with a large (50 cm) coulter ahead of each transplanter shoe. Treatments received the same fertilizer applications with dry fertilizer (11–52–0 N–P–K) applied pre-plant at 89.2 kg ha^{-1} (9.8 kg ha^{-1} N and 46.4 kg ha^{-1} P) using a standard straight fertilizer shank at about 15 cm below the transplants. Additional N (urea) was side dress applied at 111.5 kg ha^{-1} for a total of 51.3 kg N ha^{-1} in two lines about 18 cm from the transplants and about 15-cm deep about 4 wk after transplanting.

The RoundUp Ready transgenic upland cotton variety Riata was used from 2000 to 2007 in all cotton systems and was established using a John Deere (John Deere, Moline, IL) 1730 No-till Planter. In 2008 and 2009, an experimental RoundUp Ready Flex Pima variety, Phy-8212 RF, was grown. Approximate plant populations in all years were 148,000 ha^{-1}. Dry pre-plant fertilizer (11–52–0) was applied at 224 kg ha^{-1} using shanks at about 20-cm depth and then mixed throughout the CT beds using bed preparation tillage implements (Table 1) and shanked in the RT systems (Table 2).

The basic equation

$$ET_c = K_c \times ET_o$$

where ET_c is the projected evapotranspiration of the tomato crop, K_c is a corresponding growth-stage dependent crop coefficient, and ET_o is reference evapotranspiration for a given production region (Hanson and May, 2006a, 2006b) was used to schedule furrow irrigations of both crops throughout the study. The ET_o data were acquired from a California Irrigation Management Information System (CIMIS) (http://wwwcimis.water.ca.gov/cimis/welcome.jsp) weather station located about 200 m from the study field. Crop coefficient (K_c) values were based on crop canopy estimates for each irrigation plot. Applied water amounts averaged about 71 cm ha^{-1} for tomato and 61 cm ha^{-1} for cotton, which are close to historical estimates for ET_c and commercial application volumes in the region (Hanson and May, 2006b). An additional application of 124.9 kg ha^{-1} of urea fertilizer per acre was made at the time when plants were about to cover the entire soil surface or just before they would have been too large for tractor intervention in each year in

Table 1. Comparison of conventional tillage (CT) and reduced tillage (RT) system operations with and without cover crops used in this study for tomato. (Each "X" indicates a separate instance of each operation.)

Operation	With cover crop CT	With cover crop RT	Without cover crop CT	Without cover crop RT
Shred cotton	X		X	
Undercut cotton	X		X	
Disc	XXXX		XX	
Chisel	X		X	
Level (Triplane)	X		X	
List beds	XX		X	
Incorporate/Shape beds	X		X	
Clean furrows		X		X
Shred bed		X		X
Spray herbicide: Treflan	X		X	
Incorporate Treflan (Lilliston)	X		X	
Spray herbicide: Roundup			X	X
Spray herbicide: Shadeout	X	X	X	X
Cultivate–Sled cultivator	XXX		XXX	
Cultivate– High residue cultivator		XXX		XXX
Plant tomato	X	X	X	X
Fertilize	XX	XX	XX	XX
Plant cover crop	X	X		
Mow cover crop	X	X		
Harvest-Custom	X	X	X	X
Times over field	23	12	19	11

Table 2. Comparison of conventional tillage (CT) and reduced tillage (RT) operations with and without cover crops used in this study for cotton. (Each "X" indicates a separate instance of each operation.)

Operation	With cover crop CT	With cover crop RT	Without cover crop CT	Without cover crop RT
Disk	XX		XX	
Chisel	X		X	
Level (Triplane)	X		X	
List beds	X		XX	
Spray herbicide: Treflan	X		X	
Incorporate Treflan (Lilliston)	XX		XX	
Spray herbicide: Roundup	XX	XXX	X	XXX
Cultivate– Rolling cultivator	XX		X	
Chain beds	X	X		
Plant cotton	X	X	X	X
Fertilize	X	X	X	X
Plant cover crop	X	X		
Mow cover crop	X	X		
Spray insecticides/growth regulation	XX	XX	XX	XX
Spray: Defoliate	X	X	X	X
Spray insecticides	XX	XX	XX	XX
Harvest-Custom	X	X	X	X
Times over field	23	14	19	11

each system using a fertilizer shank fitted with a 45.7-cm coulter to cut residues about 25 cm to the side of plants and about 15-cm deep. All tractor traffic was restricted to the furrows between planting beds in the RT systems; no tillage was done in the RT plots following tomatoes and preceding the next cotton crop, and only two tractor passes were conducted following cotton and preceding each subsequent tomato crop. These operations included shredding and uprooting the cotton stalks to comply with "plowdown" regulations for pink bollworm (*Pectinophora gossypiella*) (PBW) control in the region and a furrow sweep operation to clean out furrow bottoms to improve irrigation water movement down the furrows. Tomato yields were determined in each year using field-weighing gondola trailers following the commercial machine harvest of the inner two beds in each six-bed plot. Cotton lint yields were determined using seed cotton weights from the inner four rows in each 12-row plot multiplied by gin turnout percentages determined on samples sent through the University of California Shafter Research and Education Center research gin. Crop residues were worked into the soil following harvest in the CT systems and left on the soil surface in the RT systems. Aboveground tomato, cotton, and cover crop residue was determined on 25 Nov. 2002 and 20 Dec. 2003 by collecting all loose surface plant material in a 1-m^2 area in each plot, drying at 58°C to constant weight, and weighing. Following an average 141-d winter growing period, cover crop biomass was harvested in mid-March of each year by collecting all aboveground plant material in a 1 m^{-2} area of each plot, drying at 58°C generally for 4 to 5 d to constant weight, and weighing. Percent surface residue was determined using the line-transect method on 20 Apr. 2004 and 18 Dec. 2009 (Bunter, 1990), and surface residue biomass was determined on 25 Nov. 2002 by collecting, drying, and weighing all material within a 1 m^{-2} area in each plot.

Soils were sampled in 1999 and 2007 at two depths (0–15 cm and 15–30 cm) in the fall after harvest. Six to eight 7.6-cm-diam. cores per depth were taken in each plot and composited before air drying, sieving through a 2-mm sieve and grinding using a soil pulverizer to pass through a 60 mesh screen according to protocols of the University of California, Davis Analytical Laboratory (http://anlab.ucdavis.edu/sampling/soil-sampling-and-preparation). From these samples, total C and total N were measured by combustion using a combustion C analyzer (CE Elantech, Inc., Lakewood, NJ). Particulate soil C fractions (free light, occluded, and mineral) were isolated by the methods of Sohi et al. (2001). Briefly, the free light fraction is floated on NaI, the occluded fraction is floated on NaI after sonication, and the mineral fraction is the remainder. The C concentration of these fractions was also measured by combustion. Bulk density was measured by the compliant cavity method (USDA NRCS, 2004) for the two depths in 2003 and in 2007. For total C calculations in 1999, at the beginning of the study, we used the bulk density data for the CTNO treatment in 2003. The research plot used for this study had been under conventional management practices before the study, so we assumed that bulk densities in 1999 were similar to those we measured in 2003. For total C calculations for 2007, we used the bulk densities measured for each sampling site.

A calendar of operations was maintained for each of the systems, and the equipment used and materials applied were recorded. Specific management practices described above and in Tables 1 and 2 and tomato and cotton yields were used to estimate soil loss using the Revised Universal Soil Loss Equation (RUSLE) 2, to compute the SCI and the soil tillage intensity index (STIR), and to estimate fuel use of each tillage/cover crop management system using procedures described in the USDA NRCS National Agronomy Manual Part 508 (USDA NRCS, 2002) and summarized by Zobeck et al. (2007, 2008). The SCI is a predictive tool used to estimate impacts of management on soil organic matter (SOM) contents (USDA NRCS, 2003). It takes into account biomass production, field operations, and erosion rates and gives an overall rating of the trend of SOM. The STIR is calculated using RUSLE2. Higher STIR values reflect higher

Table 3. Cover crop biomass 2000 through 2009 in Five Points, CA. Values are means with standard errors of the means.

Cover crop biomass									
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
				kg ha^{-1}					
9345†a	3912c	2934d	3736c	2552d	7467b	2634d	57f	4472c	1607c
(259)	(228)	(361)	(342)	(196)	(465)	(279)	(13)	(426)	(172)

† Means followed by the same latter are not significantly different based on transformed data according to the p diff option in SAS, $P < 0.0001$.

Table 4. Effect of previous crop and tillage type (RT–reduced tillage, CT–conventional tillage) on cover crop biomass production from 2000 through 2009 in Five Points, CA.

	Cover crop biomass†
	kg ha^{-1}
Previous crop‡§	
Fallow (1999–2000 only)	9345 (259)a
Cotton	2812 (289)c
Tomato	3509 (225)b
Tillage type	
RT	4098 (354)a
CT	3609 (316)b

† Values are means ± standard errors of the means.

‡ Within columns, means followed by the same letter are not significantly different ($P > 0.05$)

§ ANCOVA conducted on square root transformed data using previous crop in the plots as a covariate.

Table 5. Percent surface residue and surface residue biomass for tillage and cover crop treatments in Five Points, CA.

	Percent surface residue cover‡		Surface residue biomass weights‡
Treatment†	20 Apr. 2004	18 Dec. 2009	25 Nov. 2002
	%		kg
RTCC	88 (4)A§	91 (0.71)A	794 (417)A
RTNO	42 (7)B	89 (1.55)A	757 (295)A
CTCC	11 (0.5)C	6 (1.68)B	179 (163)B
CTNO	3 (0.2)D	5 (2.56)B	98 (106)B

† RT = reduced tillage, CC = winter cover crop, NO = no winter cover crop, CT = conventional tillage.

‡ Values shown are the average of four replicate values with ± 1 SD of the average given in parentheses.

§ Means with the same letter are not significantly different, Fisher's least significant difference ($P > 0.05$).

tillage intensity. The SCI and STIR predictive soil management index tools are required in several USDA Natural Resource Conservation Service (NRCS) criteria that are used to assess applications for Environmental Quality Incentives (EQIP) and Conservation Security Programs (CSP) of the Farm Security and Rural Investment Act of 2002 (Zobeck et al., 2007, 2008).).

Data were analyzed using PROC Mixed procedures with tillage and cover crop as fixed variables and years and replication as random variables using SAS statistical software (SAS Institute, 2002). Year was considered a random variable as the crops were rotated between the two experimental blocks each year. Interactions between years and the factors were also tested. Whenever there was a significant interaction between year and the factors, data were separated by years and re-analyzed. The significance level for the variables and their interactions was set at 0.05. Before the analysis, assumptions of ANOVA were tested. Data on cover crop biomass failed to meet the assumptions and were, therefore, square-root transformed before analysis. Whenever ANOVA showed significant differences ($P < 0.05$), means were separated using either Fisher's Protected Least Significant Difference method or the pdiff option in SAS. Mean separation was based on transformed data, but non-transformed means were presented for clarity.

RESULTS AND DISCUSSION

The number of tractor trips across the field was reduced by about 50% for tomato (Table 1) and 40% for cotton (Table 2) in the RT systems relative to the CT approaches. The reduction in the number of trips has been shown to reduce the amount of dust emitted in the field (Baker et al., 2005). Differences in the tillage intensity between systems were due primarily to reductions in soil-disturbing operations commonly associated with postharvest land preparation, including disking, chiseling, leveling and relisting beds, operations that are typically performed in the fall. The operations listed in Tables 1 and 2 represent average sequences for all years; slight differences occurred in certain years. For instance, we originally performed two operations subsequent to cotton harvest in the RT systems: a one-pass Shredder–Bedder (Interstate Mfg., Bakersfield, CA) to shred and undercut the cotton plant, and a furrow sweeping operation using a Buffalo 6000 High Residue Cultivator (Fleischer Mfg., Columbus, NE) modified and fitted with only furrow implements. However, since 2003, we fitted our no-till tomato transplanter with furrow "ridging wings" and thereby cleared out residues from furrow bottoms at the time of transplanting and only performed a cotton stalk shredding using a flail mower and a root pulling operation (Sundance Wide Bed Disk, Coolidge, AZ) following cotton harvest.

Cover Crop Biomass and Surface Residue

Amounts of cover crop biomass produced during the study varied widely (Tables 3 and 4) and closely corresponded to rainfall (Fig. 1). In 1999 to 2000, the cover crop was sprinkle-irrigated to establish the experimental treatments, however, in each of the following years, cover crop establishment and growth depended on winter rain reflecting more accurately what farmers in the region would most likely do in the face of uncertain water supplies and sustained drought. With the exception of 1999 to 2000, annual cover crop biomass averaged 3167 kg ha^{-1} yr^{-1} during the rainfed period. This production is on average about one-third of what might be expected in this region when supplemental irrigation is used during the winter, as was done in 1999–2000 (Mitchell et al., 1999), and was generally higher in winters with greater rainfall, although there was no significant correlation between total precipitation and cover crop biomass. Biomass data for the 3 yr, 2005 to 2007, illustrate this finding. In 2005, the highest biomass (other than in 2000 with supplemental irrigation) was attained with the second highest total November to March precipitation and in 2007 the lowest biomass was recorded with the second lowest precipitation. However, in 2006, which had the highest total winter rainfall, only a low-intermediate level of biomass was produced. These long-term relationships between cover crop biomass and precipitation suggest that it is not only winter

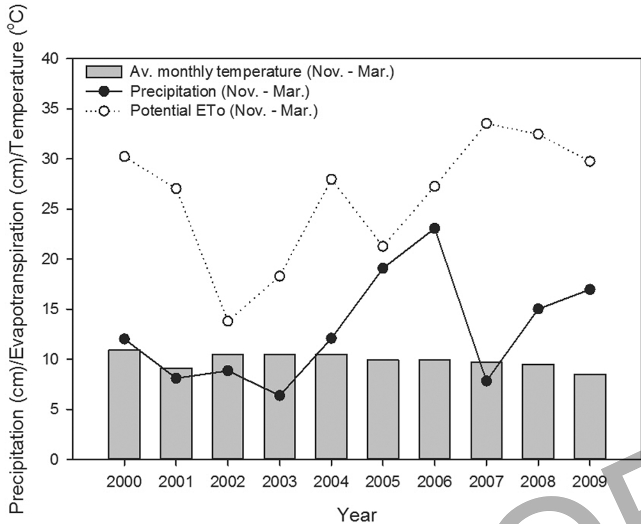

Fig. 1. Average monthly precipitation (cm), potential evapotranspiration (ET_o, cm), and average monthly temperatures (°C) for Five Points, CA, study site.

seasonal total precipitation, but also likely the timing of precipitation that is important to sustain largely rainfed cover crop biomass accumulation.

Cover crop biomass was significantly different between years. Both tillage type, CT or RT, and previous crop affected cover crop biomass (Table 4), however, there was no interaction between tillage type and previous crop and year and tillage type. Greater cover crop biomass was achieved following tomato than cotton, probably due to higher rootzone residual soil water content following tomato as compared to the longer-season cotton. There was also greater biomass produced in the RT system than in the CT system, suggesting that greater stored soil water was available in the reduced disturbance RT plots relative to the CT plots that were tilled each fall ahead of cover crop seeding (Mitchell et al., 2012). Over the 10-yr period of this study, a total of 38.7 t ha^{-1} of dry biomass was produced with 10 cm of supplemental irrigation. Surface residue biomass in the RT systems was significantly higher than in both the CTNO and CTCC treatments after 2 yr (Table 5). Residue percent cover averaged 6 (CTNO), 9 (CTCC), 64 (RTNO), and 89 (RTCC) across the two sampling times and represent, we believe, the first published data set of high residue cropping systems in California (Table 5).

Tomato Productivity

Excluding the period 1999–2000, during which time the treatment effects were becoming established, tillage affected tomato yields in 4 out of the remaining 9 yr of the study (Table 6). In each of these 4 yr (2002, 2003, 2004, and 2006), tomato yield were greater in the RT than in the CT treatments, whereas in 2000, 2005, 2007, and 2008 tomato yields were similar between the two tillage systems. However, in 2001 and 2009, there was an interaction between the tillage system and the cover crop. In 2001, the CTCC plots had greater tomato yields than in the CTNO plots, but cover crops had no effect on tomato yields in the RT plots. Contrary to 2001, the effect of cover crops was observed in 2009 only in the RT systems, where the presence of cover crop in this tillage system had lower tomato yields than the plots without cover crops. Similarly, cover crops affected tomato yields in 3 (2000, 2002, and 2005) out of the 9 yr of the rotation. In each of these years, plots with no cover crops resulted in higher tomato yield than the plots with cover crops. No such differences were observed in 2003, 2004, 2006, 2007, and 2008.

Higher tomato yields in the NO systems relative to the CC systems may have resulted from greater difficulties we experienced in no-till transplanting tomatoes into the generally higher surface residue conditions of the CC systems (Table 5). Also soil N sequestration may have occurred in the CC systems. The cover crops were predominantly composed of more triticale and rye relative to

Table 6. Processing tomato yields for conventional and reduced tillage systems with and without cover crops, Five Points, CA, 2000 to 2009.

Treatment	Tomato yield									
	2000†	2001‡	2002†	2003†	2004†	2005†	2006†	2007	2008	2009§
	t ha^{-1}									
Tillage										
RT	120.2	–	112.4a	120.2a	113.3a	101.3	101.6a	89.9	107.2	–
CT	125.6	–	100.0b	97.5b	98.9b	102.5	62.0b	89.9	110.3	–
Cover crop										
Cover	117.8b	–	98.0b	110.1	101.1	94.6b	81.1	87.4	109.7	–
No cover	128.1a	–	114.4a	114.4	110.8	109.4a	82.7	92.4	107.9	–
RTCC	–	139.3	–	–	–	–	–	–	–	111.9b
RTNO	–	145.8	–	–	–	–	–	–	–	120.2a
CTCC	–	142.2a	–	–	–	–	–	–	–	115.1
CTNO	–	131.5b	–	–	–	–	–	–	–	110.3
ANOVA	Significance level ($P > F$)									
Tillage	0.0785	0.1190	0.0194	<0.0001	0.0115	0.7684	0.0001	0.9143	0.1865	0.1777
Cover crop	0.0033	0.5370	0.0047	0.4300	0.0638	0.0053	0.7319	0.2169	0.4814	0.4660
Tillage × Cover crop	0.3494	0.0295	0.0996	0.0768	0.8999	0.2094	0.2705	0.0920	0.3127	0.0194

† Means followed by different letters within a column averaged for tillage or cover crop are significantly different according to Fisher's protected LSD at a 0.05 level of significance.

‡ Interaction between tillage and cover crop was caused because cover crop had a significant effect in conventional tillage (CT) but not in reduced tillage (RT). Therefore, means followed by different letters for conventional tillage winter cover crop (CTCC) and conventional tillage no winter cover crop (CTNO) are significantly different according to Fisher's protected LSD at a 0.05 level of significance.

§ Interaction between tillage and cover crop was caused because cover crop had a significant effect in RT but not in CT. Therefore, means followed by different letters for RTCC and RTNO are significantly different according to Fisher's protected LSD at a 0.05 level of significance.

the legume, vetch, and had an average C/N ratio that averaged 42:1. While not quantified, observations of early-season tomato growth in the CC system indicated slower initial growth in these systems that may also have been attributable particularly in the RTCC system to both lower above- and below-residue temperatures (Mitchell et al., 2012). As discussed earlier, cover crops interacted with the tillage system in 2001 and 2009. In summary, the RT system generally resulted in greater or similar tomato yields compared to CT in most years of the study. We speculate that yields in the RT systems were maintained relative to the CT system despite the fact that very little intercrop tillage was used because adequate transplant populations were achieved, beneficial changes in soil properties and function were achieved in the RT systems that led to improved tomato crop growth. Similarly, presence of a cover crop generally resulted in lower or similar tomato yields in most years of the study. Therefore, it can be concluded that tomato yields can be maintained or increased by using RT systems under the conditions and time frame of this study. Further, use of this cover crop program will not have direct effects in increasing tomato yields, but rather yields will be compromised.

Cotton Productivity

Similar to the results for tomato, yield differences in cotton yield due to the treatments were not consistent in each year of the study (Table 7). Following the establishment of the tillage and cover crop comparisons after the first summer crops in 2000 and up to 2008 when the Pima cotton variety was grown, cotton yields were greater in the CT plots than in the RT plots in 2003, 2004, and 2007. While cotton yield was similar between the two tillage systems in 2000, 2005, 2006, and 2009, there was interaction between tillage system and the presence of a cover crop in 2001 and 2002. In 2001, the presence of a cover crop resulted in lower cotton yield in the CT system but not in the RT system. Contrary to 2001, cover crop resulted in lower cotton yield in the RT system, but had no effect on yield in the CT system. As mentioned in the discussion for tomato, crop establishment effects and their interaction with the tillage or cover crops may have resulted in these differential effects in certain years of the study. Cover cropping itself had no consistent effect on cotton yield. On the other hand, CT systems generally resulted in greater or similar cotton yields compared to the RT systems, although in most years the difference was not significant. Only in 1 yr of the entire study did the RT systems result in greater yields than the CT systems. Overall, we conclude that the CT systems produced slightly higher cotton yields than the RT systems, and cover crops had no consistent effect on cotton yield. Interactions between tillage system and cover cropping were also not consistent.

In the 2000 season, all cotton system yields were low due to a devastating infestation of mites (*Tetranynchus urticae*) that persisted all season, exacerbated by likely pesticide resistance problems that developed with repeated miticide application (Mitchell et al., 2008). During the 2008 and 2009 seasons, the Pima cotton variety, Phy-8212 RF, was grown, and yields were lower for all treatments than in prior years. The relatively aggressive indeterminate growth habit of the Pima variety presented a significant change from the Acala variety. Pima with this growth habit can be more difficult to manage for high yields unless the right combination of plant growth regulator and deficit irrigation management are used to control vegetative crop growth (Munk et al., 2008), and the result was reduced yield in the Pima part of this study. This variety of cotton was used to follow the Acala cotton work to gain RT experience with Pima cotton and because Pima is an increasingly attractive and economically viable cotton variety option for SJV producers. If it is necessary to water stress the Pima variety to control vegetative growth, it is likely that it would respond negatively to systems with more soil water. Thus, it would be necessary to manage treatments separately relative to water applications with the net result being similar yield with less water in the RT systems.

Table 7. Cotton yields for conventional and reduced tillage systems with and without cover crops, Five Points, CA, 2000 to 2009.

Treatment	Cotton yield									
	2000†	2001‡	2002§	2003†	2004†	2005†	2006†	2007	2008	2009
	t ha^{-1}									
Tillage										
RT	285.6	–	–	1107.9b	1651.1b	1490.8	1196.6	2023.3b	456.4a	755.9
CT	346.5	–	–	1281.9a	2013.9a	1561.5	1259.8	2117.6a	327.9b	708.6
Cover crop										
Cover	352.5	–	–	1246.5	1738.1b	1539.4	1177.8	2099.4	402.6	763.8
No cover	279.6	–	–	1143.3	2016.9a	1512.9	1278.6	2041.5	381.6	700.8
RTCC	–	1565.5	1251.8b	–	–	–	–	–	–	–
RTNO	–	1646.3	1736.3a	–	–	–	–	–	–	–
CTCC	–	1505.7b	1920.5	–	–	–	–	–	–	–
CTNO	–	1860.8a	1929.5	–	–	–	–	–	–	–
ANOVA	Significance level ($P > F$)									
Tillage	0.2952	0.0173	<0.0001	0.0112	0.0041	0.1582	0.2631	0.0160	0.0391	0.3180
Cover crop	0.2161	<0.0001	<0.0001	0.0919	0.0434	0.5785	0.0888	0.1032	0.7027	0.1923
Tillage × Cover crop	0.1030	0.0010	<0.0001	0.9363	0.6745	0.4069	0.8777	0.0982	0.3524	0.9957

† Means followed by different letters within a column averaged for tillage or cover crop are significantly different according to Fisher's protected LSD at a 0.05 level of significance.

‡ Interaction between tillage and cover crop was because cover crop had a significant effect in conventional tillage (CT) but not in reduced tillage (RT). Therefore, means followed by different letters for conventional tillage winter cover crop (CTCC) and conventional tillage no winter cover crop (CTNO) are significantly different according to Fisher's protected LSD at a 0.05 level of significance.

§ Interaction between tillage and cover crop was because cover crop had a significant effect in RT but not in CT. Therefore, means followed by different letters for RTCC and RTNO are significantly different according to Fisher's protected LSD at a 0.05 level of significance.

Soil Carbon

Soil bulk density is important in the interpretation of changes in soil C. Often total soil C is measured on a mass-per-mass basis (%); however, using this method, soils with similar C percentages, but different bulk densities, would have different total soil C contents on a mass-per-volume basis (Veenstra et al., 2007). We did not measure bulk density in 1999. As described in the methods section, we measured the bulk density in 2003, and assumed that the 2003 CTNO bulk densities reflected conditions at the beginning of the field experiment. We used average values of 1.24 g cm^{-3} (0–15 cm) and 1.35 g cm^{-3} (15–30 cm) to calculate initial soil C stocks. For total C calculations for 2007, we used the bulk densities measured for each sampling site. In 2007, average soil bulk density (g cm^{-3}) in the 0- to 15-cm depth were as follows: 1.25 RTCC, 1.25 RTNO, 1.25 CTCC, and 1.20 CTNO, and in the 15- to 30-cm depth: 1.49 RTCC, 1.49 RTNO, 1.43 CTCC, and 1.32 CTNO. Thus, treatments had little effect on bulk density in the 0- to 15-cm depth, but RT treatments, in particular, produced an increase in bulk density in the 15- to 30-cm depth, presumably due to the lack of tillage disturbance at that depth.

After 8 yr of the tillage and cover crop treatments, soil carbon content in the 0- to 30-cm depth increased relative to initial conditions in 1999 for all treatments (Table 8). Initial soil C averaged 19.72 t ha^{-1} in 1999 for all treatments. The RTCC treatment had the highest soil C content of all treatments, but did not have a significantly higher content than the CTCC treatment. Similarly, the RTNO soil C content was not significantly different from the CTNO treatment. Thus, increased soil C storage appears to be the result primarily of the cover crop treatment, rather than the reduced tillage treatment, although the combination of the two treatments (RTCC) resulted in significantly higher soil C stocks than the CTNO treatment. The degree of stratification of soil C with depth, expressed as a ratio, has been proposed as an indicator of soil quality or soil functioning that may be useful for comparing management impacts on soils that differ in inherent C levels (Franzluebbers, 2002). Stratification ratios (0–15 cm/15–30 cm) of soil C were 0.92 for the CTNO and CTCC systems, 1.20 for the RTNO system, and 1.25 for the RTCC system, clearly demonstrating the effect of not incorporating residues in the RT treatment. Franzluebbers (2002) hypothesized that sustained RT management would produce larger ratios than CT management, but also suggested that even larger differences might be expected in regions such as California with high temperatures, irrigation and inherently low soil C stocks. The RT systems resulted in larger stratification ratios than those in the CT systems, but the ratios are probably not as high as could be achieved in a no-till system. Our RT experimental systems relied on a number of soil disturbing operations such as cultivation for tomato and postharvest stalk management for cotton, so some mixing of soil C into the 15- to 30-cm depth probably occurred, thereby reducing the stratification ratio.

Treatment effects on the distribution of particulate soil C fractions varied (Table 9). The free light fraction C content was similar among all treatments and depths with the exception of the RTCC treatment where light fraction C content was higher in the 0- to 15-cm depth than in the 15- to 30-cm depth. RT treatments generally resulted in higher C contents in the occluded light fraction and the mineral fraction compared to CT treatments, and the effect was most pronounced in the 0- to 15-cm depth, compared to the 15- to 30-cm depth. These results suggest that RT practices may result in soil C storage pools that turn over more slowly than C pools in soils under CT practices, although the effect is limited to the near-surface layer due to the lack of mixing by tillage operations.

Soil Conditioning Index

The SCI has been proposed by NRCS as a predictor of the consequences of management actions on soil organic C, but has recently been shown to be more closely associated with a more labile form of soil organic C known as particulate organic matter, or POM-C, as well as what have been termed the residue equivalent value (REV) that drives organic matter accumulation in the soil. The NRCS currently uses the SCI as one of its criteria for practice standards including Conservation Crop Rotation and Residue Management and for determining eligibility for Farm Bill conservation programs such as EQIP and CSP (Zobeck et al., 2007). The computed SCI values in Table 10 seem to be closely associated with the field operations that were used in the farm tillage and cover crop systems (Tables 1 and 2). The SCI values

Table 8. Soil C mass for tillage and cover crop treatments† at two soil depths at the start of the study in the fall of 1999 and in the fall of 2007.

1999			2007		
Depth	Treatment†	Mean‡	Depth	Treatment	Mean§
cm		t ha^{-1}	cm		t ha^{-1}
0–15	RTCC	9.33 (0.18, A)	0–15	RTCC	16.20 (0.53, A)
	CTCC	9.25 (0.40, A)		CTCC	12.69 (0.29, AB)
	RTNO	9.27 (0.41, A)		RTNO	13.13 (0.46, AB)
	CTNO	8.87 (0.31, A)		CTNO	10.84 (0.19, B)
15–30	RTCC	10.39 (0.30, A)	15–30	RTCC	12.91 (0.62, AB)
	CTCC	10.66 (0.99, A)		CTCC	13.67 (0.65, A)
	RTNO	11.40 (1.11, A)		RTNO	10.96 (0.51, B)
	CTNO	9.69 (0.52, A)		CTNO	11.81 (0.31, AB)
Total	RTCC	19.72 (0.45, A)	Total	RTCC	29.11 (0.94, A)
	CTCC	19.91 (1.20, A)		CTCC	26.36 (0.78, AB)
	RTNO	20.67 (1.03, A)		RTNO	24.09 (0.81, BC)
	CTNO	18.56 (0.75, A)		CTNO	22.65 (0.26, C)

† CT = conventional tillage; RT = reduced tillage; NO = no cover crop; CC = winter cover crop.

‡ Values in parentheses are standard error of the means (n = 8). Within a column, means followed by the same letters are not significantly different using a one-way ANOVA analysis with Tukey HSD means comparison.

Table 9. Mass of C in the free light fraction (FLF), occluded light fraction (OLF), and mineral fraction (MF) for tillage and cover crop treatments† in Fall 2007 with the corresponding ANOVA significance levels.

Depth	Treatment	ELF	OLF	MF
0–15	RTCC	2.55	0.26	14.42
	CTCC	2.20	0.11	12.04
	RTNO	2.17	0.15	12.55
	CTNO	2.29	0.10	10.16
15–30	RTCC	1.44	0.12	13.25
	CTCC	2.15	0.11	12.11
	RTNO	1.03	0.07	11.81
	CTNO	1.64	0.08	12.40
			$P > F$	
		FLF	OLF	MF
Depth		0.03	0.01	0.86
Treatment		0.68	0.02	0.01
Interaction		0.62	0.14	0.15

† RTCC = reduced tillage with cover crop, CTCC = conventional tillage with cover crop, RTNO = reduced tillage no cover crop, CTNO = conventional tillage no cover crop.

were negative for the two CT systems and positive for the RT systems indicating that the level of SOM is predicted to increase under RT and decrease under CT management (Table 10). The lower STIR values calculated using RUSLE2 for the RT systems indicate potentially desirable soil outcomes such as lower C losses from soil to the atmosphere, less soil consolidation, and higher infiltration rates (USDA NRCS, 2012).

Our results contrast somewhat with the SCI predictions in that soil C content increased with all treatments. The soil C increase in the CTNO treatment may reflect the effect of a change in management inputs beginning in 1999 (start of the experiment) compared to the prior long-term management of the experimental plots, wherein a variety of low biomass crops were grown (e.g., cotton without tomato), or where most crop residues were removed during harvest (green wheat chopped for feed). The soil C increase may reflect an inherent capacity for these soils to store C, if crops with higher biomass production are grown. Further, our conventional tillage system allowed tillage in only one direction to preserve the beds of adjacent treatments. This management approach contrasts with large-scale conventional tillage, where fields are often tilled in two directions (often in an orthogonal pattern). As a result, we speculate that crop residues, even in the CTNO treatment, were concentrated in the row and led to an increase in soil C content. This result is somewhat of an artifact of our experimental set-up, and may partly explain why our soil C results contrast with the SCI predictions. Lastly, the SCI places considerable emphasis on tillage operations. Given that our RT treatments reduced the number of operations by about half, compared to the CT treatments, the SCI may overestimate the relative STIR of the two systems and overpredict C loss in the CT treatments.

Implications for Row Crop Management in the San Joaquin Valley

The general RT approach pursued in this study was to more severely restrict tillage operations than is customarily done today throughout the SJV. As a result of this, more residues accumulated on the soil surface, particularly in the RTCC systems (Table 5). This at least partly explains the lower numbers of cotton plants that were established in this system during the first 4 yr of the study due to difficulties at seeding as well and the lower yields in this system early in the study (Mitchell et al., 2008). In addition, we were initially concerned that residues would interfere with the action of the “over-the-top” tomato herbicide *rimsulfuron* [1-(4,6-dimethoxypyrimidin-2-yl)-3-(3-ethylsulfonyl-2-pyridylsulfonyl)urea], which can be sprayed after transplanting and sprinkled in to activate. By 2003, however, this herbicide was used in all systems with observed benefits. For RT cotton, we relied solely on one or two in-season applications of glyphosate; no cultivation was done in these systems. For all tomato treatments, we typically cultivated two to three times, but based on visual estimates of weed populations, this did not achieve a comparable level of weed control in the RT systems as in the CT systems in all years, and this is one aspect of our RT approach that needs future attention.

It is important to point out that while the RT systems we employed in this study dramatically reduced overall tillage and soil disturbance relative to the CT norms for the SJV, they by no means constitute what is customarily considered “no-till” production. In classic no-till, or “direct seeding” systems, crops are planted directly into residues and no additional soil disturbance is generally done before harvest. We employed an intermediate or incremental tillage reduction strategy in part to clear channels for irrigation water movement down furrows and in part to meet California Department of Food and Agriculture (CDFA) mandates for PBW pest control in cotton. Current CDFA regulations require uprooting cotton roots post-harvest and residue mixing with the soil. Recent changes in the CDFA PBW Control and Eradication Program allow for reduced post-harvest tillage in cotton fields with no PBW findings, or in fields outside of a nine square mile radius from a PBW trapping find. These changes should make it easier to adopt RT practices in cotton rotations in the SJV.

In summary, the long-term aspect of this study has been quite valuable in providing information on the variable nature of rainfed cover crop biomass production in this region. It has revealed challenges and opportunities for improving tomato and cotton productivity under the RT, high residue management that was

Table 10. Tillage and cover crop system erosion estimates, soil condition index subfactors, and soil tillage intensity rating.

Cropping system†	Erosion estimates‡		Soil conditioning index factors§				STIR average annual
	WEPS	RUSLE2	OM	FO	ER	SCI	
	Mg ha^{-1}						
CTNO	2.1	0.2	−0.19	−1.6	0.011	−0.71	261
CTCC	1.0	0.07	0.20	−2.9	0.53	−0.96	390
RTNO	0	0.04	−0.11	0.70	0.98	0.43	30.6
RTCC	0	0.03	0.18	0.63	0.99	0.52	37.1

† CTNO = conventional tillage no cover crop, CTCC = conventional tillage with cover crop, RTNO = reduced tillage no cover crop, RTCC = reduced tillage with cover crop.
‡ WEPS = wind erosion; RUSLE2 = revised universal soil loss equation.
§ SCI = soil conditioning index value; OM = organic matter subfactor; FO = field operations subfactor; ER = erosion subfactor; STIR = soil tillage intensity rating.

used. Finally, it provided the first demonstration of the potential for increasing soil C stocks in the semiarid SJV with cover crops and RT. The alternative practices that were pursued over the course of this work borrowed heavily from the core principles of various sorts of conservation agriculture systems that have been developed around the world, but that are yet to be used in the historically very productive SJV.

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