Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA

Abstract

The impact on soil health of long-term no-tillage (NT) and cover cropping (CC) practices, alone and in combination, was measured and compared with standard tillage (ST) with and without cover crops (NO) in irrigated row crops after 15 years of management in the San Joaquin Valley (SJV) CA, USA. Soil aggregation, rates of water infiltration, content of carbon, nitrogen, water extractable organic carbon (WEOC) and organic nitrogen (WEON), residue cover, and biological activity were all increased by NT and CC practices relative to STNO. However, effects varied by depth with NT increasing soil bulk density by 12% in the 0 – 15 cm depth and 10% in the 15 – 30 cm depth. Higher levels of WEOC were found in the CC surface (0 – 5cm) depth in both spring and fall samplings in 2014. Surface layer (0 – 15 cm) WEON was higher in the CC systems for both samplings. Tillage did not affect WEON in the spring, but WEON was increased in the NT surface soil layer in the fall. Sampling depth, CC, and tillage affected 1-day soil respiration and a soil health index assessment, however the effects were seasonal, with higher levels found in the fall sampling than in the spring. Both respiration and the soil health index were increased by CC with higher levels found in the 0 – 5 cm depth than in the 5 -15 and 15 – 30 cm depths. Results indicated that adoption of NT and CC in arid, irrigated cropping systems could benefit soil health by improving chemical, physical, and biological indicators of soil functions while maintaining similar crop yields as the ST system.

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Keywords

No-tillage, soil health, cover crops, arid regions, conservation agriculture

Acknowledgements

This study was sponsored by the USDA National Research Initiative from 1999 – 2003, the California Tomato Research Institute, and the University of California Kearney Foundation of Soil Science. We thank the two anonymous reviewers and the Editor of Soil and Tillage Research for their constructive comments.

1. Introduction

Soils are a finite natural resource that are nonrenewable under agricultural production without implementation of sustainable management practices (SSSA, 2015). Since the publication of '*Soil Quality, A Concept, Definition, and Framework for Evaluation (A Guest Editorial*)' by Karlen et al. (1997), and the pointed rebuttal, '*Reservations Regarding the Soil Quality Concept*,' by Sojka and Upchurch (1999), an energetic and at times acrimonious debate has been waged between proponents and critics of the concept of soil quality, or more recently, the related concept of soil health. Supporters point to the urgent needs, globally, to protect soils to ensure food security and ultimately human security (Wall and Six, 2015; Amundson et al., 2015). Skeptics argue, however, that relationships between soil attributes and how a given soil functions are poorly understood, that it is difficult to apply soil health practices broadly across diverse environments, and that the entire notion of soil health is abstract, particularly in regions like California where farmers achieve some of the highest crop yields, and yet soil quality assessments generally indicate low inherent quality (Andrews et al., 2002; Sojka and Upchurch, 1999).

Soil carbon (C) is one of the more important soil quality indicators that influence a variety of soil functions including nutrient and moisture retention (Hudson, 1994; Bettner, 2012). In California (Figure 1), intensive tillage, irrigation practices, and a hot, arid environment limit the potential to accumulate organic C in soil. Intensive irrigation practices over the past 60 years have led to an average increase of 1 to 1.3% soil C in agricultural soils, likely through the increases in crops yields and associated residue inputs as well as changes in the types and variety of crops grown (DeClerck and Singer 2003). Though challenging in hot, arid environments, increasing soil C above what can be gained through in increased crop productivity due to irrigation practices can be achieved through increased crop residue inputs, particularly from cover crops (Clark et al., 1998; Mitchell et al., 2015). The benefits of cover crop (CC) practices include more productive soil, increased water use efficiency, reduced disease and pest pressure, and other ecosystem services (Follett, 2001; Alcantura et al., 2011; Ruiz-Colmenero et al., 2011; Schipanski et al., 2014).

Adoption of cover crops and no-tillage (NT) to increase soil quality and health has been difficult to promote in the California agricultural community (Mitchell et al., 2007; Mitchell et al., 2015). Crop yields in the state are on an ever-increasing trajectory due to sustained breeding and genetic improvement efforts, a number of parallel advances in production technology including particularly the adoption of precision micro-irrigation systems, giving little incentive to consider indicators of soil health (Mitchell et al., 2012; Phene, 2010). For example, tomato yields have increased by 50-80% with the adoption of subsurface drip irrigation (Hartz and Bottoms, 2009). Regardless of the demonstrated and perceived benefits of cover crops, the majority of growers do not adopt them due to costs of establishment and management, risk associated with timing of planting of cash crops, and other issues related to their compatibility with residue management and irrigation practices. Further, many are concerned that practices currently adopted to promote soil health approach are not relevant to the climate and crops of California because these practices were developed for rainfed, commodity crop farming systems with a winter fallow period and with typically higher soil organic matter (SOM) levels (Personal communication, T.K. Hartz). With the state's diverse base of high-value crops (CDFA, 2012) and given high yields achieved with existing management practices over the past century, there has been little incentive to explore and/or adopt soil health principles in California crop production. Furthermore, the value of the concept of soil quality or soil health in guiding soil research and conservation policy has been questioned (Sojka and Upchurch, 1999). If these practices are ever to be adopted, they need to be show value and also be achievable (Pannell et al., 2006).

Progress to identify general and unifying concepts linking specific agricultural management practices and soil function continues to advance (Ferris and Tuomisto, 2015) as does our ability to monitor and assess changes in soil health (SQI, 2001; Doran and Jones, 1996; Haney et al., 2008, 2010). Obade and Lal (2016), however, point out that "a universal model that quantifies soil quality remains elusive" because it cannot be directly measured and is only inferable by determining soil physical, chemical, and biological properties. Various minimum data sets (Franzluebbers, 2010) and measurement techniques (Haney et al., 2012; Obade and Lal (20160 have been proposed as means for achieving sensitive, easy to measure, and cost-effective indicators of soil health. Comparisons of these assessment tools with commonly-reported, traditional, volume-based assays of total soil C and N are needed (Franzluebbers, 2016). Over the past 20 years, a number of techniques or methods have been developed and used in a variety of formal assessments of various aspects of what was initially termed "soil quality," (Karlen et al., 1997), and is now generally defined as "soil health." Field monitoring procedures for infiltration (Stamatiadis et al., 1999; Liebig et al., 1996), soil aggregate stability (Herrick et al., 2001), slaking (Seybold et al., 2002), and respiration (Liebig et al., 1996) were developed. Studies comparing these field tests to standard laboratory analyses have indicated that they have sufficient accuracy and precision to be of value in providing useful information (Liebig, Doran and Gardner, 1996; Herrick et al., 2001). Several of these field assessment tools have been combined by the USDA NRCS (2013) and have been used in a variety of evaluation context (Franco-Vizcaino, E. 1996; Parkin et al., 1996). Given that roughly 36 to 40% of our planet consists of arid lands and many of these soils support critical food production (White et al., 2009), it is particularly important to develop practices and assessment tools for improving soil function in these areas (Neary et al., 2002; Ladoni et al., 2010) and for providing reliable, inexpensive techniques for monitoring the performance of management efforts aimed at this goal.

The long-term University of California Conservation Agriculture (CA) Systems Project (UCCASP) was initiated in the fall of 1999 by a group of San Joaquin Valley (SJV) farmers, USDA Natural Resource Conservation Service (NRCS), private sector, and university partners to measure changes in soil and crop productivity with implementation of cover crops and NT in California's arid SJV. The original intent was to investigate farming practices that would reduce particulate matter emissions and increase soil C relative to the historically high soil disturbance practices that had been used in the region for over 80 years (Mitchell et al., 2015). At that time, NT practices were used on less than 2% of annual crop acreage in the SJV (Mitchell et al., 2007) and informal estimates indicated that the extent of cover cropping was at similar low levels of adoption. Results from the project demonstrated that cover crop inputs and reduced tillage resulted in much lower soil disturbance and increases in SOM (Mitchell et al., 2006, 2008, 2009; Veenstra et al., 2007). Various aspects and findings of the early stages of this long-term study including the ability of NT systems to increase soil C and N (Veenstra et al., 2006, 2007; Mitchell et al., 2009), reduce dust emissions (Baker et al., 2005) and production costs (Mitchell et al., 2009) and provide biomass to the soil via CC inputs (Mitchell et al., 2015) have been previously reported. Dust production was reduced by about 70% by the NT no cover crop (NO) treatment relative to the standard tillage (ST) NO system (Baker et al., 2005), soil C stocks increased with adoption of CC and NT (Mitchell et al., 2015), and computed values of the USDA Natural Resources Conservation Service (NRCS) soil conditioning index predicted SOM increases under NT and decreases under ST management (Mitchell et al., 2015).

The widespread adoption of subsurface drip irrigation in California over the past decade has increased the feasibility of adoption of reduced tillage systems because there is less need to disturb soil compared to surface irrigation systems. Because of these increased opportunities, it is especially important to evaluate and possibly modify indicators of soil health in irrigated, arid agricultural systems such as found in the SJV. Our objectives were to measure changes in soil properties and processes to provide a framework for assessing indicators of soil health in a long-term tomato (*Solanum lycopersicum* L.)-cotton (*Gossypium hirsutum* L.) rotation study (1999 to

2014) measuring different tillage (standard and no-tillage) and cover crop (with and without) systems. We hypothesized that long-term cover cropping and NT would result in changes in soil health as measured by a variety of recently-introduced soil physical, chemical and biological assays.

2. Methods

2.1 Site

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). Soils are Panoche clay loam (fine-loamy, mixed superlative, thermic Typic Haplocambids) (Arroues, 2006). Average monthly maximum and minimum temperatures are provided in Table 1. In 1998 before the study began, 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 may have existed due to previous research.

2.2 Cropping systems descriptions

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 (Baker et al., 2005). A tomato-cotton rotation was planted in one half, and a cotton-tomato rotation in the other half so that both entry points were represented each year from 2000 to 2013. To better achieve the conservation agriculture goal of crop rotation diversity (Mitchell et al., 2015), the systems were changed to sorghum (*Sorghum bicolor*) and garbanzo beans (*Cicer arietinum*) in 2014 (Mitchell et al., 2016). Management treatments included a factorial arrangement of tillage and CC, including 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 in 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. Both the ST and the NT systems were previously described in detail (Veenstra et al., 2006; Mitchell et al., 2015) and in summary consisted of conventional intercrop tillage operations of residue shredding, multiple diskings to incorporate residues to a depth of 20 cm, use of a subsoiling shank before the tomato and cotton crops to a depth of about 30 - 45 cm, additional disking to 20 cm to break up soil clods created by the subsoiling shank following tomatoes, listing of beds, and power incorporation of the surface 10 cm of soil using a cultimulcher (BW Implement, Buttonwillow, CA) which is a PTO (power take off)-powered aggressive tillage operation that pulverizes the surface 20 cm of soil creating a fine, powdery seed bed for both the STNO and the STCC systems. Conventional intercrop tillage practices that break down and establish new beds following harvest were used in the CT systems. The NT 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 NT systems, and planting beds were not moved or destroyed in these systems during the entire study period. Following this series of tillage operations that were used in the ST systems, percent surface residue amounts averaged typically over 90 for the NTCC, between 40 and 70 for the NTNO, between 10 and 20 for the STCC, and below 5 for the STNO (Mitchell et al., 2015). The only soil disturbance operations used in the NT systems were shallow cultivation during the first eight years for the tomato crops. As the project progressed, the NT treatments became true no-tillage systems in 2012 with the only soil disturbance occurring at the time of seeding or transplanting. While there were some shallow weed cultivation disturbance during the early years of the study, we believe that the term "no-tillage" most aptly characterizes this tillage system and is a better descriptor than any of the alternatives such as "reduced," "minimum," or "conservation tillage" that have been used (Reicosky, 2015, Mitchell et al., 2012).

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 NPK) applied preplant 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 four weeks after transplanting.

The RoundUp Ready™ transgenic upland cotton variety '*Riata*' was used from 2000 - 2007 in all cotton systems and was established using a 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 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.

The tomato and cotton crops were furrow irrigated from 2000 – 2012. In keeping with trends in the region toward more efficient systems, however, the study site was converted to subsurface drip irrigation in 2013 with 34 mm diameter tape buried 30 cm in the centers of each 150 cm-wide planting bed. Installation of the drip tape at this time constituted a tillage operation to all systems. 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; Hanson and May, 2006) was used to schedule furrow irrigations of both crops 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 71 cm ha^{-1} for tomato and 61 cm ha^{-1} for cotton, which are close to historical estimates for ETc and commercial application volumes in the region (Hanson and May, 2006).

A CC mix of Juan triticale (*Triticosecale* Wittm.), Merced rye (*Secale cereale* L.) and common vetch (*Vicia sativa* L.) was seeded using either a 5-m John Deere 1530 no-tillage single-disc opener seeder (Moline, IL) or a 5-m Sunflower 1510 double-disc opener no-till drill (Beloit, KS) at 19 cm row spacing and at a rate of 89.2 kg ha^{-1} (30% triticale, 30% rye and 40% vetch by weight) in late October in the STCC and NTCC plots and irrigated once with 10 cm of water in 1999 and again with 5 cm in 2012 and 5 cm in 2014. The legume species was inoculated with 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. Between 2010 and 2014, the basic CC mixture was changed to include a greater diversity of species including pea (*Pisum sativum* L.), faba bean (*Vicia faba* l.), radish (*Raphanus sativus*), and Phacelia (*Phacelia tanacetifoli*) (Mitchell et al., 2015). Cover crop biomass was determined in mid-March of each year of the study by harvesting all aboveground plant material in a 1 m^2 (11 ft^2) random area in each plot, drying the material to constant weight, and weighing (Mitchell et al., 2015). Percent surface residue was determined using the line-transect method on April 20, 2004, December 18, 2009, and August 10, 2014 (Bunter, 1990).

2.3 Soil and Plant Analysis

Soils were sampled in 1999 and 2014 at two depths (0 to 15 cm and 15 to 30 cm) in the fall after harvest. In each plot, six to eight 7.6-cm-diameter cores per depth were composited before air drying, sieving through a 2 mm sieve and grinding using a soil pulverizer to pass through a 60 mesh screen, and dried to constant weight according to protocols of the University of California, Davis Analytical Laboratory (http://anlab.ucdavis.edu/sampling/soil-sampling-and-preparation). Total C and total N were measured using a combustion C analyzer (CE Elantech, Inc., Lakewood, NJ). Bulk density was measured by the compliant cavity method (USDA NRCS, 2004) for the two depths in 2014. To calculate total C and N in 1999, the bulk density (BD) that had been measured for STNO treatment in 2003 was taken and it was assumed that all plots at this time, before the start of the experiment, were the same. Surface soil water stable aggregate percentages, slaking, and water infiltration were determined in 2012 using USDA NRCS Soil Quality Test Kit procedures (USDA, 1999) with eight, ten, and four subsamples per plot for each of these assays, respectively (Soil Quality Institute, 2001). Soil water infiltration was determined using a single ring (15 cm diameter) inserted into the soil to a depth of 7.5 cm. A volume (400 ml) equivalent to 2.54 cm of water was applied to the surface soil in the ring and the time required for infiltration was recorded. Aggregation was determined by gradually wetting and subsequent immersing of a known weight of 2 mm soil aggregates followed by reweighing, dispersal using sodium hexametaphosphate, and a final reweighing. Slaking was assessed by visually determining the stability of soil aggregates exposed to rapid wetting using 1.5 cm diameter sieves. In spring and fall of 2014, soil samples at 0 – 5 cm, 5 – 15 cm, and 15 – 30 cm depths were collected to determine water extractable organic C (WEOC) and water extractable organic N (WEON) and 1-day CO_2-C respiration using procedures developed as part of the Soil Health Index (SHI) (Haney, 2015). These values are then used to calculate a soil health index according to:

$$\mathrm{SHI} = \frac{\text{1-day } \mathrm{CO_2\text{-}C}}{\mathrm{C{:}N} + (\mathrm{WEOC}/100 + \mathrm{WEON}/10)}$$

(Haney, 2015). Throughout the entire long-term study, soils were consistently sampled in the fall, typically following postharvest tillage operations (Mitchell et al., 2015), however, we also added a spring sampling in 2014 in an effort to compare data during the spring when soil water contents are higher than they are in the fall.

In fall 1999, soil C, N, pH, electrical conductivity (EC), K, and P (Dhainaut, 2015) and texture (Baker et al., 2005) were measured. Results indicated that the study field was relatively uniform with respect to these properties except texture (Baker et al., 2005). Soil particle size analysis showed a distinct texture gradient from south to north across the field. Textures varied from clay loam (32% clay, 33% silt, 35% sand) at the south end (13m) to sandy clay loam (23%, clay, 23% silt, 54% sand) at the north end (360 m). Although the soil is mapped as Panoche clay loam, our data indicated a variation from the named soil phase within the field and demonstrate the natural variability inherent in soils at this level of mapping. We do not have baseline data for infiltration or aggregate stability; however, based on the uniformity of cropping patterns and the ST management across the field for decades prior to our experiment, we believe that pre-existing differences in these processes across our test plots were minimal.

2.4 Statistical Analysis

Data were analyzed using PROC Mixed procedures with tillage and CC 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 years 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. Prior to the analysis, assumptions of ANOVA were tested. Data for total C and total N were log transformed for analysis to meet the assumption of homogeneity of variance. 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.

3. Results and Discussion

3.1 Cover crop biomass

Over the 15 years of the project that was characterized by recurring drought (Figure 2), a total of 56 t ha^{-1} of aboveground CC biomass representing 1,196 kg ha^{-1} of N and 21,722 kg ha^{-1} of C was produced with a total precipitation of 344 cm and 20 cm of supplemental irrigation applied in 1999, 2012, and 2014 (plus residual soil moisture following summer crops which is assumed to have been negligible). 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). Cover crop aboveground biomass was similar between tillage treatments (Mitchell et al., 2015), but tended to be higher following tomato than following cotton (Mitchell et al., 2015) presumably due to the higher residual soil N that may have been present following tomato.

3.2 Soil physical health indicators

Both CC and tillage impacted the infiltration of both the first and second 400 ml (equivalent to 2.54 cm) of applied water with faster infiltration occurring in the NT and CC systems (Table 2). The fastest infiltration rates were observed in NTCC (Table 2). When treatments were isolated, means for CC infiltration times for the first 2.54 cm of applied water were 2.8 times more rapid than with no CC (0.71 minutes CC, 1.46 minutes NO) whereas tillage produced a two-fold difference in favor of NT treatments (0.57 minutes NT, 1.6 ST). For the second 2.54 cm of applied water, CC infiltration times were 2.2 times more rapid than no CC (4.02 minutes CC, 8.69 minutes NO), and infiltration under NT was 1.4 times more rapid than under ST (5.38 minutes NT, 7.33 minutes ST).

Differences in sustained infiltration between NT and ST may have resulted from increased slaking associated with ST that could have clogged soil pores and contributed to slower infiltration rates. Slower infiltration of the second 400 ml in the NTNO treatment may have resulted from the higher soil BD of this system (Table 2). Increased infiltration rates in NT soils observed in other studies were attributed to formation of macropores, often caused by earthworms (Edwards et al., 1988), as well as to the continuity of soil pores throughout several horizons in the profile (Ehlers, 1975; Barnes, 1979; Beisecker, 1994; and Hagen et al., 2002). Increased aggregate stability under NT ensures that aggregates are less likely to slake and clog pores. Tillage disrupts pore continuity and destroys large aggregates, thereby increasing the likelihood of particle slaking and pore clogging, resulting in lower infiltration rates.

The faster initial infiltration rates observed under CC may result from development of root channels, and the absence of tillage under NT probably helps maintain these channels as relatively continuous macro- and micropores. This, in addition to a lack of disturbance of earthworm tunnels, would explain why infiltration rates were most rapid in NTCC than in the other treatments. Our prior work with NTCC systems (Herrero et al., 2001), as well as unpublished recent measurements in the UCCASP field have documented higher earthworm populations in surface NTCC soils than in STNO soils.

The NRCS Soil Quality Test Kit used in this study contains two protocols, the slake test and the aggregate stability test, that provide indications of soil stability (SQI, 2001) for surface soil layers. Both tillage and cover crops decreased slaking, a determination that is based on a visual assessment of the stability or structural integrity of soil fragments (~ 1.25 cm in diameter) upon rapid wetting. (Table 1). These relative differences among treatments seen in the slake test contrasted with results from the stable aggregate measurements. For water stable aggregates, CC was the dominant factor driving treatment differences, while the larger aggregates used in the slake test are influenced by CC, as well as tillage (Table 2). Tisdall and Oades (1982) categorize aggregate binding agents as transient (polysaccharides), temporary (roots and fungal hyphae) and persistent (resistant aromatic compounds associated with polyvalent cations). Cover crop treatments may have some advantage in generating aggregate stability due to the continuous supply of C to fungi and polysaccharide-producing bacteria throughout the year (Le Guillou et al., 2012). The larger macroaggregates as measured in the slake test are affected by CC and tillage. Tillage affects both macro- and microaggregates. The reduced rate of macroaggregate turnover under NT practices has been shown to lead to the formation of stable microaggregates in which C is sequestered and stabilized in the long term (Six et al., 2000; Six and Paustian, 2014).

While the stationary submersion slake test provides an indication of soil strength, the repeated submersions slake test and water stable aggregates test measure the integrity of soil when water flows across the surface and through pores. In these tests, and under more intense precipitation, aggregates that break apart as water flows over them and through the pore space are more likely to clog pores (Helalia et al., 1988), reducing the overall continuity of pores and impeding downward infiltration. Micro and macro-aggregate stability measurements are thus indicative of the tendency of a soil to break apart into smaller particles and cause clogging or crusting, thereby affecting water infiltration rates. In addition, although not measured in this study, we have observed evidence of earthworms and associated holes in the CC and NT systems which may have also contributed to the more rapid water infiltration in these systems (Herrero et al., 2001; Mitchell et al., 2015;).

3.2 Surface residue

Percent residue cover for the August 10, 2014 sampling is shown in Figure 3. Averaged over the three sampling times, percent residue cover was 4 (STNO), 14.7 (STCC), 67.3 (NTNO), and 92 (NTCC). In regions of the world where NT systems are common — such as Brazil, Argentina, Paraguay, Canada, Western Australia, the Dakotas and Nebraska — generating and preserving residues are an indispensable part of management and major, even primary, goals of sustainable production and of conservation agriculture systems (Dumanski et al., 2006; Crovetto, 1996, 2006). Residues can reduce erosion (Shelton et al., 2000a and b; Skidmore 1986), provide C and N to soil organisms (Crovetto 2006) and reduce soil water evaporation (Klocke et al. 2009; van Donk et al. 2010), and lower soil temperatures (Mitchell et al., 2012). Potential drawbacks of residues, however, may include difficulties with crop seeding, their harboring of seedling pests, and rodents, all of which may be serious particularly for high value vegetable crops in terms of food safety concerns.

3.3 Soil carbon, nitrogen and bulk density

Data were analyzed separately for each depth because of an interaction between depth and tillage for the variables. Year, tillage, and CC had an effect on total C and total N. However, these effects were only significant in the 0 to 15 cm for BD (Table 3). There was no interaction between year and the other variables for total C, total N and BD; therefore, data were combined for the years and analyzed. Total C and total N was greater in 2014 than in 2012 at both soil depths (Table 3). Total C was approximately 53% and 22% greater in the NT than in the ST system in the 0-15 cm and 15-30 cm depth, respectively. Total N was also 47% and 15% greater in the NT than in the ST system in the 0-15 cm and 15-30 cm depth, respectively. Similarly, BD was also 8% and 15% greater in the NT than in the ST system in the 0-15 cm and 15-30 cm depth, respectively. Total C and total N was also increased by the inclusion of cover crops at both soil depths regardless of tillage system. For example, total C was 20% and 13% greater in the CC than in the NO system in the 0-15 cm and 15-30 cm depth, respectively. Total N was 12% and 10% greater in the CC than in the NO system in the 0-15 cm and 15-30 cm depth, respectively. Soil BD, however, was greater in the plots with no cover crops at the 0-15 cm depth but this difference did not occur at the 15-30 cm depth (Table 3,). Therefore, these results showed that NT resulted in greater total C and N than the ST system, regardless of the presence of a CC; whereas, CC increased total C and N regardless of the tillage system. Other studies conducted in arid and semi-arid regions under irrigation (Munoz et al., 2007; Kong et al., 2005) have shown similar increases in soil C with cumulative C inputs. Kong et al. (2005) reported a direct relation between soil C stabilization and aggregation with C inputs from crop residue and added C amendments. Munoz et al. (2007) similarly showed increases in C, N, aggregate stability, water content, and total culturable microorganisms with direct seeding and direct seeding with winter cover crops.

3.4 Soil Health Assessment Index

Soil depth was a significant factor for each determination in both the 2014 spring and fall SHI samplings with generally higher values for each assay associated with shallower soil depth (Tables 5a and b). This enrichment of nutrients, organic matter, and biological activity in surface layers in soils transitioning to no-till and high residue conditions as in the NT systems and in particular, in the NTCC systems, is quite common (Crovetto, 1996, 2006; Franzluebbers, 2002). In the CC systems, respiration, water extractable organic C and N, and the overall SHI were higher than in the other treatments. Both spring and fall respiration (1-day CO_2 evolution) was sorted by depth and then analyzed further because of interactions that occurred within both datasets (Tables 4a and b). In the top (0 – 5 cm) depth, higher 1-day CO_2 evolution values were found in the CC systems in the spring most likely due to an actively growing root which would add an easily mineralizable C source upon which the microbial biomass could feed, and with both the CC and NT in the fall due to increased temperature from the summer months. Cover crop raised respiration in both the 5 – 15 cm and the 15 – 30 cm depths in both spring and fall. Soil WEOC was highest in the NT systems. Since WEOC is a subset of the SOM, it follows that WEOC is higher in the NT system as is total C. However, WEOC is likely a more precise measurement of the immediate potential activity of the soil microbes since WEOC is the C pool that is readily acted upon by the soil microbes (Haney et.al. 2012).

In the fall, both CC and NT resulted in higher surface (0 – 5 cm) WEOC again due to the higher summer temperatures, but in the spring, only the presence of CC led to higher WEOC in the shallow, 0 – 5 cm depth with active roots providing the enhanced C values. For the 5 – 15 cm depth, CC systems were again higher than the no CC systems for both samplings, but in the spring, ST systems had slightly higher WEOC levels than the NT systems, though an opposite trend surfaced in the fall. At the 15 – 30 cm depth, CC resulted in higher WEOC levels in both the spring and fall samplings with the ST system having higher levels at this depth in the spring only.

The interactions indicated in Tables 5a and b, required that WEON data be sorted and analyzed by depth. Cover crop resulted in higher WEON at all three depths for both samplings and there was no impact of tillage system at any depth. The ratio of WEOC: WEON was lower in the CC systems at 5 – 15 cm and 15 – 30 cm layer in the spring reflecting lower C levels in the CC systems. The ratio was also lower in the ST than NT systems in fall 2014, in the 0 – 5 cm depth, but there were no other differences observed in any other depths.

Several interactions among factors were observed for the SHI, thus, data were sorted and analyzed by depth for both the spring and fall datasets. Overall, SHI values were higher in fall 2014 than spring again due to higher temperatures from spring to fall as opposed to fall to spring. Cover crop systems had higher SHI values than NO treatments at all depths for both sampling times with the greatest differences in the shallowest (0 – 5 cm) depth which is not surprising since the SHI is calculated from respiration, WEOC and WEON. The spring and fall samplings differed, however, with respect to the impact of tillage. In the spring, the NT systems had higher values in the shallow than in the 15 – 30 depth, whereas in the fall, NT had higher SHI values in both the shallow and 15 – 30 cm depths, however, the difference between treatments was less evident in the deeper than shallower depth.

There was no significant relationship between total C and WEOC or total N and WEON at either depth (0 – 15 cm of 15 – 30 cm) for the spring 2014 sampling. However, the factors were correlated in the fall sampling ($p=0.04$), although the r^2 values were relatively low (0.54 and 0.32 for the 0 – 15 cm and 15 – 30 cm C data, and 0.44 and 0.45 for the N data at 0 – 15 cm and 15 – 30 cm).

Our data from the SHI reveal that sustained cover cropping may have pronounced effects on soil health and also on the generally more surface-related improvements that were seen in the NT systems. Our dataset thus serves as a test or application of the SHI and other determinations of soil physical functions provided by the NRCS Soil Quality Test Kit in conjunction with standard laboratory determinations of soil total C and N as a potential battery of soil health diagnostic indicators that may be useful in monitoring efforts aimed at determining time-course changes in soil function.

Yield data for the systems that were evaluated in this long-term study have been reported previously for 2000 to 2009 (Mitchell et al., 2015), and for 2010 to 2014 (Mitchell et al., 2016; Mitchell et al., In press). For the 2000 – 2009 period, tomato yields were 9.5% higher in the NT vs. ST systems and 5.7% higher in NO vs. CC systems. The ST cotton yields were 10.0% greater than NT yields and 4.8% greater in NO systems overall from 2000 to 2009, but yield patterns were not consistent from 2005 to 2009, and there were no yield differences between systems for cotton from 2010 to 2013. The specific differences in yields among the tillage and CC systems resulted, we believe, from various ‘learning curve” challenges that the alternative management approaches posed including stand establishment difficulties of the transplanted tomatoes into CC surface residue and also for cotton plant establishment into residues during the early years. Yield data for sorghum in 2014 and 2015 were combined as there were no interactions between the years and treatments. Tillage or CC had no effect on grain yield indicating that similar yields can be achieved with NT as with ST (Mitchell et al., 2016). The lack of a yield reduction with CC was an important finding because soil moisture depletion by cover crops in semi-arid and arid areas is a concern for subsequent crops (Mitchell et al., 2015). These results indicate that attention to maintaining yield stability as a part of the transition to improved soil health is a critical aspect (Lundy et al., 2015; Pittelkow et al., 2015). They also suggest that the several presumed indicators of improved soil function, or health, (infiltration, aggregation, resistance to slaking, respiration, and both total and WEOC and WEON) that were found in this study with NT and CC, did not necessarily result in increased crop yields. There may, however, be other important metrics for gauging the overall value of these practices in this region including lower production costs, reduced inputs, water conservation, higher amounts of C and N production and storage in the crop/soil system, as well as the ability to lower dust or particulate matter emissions (Baker et al., 2005; Madden et al., 2008).

After 14 years of the tillage and CC treatments, soil C content in the 0 – 30 cm depth increased relative to the initial condition in 1999 for all treatments (Mitchell et al., 2015). Initial soil C averaged 19.72 t ha^{-1} in 1999 for all treatments. The NTCC treatment had the greatest net increase in soil C with 29.1 t ha^{-1} more in 2014 than in 1999, followed by the NTNO with 21.6 t ha^{-1}, the STCC with 16.8 t ha^{-1},and the STNO system with 11.5 t ha^{-1} additional C.

4. Conclusions

In sum, cover cropping and NT practices positively affect soil health in California's SJV. Though this response is expected in rainfed and humid systems, the magnitude of the response is not well established for arid irrigated agricultural systems. Our results showed that CC and NT practices can have a large impact on soil health in arid, irrigated agricultural systems without directly influencing immediate crop yields. This may be a positive attribute as popular belief in the SJV is that NT and CC systems are detrimental to crop yields. When considered in the aggregate, our data point to significant functional benefits being derived from the overall improvements in soil chemical, physical and biological properties and reinforce the value of future efforts to expand the adoption of conservation agriculture systems in the region to improve soil health. Information developed by this study may be useful to farmers in California's SJV who have lacked data on cost-benefit tradeoffs associated with CC and NT practices. Our findings may also be relevant for other similar regions in which there is interest in adopting these practices to achieve food security and sustainability goals.

Figures

Figure 1. Map of California’ San Joaquin Valley in western United States. ■ indicates approximate location of Five Points, CA

Figure 2. Total annual precipitation (1999 to 2014) and the 30-year average (represented by the dotted line) at the University of California, West Side Research and Extension Center, Five Points, CA.

Figure 3. Percent surface residue in August 2014 for tillage and cover crop treatments in Five Points, CA. Bars with the same letter within each tillage system are not significantly different according to Fisher’s LSD test at 0.05 level. Analysis was conducted on arcsine square root transformed data.

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Table 1. Thirty-year average monthly maximum and minimum temperatures (^oC) for Five Points, CA

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
average maximum temperatures	13.4	17.3	20.9	24.3	29.5	33.1	35.5	34.9	32.1	26,7	18.7	13.3
average minimum temperatures	3.9	5.2	6.8	8.8	12.2	14.8	17.2	16.8	14.8	10.6	5.9	3.3

Table 2. Determinations of soil water infiltration, slaking, and water stable aggregates using the USDA NRCS Soil Quality Test Kit for standard tillage (ST), no-tillage (NT), with cover crop (CC) and without cover crops (NO) in Five Points, CA

Source of variation	Infiltration 1st 400 ml[*]	Infiltration 2nd 400 ml	Slaking after 5 min	Slaking[†] after 5 dips	Water stable aggregates
	(min)	(min)			(%)
Tillage					
ST	1.46 a[††]	7.33 a	2.13 b	3.89 b	50
NT	0.71 b	5.38 b	2.70 a	5.01 a	51
Cover crop					
CC	0.57 b	4.02 b	2.62 a	5.09 a	57 a
NO	1.60 a	8.69 a	2.20 b	3.81 b	44 b
STNO	2.07	8.29	1.94	3.19	41
STCC	0.86	6.37	2.31	4.59	58
NTNO	1.13	9.10 A°	2.47	4.44	46
NTCC	0.28	1.67 B	2.92	4.58	57
P-values					
Tillage	0.0030	0.0036	<0.0001	<0.0001	0.9313
Cover crop	0.0036	0.0007	0.0023	<0.0001	<0.0001
Tillage*Cover crop	0.6785	0.0109	0.8177	0.7940	0.4621

[*] Soil water infiltration determined using 15 cm diameter ring with a measured area of 176.9 cm^2

[†] Soil stability class visual ratings (1-6, with indicating greater stability) using the USDA NRCS Soil Quality Test Kit (2001).

[††] For tillage and cover crop systems main effect, means followed by the same lowercase letters within columns are not significantly different according to LSD (0.05).

° For the 2nd 400 ml infiltration, significant difference occurred between the NTNO and NTCC treatments but not between STNO and STCC treatments as denoted by the uppercase letters based on LSD (0.05) test.

Table 3 Soil carbon (C), nitrogen (N), and bulk density for standard tillage (ST) and no-tillage (NT) systems with (CC) and without (NO) cover crops at 0 – 15 cm and 15 – 30 cm depths (combined for fall 2012 and 2014) in Five Points, CA

Source of variation	Total C	Total N	Soil bulk density
	g cm^{-3}	g cm^{-3}	g cm^{-3}
Soil depth (0 – 15 cm)			
Year			
2012	16.43 b†	1.84 b	1.13 b
2014	22.53 a	2.48 a	1.18 a
Tillage			
ST	15.42 b‡	1.75 b	1.11 b
NT	23.55 a	2.57 a	1.20 a
Cover crop			
CC	21.24 a‡	2.32 a	1.13 b
NO	17.73 b	2.00 b	1.18 a
STNO	13.90	1.61	1.13
STCC	16.95	1.90	1.09
NTNO	21.56	2.39	1.24
NTCC	25.53	2.75	1.17
ANOVA			
		P-value	
Year	<0.0001	<0.0001	0.0350
Tillage	<0.0001	<0.0001	0.0001
Cover crop	0.0017	0.0026	0.0191
Year X tillage	0.6592	0.5107	0.8519
Year X cover crop	0.9200	0.9649	0.3052
Tillage x cover crop	0.0579	0.6491	0.3839
Year X tillage X cover crop	0.9005	0.7397	0.4871
Soil depth (15 – 30 cm)			
Year			
2012	13.83 b†	1.71 b	1.45
2014	16.92 a	2.05 a	1.45
Tillage			
ST	14.43 b‡	1.75 b	1.35 b
NT	16.33 a	2.01 a	1.55 a
Cover crop			
CC	16.28 a‡	1.97 a	1.45
NO	14.47 b	1.79 b	1.45
STNO	13.23	1.64	1.36
STCC	15.62	1.87	1.35
NTNO	15.72	1.94	1.55

NTCC	13.23	2.08	1.55
ANOVA			
		P-value	
Year	<0.0001	<0.0001	0.8408
Tillage	0.0026	<0.0001	<0.0001
Cover crop	0.0038	0.0041	0.8505
Year X tillage	0.9644	0.6672	0.0594
Year X cover crop	0.6408	0.9461	0.5014
Tillage x cover crop	0.1825	0.2823	0.8192
Year X tillage X cover crop	0.7167	0.7238	0.3028

Table 4. Analysis of variance table for Soil Health Tool determinations of 1-day respiration, water extractable organic carbon, water extractable organic nitrogen, the ratio of water extractable carbon to nitrogen, and the soil health calculation for standard tillage (ST), no-tillage (NT), with (CC) and without (NO) cover crops at 0-5 cm, 5-15 cm, and 15-30 cm soil depths in Five Points, CA in the spring and fall of 2014.

Source of variation	1-day CO_2-C	Organic C	Organic N	Organic C:N	Soil Health Calculation
			P-values		
Spring 2014					
Tillage	0.9082	0.0155	0.8157	0.0510	0.0781
Cover crop	<0.0001	<0.0001	<0.0001	0.0002	<0.0001
Depth	<0.0001	<0.0001	<0.0001	0.0702	<0.0001
Tillage x cover crop	0.7040	0.3405	0.0317	0.0128	0.0456
Tillage x depth	0.0909	0.0009	0.4475	0.3655	0.1859
Cover crop x depth	<0.0001	0.0024	0.0294	0.7946	<0.0001
Tillage x cover crop x depth	0.0989	0.8405	0.6011	0.2528	0.6056
Fall 2014					
Tillage	<0.0001	<0.0001	<0.0001	0.0077	<0.0001
Cover crop	<0.0001	<0.0001	<0.0001	0.1473	<0.0001
Depth	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Tillage x cover crop	<0.0001	0.0024	0.0009	0.0492	<0.0001
Tillage x depth	<0.0001	<0.0001	<0.0001	0.0095	<0.0001
Cover crop x depth	<0.0001	<0.0001	0.0001	0.5972	<0.0001
Tillage x cover crop x depth	<0.0001	0.0011	0.0101	0.4049	<0.0001

Table 5a. Soil Health Tool determinations of 1-day respiration water extractable organic carbon, water extractable organic nitrogen, the ratio of water extractable carbon to nitrogen, and the soil health calculation for standard tillage (ST), no-tillage (NT), with (CC) and without (NO) cover crops in Five Points, CA in the spring of 2014.

Source of variation	1-day CO_2-C	Organic C	Organic N	Organic C:N	Soil Health Calculation
	ppm	ppm	ppm		
Soil depth (0 – 5 cm)	31.9	267.2	21.2	14.7	8.0
Tillage					
ST	23.4†	253.5	20.4	14.6	6.9
NT	40.4	280.9	21.9	14.8	9.0
Cover crop					
CC	51.7 a‡	337.8 a	28.5 a	13.7	11.4 a
NO	12.2 b	196.5 b	13.8 b	15.7	4.6 b
STNO	11.6	187.8	12.0	18.1	4.2
STCC	35.3	319.2	28.8	11.1	9.6
NTNO	12.7	205.3	15.6	13.3	4.9
NTCC	68.1	356.4	28.3	16.3	13.2
ANOVA			*P*-values		
Tillage	0.1155	0.0901	0.4927	0.9886	0.5077
Cover	<0.0001	<0.0001	<0.0001	0.1741	<0.0001
Tillage x cover	0.0875	0.9261	0.1284	0.0294	0.2894
Soil depth (5 – 15 cm)	9.1	154.2	13.9	12.2	3.8
Tillage					
ST	10.1	170.4 a	14.6	13.6	4.2 a
NT	8.2	138.0 b	13.2	10.8	3.5 b
Cover crop					
CC	11.9 a	181.9 a	17.7 a	10.4 b	4.8
NO	6.4 b	126.5 b	10.2 b	14.0 a	2.9
STNO	7.3	136.3	10.4	16.0	3.1
STCC	13.0	204.5	18.9	11.2	5.2
NTNO	5.5	116.7	10.0	12.0	2.7
NTCC	10.8	159.3	16.5	9.6	4.3
ANOVA			*P*-values		
Tillage	0.0995	<0.0001	0.4121	0.0503	0.0051
Cover	0.0002	<0.0001	<0.0001	0.0102	<0.0001
Tillage x cover	0.8308	0.2019	0.4120	0.5572	0.2984
Soil depth (15 – 30 cm)	9.7	140.1	11.3	13.4	3.5
Tillage					

ST	11.5	154.3 a	11.9	14.9	3.9
NT	7.8	125.8 b	10.7	12.0	3.1
Cover crop					
CC	51..7 a	337.8 a	28.5 a	13.7 b	11.4 a
NO	12.2 b	196.5 b	13.8 b	15.7 a	4.6 b
STNO	6.0	131.0	8.6	17.9	2.8
STCC	17.1	177.6	15.3	11.8	5.0
NTNO	6.6	113.3	8.8	12.9	2.7
NTCC	9.0	138.3	12.6	11.1	3.5
ANOVA			*P*-values		
Tillage	0.2872	0.0033	0.3291	0.0914	0.1356
Cover	0.0165	0.0004	<0.0001	0.0118	<0.0001
Tillage x cover	0.2009	0.4490	0.1136	0.2498	0.3284

†Means within a column for tillage treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher’s LSD test at 0.05.

‡ Means within a column for cover crop treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher’s LSD test at 0.05.

Table 5b. Soil Health Tool determinations of 1-day respiration, water extractable organic carbon, water extractable organic nitrogen, the ratio of water extractable carbon to nitrogen, and the soil health calculation for standard tillage (ST), no-tillage (NT), with (CC) and without (NO) cover crops at 0-5 cm, 5-15 cm, and 15-30 cm soil depths in Five Points, CA in the fall of 2014.

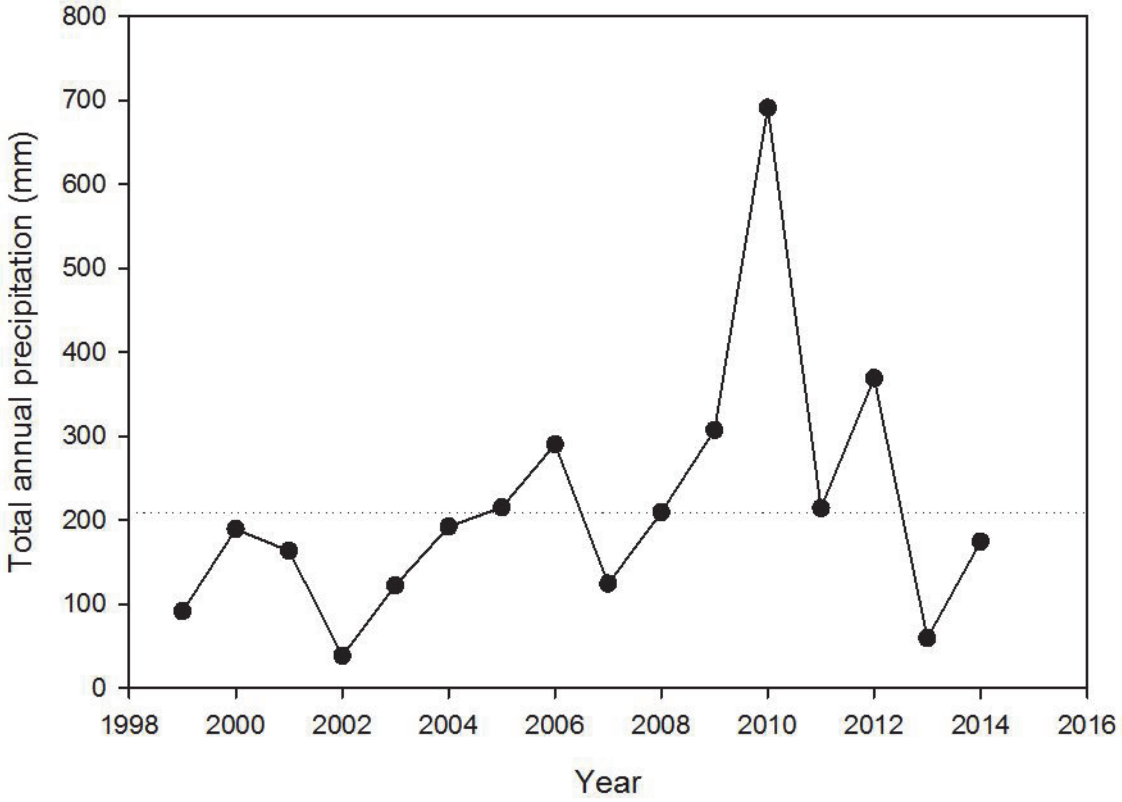
Source of variation	1-day CO_2-C	Organic C	Organic N	Organic C:N	Soil Health Calculation
	ppm	ppm	ppm		
Soil depth (0 – 5 cm)	110.4	344.3	36.5	9.4	18.1
Tillage					
ST	45.6 b†	256.1 b	29.0 b	8.8 b	10.0 b
NT	175.2 a	432.5 a	44.0 a	10.1 a	26.2 a
Cover crop					
CC	182.7 a‡	430.7 a	45.2 a	9.4	27.1 a
NO	38.2 b	257.9 b	27.8 b	9.4	9.2 b
STNO	25.0	209.7	24.7	8.5	7.1
STCC	66.2	302.5	33.4	9.0	13.0
NTNO	51.4	306.2	31.0	10.3	11.3
NTCC	299.1	558.8	57.1	9.8	41.2
ANOVA			*P*-values		
Tillage	<0.0001	<0.0001	<0.0001	0.0035	<0.0001
Cover	<0.0001	<0.0001	<0.0001	0.9904	<0.0001
Tillage x cover	<0.0001	0.0002	0.0004	0.1870	<0.0001
Soil depth (5 – 15 cm)	36.3	273.6	31.4	8.8	9.5
Tillage					
ST	34.8	254.5 b	29.8	8.5	9.0
NT	37.8	292.7 a	32.9	9.0	10.0
Cover crop					
CC	52.6 a	325.0 a	36.5 a	9.0	12.2 a
NO	20.0 b	222.2 b	26.2 b	8.5	6.8 b
STNO	19.8	209.2	26.2	7.9	6.7
STCC	49.7	299.7	33.3	9.0	11.3
NTNO	20.2	235.2	26.2	9.1	7.0
NTCC	55.4	350.3	39.7	8.9	13.0
ANOVA			*P*-values		
Tillage	0.5526	0.0337	0.1745	0.1084	0.2080
Cover	<0.0001	<0.0001	0.0002	0.2044	<0.0001
Tillage x cover	0.6046	0.4737	0.1668	0.0763	0.3687
Soil depth (15 – 30 cm)	16.4	191.9	24.0	8.1	5.9
Tillage					

ST	16.0	182.2	22.6	8.2	5.5 b
NT	16.8	201.5	25.4	7.9	6.2 a
Cover crop					
CC	18.7 a	217.6 a	26.4 a	8.3	6.7 a
NO	14.1 b	166.1 b	21.6 b	7.8	5.1 b
STNO	14.0	154.6	20.1	8.0	4.6
STCC	18.1	209.8	25.0	8.4	6.4
NTNO	14.2	177.6	23.0	7.7	5.5
NTCC	19.3	225.5	27.8	8.1	7.0
ANOVA			*P*-values		
Tillage	0.4191	0.0800	0.0517	0.4898	0.0176
Cover	<0.0001	<0.0001	0.0020	0.2157	<0.0001
Tillage x cover	0.5553	0.7322	0.9986	0.9506	0.6097

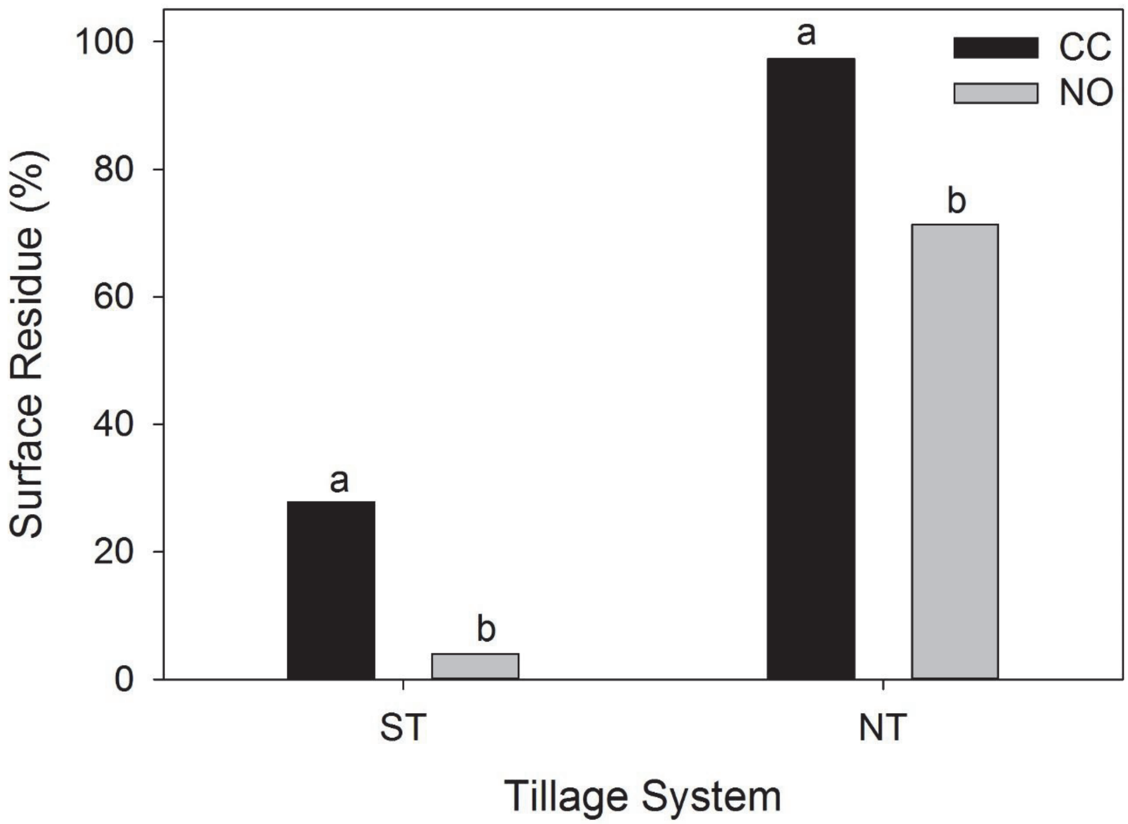
†Means within a column for tillage treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher's LSD test at 0.05.

‡ Means within a column for cover crop treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher's LSD test at 0.05.

Figure



Total annual precipitation (mm)
0
100
200
300
400
500
600
700
800
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Year



Surface Residue (%)
0
20
40
60
80
100
a
b
a
b
CC
NO
ST
NT
Tillage System