Conservation tillage supports soil macrofauna communities, infiltration, and farm profits in an irrigated maize-based cropping system of Colorado

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Abstract
In the past several decades conservation tillage systems have been introduced to address the negative impacts of intensive tillage, but the potential of these technologies to improve soil function and maintain yields is still not fully understood. This study sought to examine the effects of conservation tillage on key soil quality parameters and profitability at a production scale. We evaluated soil properties and yields during the fifth and sixth years (2015 and 2016) of a field study comparing two conservation tillage systems: minimum tillage (MT) and strip tillage (ST), versus a conventional tillage control (CT). Measurements included residue cover, macrofauna abundance and diversity, permanganate oxidizable carbon (POXC), aggregate stability, and infiltration. Results from both years suggest that conservation tillage can enhance macrofauna abundance (especially earthworms) and diversity. For example, ST had higher abundance of macrofauna (486 ind. m\(^{-2}\)) than CT (178 ind. m\(^{-2}\)) in 2015, while MT had greater species richness than CT (4.12 vs. 2.00 taxa sample\(^{-1}\); respectively). Infiltration rate in the ST treatment was 18% higher when compared with CT in 2015. Residue cover was positively correlated with earthworm abundance, while earthworm abundance was positively correlated with aggregated stability and infiltration. When comparing economic costs and profitability across systems, ST and MT treatments had a 34% and 22% greater net return relative to CT. These results suggest that conservation tillage has potential to improve soil quality, water dynamics, and increase farmer incomes within furrow-irrigated systems of Colorado and beyond.

1 INTRODUCTION

Soils play a fundamental role in maintaining agroecosystem productivity and multiple ecosystem services; thus, there is great interest in understanding management impacts on soils and the implications for long-term agricultural sustainability (Kibblewhite, Ritz, & Swift, 2008; Lavelle et al., 2014). Degradation of soils continues to be a widespread issue and can have long-lasting impacts on soil productivity and food security (Lal, 2015). Intensive tillage and residue removal are common agricultural practices that can accelerate soil
degradation by reducing soil organic matter (SOM), aggregation, and soil biological activity, as well as increasing susceptibility to erosion, ultimately leading to a decline in overall soil quality (Carter, Berg, & Sanders, 1985; Lal, 1993; Montgomery, 2007). Growing concern over soil degradation in conventionally-tilled systems has led to considerable interest in conservation tillage—defined as any tillage practice that leaves at least 30% of the soil surface covered after planting with residue from the previous year (CTIC, 2004). Conservation practices can range from no-till to reduced tillage operations with considerably less soil disturbance than standard practices (Wang, Cai, Hoogmoed, Oenema, & Perdok, 2006).

In furrow-irrigated agriculture, CT typically inverts the soil and buries residues, thus leaving the surface unprotected from environmental factors. This form of tillage is commonly practiced to ensure unobstructed (clean) furrows that facilitate uniform flow of irrigation water moving down the furrow. However, in recent years, new tillage strategies, precision farming technologies, and greater recognition of the potential for conservation tillage to improve soil quality, as well as reduce operational costs (DeVuyst & Halvorson, 2004), have made it an attractive best management practice for furrow-irrigated systems.

Conservation tillage can benefit a number of soil quality parameters and reduce soil degradation relative to conventional practices. For example, conservation tillage practices and associated improvements to surface residue cover have been shown to contribute to the maintenance of soil structure and associated protection of SOM, a fundamental component of soil quality (Hajabbasi & Hemmat, 2000; Six, Conant, Paul, & Paustian, 2002). Due to effects on soil physical properties, conservation tillage can also help to improve soil water capture and storage as well as reduce erosion in surface runoff (Blevins, Frye, Baldwin, & Robertson, 1990). Lower levels of disturbance and increases in organic residues under conservation tillage generally benefit soil biological communities (Alvear, Rosas, Rouanet, & Borie, 2005), which are essential to healthy soils due to their role in regulating a range of soil functions such as the processing of organic matter, soil aggregation, and biocontrol of pests in agricultural systems (Barrios, 2007). Soil organisms can also serve as valuable diagnostic tools for assessing soil quality and overall ecosystem health (Rousseau, Fonte, Téllez, van der Hoek, & Lavelle, 2013). Soil macrofauna (i.e., earthworms, beetles, ants, etc.) are an important group that often benefit considerably from conservation tillage practices (Chan, 2001; Melman, Kelly, Schneekloth, Calderon, & Fonte, 2019) and can enhance soil structure and nutrient cycling processes (Castellanos-Navarrete et al., 2012; Lavelle et al., 2006; Mutema, Nyagumbo, & Chikukura, 2013). Earthworms, in particular, are known to have marked impacts on aggregation and SOM stabilization (Fonte & Six, 2010), with important implications for soil water dynamics, erosion, and the long-term fertility of soils (Andriuzzi, Pulleman, Schmidt, Faber, & Brussaard, 2015). While past research has evaluated the impact of different conservation tillage practices of soil quality parameters, few studies have clearly linked improved soil biological properties (e.g., soil macrofauna) to parallel changes in soil physical and chemical functions.

Benefits to soil quality and improved belowground function are important incentives for the adoption of conservation tillage practices; however, this alone is often insufficient to convince farmers to adopt, particularly in furrow-irrigated systems where potential risks may be higher. The impact of conservation tillage on yields is not entirely clear and may depend largely on site-specific agroecosystem characteristics (Pittelkow et al., 2014). While yield benefits are not always apparent, conservation tillage practices significantly reduce fuel and labor inputs (Mitchell et al., 2015), thus potentially offsetting the economic impact of yield reductions. For research to generate meaningful impacts and inform policy and management decisions, it is necessary to provide stakeholders with a multi-functional assessment of conservation tillage impacts that contributes to our understanding of soil quality effects, as well as overall profitability. It is also important to conduct research under realistic farm conditions and field scales; this is often overlooked in manipulative field trials that more commonly rely on smaller plots, so as to include multiple experimental factors with high degree of replication.

To understand the potential of conservation tillage to improve soil quality and long-term farm sustainability, this research monitored key soil quality parameters of two conservation tillage practices as compared to CT five years after their implementation. Research was carried out on production-scale field plots under furrow irrigation in northern Colorado. The specific objectives of this study were to: 1) evaluate the effect of conservation tillage on a suite of soil quality measures; 2) explore relationships between soil macrofauna, chemical and physical soil parameters; and 3) understand the potential economic benefits of conservation vs. conventional tillage practices under furrow irrigation. We hypothesized that the conservation tillage practices would improve multiple soil quality indicators relative to conventional tillage, with minimal impacts to yield and overall profitability of the farming system.
FIGURE 1  Plot layout and approximate sampling locations for key soil parameters measured in a field-scale farming trial in northern Colorado comparing two conservation tillage systems: minimum tillage (MT) and strip tillage (ST), versus conventional tillage (CT). Soil sampling was conducted during the field season (March-November) of 2015 and 2016. Sampling points indicated in the CT plot of Block 1 were repeated across all six plots in both years.

2 | MATERIALS AND METHODS

2.1 | Site description

Research was conducted at the Colorado State University Agricultural Research, Development and Education Center (ARDEC) (40°40′40″N, 104°59′51″W) near Fort Collins, CO. Located at 1570 m above sea level, this area has an average annual precipitation of 407 mm with an average monthly maximum temperature of 17.6 °C in July and a minimum of 2.7 °C in January. Soils at the site are dominated by Garrett sandy-loams (fine-loamy, mixed, mesic type of Pachic Argiustoll; Soil Survey, 2016) with an organic matter content of 1.8%, a pH of 7.8, and a textural profile of 52 % sand, 18 % silt, and 30 % clay.

2.2 | Experimental design and management

In 2011, a field-scale experiment was established to compare two conservation tillage treatments, minimum till (MT) and strip till (ST), with a conventional tillage control treatment (CT) that is representative of typical practices in furrow-irrigated systems of northern Colorado. The MT and ST treatments were selected in collaboration with a group of advising farmers interested in the feasibility of conservation tillage for furrow-irrigated systems in the region. The experiment was arranged in a randomized complete block design (RCBD) with two replicate blocks and all three tillage treatments present in each block (Figure 1). Based on consultation with local farmers, large field plots (320 m long × 27 m wide) were prioritized for use over small plots with greater replication, to realistically represent water movement in furrows and associated challenges with commercial production fields in the region. Each plot was oriented in a north-south direction and was 36 furrows wide, with every other row being irrigated. From 2011 to 2015, the field was under continuous corn (Zea mays). Prior to the start of the experiment (2005-2011), the entire field was managed with a crop rotation of sunflowers (Helianthus annuus), corn and dry beans (Phaseolus vulgaris) under plow-based conventional tillage.

Primary operations (cultivation, planting, and harvesting) were performed using six-row implements (i.e., each tractor pass spans six rows at a time). After harvest, residue in all tillage systems was chopped using a 4.6 m flail chopper, windrowed, and bailed, removing less than 50% of the residue from the previous crop. Following residue management, CT, MT, and ST received nine, seven, and six field operations, respectively, in 2015 and ten, seven, and six operations, respectively, in 2016 (Table 1). The CT treatment used a moldboard plow to invert the soil, thus completely
Table 1  Field operations and (depth) for Conventional, Minimum, and Strip tillage treatments for the 2015 and 2016 seasons in a field-scale tillage trial near Fort Collins, Colorado

| 2015               | Conventional Till | Minimum Till | Strip Till |
|--------------------|------------------|--------------|------------|
| Date               | Operation        | Date         | Operation  | Date         | Operation   |
| 3/23/15            | Disk (15 cm)     | 3/23/15      | Verti-Till (7.5 cm) | 4/13/15      | Strip Till (25 cm) |
| 3/23/15            | Plow (30 cm)     | 4/13/15      | Strip Till (25 cm) | 4/13/15      | Fertilize   |
| 3/27/15            | Mulch b          | 4/13/15      | Fertilize  | 4/30/15      | Plant       |
| 4/14/15            | Fertilize        | 4/30/15      | Plant      | 6/24/15      | Cultivate/bed d |
| 4/14/15            | Bed              | 6/24/15      | Cultivate/bed d | 6/24/15      | Fertilize |
| 4/14/14            | Cultipack c      | 6/24/15      | Fertilize  | 11/16/16     | Harvest     |
| 3/30/15            | Plant            | 11/16/15     | Harvest    |             |             |
| 6/24/15            | Cultivate d      |             |           |             |             |
| 11/16/15           | Harvest          |             |           |             |             |
| # of Field Operations | 9                | 7            | 6          |             |             |

| 2016               | Conventional Till | Minimum Till | Strip Till |
|--------------------|------------------|--------------|------------|
| Date               | Operation        | Date         | Operation  | Date         | Operation   |
| 12/11/15           | Verti-Till b (7.5 cm) | 12/11/15      | Verti-Till b (2x) (7.5 cm) | 12/11/15      | Verti-Till b (7.5 cm) |
| 12/11/15           | Disk (15 cm)     | 3/01/16      | Strip Till (25 cm) | 3/01/16      | Strip Till (25 cm) |
| 12/11/15           | Plow (30 cm)     | 3/01/16      | Fertilize  | 3/01/16      | Fertilize   |
| 2/22/16            | Mulch b          | 3/02/16      | Bed        | 3/02/16      | Bed         |
| 3/01/16            | Fertilize        | 3/03/16      | Plant      | 3/03/16      | Plant       |
| 3/02/16            | Bed              | 7/25/16      | Harvest    | 7/25/16      | Harvest     |
| 3/02/16            | Cultipack c      |             |           |             |             |
| 3/03/16            | Plant            |             |           |             |             |
| 3/03/16            | Cultivate d      |             |           |             |             |
| 7/25/16            | Harvest          |             |           |             |             |
| # of Field Operations | 10              | 7            | 6          |             |             |

a Strip tillage (Orthman 1RIPr) - a narrow (15 – 20 cm) strip of soil is tilled and cleared of crop residue with coulters, a ripper shank and a finishing roller to create a seed bed while the area in between the strips remains undisturbed.
b Mulch (Brillion) operation breaks up large aggregates, smoothing and leveling the soil surface and stirs soil surface to weed and incorporate fertilizer.
c Cultipack (Schmeiser packer) operation breaks soil clods and firms up soil surface.
d Cultivate (Orthman 8375) operation that partially clears furrows of crop residue, uproots weeds and throws soil into crop rows forming beds and irrigatable rows.

Vertical tillage (Landoll 7431) uses flat disks at 10% angle that slice and fragment the crop residue, break surface compaction, and causes some surface soil mixing without burying significant amounts of residue.

burying residues, while MT and ST use vertical and strip tillage operations, respectively, that left most of the residue on the soil surface. Furrows were cleared by hand as needed in conservation tillage treatments, but labor was minimal.

In 2015, a hybrid ‘Mycogen 2V357’ corn variety with a 91 to 95-d maturity was planted on April 30th. Seed was sown approximately 5 cm deep with 75 cm between rows and in-row spacing of 15 cm, for a target plant population of 83,950 seed ha⁻¹. On 3 Mar. 2016, a seed drill was used to plant barley (Hordeum vulgare L.) at a target seeding rate of 112 kg ha⁻¹. In the CT plots, a mixed dry blend of fertilizer (Urea, 46-0-0 and Monoammonium phosphate, 11-55-0) was applied prior to planting by broadcasting and uniformly distributing fertilizer on the soil surface. In the CT plots, liquid starter fertilizer (Ammonium polyphosphate, 10-34-0) was split-applied by banding during tillage and then side dressed in late June by applying Urea-ammonium nitrate, 32-0-0 in the subsurface along the side of the plant row (Table 1). In 2015 a total of 180 kg N ha⁻¹ was applied to the corn in all treatments, while in 2016 a total of 78 kg N ha⁻¹ was applied to the barley. Applications were based on estimated nutrient removal in previous harvest, soil tests, current crop needs, and application strategy. Banding allowed us to reduce P application for the CT treatments since P was applied (as Ammonium...
polyphosphate, 10-34-0) in the immediate vicinity of the crop root (Davis & Westfall, 2016). Therefore, CT plots received 68 kg P₂O₅ ha⁻¹ in 2015 and 90 kg P₂O₅ ha⁻¹ in 2016, and the MT and ST plots received just half of the CT rate in both years.

Irrigation was conducted on alternate furrows with total inflow kept uniform between the CT, MT, and ST treatments, receiving approximately 4,500 m³ ha⁻¹ in 2015 and 2,700 m³ ha⁻¹ in 2016. The 2015 corn crop received six irrigations during the growing season and the shorter season barley in 2016 received just two irrigations. Irrigation scheduling was determined using the water balance method, using the Water Irrigation Scheduler for Efficient Application (WISE) online irrigation scheduling tool (Andales, Bauder, & Arabi, 2014).

### 2.3 Surface residue evaluation

Residue cover and biomass were assessed shortly after soil cultivation in all treatments, 27 May 2015 and 14 Apr. 2016. We used a line transect method outlined by Laflen, Amemiya, and Hintz (1981) to measure percent residue cover. Measurements were taken at the north and south end of each plot (Figure 1) along a 15-m transect placed diagonally across six beds, then again, along another transect 15 m that was oriented perpendicular to the first. Additionally, residue biomass was measured at the center of the two transects using a 1 m² quadrat (two sub-samples per plot). Care was taken to ensure the quadrat included both bed and furrow elements of the row. Residue collected within each quadrat was oven-dried at 65°C and weighed.

### 2.4 Soil sampling approach

With the exception of infiltration (details below), all soil sampling was conducted at both the north and south end of each plot and considering both bed and furrow locations, for a total of four sub-samples per replicate plot (Figure 1). While different parameters were evaluated at different times of the year, all samples were collected within approximately 5 m of the residue biomass sample. Sub-samples were analyzed separately, but later averaged to obtain a single mean value for each plot that was used in treatment comparisons (see Statistical analysis below).

### 2.5 Soil macrofauna

Soil macrofauna communities were evaluated 9–11 Sept. 2015 and 30–31 May 2016 according to methods adapted from Anderson and Ingram (1993). Soil monoliths (25 × 25 cm with a depth of 25 cm) were excavated, and soil was hand-sorted for all visible invertebrates (2 > mm). All specimens were immediately stored in a 70% ethanol solution for identification in the lab. Macrofauna were identified to the level of order or family and diversity was assessed via taxonomic richness (S; i.e., number of taxa in a particular sample) and the Shannon diversity index (H; Shannon, 1963).

### 2.6 Physical properties

Soil physical properties assessed were bulk density, infiltration, and aggregate stability. Bulk density was measured on 19 June 2015 and 7 April 2016. Samples were collected to a depth of 3-10 cm using a Madera probe (3.5 mm diameter; Dickey, Allen, Wright, Murray, & Stone, 1993). In the lab, soils were weighed moist and dried at 105°C for determination of oven-dry weight.

Infiltration was assessed 6–9 Aug. 2015 and 15–17 June 2016 using a Cornell Sprinkler Infiltrometer. Two subsamples per plot were taken on the north end of the field (Figure 1). Infiltration measurements were conducted near samples taken for the other soil parameters (e.g., residue, macrofauna, bulk density), but only at the north end of the field due to logistical constraints (Figure 1). Given that the field receives much of its water from irrigation, infiltration measurements were taken only in the furrows that convey irrigation water. In brief, a metal ring (24-cm diam.) was inserted into the soil to a depth of 7.5 cm and the infiltrometer delivered water to the soil from a height of 10 cm at a controlled steady rate of 350 mm h⁻¹ until steady-state infiltration was met, which took approximately 30 min. Runoff volume was measured through an outlet hose leveled with the soil surface in a time step method and subtracted from total volume of water applied to determine infiltration rate (Ogden, van Es, & Schindelbeck, 1997; Schindelbeck, Moebius-Clune, Moebius-Clune, Kurtz, & van Es, 2016).

Aggregate stability was assessed on 2 Nov. 2015 and 3 June 2016 (several weeks before harvest of corn and barley, respectively) adjacent to the bulk density measurements. Samples were collected by digging a small hole and carefully cutting away a section of soil (15 × 6 × 15 cm deep). Upon return to the lab, soil was air-dried and wet aggregate stability was assessed separately on each of the subsamples using a rainfall simulation method that delivers a steady rate of water droplets (2.5 mm min⁻¹) from a height of 50 cm onto a 250 μm sieve containing a known weight (~25 g) of soil (Moebius et al., 2007; Schindelbeck et al., 2016). Soil passing through the sieve was collected on a filter paper and oven-dried at 40°C. Aggregate stability was determined as the proportion of soil remaining on the sieve after 5 min. of simulated rainfall, calculated by difference (starting mass – soil collected on the filter paper), after correcting for large sand and
2.7  |  Soil chemical parameters

Soils were analyzed for permanganate-oxidizable carbon (POXC), pH, and electrical conductivity (EC) using the same subsamples collected for assessment of aggregate stability (timing and location described above). The air-dried soil was passed through a 2-mm sieve in preparation for subsequent analyses. To provide information about potentially labile or recently active soil C, soils were evaluated for POXC according to methods outlined by Weil, Islam, Stine, Gruver, and Samson-Liebig (2003). Soil pH was measured in a soil paste (1:1 soil/water mixture) using a Hach IntelliCAL pH probe (Model PHC20101). The soil-water solution was then passed through a 0.25-µm filter and the liquid collected to measure soil electrical conductivity using a Hach IntelliCAL EC probe (Model MTC30101; Dellavalle, 1992).

2.8  |  Grain yield

On 16 Nov. 2015 and 31 July 2016, plots were harvested and grain yield was evaluated in the center six beds (6.1 m) of each 320 m long plot. Plots were harvested using a grain combine followed by a calibrated grain cart with load cells. Grain moisture was determined using a Dickey John moisture meter and yields were adjusted to 15.5 and 14.5% for corn and barley, respectively.

2.9  |  Enterprise budget analysis

Profitably for all three treatments was determined by comparing gross revenue vs. fixed and variable costs using enterprise budgets according to Colorado State University Extension Agri-business Management (ABM, 2016). Gross revenue was calculated using annual commodity price for corn in 2015 and malting barley in 2016, multiplied by yield for each treatment. Fixed costs included the price of purchase and maintenance of equipment. Machinery cost was estimated using Estimated Costs of Crop Production in Iowa (Plastina, 2016). Variable costs are production expenses such as labor, seed, fuel, irrigation water, and other expenses directly related to farm operations, which change from year to year. Net income was calculated for the 2015 and 2016 growing seasons to evaluate the economic feasibility of the two conservation tillage practices studied here.

2.10  |  Statistical analyses

Comparisons of soil parameters as well as yield and profitability were conducted separately for 2015 and 2016 using ANOVA, with tillage treatment as the main effect and block considered as a random variable. Separate measurements (i.e., subsamples) within each plot were averaged across bed and furrow positions and/or north and south plot locations to generate a single mean value for each plot and all comparisons were conducted using these plot averages \((n = 6)\). Assumptions of ANOVA (normality and homogeneity of variance) were evaluated, and natural log transformations applied as necessary to meet these assumptions. Tukey multiple comparisons tests were used to evaluate all pairwise comparisons.

Bivariate correlations between soil quality parameters were also examined using simple linear regression to understand relationships between macrofauna and soil chemical and physical parameters. Analyses were conducted on spatially corresponding subsamples within each field plot and run separately for data collected in 2015 and 2016. For example, correlations between residue biomass and earthworms used data for both the north and south ends of the field \((n = 12)\), while the correlation between infiltration and earthworms considered only abundance data from the furrows at the north end of the field \((n = 6)\). All statistical analyses were conducted using the CAR package (Fox & Weisberg, 2011) in R (R Core Team, 2013).

3  |  RESULTS

3.1  |  Surface residues

Tillage treatment significantly affected residue cover in both 2015 and 2016. Mean surface cover in 2015 was 43% for MT and 47% for ST, compared to only 4% under CT \((p = 0.03)\). Differences in 2016 were similar, with 53% and 55% cover for MT and ST, respectively, and 22% residue cover under CT \((p = 0.02)\). Residue biomass followed a similar pattern in both years with ST having about ten-fold higher surface residue biomass than CT, while MT was intermediate (Figure 2).

3.2  |  Soil macrofauna

In the 2015 season, ST displayed significantly higher \((p = 0.048)\) macrofauna abundance (486 ind. m\(^{-2}\)) than CT (178 ind. m\(^{-2}\)), but not MT (210 ind. m\(^{-2}\)). In 2016, the conservation tillage treatments tended to have higher macrofauna abundance than CT, but no significant differences were observed (Table 2). Earthworms were the most abundant taxa.
TABLE 2  Mean values for soil quality parameters under Conventional (CT), Minimum (MT), Strip (ST) tillage treatments sampled in 2015 and 2016 in a field-scale tillage trial near Fort Collins, Colorado. *P*-values for tillage treatments effects are present to the right of each group of means, while numbers in italics below each mean represent the standard error of each mean. Means within the same year followed by different letters are significantly different (*P* < 0.05)

| Parameters                  | 2015 | 2016 | P-Value |
|-----------------------------|------|------|---------|
|                             | CT   | MT   | ST      | CT   | MT   | ST |
| Biological                  |      |      |         |      |      |    |
| Macofauna Abundance (ind. m⁻²) | 178 a | 210 ab | 486 b | 0.05 | 78 a | 278 a | 212 a | 0.36 |
| Taxonomic Richness (taxa sample⁻¹) | 2.00 a | 2.00 a | 3.50 a | 0.08 | 2.00 a | 4.12 b | 3.38 a | 0.03 |
| Shannon Index               | 0.29 a | 0.32 a | 0.52 a | 0.33 | 0.55 a | 0.98 b | 0.69 a | 0.04 |
| Chemical                    |      |      |         |      |      |    |
| POXC (mg kg⁻¹)              | 126 a | 265 a | 212 a | 0.08 | 368 a | 392 a | 414 a | 0.29 |
| pH                           | 8.10 a | 8.10 a | 8.00 a | 0.75 | 8.20 a | 8.20 a | 8.10 a | 0.88 |
| EC (dS m⁻¹)                  | 1.13 a | 1.28 a | 1.35 a | 0.37 | 0.90 a | 1.13 a | 0.69 a | 0.16 |
| Physical                    |      |      |         |      |      |    |
| Infiltration (mm h⁻¹)        | 164 a | 167 a | 200 b | 0.04 | 233 a | 243 a | 275 a | 0.24 |
| Stability of Aggregates (% 0.25 mm-2 mm) | 11.8 a | 20.0 a | 25.9 a | 0.49 | 18 a | 17 a | 15 a | 0.50 |
| Bulk Density (g cm⁻³)        | 1.48 a | 1.47 a | 1.50 a | 0.88 | 1.50 a | 1.56 a | 1.48 a | 0.13 |
|                             | 0.03 | 0.04 | 0.05 | 0.03 | 0.03 | 0.03 |

*1:1 soil test.
plotted \( p = 0.04 \); Table 2). However, these differences were not significant in 2016. While aggregate stability was not significantly different between the treatments for either 2015 or 2016, we note a general trend of higher aggregate stability in the conservation tillage treatments for 2015, similar to the pattern observed for infiltration rate that year. Bulk density did not differ significantly between treatments for either 2015 or 2016.

### 3.4 Chemical properties

The POXC was generally higher under conservation tillage (265 and 213 mg kg\(^{-1}\) for MT and ST; respectively) vs. CT (126 mg kg\(^{-1}\)), but this difference was only marginally significant \( p = 0.08 \) for 2015 and not significant in 2016 (Table 2). Soil pH and EC were not significantly different between treatments at either sampling time.

### 3.5 Relationships between soil quality parameters

Regression analyses revealed several important correlations between soil parameters of interest, especially for the 2015 season (Figure 4, Table S2). Earthworm abundance was positively correlated with surface residue mass \((R^2 = 0.70, p < 0.001;\) Figure 4a). Earthworm abundance was also positively associated with infiltration rate \((R^2 = 0.96, p = 0.001;\) Figure 4b) and aggregate stability \((R^2 = 0.71, p < 0.001;\) Figure 4c). Aggregate stability demonstrated a positive relationship with infiltration rate \((R^2 = 0.84, p = 0.01;\) Figure 4d) and POXC \((R^2 = 0.40, p = 0.03;\) Figure 4e). In 2016, POXC was positively associated with macrofauna abundance \((R^2 = 0.66; p = 0.001)\) and earthworm abundance \((R^2 = 0.74; p < 0.001)\). A positive correlation was also observed between residue mass and infiltration rate \((R^2 = 0.71, p = 0.03;\) Table S3).

### 3.6 Enterprise budget analysis

Corn grain yields for 2015 had small, but statistically significant differences between treatments \((p = 0.02)\), such that CT yielded more grain \((12.8 \text{ Mg ha}^{-1})\) than the two conservation tillage treatments \((12.4 \text{ and } 12.3 \text{ Mg ha}^{-1} \text{ for MT and ST; respectively})\). Barley grain yield for 2016 was not significantly different between the treatments (average of 5.2 Mg ha\(^{-1}\); Table 3). Gross revenue for the tillage treatments average over the 2 yr of study was $266, $251, and $257 ha\(^{-1}\), for CT, MT and ST, respectively (Table 3). Meanwhile, fixed cost and operational variable cost such as machinery ownership, fuel, machinery operation, machinery repair, and labor

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**FIGURE 2** Dry surface residue mass for the Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments in a field experiment near Fort Collins, CO. Samples were collected in 1 May 2015 and 14 Apr. 2016 and represent averages across bed and furrow locations \((n = 2 \text{ per treatment, per year}). Error bars represent the standard error of the mean. Means within the same year followed by different letters are significantly different \((P < 0.05)\)

**FIGURE 3** Earthworm abundance for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments in a field experiment conducted near Fort Collins, CO. Samples were collected in September 2015 and May of 2016 and represent averages across bed and furrow locations. Error bars represent the standard error of the mean. Means within the same year followed by different letters are significantly different \((P < 0.05)\)

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In both years (87% of total in 2015 and 54% in 2016) and displayed similar trends as total macrofauna abundance, being generally higher in the conservation tillage treatments relative to CT \((p = 0.004;\) Figure 3). Of the several mature individuals collected, all earthworms appeared to be *Apporectodea trapezoides*. The second most important taxonomic group was Coleoptera (7% of total) in 2015, and Diptera (24% of total) in 2016 (Table S1). When examining macrofauna diversity, the conservation tillage treatments were generally higher than CT in terms of taxonomic richness and Shannon index; however, this was only significant for MT in 2016 (Table 2).

### 3.3 Physical properties

The ST treatment demonstrated the highest infiltration rate in 2015 and had an infiltration rate 22% higher than that of CT.
FIGURE 4 Bivariate correlations between key soil quality parameters measured in 2015 in a field experiment near Fort Collins, CO. The relationships presented are: a) Residue abundance vs. Earthworm abundance, b) Earthworms abundance vs. Infiltration rate, c) Earthworm abundance vs. Aggregate stability, d) Aggregate stability vs. Infiltration rate, and e) Aggregate stability vs. Permanganate oxidizable carbon (POXC). The correlations examine spatially corresponding subsamples within each field plot, such that the values and number of replicates vary depending on what parameters are being considered. $R^2$ and $P$-values are provided in the upper left-hand corner of each graph.

were 11% lower for MT and ST, compared to CT. Thus, overall MT and ST had average profit increases of 22 and 34%, respectively, when compared to the CT treatment (Table 3).

4 | DISCUSSION

Results from this study indicate that conservation tillage under furrow irrigation can have notable impacts on farming system profitability, macrofauna abundance, and soil physical properties.

4.1 | Impacts of conservation tillage on soil quality

Perhaps the greatest impact of conservation tillage was observed for soil macrofauna communities. We found that ST, the least disturbing tillage practice, resulted in significantly higher macrofauna abundance in 2015, largely driven by differences in earthworms. While not significant, MT generally supported higher macrofauna densities than CT in both years. The conservation tillage treatments also supported higher macrofauna diversity, as demonstrated by significantly higher taxonomic richness and Shannon index in 2016, relative to CT. We note that similar trends were apparent for 2015, but not statistically significant. Our results agree with previous research suggesting that soil disturbance plays an important role in regulating macrofauna communities. Tillage can impact macrofauna via direct mortality, that is, by cutting or crushing organisms as implements pass through the soil, but indirect effects are also important and are often associated with changes in resource availability and distribution as well as modification to environmental conditions (Chan, 2001; Hendrix et al., 1986). For example, conventional tillage inverts and mixes residues with the soil, thus
TABLE 3  Two-year average yields and enterprise budget for Conventional (CT), Minimum (MT), Strip (ST) tillage treatments in a field-scale tillage trial near Fort Collins, Colorado. Means within the same year followed by different letters are significantly different ($P < 0.05$)

|                        | Conventional Tillage | Minimum Tillage | Strip Tillage |
|------------------------|----------------------|-----------------|---------------|
| **Yields**             |                      |                 |               |
| 2015 (corn)            | 12.8 a               | 12.4 b          | 12.3 b        |
| 2016 (barley)          | 5.4 a                | 5.0 a           | 5.2 a         |
| **Gross Revenues**     |                      |                 |               |
| Returns per Hectare    | $266                 | $251            | $257          |
| **Key Variable Costs** |                      |                 |               |
| Machinery Operating    | $19.42               | $7.58           | $8.74         |
| Fuel                   | $10.71               | $7.91           | $7.79         |
| Machinery Repair       | $2.83                | $1.19           | $1.42         |
| Machinery Labor        | $3.64                | $1.53           | $1.82         |
| **Total Variable Costs** | $196.16             | $176.28         | $177.98       |
| **Total Fixed Costs**  |                      |                 |               |
| Machinery Ownership    | $24.87               | $19.57          | $18.39        |
| **Total Cost**         | $221                 | $196            | $196          |
| **Profit (Return to Land and Management)** | $45 | $55 | $60 |

accelerating decay and leaving the soil surface bare which can increase temperature and moisture fluctuations (Nyborg & Malhi, 1989). The observed higher macrofauna diversity under reduced tillage is likely associated with a greater complexity of soil habitats, since there is a distinct residue layer at the soil surface (House & Parmelee, 1985). Additionally, increased earthworm populations have been shown to enhance arthropod diversity due to greater habitat and movement associated with earthworm tunneling activities (Lorang, Ponge, Blanchart, & Lavelle, 1998). The relatively high sensitivity of macrofauna to tillage observed here corroborates past research suggesting that macrofauna are valuable indicators of land management practices, as they are sensitive and respond rapidly to a variety of management induced changes (e.g. Rousseau et al., 2013).

While total soil organic carbon (SOC) was not measured in this study, we did evaluate POXC, which is thought to be a relatively labile and/or recently processed SOC fraction and a sensitive indicator of SOM accrual in agricultural soils (Culman et al., 2012; Hurisso, Culman, Horwath, Wade, & Cass, 2016). In parallel with effects on soil macrofauna, the conservation tillage treatments tended towards higher POXC concentrations for both growing seasons, although this was only marginally significant in 2015. Continuous plow-based tillage has been shown to reduce other forms of labile C by destroying soil aggregates and exposing physically protected organic matter to microbial degradation (Chen, Billen, Stahr, & Kuzyakov, 2007). Faster decay of fresh residues under CT may also contribute to the generally higher POXC levels in the conservation tillage treatments, as others have shown reduced tillage intensity to slow residue decomposition rates and promote SOM storage in semi-arid regions (Rasmussen, Albrecth, & Smiley, 1998).

Similar to results for the soil quality parameters mention above, infiltration rates were generally higher under the conservation tillage treatments. This was most evident during the 2015 season, where infiltration rates were significantly higher under ST than CT. Others have reported infiltration rates to be as much as three times higher under reduced tillage compared to a chisel or plow-based systems (Wuest, 2001). Low infiltration rates in the CT treatment could be due to surface sealing associated with greater clay particle deposition on the furrow surface. During irrigation events, clay particles can be released from unprotected soils and sediment from ruptured aggregates deposited down the furrow, thus increasing clogging of soil pores and decreasing infiltrate rate (Sojka et al., 2007; Trout, 1996). In a complementary study looking at water quality impacts of conservation tillage in the same field trial, the detachment, transport, and deposition of sediment in tail water (running off the furrows at the end of the field) was reduced dramatically in the conservation tillage treatments (Deleon, 2017).

We note that many of the soil quality improvements observed under conservation tillage were more evident in 2015 than in 2016. While general trends largely remained constant across both years, we suspect that an extra tillage operation at the end of the 2015 season (needed to reform beds and clean furrows; Table 1) may have had adverse effects on
many of the parameters discussed above. Thus, while some have noted that the benefits of conservation tillage tend to become more pronounced over time (Lafond et al., 2008), our findings suggest that the impacts on soil quality may be somewhat fragile and that careful consideration of management interventions and crop choice is needed to ensure continued benefits of conservation tillage from year to year. Crop type and associated sampling and microclimatic factors may also play a role in our findings. In 2016, sampling was conducted in late spring while the field was under barley and soils were cooler, but in 2015, soil parameters were sampled in late summer under corn in warmer conditions. Soil biological communities are likely to be more active at this time of the year and the change in timing may partially explain the higher observed macrofauna activity and differences in other soil properties on this sampling date.

### 4.2 Relationships between soil quality parameters

Crop residues and overall surface cover appeared to have a positive impact on earthworm abundance, as residue biomass on the soil surface was positively correlated with earthworm abundance (Figure 4a). While earthworms are likely to benefit from the decrease in tillage intensity and systems with more residue (i.e., ST), the positive correlation also suggests that earthworms may benefit from increased substrate availability as well as reduced fluctuations of soil temperature and moisture (Chaney & Haydock, 2011). Earthworms feed upon plant-derived organic residues in varying stages of decomposition together with soil particles, which are then excreted as earthworm casts, forming highly stable soil aggregates (Fonte & Six, 2010). This is supported by the positive relationship between earthworm abundance and aggregate stability observed in our study (Figure 4c). Increased earthworm activity could have contributed to the positive relationship between POXC and soil aggregate stability (Figure 4e), as earthworms are known to enrich soil aggregates with fresh residue C (Bossuyt, Six, & Hendrix P, 2006; Fonte, Kong, van Kessel, Hendrix, & Six, 2007). It should also be noted that the same factors that promote earthworms (organic matter inputs, reduced disturbance) are also likely to support improved aggregation (Six et al., 2002), thus causal mechanisms between earthworms, water stable aggregation and POXC need to be interpreted with caution.

Along with aggregation and residue cover, earthworms were positively associated with soil infiltration rates (Figure 4b). This is likely due, at least in part, to casting and burrowing activities that form stable macroaggregates and create a network of macropores that facilitate vertical movement of water down through the soil profile (Andriuzzi et al., 2015). In study under furrow irrigation from south central Idaho, infiltration increased by 30% and this was attributed to the abundance of earthworms penetrating the wetted furrow perimeter during irrigation events (Trout & Johnson, 1989). Others have indicated a beneficial impact of earthworms on infiltration by increasing preferential flow paths (Kribaa, Hallaire, Curmi, & Lahmar, 2001; Lamandé, Hallaire, Curmi, Péres, & Cluzeau, 2003). The positive relationship between earthworms and aggregate stability as well as earthworms and infiltration rate suggest that earthworm activities, increased by reduced tillage and greater surface residue, likely mediated at least some of the beneficial impact of reduced tillage on key soil physical properties (i.e., soil structure and infiltration). However, other soil biota (e.g., fungi) can also have important impacts on aggregation under reduced tillage scenarios. It is worth noting that the majority of these correlations were only found to be significant in the 2015 field season. Again, we suspect that this is due to the extra tillage operation conducted prior to planting barley that likely had adverse impacts on soil structure and many of the associated soil quality parameters measured in the conservation tillage treatments in 2016.

### 4.3 Economic and management implications

From a farmer’s perspective, the implementation of conservation tillage represents a longer-term investment, where observable benefits may take several years to materialize. While the impacts of conservation tillage on soil quality are clear, at least for 2015, the impacts on crop yield were relatively subtle. Yields showed only small differences between the treatments; hence, gross revenue was the similar across the different tillage practices (Table 3). However, taking management costs into account reveals important differences for the conservation tillage treatments, mainly a reduction of fuel machinery operation, repairs, and labor costs. This finding agrees with previous economic analyses of conservation tillage (Mitchell et al., 2012; Zhou, Helmers, Al-Kaisi, & Hanna, 2009), since conservation tillage generally has fewer operations, and this translates into savings in fixed and variable costs relative to conventional tillage. In agreement with our findings, others have demonstrated that conservation tillage can improve net profits due to reduced costs such as fuel and labor (Smart, Bradford, Lockammy, Dugger, & Richter, 1998). Despite the potential benefits, the initial costs of converting to conservation practices can present a substantial barrier to adoption by producers. Also, there is evidence that crop yields can initially be reduced when converting to conservation tillage, but that yields tend to stabilize after the transition period of 3-5 yr (Logan, Lal, & Dick, 1991; Wang et al., 2006). In fact, the 6-yr cost-benefit analysis for the MT treatment in this study indicated a 7% loss in profit overall.
when compared with CT (data not shown). However, it should be noted that the MT treatment was originally under no-till, but because of soil compaction and poor plant establishment, yields were drastically reduced. When no-till was converted to MT in the third year of the study, profits for MT improved and became much more comparable to CT. While not a problem in this study, changes to residue management under conservation tillage can complicate management by increasing potential for the obstruction of water flow down the furrows. Additionally, having surface residue can slow soil warming in the early spring and impede germination resulting in late seed emergence that could decrease yields (Licht & Al-Kaisi, 2005). This is especially relevant in cooler climates like that of Northern Colorado (Logan et al., 1991). These potential drawbacks of conservation tillage and practical management guidelines need to be fully addressed before widespread adoption of reduced tillage practices can occur.

5 | CONCLUSION

Intensive tillage in agricultural systems can have important consequences for long-term fertility and a range of important functions in soils. Our findings suggest that conservation tillage offers promise for the restoration of soil quality in furrow-irrigated systems of the High Plains region in Colorado. We observed marked impacts on soil biological and physical parameters five years after the implementation of reduced tillage practices. More importantly, strong positive relationships between earthworms and soil physical attributes, such as aggregate stability and infiltration, highlight the importance of understanding tillage impacts on soil biological functioning and the implications for water movement and erosion. In addition to improved soil quality and function, our findings also suggest that conservation tillage practices can increase profits by lowering fixed and variable management costs. Despite the clear benefits suggested by our research, large-scale adoption of conservation tillage practices in furrow-irrigated agriculture requires careful consideration of multiple agronomic, cultural, and economic factors to facilitate learning in the agricultural community and minimize potential risks to land managers.

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