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AGRONOMY AND SOILS

Cotton Response to Long-Term No-Tillage and Cover Cropping in the San Joaquin Valley

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ABSTRACT

Despite approximately 45% of U.S. cotton being produced using no-tillage (NT) or strip-tillage, these seeding techniques are not yet being used commercially in California. From 2010 to 2013, we compared cotton production under NT versus standard tillage (ST) practices with a winter cover crop (CC) or without (NO) cover crops in Five Points, CA. Tractor trips across the field were reduced by 40% in the NT systems relative to the ST approaches. Residue cover was 93, 83, and 2% for the NTCC, NTNO, and the ST systems, respectively. Average lint yields combined over the four years of this study were similar between ST and NT (1481.4 vs 1484.7 kg ha^{-1}), however, the average yield with NO was higher than with CC (1526.1 vs 1440.0 kg ha^{-1}). There was a tillage X cover crop interaction in 2011 with a yield difference between CC and NO within ST, but not NT. There were no differences between the STNO and NTNO systems across the four years. As long as yields can be maintained, externalities such as shifts in irrigation systems away from surface to drip and overhead irrigation, as well as continued water shortages could warrant the learning curve effort and the retooling that will be required to scale up the conversion from traditional tillage cotton production to NT in this region.

Cotton is grown using no-tillage (NT) or strip-tillage seeding techniques on approximately 45% of total acreage throughout the U.S. Cotton Belt (Reed et al., 2009), but in California, there is no commercial cultivation of NT cotton (Mitchell et al., 2009a, b; 2012). NT is a direct seeding system in which the soil is left undisturbed from harvest to planting and strip-tillage is a seeding system in which the seed row is tilled prior to planting to allow residue removal, soil drying and warming, and in some cases, subsoiling (Mitchell et al., 2009a). Other than a small 11.3-ha farm trial that was conducted in Riverdale, CA in 2003 (Mitchell et al., 2006), and a 54.6-ha strip-till effort that was carried out at a farm in Firebaugh, CA in 2013, these reduced tillage alternatives are not used for cotton in the state. Standard tillage (ST) systems that were developed for cotton in California during the second half of the 20th century have changed in relatively small ways and tend to be widely used today (Abernathy et al., 1975; Carter and Colwick, 1971).

California cotton farmers have maintained the traditional pre-plant tillage practices that have been used essentially with minor modifications since the advent of irrigation pumps in the 1930s, because these customary production approaches have worked reliably over the years and have been partially responsible for the cotton yield increases that have occurred steadily during the past 80 years (Geisseler and Horwath, 2013). In addition, because tillage costs tend to be a relatively small part of overall production budgets for California cotton (Mitchell et al., 2006), cost-benefit risk analyses for switching to NT cotton production have not tipped the balance toward conversion or adoption of NT in California.

Depending on the specific crop that precedes cotton, production fields in California under current standard practices are prepared using a well-honed sequence of tillage passes so as to provide clean (residue-free) cultivation conditions, with fine and uniformly-sized soil aggregates that are used to create raised seeding beds (Mitchell et al., 2006). Prior to cotton seeding, residues from prior crops are shredded and incorporated into the soil using disks or other similar implements (Hutmacher et al., 2012). Depending upon a farmer's assessment of the need for subsoiling or deeper soil profile

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loosening, a chisel or heavy shank implement might be used to break up compacted subsoil layers in the typical tillage-induced plow pan zone that typically develops from 20 to 40 cm deep ahead of planting. This deeper tillage generally is followed by additional diskings to break up clods that tend to be created by these prior primary tillage operations, a bed listing or forming pass, and a dry-mulching surface operation in the spring to perform a final seedbed preparation as well as to provide more uniform seedbed moisture conditions (Personal communication, K. Collins). Cotton is then seeded into moisture following these preparatory operations and a cap of loose, dry soil is pulled up over the planted seed during seeding to protect the seed from drying by strong winds that are common during the customary March to April California cotton seeding window (Hake et al., 1996). This cap is scraped off using an additional field pass just before the cotton seedling emerges from the soil.

Despite the historical success of these traditional tillage approaches for California cotton, there is evidence of a number of drivers including decreasing costs, switching to more efficient irrigation systems, and preserving soil moisture, that might now favor consideration of NT practices. No-tillage cotton could have a greater fit for California farmers in the future if high levels of production can be maintained because of relatively wholesale changes in irrigation practices within California's cotton-growing region, the San Joaquin Valley (SJV), that are rapidly occurring in recent years. Increasingly, surface or gravity irrigation is being replaced by drip, and to a lesser extent by overhead irrigation precision, due to the benefits of these systems to apply uniformly small amounts of water across a field (Mitchell et al., 2015 thereby permitting farmers to apply water carefully. The increased adoption of these precision irrigation systems also has the adjunct benefit of reducing costs associated with tillage that is involved with creating beds and furrows in a field for surface irrigation. If raised beds are no longer required for irrigation as they have been with surface irrigation, tillage costs related to preplant bed preparations are no longer incurred.

A second driver for NT cotton in California is related to the sustained exceptional drought that the state has experienced in recent years (Howitt et al., 2014). The applicability or relevance of NT cotton within the water-short production constraints that SJV cotton farmers face and will face in the future has to do with the well-documented benefits that can be derived from reduced-disturbance, residue-preserving practices in terms of reducing soil water evaporation (Klocke et al., 2009; Mitchell et al., 2012; van Donk et al., 2010), and over time, the ability of such practices to increase soil water-holding capacity (Hudson, 1994). At this time, SJV cotton farmers have not pursued prominently or deliberately such goals of reduced disturbance and residue preservation as are now common in several other regions of the country (Mitchell et al., 2012), but it is conceivable that they might find such options more attractive as water shortages intensify as is projected (Howitt et al., 2014), and if reliable NT production paradigms can be shown to warrant the learning curve effort and the retooling that will be required in scaling up the conversion from traditional tillage to NT.

To address the knowledge and experience gaps related to NT cotton production in California's SJV, we took advantage of the long-term National Research Initiative Conservation Agriculture (NRI-CA) Systems Project that was initiated in the fall of 1999 by a group of farmers, the National Resources Conservation Service, private sector, and university partners originally to develop information on conservation tillage and cover crop production systems and their ability to reduce particulate matter emissions and increase soil carbon (C) relative to the historically high soil disturbance tillage practices that had been used in the region for more than 80 years since the advent of irrigation wells in the 1930s (Mitchell et al., 2015). At the time the NRI-CA Project was started, NT practices were used on less than 2% of annual crop acreage and 0% of cotton acreage in the SJV (Mitchell et al., 2007) and informal estimates of the extent of cover cropping were on a similar level. Since 1999, the project consistently has implemented cover crop and tillage system comparisons that differ substantially in terms of soil disturbance intensity and C inputs via cover crops (Mitchell et al., 2006, 2008, 2009a; Veenstra et al., 2007). Various aspects and findings of the early stages of this long-term study have been reported previously including impacts of NT on soil C and nitrogen (N) (Veenstra et al., 2006, 2007), dust emissions (Baker et al., 2005), economics (Mitchell et al., 2009a) and cover crop inputs (Mitchell et al., 2015).

Cotton yield data from the early years of this long-term study indicate two general periods of performance of the NT and winter cover crop (CC) systems relative to the ST, no cover crop (NO), control system. In the establishment years of the study, excluding 2000 when all cotton system yields were low due to a devastating infestation of mites (*Tetranynchus urticae* C. L. Koch) that lasted all season and was worsened by likely pesticide resistance problems that developed with repeated miticide applications (Mitchell et al., 2008), cotton yields were greater in the ST plots than in the NT plots in 2001, 2002, 2003, 2004, and 2007. In previously published reports of this early phase of the work (Mitchell et al., 2015), these lower yields in the NT systems were related largely to crop establishment problems or challenges that occurred particularly in the NTCC system. These early-phase findings that the NT systems produced less than the ST approach stemmed from seeding and establishment difficulties that were not overcome successfully in the NT treatments in these early years. Then, during the 2008 and 2009 seasons, the Pima cotton variety, Phy-8212 RF, was grown and yields were lower for all treatments than in earlier years (Mitchell et al., 2015). In this paper, we provide information on NT cotton performance over the course of the study from 2010 through 2013 as the systems further matured and as our ability to manage them improved.

MATERIALS AND METHODS

Cropping systems descriptions. The study site is located at the University of California's West Side Research and Extension Center (WSREC) in Five Points, CA (36°20′29″N, 120°7′14″W). The field size was 427 m by 100 m and the soil type was Panoche clay loam (fine-loamy, mixed superlative, thermic Typic Haplocambids) (Arroues 2006) with a particle size distribution of 25% sand, 37% silt, and 39% clay. During the year before the onset of the study, a uniform barley (*Hordeum vulgare* L.) crop was grown and removed as green chop silage to even out differences in soil water and fertility that might have existed due to previous research.

The 3.56-ha field consisted of 32 plots each 10-m wide by 100-m long with 10-m buffer or border plots between treatment plots. The field was divided into two halves; a tomato (*Solanum lycopersicum* L.)-cotton *(Gossypium hirsutum L.)* rotation was used in one half, and a cotton-tomato rotation was used in the other half to allow tomato and cotton plantings to occur within each year. Management treatments included a factorial arrangement of tillage and cover crop that included standard tillage without cover crop (STNO), standard tillage with cover crop (STCC), no-tillage without cover crop (NTNO), and no-tillage with cover crop (NTCC). Each treatment was replicated four times in a randomized complete block design on each half of the field. Treatment plots consisted of six beds, each measuring 9.1 x 82.3 m. Six-bed buffer areas separated tillage treatments to enable the different tractor operations that were used in each system. The tillage systems that were used have been described previously in detail (Mitchell et al., 2015; Veenstra et al., 2006), but in summary consisted of conventional intercrop tillage operations of residue shredding, multiple diskings to incorporate residues, subsoiling to a depth of approximately 45 cm, additional disking to break up soil clods created by the subsoiling chisel, shaping of beds, and power incorporation of the surface soil using a cultimulcher (BW Implement, Buttonwillow, CA) (Table 1). The only soil disturbance operations used in the NT systems other than seeding or transplanting passes were shallow cultivation during the first eight years for the tomato crops, but as the project progressed, the NT treatments became true no-tillage systems.

Table 1. Cotton planting date, harvest date, growing season duration, seeds ha^{-1}, and cumulative seasonal reference evapotranspiration (ETo) (mm) for 2010, 2011, 2012, and 2013 experimental crops in Five Points, CA

	2010	**2011**	**2012**	**2013**
Planting date	**6 May**	**14 May**	**3 May**	**16 April**
Harvest date	**3 November**	**3 November**	**31 October**	**17 October**
Growing season (days)	**181**	**173**	**181**	**184**
Cotton variety	**Phy 725RF**	**Phy 725 RF**	**Phy 725 RF**	**Phy 802 RF**
Reference ETo (mm)	**1130**	**993**	**1147**	**1256**
Seeds ha^{-1}	**133,600**	**163,400**	**153,500**	**163,400**

Cultural practices. A cover crop mix of Juan triticale (*Triticosecale* Wittm.), Merced ryegrain (*Secale cereale* L.) and common vetch (*Vicia sativa* L.*)* was seeded using either a 5-m John Deere 1530 no-tillage seeder (Moline, IL) or a 5-m Sunflower 1510 no-till drill (Beloit, KS) at 19-cm row spacing and at a rate of 89.2 kg ha^{-1} (30% triticale, 30% ryegrain, and 40% vetch by weight) in late October in the STCC and NTCC plots and irrigated once with 10 cm of water in 1999 (Fig. 2). The legume species was inoculated with its particular rhizobium before seeding. In each of the subsequent years through 2012, no irrigation was applied to the cover crops, which were planted in advance of winter rains. Beginning in 2010 and persisting through 2014, the basic cover crop mixture was changed in an attempt to diversify (Mitchell et al., 2015). Specific information for each season including planting and harvest dates, seeding rates, the varieties that were used, and seasonal reference evapotranspiration (ETo) are provided in Table 1. The number of tractor passes across the field was recorded for each system.

The specific operations that have been used in this long-term study have evolved since its initiation in 1999. Whereas the early-phase reduced tillage systems that we employed dramatically decreased overall tillage and soil disturbance relative to the ST norms for the SJV early on, they did not constitute what is commonly 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 prior to harvest. We employed an intermediate or incremental tillage reduction strategy during that early phase, 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 pink bollworm (PBW) pest control in cotton. Current CDFA regulations require uprooting cotton plants post harvest and potentially some residue burial. Recent changes in the CDFA PBW Control and Eradication Program allow for reduced postharvest tillage in cotton fields with no PBW findings, or in fields outside of a nine square mile radius from a PBW trapping find. During the four years of the study that are reported here, however, cotton was essentially produced as a NT crop with zero preplant tillage and only in-season directed herbicide application using a hooded sprayer. The field was periodically monitored for PBW by the local Agricultural Commissioner and no PBW was found during the duration of the study.

During the first 12 years of the study (2000-2011), surface (furrow) irrigation was used. Then, with the 2012 season, subsurface drip tape was installed at a depth of 30 cm with one line of tube along the center of each 150-cm-wide bed. Percent surface residue was determined using the line-transect method on 29 May 2010 at the start of the study (Bunter, 1990).

Dry preplant fertilizer (11-52-0) was applied at 224 kg ha^{-1} using shanks at about 20-cm depth and then mixed throughout the ST beds using bed preparation tillage implements and shanked in the NT systems. Irrigations were scheduled using the basic equation

$$ETc = Kc \cdot ETo$$

where ETc is the projected evapotranspiration of the tomato crop, Kc is a corresponding growth-stage dependent crop coefficient, and ETo is reference evapotranspiration for a given production region (Hanson and May, 2005, 2006) throughout the study. ETo 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 (Kc) values were based on crop canopy estimates for each irrigation plot. Applied water amounts averaged about 61 cm ha^{-1}, which are close to historical estimates for cotton ETc and commercial application volumes in the region (Hanson and May, 2006).

Cotton plant height was monitored in the 2011 season by measuring the distance from the soil to the highest growing shoot to determine crop growth and development in the tillage and cover crop treatments. 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 Extension Center research gin. A calendar of operations was maintained for each of the systems, and the equipment used and materials applied were recorded.

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. A significant interaction occurred between year and the factors; therefore, data were separated by years and re-analyzed. The significance level for the variables and their interactions was set at 0.05. Prior to the analysis, assumptions of ANOVA were tested. Data within each year were normal for all the variables. Significantly different ($p < 0.05$) treatment least square means were separated using the probability of differences option (PDIFF).

RESULTS AND DISCUSSION

Research on various aspects of no-tillage cotton production systems has been conducted throughout several regions of the U.S. cotton belt for a number of decades on a variety of topics (Balkcom et al., 2007; Denton and Tyler, 2002; Schwab et al., 2002). During these years, NT production has been refined and improved so that it is now the dominant seeding system in some areas (Denton and Tyler, 2002) and a common approach in several others (Reed et al., 2009). This study provides the first long-term evaluation of NT in the SJV, a historically major cotton production region.

The number of tractor trips across the field was reduced consistently by 40% (Table 2) in the NT systems relative to the ST approaches. This reduction in the number of trips has been shown to reduce the amount of dust emitted in the field (Baker et al., 2005). As reported for the earlier years of this long-term study (Mitchell et al., 2008), 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 Table 2 represent average sequences for all years; slight differences occurred in certain years. For instance, in the early years of the study, we originally performed two operations subsequent to cotton harvest in the reduced-tillage 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 NT 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.

Table 2. Comparison of standard tillage (ST) and no-tillage (NT) 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		Without cover crop	
	ST	NT	ST	NT
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 Reg	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

Over the 15 years of the project that were characterized by recurring drought, a total of 56 t ha^{-1} of aboveground cover crop biomass representing 1,196 kg ha^{-1} of N and 21,722 kg ha^{-1} of C was produced with a total precipitation of 209 cm and 20 cm of supplemental irrigation applied in 1999, 2012, and 2014. Cover crop biomass varied from 39 kg ha^{-1} in the low precipitation period (winter 2006-2007) to 9,346 kg ha^{-1} (winter 2000-2001) (Mitchell et al., 2015).

At the start of the study in May 2010, large differences in percentage of residue cover existed across the study treatments due to the history of NT and CC that had preceded the four years of cotton performance evaluations that are reported here (Fig. 1). Both tillage and cover crop affected percentage of residue cover. However, there was an interaction between tillage type and cover crop for residue cover. The interaction was because cover crop resulted in more residue cover in the NT but not in the ST system. Residue cover was 93% for the NTCC, 83% for the NTNO, and 2% for the ST systems (Figures 1 and 3).

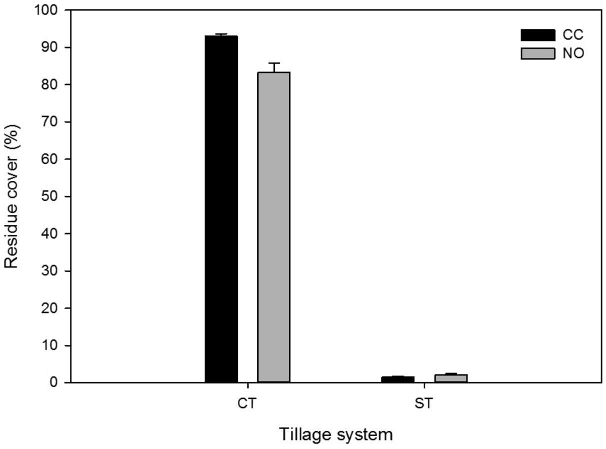

Figure 1. Residue cover (%) at the start of the cotton planting system study in Five Points, CA, May 2010

Figure 2. Cover crop seeding using Sunflower 3-m no-tillage grain drill into cotton, tomato and previous cover crop residue in Five Points, CA

Figure 3. Cotton plants established in no-tillage with cover crop experimental system in Five Points, CA

Plant population was affected by year, but tillage and cover crop had no effect (Table 3). There were no significant year X tillage, year X cover crop, or year X tillage X cover crop interactions. Higher numbers of plants per hectare were achieved in 2013 than in 2011 (111,624 vs 99,587) despite similar seeding rates used for both years (Fig. 4). The plant populations achieved in both years for all treatments were within the optimal range of 74,000 to 123,000 plants /ha according to guidelines established by the UC Cooperative Extension for cotton (Kerby et al., 1996). Measurements of cotton plant height in 2011 showed no differences between tillage or cover crop systems (data not shown).

Average lint yields combined over the four years of the study were similar between ST and NT (1481.4 vs 1484.2 kg ha^{-1}) systems, however, the average yield with NO was higher than with CC (1526.1 vs 1440.0) (Table 2). However, due to the interactions that are shown in Table 4, data were sorted by year and analyzed separately (Table 5).

Table 3. Cotton plant populations (means ± standard errors) 2011 and 2013 in Five Points, CA

	2011, 22 June (#plants ha^{-1})	2013, 29 May (#plants ha^{-1})
Standard tillage no cover crop	75,083 ± 5,738	115,718 ± 14,016
Standard tillage with cover crop	109,220 ± 4,586	107,673 ± 8,178
No-tillage no cover crop	114,790 ± 3,760	126,856 ± 9,282
No-tillage with cover crop	93,131 ± 7,850	100,248 ± 11,806

Figure 4. Cotton plants in no-tillage with cover crop experimental system in Five Points, CA

Table 4. Analysis of variance for cotton yields in STNO[z], STCC[y], NTNO[x], and NTCC[w] systems in 2010, 2011, 2012, and 2013 in Five Points, CA

Source	DF	Pr > F
Tillage	1	0.8177
Cover	1	0.0006
Year * Tillage	3	<0.0001
Year * Cover	3	0.0002
Tillage * Cover	1	0.1712
Year * Tillage * Cover	3	0.0070

[z] STNO, standard tillage no cover crop, [y]STCC, standard tillage with cover crop, [x]NTNO, no-tillage no cover crop, and [w]NTCC, no-tillage with cover crop.

In 2011, because of a tillage X cover crop interaction, comparisons were made for the cover crop vs NO crop with each tillage system. There was a difference between CC and NO within ST, but not for the NT. In the other years (2010, 2012, and 2013), because there was no tillage X cover crop interaction, the mean separations are shown for the four systems (Table 5). Lint yield was greater with the ST than with the NT system in 2010 and 2013, whereas in 2011 the opposite was true. In 2012, both tillage systems resulted in similar lint yields. Cover crop had an effect on lint yield only in 2011 (Table 5). The interaction in 2011 was because the presence of cover crops resulted in reduced lint yield in the ST system but not in the NT system.

As reported for the earlier phase of this study, lower yields in the NT system were due to our inability to secure good stands of vigorous cotton seedlings. However, in the four years of this study, this was probably not a factor contributing to yield differences as plant populations were similar between the two tillage systems. Observations early in the season in 2010 and 2013 indicated weaker plant vigor in the NT than in the ST systems. Although the reason for this phenomenon is not known, weaker plant vigor also was noted by Mitchell et al. (2008) and they attributed it to poorer seeder performance in the presence of CC in the NT system. As mentioned earlier, cover crop did not benefit the crop directly in terms of lint yield; however, there might be other benefits of cover crops that are not reported here but are discussed later. Shrestha et al. (2015) reported that from a long-term perspective, presence of cover crops in this cotton-tomato rotation resulted in increased number of weed seeds in the soil seedbank because of lack of weed control practices during winter allowing the weeds to set seeds. In the same study, the 2011 data showed that weed density in the cotton plots in June was greater in the ST than in the NT system (190 vs 61 plants m^{-2}, respectively). Therefore, this difference in weed density in 2011 could have resulted in reduced lint yield in ST compared to the NT system (Table 5).

Table 5. Cotton yields for standard tillage (ST) and no-tillage (NT) with (CC) and without (NO) cover crops in 2010, 2011, 2012, and 2013 in Five Points, CA

Treatment	2010	2011	2012	2013
Tillage				
NT	**1436.9b[z]**	**1632.6a**	**1443.9**	**1425.4b**
ST	**1561.8a**	**1391.9b**	**1422.5**	**1549.4a**
Cover crop				
Cover	**1493.0**	**1371.9b**	**1414.0**	**1481.1**
No cover	**1505.6**	**1652.6a**	**1452.4**	**1493.6**
NTCC	**1416.0**	**1571.8**	**1428.3**	**1404.8**
NTNO	**1457.8**	**1693.5**	**1459.5**	**1446.0**
STCC	**1570.0**	**1172.0b[y]**	**1399.8**	**1557.5**
STNO	**1553.5**	**1611.8a**	**1445.3**	**1541.3**
		Significance level (Pr > F)		
ANOVA		***P*-values**		
Tillage	**	**	NS	**
Cover crop	NS	**	NS	NS
Tillage X Cover crop	NS	*	NS	NS

[z] Means within a column with different letters are significantly different according to the pdiff option.

[y] Difference was significant between the CC and NO treatment only under ST.

****Significant at 0.01 level.**

***Significant at 0.05 level.**

Our previous work for cotton as well as for other crops common in the SJV suggests that because tillage costs are a relatively small part of overall production costs, the savings gained by converting to NT practices tend to be relatively modest, typically on the order of \$62 ha^{-1}, or approximately 14 to 18% of overall costs compared to standard operations (Mitchell et al., 2006). Thus, our findings suggest that for NT practices to be used at a wider scale in California, learning curve lessons particularly with respect to seeding and stand establishment must be mastered to enable adequate plant populations for desired yields so as to offset the inherent risk of converting to NT. This was achieved in our study as there were no differences in the plant population between the two tillage systems during our study compared to our own results in the initial years of such studies in the SJV.

There are, however, other system externalities such as improved water-use efficiency that might be achieved by sustained NT, high residue approaches (Mitchell et al., 2012). If, for example, cotton is NT seeded with zero disturbance into high residues that might be generated over time through strategic rotations and the use of cover crops, these residues and the reduced soil disturbance that comes with NT might theoretically reduce soil water evaporation by as much as 15%, or about 11 cm during a typical summer cropping season (Mitchell et al., 2012). There are other additional ecosystem services (Schipanski et al., 2014) associated with NT and CC practices for cotton production in the SJV that might add to the attractiveness of these alternative practices, provided yields are maintained. Although not reported here, our companion work on changes in soil properties and function that has paralleled the cotton agronomic performance findings that we report here has documented several distinct improvements in a number of soil health attributes including increased soil C and N (Mitchell et al., 2015), aggregation, infiltration, and biological activity (Mitchell et al., In Review). These added benefits of the NT and CC systems could encourage broader adoption of these practices in the future.

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