THESIS

IMPACTS OF CONSERVATION TILLAGE ON WATER QUALITY AND SOIL HEALTH CHARACTERISTICS UNDER FURROW IRRIGATION

Submitted by

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ABSTRACT

IMPACTS OF CONSERVATION TILLAGE ON WATER QUALITY AND SOIL HEALTH CHARACTERISTICS UNDER FURROW IRRIGATION

Furrow irrigation-induced sediment and nutrient loss continues to be a serious problem in the Western States of the US. Sediment and nutrients in runoff can eventually be discharged into streams and rivers impairing water quality, causing adverse effects on the environment and reducing soil productivity over time. Continuous intensive tillage along with excessive sediment and nutrient loss ultimately lead to the degradation of soil quality. We hypothesize that conservation tillage under furrow irrigation can reduce the sediment and nutrient losses in surface runoff as well as improve soil quality parameters. The objectives of this research are to compare two conservation tillage treatments, minimum tillage (MT) and strip tillage (ST), to a traditional conventional tillage (CT) system under furrow irrigation and understand the impacts of these practices on annual sediment and nutrient concentrations and loads from irrigation and storm events. We quantified total suspended solids (TSS), total Kejdahl nitrogen (TKN), nitrate (NO_3), ammonium (NH_4), total nitrogen in aqueous solution (TNa), total phosphorus (TP), dissolved reactive phosphorus (DRP), and total soluble phosphorus (TSP) loads from irrigation runoff over two growing seasons for the three treatments. Relative to CT, conservation tillage reduced TSS loads by 84% and 88% in 2015 and by 98% and 87% in 2016 for MT and ST, respectively. In 2015, TKN was reduced by 80% and 86% in MT and ST respectively when compared to CT. Total P was significantly higher in CT, with an 87% load reduction under MT and ST in 2015 and an 85% load reduction under MT in 2016. Total P concentration (mg L^{-1}) correlated well with TSS concentrations (g L^{-1}) ($R^2 = 0.72$, $P < 0.001$). Total soluble P loads were significantly higher in the CT treatment when compared to the conservation treatments in the 2015 season. Reduced tillage and residue management in the conservation treatments improved irrigation flow parameters such as reduced runoff. The conservation treatments had a greater impact on sediment-bound than soluble nutrients largely due to surface residue reducing erosion in the furrows. Results show that reduced tillage and residue management are an effective best management practices (BMPs) in sediment and nutrient abatement in irrigation and storm runoff.

Furrow irrigation is still practiced in 40% of all irrigated lands in Colorado and it is expected to continue across much of the State. Under furrow-irrigated systems, CT practices are common, but such practices can degrade soil quality. The project sought to examine the effects of conservation tillage on soil health at a production scale, understand relationships between soil parameters, and to evaluate the economic feasibility of conservation practices. Soil biological, physical, and chemical parameters were evaluated during the fifth and sixth years of a study (2015 and 2016) comparing two different management systems, MT and ST, verses CT (the control). Measurements included Active C (POXC), macrofauna diversity and abundance, aggregate stability, infiltration, and residue cover. POXC was significantly higher for MT when compared to CT and ST. Results from both years suggest that conservation treatments increased macrofauna abundance, especially earthworms, and diversity (richness) relative to the control. Aggregate stability was significantly higher in the conservation treatments for 2015, but not in 2016. Infiltration rates in the ST treatment was 18% higher when compared to CT. Residue cover was positively correlated with earthworm abundance while earthworm abundance was positively correlated with aggregated stability and infiltration. When comparing economic cost, and returns among systems, ST and MT treatments had a 39% and 32% greater net return when compared to

CT plots. These preliminary results show potential for conservation tillage under furrow-irrigation to improve soil quality parameters as well as increasing net income.

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“When the well is dry, we know the worth of water.”

Ben Franklin

“... the Latin name for man, homo, derived from humus, the stuff of life in the soil.”

Dr. Daniel Hillel

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INTRODUCTION

Water quality degradation from agricultural surface runoff across much of the Western United States has had adverse effects on many streams, rivers, and lakes, as well as long-term soil fertility due to irrigation-induced erosion and nutrient loss (Sojka et al., 2007). Only one-sixth of harvested croplands are irrigated but produce one-third of the nation's annual harvest and nearly half of the overall agricultural production value (Economic Research Service, 2012). To keep up with projected food and fiber needs of the growing population without worsening water quality issues, it is necessary to improve conservation practices to mitigate soil and nutrient loss. While soil and nutrients are generally lost at higher rates in furrow irrigated systems (Allmaras, 1985; Bjorneberg, 2012), furrow irrigation remains common in much of the western US because conversion to more efficient irrigation systems, such as sprinkler or drip irrigation, can be cost prohibitive to land owners. Furrow irrigation is currently being utilized on 4.3 million ha, or about a quarter of the irrigated cropland in the United States (USDA, 2013). In the state of Colorado, furrow irrigation is used on about 223,000 ha, comprising 40% of all irrigated lands. Therefore, the development of improved soil and irrigation management practices offers great potential to improve water quality throughout the region.

With furrow irrigation, water is applied between the crop rows and infiltrates by spreading downward and laterally, percolating into the root zone of the bedded crop. Because irrigation is largely a controlled event, the volume of runoff can be managed by adjusting the inflow rate. However, an appropriate application rate that ensures uniform infiltration throughout the field will usually generate runoff. When inflow rates are too low, the top of the field will receive a larger amount of water compared to the bottom and leaching can occur at the top of the field. If the inflow rate is too high, it will increase soil and nutrient loss off the field as well as possible nutrient leaching, which can cause adverse effects on groundwater.

Furrow irrigation is typically associated with intensive tillage, as irrigators prefer unobstructed (clean) furrows to allow uniform flow and infiltration as water moves down the furrow. While plowing and other secondary tillage operations bury crop residue, aerates the soil, incorporates fertilizers, and offers a good seedbed for germination, pulverized bare soil is more susceptible to sediment and nutrient losses during storm and irrigation events. For example, in one study of 49 irrigated fields in Idaho, a range of 0.5 to 141 Mg ha^{-1} yr^{-1} of sediment loss was reported under furrow irrigation (Berg and Carter, 1980). Koluvek et al., (1993) also reported high rates of furrow irrigation-induced erosion in Washington, Idaho, Wyoming, and Utah, suggesting that this phenomenon is widespread. Associated with this soil loss, furrow irrigation-induced erosion caused up to a 25% decrease in crop yields in an eight year study by Carter (1993), suggesting important consequences for long-term sustainability. Nutrient loss due to runoff has also become a growing concern with furrow irrigation. For example, annual total phosphorous (TP) losses in runoff have been reported ranging from 0.3 to 131 kg ha^{-1} in different studies, while TP concentration in runoff was reported from 0.08 to1.08 mg L^{-1} (Berg et al., 1980; Bjorneberg et al., 2002b; Westermann et al., 2001). This is cause for concern, as TP concentrations can cause eutrophication at levels as low as 0.02 mg L^{-1} (USEPA, 1998). Total P has been found to be positively correlated with total suspended solids in runoff (Fitzsimmons et al., 1972; Westermann, 2001). Dissolved reactive P (DRP), largely associated with fertilizer inputs of orthophosphates and high soil test P levels, tends to be much lower, but of greater concern for water quality. Berg and Carter (1980) found DRP loads ranging from 0.02 to 2.35 kg ha^{-1} for seasonal runoff losses from 33 furrow irrigated fields, but much lower loads have also been reported (Bjorneberg et al., 2006). To date, little research has been conducted on N loss from furrow irrigated systems. Fitzsimmons (1972) reported concentrations of 1.21 mg NO_3 L^{-1} and 2.02 mg NH_4 L^{-1} in surface runoff for a gravity-irrigated field. Another study measured annual N (NO_3 + DON + DON) loss from storm and irrigation events at 5.4 kg N ha^{-1} yr^{-1} (King et al., 2009). Though these levels of NO_3 do not exceed the drinking water quality standard of 10 ppm (USEPA, 2009), there have been reports of up to 40 mg NO_3 L^{-1} in return flows in an irrigated system in Spain (Barros et al., 2012). As concern for water quality increases, a greater understanding of soil and nutrient losses from furrow irrigated systems is vital to mitigating these issues.

CONSERVATION TILLAGE

Conservation tillage practices offer a promising alternative to conventional tillage and have been shown to reduce sediment and nutrient losses under furrow irrigation. Conservation tillage encompasses many different practices, including no till, reduced till, and mulch till, and generally promotes higher surface residue cover and reduction of soil disturbance. This complicates management of conservation tillage because residue can cause uneven water distribution throughout the field, which causes yield reductions. However, research has shown that reduced or no-till practices have the potential to eliminate 90% of soil loss under furrow irrigation (Carter and Berg, 1991; Sojka and Carter, 1994). Conservation tillage can reduce nutrient loss as well, with one study reporting a 50% reduction in N and up to 75% reduction in TP loss relative to conventional tillage (Dickey et al., 1984). Also, conservation tillage has been shown to increase net profits due to reduced tillage costs (Carter, 1991). Despite several potential benefits, farmers are reluctant to adopt conservation tillage practices under furrow irrigation systems due to management complications and many socioeconomic and cultural factors (e.g., new equipment, labor, and knowledge of proper residue handling). Continued research and education is crucial to enhance the profitability and adoption of conservation practices.

To address the above issues, this project sought to explore and better quantify the impact of conservation tillage on furrow irrigation systems for controlling sediment, sediment-bound and soluble nutrient losses. Our specific objectives were to: 1) evaluate the effect of conservation tillage on irrigation flow characteristics, 2) determine the effectiveness of conservation tillage in reducing sediment and nutrient concentrations and loads in surface runoff, and 3) examine the relationship between sediment and nutrient concentrations.

MATERIALS AND METHODS

SITE DESCRIPTION

The research site is located 14 km northeast of Fort Collins at the Colorado State University Agricultural Research, Development and Education Center (ARDEC) (40°67' N, -104°99' W). With an elevation of 1570 meters, this area experiences an annual precipitation of 407 mm, average maximum temperature of 17 C, average minimum temperature of 2.7 C, and overall average temperature of 10 C. The site consists of the Garrett soil series, a fine-loamy, mixed, mesic type of Pachic Argiustoll (Soil Survey Staff, 2017). The soil is comprised of 1.8% of organic matter and a texture profile of 52% sand, 18% silt, and 30% clay, pH 7.8 and a slope of 0.75%.

EXPERIMENTAL DESIGN

In 2011, two conservation tillage treatments were established, minimum (MT) and strip (ST) tillage and compared conventional tillage (CT), designated as a control. Plow-based conventional tillage is utilized by most Colorado furrow irrigating farmers. Conservation practices were chosen from a group of advising farmers interested in the feasibility of conservation tillage on furrow-irrigated systems. The experiment was arranged in a randomized complete block design with two replicate blocks and three randomly assigned treatments to each block. To mimic the dynamics of commercial furrow irrigation in Colorado, a large field sizes of 320 by 164m (5.9 ha) was used and each plot (6 plots total) was 27 m wide with 320 m long furrows. The field was divided into six plots, each with 36 furrows 90-cm wide in which every other row is irrigated. To account for variability between furrows, we merged two irrigated furrows 6-m before the automated water sampler located on the edge of the field that will be referred to as the sample row.

All operations were performed by six row wide implements. After harvest, residue in all tillage systems was chopped using a 4.6-m wide flail chopper, windrowed, and bailed. Flailing and baling operations were performed to remove less than 50% of the previous crop residue. Following the residue management, CT, MT, and ST received nine, seven, and six field operations, respectively, in 2015 and eight, six, and five operations, respectively, in 2016 (Table 1.2). Conventional tillage is a plow-based treatment that inverts the soil, burying residue. The conservation tillage, MT and ST, use vertical and strip till operations respectively, which leaves most of the residue on the surface.

In 2015, a hybrid Mycogen 2V357 corn (*Z. mays* ssp. *Mexicana* **x** *T. dactyloidies)* variety with a 90 to 95-day maturity was planted on April 30. Seed was sown approximately five cm deep at an in-row spacing of 15 cm and 75 cm row spacing for a target plant population of 83,950 seed/ha (34,000 seed/ac). On March 3, 2016, barley (*Hordeum vulgare* L.) was planted at a target seeding rate of 112 kg ha^{-1} (100 lbs ac^{-1}). Agronomic fertility rates were determined using Colorado State University Extension Corn Fertilizer Recommendations (Davis et al., 2014) and pre plant soil samples, 0-15 cm were used for fertilizer requirements analysis (Table 1.1).

Fertility requirements were met in the conventional plots by broadcasting, or uniformly distributing fertilizer, on the soil surface followed by incorporation. In the conservation plots, liquid fertilizer was applied by side-dressing techniques. This involves fertilizer being applied in the subsurface bands along the side of the plant row. As per university recommendation, banding allowed the P application for the conservation plots to be reduced by half. Fertilization application information is provided in Table 1.3.

Manual and tipping bucket rain gauges were located near the field to measure rainfall for the study area. Additionally, a nearby Colorado Agricultural Meteorological Network (CoAgMet) station was utilized for air temperature, vapor pressure deficit, wind run, and precipitation to calculate evapotranspiration. Using this information, irrigation scheduling was determined using the water balance method, confirmed by the Water Irrigation Scheduler for Efficient Application (W.I.S.E) online irrigation scheduling tool (Andales et al., 2014) and further confirmed with soil moisture monitoring with Watermark® sensors.

SOIL AND WATER SAMPLING AND ANALYSIS

Using the Laflen (1981) line transect method, percent residue cover was measured for each tillage plot for both years within a week of planting. Measurements were taken on the north and south side of each plot, across six beds (15 m across), then once again perpendicular to the already measured transect making an (X). Residue mass was determined by collecting all residue found within a square meter that covered the bed and furrow in the north and south section of the plots. Residue was then oven dried at 65 °C and weighed.

Gravimetric soil moisture was determined at planting for both years. Soil samples were taken at a depth of 15 cm from the beds and furrows at the north and south ends in each treatment plot for a total of 24 samples that were then weighed and placed in a 105 °C oven for gravimetric soil moisture content (Black, 1965).

To measure flow rate, a 60-degree V-notch trapezoidal furrow flume (Trout and Mackey, 1988) was installed 8-m in from the end of each sample row. The flume was previously calibrated by the CSU hydraulics laboratory. Water samples were collected with a Teledyne ISCO 6712 Portable Sampler (PS). Each sampler was equipped with a 730 Bubbler Flow Module located within the stilling well of each flume to determine water height (±0.002 m). Flow rate was determined by the calibration equation for the flume.

The PS utilized a two-part program that collects sequential and composite samples of an irrigation event. Once enabled, the PS sampled 750 mL of runoff per hour consecutively in 1 L bottles every hour and 70 mL samples per hour in a 1 L composite bottle. During an irrigation event, the PS was programed to start sampling when the height of flow reached 1.3 cm and to discontinue sampling if the height of flow dropped below this point. A secondary flow rate monitoring system was set up to continuously measure flow rate using pressure transducers (YSI Incorporated, Yellow Springs, OH and Geo-Met Instruments, New Minas, Nova Scotia, Canada) that were installed within the stilling well of each furrow flume.

Inflow rates were obtained by measuring the time required to fill a seven-liter vessel from the outflow coming from the siphon tubes. Inflow water samples were taken at least twice during an irrigation event. Since the water was sourced from a well, few changes in water quantity were expected during an irrigation event.

In the 2015 season, there were a total of six irrigation events. These sampling events occurred on July, 7, 21, 31, August 7, 17, and September 1. In the 2016 season, there were a total of two irrigation sampling events on June 8 and 20. Composite sampling with duplication was performed on the irrigation events. In 2015 the site was irrigated with shallow, alluvial well water. Water was delivered by a concrete lined ditch and distributed to every other furrow using 3.8 cm diameter siphon tubes. In 2016, well water was mixed with river water. Most irrigation events lasted 12 hours.

Storm events were captured in 2015, on May 9 and June 11. The first storm event was captured by grab sampling and two samples were taken. The storm event on June 11 was captured using the PS. Programing was set to a flow paced sampling scheme. In 2016, one storm event was captured on May 7. A one-part storm event program was used in which a paced flow weighted sampling scheme occurred. For every minute the PS would sample 10 mL for every 3.8 L of runoff, only if enough flow passed for the PS to sample 500 mL or more. A manual rain gauge and a tipping bucket rain gauge were located near the field to measure rain fall intensity and amount of total rainfall.

For irrigations, individual hourly samples and a composite sample were analyzed for each plot for the 2015 and 2016 season. For storms, all flow-weighted hourly and composite samples were analyzed. Sediment and nutrient loads were calculated using concentrations from the composite samples and total runoff per irrigation. Annual loads were calculated by the summation of the irrigation loads for the season. Sediment and nutrient concentrations from composite samples were used to calculate annual loads for the 2015 and 2016 season. Field samples were iced during the collection and transportation to the lab. Nutrient samples were preserved with a 5% sulfuric acid solution and refrigerated <4°C at the lab for analysis and a max hold time of 28 days for total Kjeldahl nitrogen (TKN), nitrate (NO_3), ammonium (NH_4), total nitrogen in aqueous solution (TNa), total phosphorus (TP), and total soluble phosphorus (TSP); seven days for total suspended solids (TSS), and two days for dissolved reactive phosphorus (DRP).

Samples for TKN, TP and TSS were analyzed without any filtering. Samples for TNa, NO_3, NH_4, DRP and TSP were filtered by a 0.45 µm membrane filter. Irrigation runoff samples were analyzed for TSS according to US EPA method 160.2. Water samples were passed through a 0.2 µm filter which was oven dried at 103 °C to determine the mass of sediment in a known amount volume. The TKN concentrations were analyzed with a Tecator 2040 Digestion Block according to US EPA method 351.1. An Alpkem Flow Solution IV automated wet chemistry system was used to analyze the samples for NO_3 and NH_4 in accordance with US EPA Method 350.1 (Collins et al., 1996), while TNa was determined with a Shimadzu TOC/TN analyzer according to US EPA Method 353.2 (Cook and Frum, 2004). Total phosphorus (TP) analysis was done by double acid digestion with nitric and perchloric acids using a Tecator 2040 Digestion Block. Samples were then analyzed with inductively coupled plasma spectrometry (TJA Solutions IRIS Advantage) for TP according to US EPA Method 365.4, (Chen et al., 2006) and EPA Method 200.8 (Wolf and Grosser, 1997). Dissolved reactive phosphorus (DRP), also known as ortho-phosphate, was determined using the ascorbic acid method according the US EPA Method 365.3. Total soluble phosphorus (TSP) was determined using the persulfate digestion method followed by color spectroscopy according to USA EPA method 365.3.

STATISTICAL ANALYSIS

Water quality data was compared for the six irrigations in 2015 and two irrigations in 2016 using ANOVA with R statistical software (R Core Team, 2013). A repeated measure analysis was performed using the lme4 and LmerTest package (Bates et al., 2015; Kuznetsova et al., 2016). In the mixed model, tillage, and irrigation were fixed while block and a repeated measures term (for sampling different irrigation event in the same plot) were treated as random factors. The model also contained treatment and irrigation interactions. The same analysis was performed to compare inflow, outflow, and irrigation advance time. Data was checked for violation of ANOVA test assumptions and log transformations were used as needed. A least squares mean using the lsmeans package in R was performed on statistically significant water quality results to summarize the effect of treatments on the response (Lenth, 2016). A squared correlation coefficient was calculated between TSS and the other measured variables. An ANOVA test was performed on residue data without a repeated measure and treated as a randomized complete block design and analyzed in R using the car package (Fox and Weisberg, 2011).

RESULTS

SURFACE RESIDUE COVER

As expected, the conservation tillage treatments, MT and ST had 43% and 47% of their soil surface covered respectively, in the 2015 season, which was significantly greater ($P < 0.001$) than CT, with approximately 4% residue cover (Figure 1.1). The mass of residues on the soil surface showed a similar trend with CT having 0.43 Mg ha^{-1} followed by MT (2.2 Mg ha^{-1}) and ST with a residue mass of 4.1 Mg ha^{-1} ($P = 0.03$). In the 2016 season, surface residue was different ($P < 0.001$) between the treatments. MT and ST having 53% and 55% residue cover, respectively, while CT had 22% of its surface residue covered. Similarly, CT had a total of 0.07 Mg ha^{-1}, while MT and ST, had a residue mass of 1.1 and 2.1 Mg ha^{-1}, respectively ($P = 0.03$) (Figure 1.1).

IRRIGATION PERFORMANCE

RUNOFF VOLUME

Irrigation total inflow was kept consistent between the CT, MT and ST treatments, receiving an average of 4500 m^3 ha^{-1} in 2015 and an average of 2700 m^3 ha^{-1} in 2016. The 2015 corn crop received six irrigations and the shorter season 2016 barley received two irrigations.

In 2015, total volume (m^3) leaving the field was 1785, 1258, and 558 m^3 ha^{-1} for CT, MT and ST, respectively ($P = 0.07$). A significant difference ($P = 0.006$) was observed between the treatments in 2016, where, CT, MT and ST had total runoff volumes of 1092, 147, and 564 m^3 ha^{-1} in sample rows, respectively (Table 1.4).

ADVANCE TIME

In 2015, it took less time for irrigation water to reach the bottom of the field (advance time) for the conventional plots (mean of 171 min) compared to MT and ST, with mean advance times of 200 and 350 min, respectively ($P < 0.001$). However, a significant interaction between treatment and irrigation event ($P = 0.018$) suggests that treatment effects were not consistent across all six irrigation events (data not shown). In 2016, annual mean advance time was also significantly different between the treatments ($P = 0.002$) with, CT having the shortest advance time and MT having the longest for both irrigations (Table 1.4).

SEDIMENT AND NUTRIENT IRRIGATION CONCENTRATIONS AND LOADS

TOTAL SUSPENDED SOLIDS

In the 2015 season, runoff samples from CT generally contained higher total suspended solids (1.54 mg L^{-1}) than MT or ST treatments ($P < 0.001$) with 0.24 mg L^{-1} and 0.09 mg L^{-1}, respectively (Table 1.5). However, the magnitude of TSS varied by irrigation as indicated by a significant treatment by irrigation interaction ($P = 0.002$; Fig. 1.2a). In 2016, TSS concentration was lower in the conservation tillage treatment but the results were not statistically significant due the low number of irrigations.

In 2015, the conservation tillage treatments had significantly lower annual TSS load than CT ($P = 0.004$), with MT and ST having a load of 0.27 Mg ha^{-1} and 0.08 Mg ha^{-1}, respectively, versus 3.27 Mg ha^{-1} under CT. A significant interaction between tillage and irrigation was measured ($P = 0.005$, Fig. 1.2b), from especially high TSS loads under CT in the second and sixth irrigation events of 2015. While CT generally demonstrated higher average TSS loads for the two irrigations in 2016, no statistically significant differences were observed for these events.

NITROGEN

For the 2015 season, TKN concentrations in runoff for CT were significantly higher than for the conservation tillage treatments ($P < 0.001$) and this translated into higher annual loads, TKN under CT (2.39 kg ha^{-1}) vs. MT and ST, 0.47, and 0.34 kg ha^{-1}, respectively ($P = 0.03$; Table 1.6). While similar trends were observed for concentrations in 2016, values were much lower than for 2015 and no significant differences were observed for TKN loads or concentrations ($P > 0.1$). In contrast to TKN, TNa concentrations in 2015 were significantly higher ($P = 0.001$) under ST (0.74 mg L^{-1}) than MT (0.52 mg L^{-1}) or CT (0.25 mg L^{-1}), with no significant differences observed for TNa concentrations in 2016 or TNa loads in either of the study years. Treatment effects on nitrate and ammonium were generally non-significant, and ammonium concentrations were too low to make any significant impact on water quality for both 2015 and 2016 seasons.

PHOSPHORUS

In the 2015 season, TP concentrations were significantly different between the treatments ($P < 0.001$) with a reduction of TP concentration (average 77%) and load (average 85%) associated with the conservation tillage treatments. In 2015, CT produced the largest annual TP load with 2.72 kg ha^{-1}, while MT and ST had loads with 0.35 and 0.36 kg ha^{-1} respectively ($P = 0.02$). A significant interaction between treatment and irrigation events ($P = 0.005$) indicates that differences were more pronounced for some irrigation events than others, but CT was consistently higher for all events (Table 1.7). In 2016, there were no significant differences in TP concentration between the treatments. However, TP load was significantly different with CT having a higher load in total runoff compared to both conservation tillage treatments ($P = 0.002$).

For both sampling seasons, there were no significant differences in overall DRP load between the treatments. However, a significant interaction in 2015 between treatment and irrigation event was seen, suggesting fluctuating load results between irrigation events (data not present).

In 2015, TSP loads and concentrations across the 6 irrigation events were significantly higher under CT than the conservation tillage treatments ($P = 0.007$; Table 1.7), such that CT had a cumulative load of 0.31 kg ha^{-1} over the six irrigation events, compared to 0.06 and 0.01 kg ha^{-1} for the MT and ST treatments, respectively. However, the relative magnitude of these differences varied across the different irrigation events in 2015, as indicated by a significant interaction between treatment and irrigation event for both TSP concentration and total load ($P < 0.001$; data not shown). No differences were observed for TSP in 2016.

STORM WATER RUNOFF

Three precipitation events produced measurable runoff during the study, two in 2015 and one in 2016. One storm event on May 9, 2015 occurred when flow measurement instrumentation was not installed and only concentrations are reported.

The duration for the first storm event on May 9, 2015 was 17.75 hours with an average rainfall intensity of 1.78 mm h^{-1}, and a maximum rainfall intensity of 6.6 mm h^{-1}, and a total rainfall of 32 mm. The storm event on June 11, 2015 was sampled to examine sediment and nutrient loads along with concentrations (Table 1.8). The storm duration was proximally 30 min with an average rainfall intensity of 36 mm h^{-1}. The CT treatment and one rep from ST treatment were the only treatments to produce enough runoff to sample. Concentrations were very similar across the measured variables for both treatments except TSS concentration. The TSS concentration for CT was twice that of ST with 8.61 mg L^{-1}. However, nutrient loads were different between the treatments. The ST treatment had much lower sediment and nutrient loads leaving the field as compared to CT. This can be explained by the overall runoff volume for the storm event, as total runoff volume for CT was approximately 86 m^3 ha^{-1}, while ST had a runoff volume of 3 m^3 ha^{-1}.

In the 2016 growing season, there was one measurable storm event on May 7 with an average rainfall intensity of 9 mm h^{-1} and duration of approximately 2.5 hours. Sediment and nutrient concentrations were very similar for CT and MT. A similar trend from the previous year appeared in which the concentration was similar but total event loads in the conservation tillage treatments were reduced by lower runoff volume. The conventional plot had a volume of 46 m^3

leaving the field while ST had 0.65 m^3. Consequently, the conventional tillage treatment has much higher sediment and nutrient loads when compared to the ST treatment even though concentrations are similar (Table 1.8). Strip-till had very little to no contaminates leaving the field except for TP and TSS with 0.02 kg ha^{-1} and 0.02 Mg ha^{-1}. Total P and TSS had high load values for CT with 1.5 kg ha^{-1} and 0.70 Mg ha^{-1} and Total P load exceeded total annual irrigation loads of 1.01 kg ha^{-1}.

RELATIONSHIP BETWEEN TOTAL SUSPENDED SOLIDS AND NUTRIENT LOADS

Total suspended solids has relationships with several other measured parameters in irrigation runoff. TSS concentration presented a strong relationship with TP concentration (R^2 = 0.73, $P < 0.001$) for the 2015 irrigation season (Figure 1.3a). When considering only the first five irrigations (since the sixth irrigation events had higher TSS concentration while TP concentration decreased) the R^2 was 0.92. Total suspended solids and DRP concentration were not correlated (R^2 = 0.07). When comparing the concentration of TSS to the other nutrient forms no correlations were found. In 2016, TSS and DRP were correlated with a R^2 of 0.54 ($P = 0.02$). TKN also showed a strong correlation with TSS with a R^2 of 0.66 ($P < 0.001$; Table 1.3b). Other nutrients losses in 2016 were not associated with TSS.

DISCUSSION

SURFACE RESIDUE COVER

As predicted, conservation tillage treatments in our study were found to have significantly higher cover and mass of surface crop residues compared to the CT plots. These residue levels meet the Conservation Technology Information Center (West Lafayette, Indiana, USA) conservation tillage definition "…any tillage or planting system in which at least 30% of the soil surface is covered by plant residue after planting to reduce erosion by water" (CTIC,

2004) . While this residue cover may offer key benefits, many furrow irrigating farmers are concerned that this material may impede advancing water and result in uneven infiltration across the field (Carter, 1991; Lehrsch et al., 2005). In our study, irrigations were monitored carefully for any water obstructions in irrigated furrows by residue buildup. While some damming occurred early in the 2015 season in the conservation tillage treatments, obstruction of water movement by residues was not observed after the second irrigation. Furthermore, small yield reductions were seen in conservation tillage treatment (see Chapter 2) but were comparable to the control suggesting uniform infiltration thought-out the field.

Based on our findings we found that surface residue may be the most important factor in controlling sediment and nutrient loss carried in runoff. A number of studies have suggested that an effective way to reduce irrigation-induced erosion and associated nutrient loss is to maintain surface residue and preferably to have standing crop stover (Berg, 1984; Carter et al., 1993; Smika and Unger, 1986). Residues can also protect the soil from water drop impact (Lehrsch et al., 2014), improve soil-nutrient-water relationships, (Allmaras 1985; Mostaghimi et al. 1992) and improve soil biological, physical, and chemical characteristics (Karlen et al., 1994; and see Chapter 2). By design, the conservation plots maintained a residue cover of greater than 40% for both years, although residue mass for 2016 was lower than 2015 due to an additional tillage event required after the 2015 harvest to assist with bed construction. This reduction of surface residue in the conservation plots likely led to minimizing the impact of conservation tillage on water quality parameters in 2016 (discussed below).

It should be noted that too much residue can also have negative impacts by slowing soil warming in the early spring, especially in the northern latitudes or high elevation climates like Colorado (Logan et al., 1991). Cold, wet soil can impede the germination rate, resulting in late seed emergence that could decrease yields and profits (Licht and Al-Kaisi, 2005; Midwest Plan Service., 1992; United States Department of Agriculture, 1999).

IRRIGATION PERFORMANCE

RUNOFF

Reductions in runoff volumes of 30% and 70% in MT and ST, respectively were observed in the conservation tillage treatments due to residue in the furrows reducing surface flow rate and increasing infiltration (Chapter 2). Because sediment and nutrients are carried in runoff, controlling runoff has a direct impact on water quality. Our study shows that as runoff volume increases there was an increase in sediment loss ($R^2 = 0.69$). A similar but a weaker relationship with runoff rate and total suspended solids ($R^2 = 0.50$) was observed. These findings suggest that managing outflow volume during irrigations should be a priority for reducing sediment loss. However it should be noted that under furrow irrigation, a successful irrigation will produce at least some runoff to ensure uniform irrigation application on the top and bottom of the field (Sojka, 2007).

The conservation tillage treatments benefited from surface residue left over by reduced tillage. With the implementation of planned surface residue management (bailing, sizing, and removal), we were successful in maintaining surface residue that reduced runoff while having relatively uniform irrigation throughout the field.

ADVANCE TIME

In 2015, irrigations one, two, three and six, had runoff that started significantly faster in the CT tillage treatments when compared to ST. In all six irrigations, no significant difference occurred between CT and MT. It is interesting to note that the MT and ST advance times decreased as the irrigation season progressed. This may be attributed to the degradation and movement of surface residue in the irrigated furrows over the course of the season. It was observed that residue was being pushed down the furrow with each irrigation, which decreased the advance time for each subsequent irrigation event (data not shown). This appears to be a possible management concern, as nonuniform advance time between irrigations are undesirable from a water conservation and labor standpoint. This nonuniformity per irrigation event was most noticeable in the ST treatment which contained the higher residue cover and mass. The CT treatment had a relatively similar advance time for each irrigation event. However, the annual average CT advance time of 171 minutes is faster than recommended for an efficient irrigation system producing excess runoff and lower infiltration. Advance time targets should be 50 to 70 percent of total irrigation time to reach the optimum infiltration (Yonts et al., 2007). For a 12-hour irrigation session, the optimum advance times should be 350 to 500 min which was similar to the ST treatment (Table 1.4). The ability to control advance times is an important management technique in reducing sediment and nutrient load in irrigation runoff. Our findings clearly indicate that increased surface residue can be an effective management tool for controlling advance time, but it does require additional management than conventionally tilled fields.

INFILTRATION

The conditions influenced by tillage on the top layer of the soil profile can have important impacts on infiltration (Matula, 2003). Conservation tillage practices, ST in particular, had a positive impact on infiltration for the 2015 and 2016 seasons. The presence of residue on the surface increased infiltration opportunity time, thus providing increased time for the conservation tillage treatments to infiltrate a larger quantity of water. Similar results occurred in several studies (Berg, 1984; Savabi et al., 2007), each reporting increase of infiltration due to residue cover. We also observed improved soil aggregation and increased earthworm abundance in ST treatment, which are a major driver of infiltration in soils (Andriuzzi et al., 2015; see Chapter 2).

SEDIMENT AND NUTRIENT

TOTAL SUSPENDED SOLIDS

Irrigation-induced erosion has been identified as a major contributor to water pollution (Sojka, 2007). The reduction of sediment in runoff in MT and ST treatments suggests conservation tillage helped to control irrigation-induced erosion. One of the factors that cause erosion, specifically the detachment of soil particles in furrow irrigation, is the drag force of flow on the soil surface. Residue has the ability to reduce the erosion by absorbing some of the drag force and minimizing the detachment of soil (Trout and Neibling, 1993). Additionally, loose cultivated soil from intensive tillage requires less drag force from irrigation water to carry soil away (Koluvek, 1993). These findings corroborate previous studies suggesting that residue cover has an overall beneficial impact on reducing sediment concentrations and annual loads (Aarstad and Miller, 1981; Carter, 1991). Similar to our findings, Carter and Berg (1991) recorded a 47 to 100 percent reduction is TSS loss from furrow irrigated fields on their fifth year of conservation tillage. Blevins et al. (1990) compared sediment loss from a conventional (19.79 Mg ha^{-1}) to a reduced (0.55 Mg ha^{-1}) tillage systems and found major reductions in TSS loads. Such results show the potential of increased surface residue because of reduced tillage has on reducing sediment loss in furrow-irrigated systems.

The first irrigation in 2015 had the lowest amount of sediment loss compared to the other five irrigation events in all treatments (Fig. 1.2a & b). This might be explained by looking at the precipitation data immediately before the irrigation event. In the five days before the first irrigation, approximately 15 mm of precipitation fell on the field, providing a pre-wetted perimeter and increased soil moisture. Others examining soil loss from pre-wetted furrow-irrigated fields found a general reduction of soil loss compared to dry furrows (Bjorneberg et al., 2002a). They concluded that as water rapidly wets a dry soil, soil aggregates rupture due to water hastily displacing the trapped air within aggregates (Elliott, 1986). Thus, having a wet soil surface during the first irrigation likely reduced the disruption of aggregates and reduced readily transportable sediment.

NITROGEN

Reduced tillage and residue management had a considerable impact on sediment-bound nitrogen but not soluble forms. In 2015, major reductions in TKN concentrations (over 50%) and loads (over 80%) were observed in the conservation tillage treatments (Table 1.6) and this was likely related to the reduction of sediment loss in these treatments. While there was no relationship between TKN and TSS concentration in 2015 when factoring all six irrigation events, total suspended solids and TKN concentrations from the last four irrigation events had a strong correlation ($R^2 = 0.72$). Concentrations of TKN in the first two irrigation events were relatively high, especially in the CT treatments, while TSS concentration was low causing a weak correlation with TSS. Fertilizer incorporated into the bare surface of the CT treatments could provide more transportable N in runoff. Fertilizer placement by banding in the conservation treatments could have reduced the available N in the surface for transport in runoff as seen in the reduction of TKN in the conservation tillage treatments. In 2016 we found a significant positive relationship between TSS and TKN ($R^2 = 0.66$; Figure 1.3b) suggesting most TKN is bound to sediment. Our results support the adoption of conservation tillage for the mitigation of sediment bound-N impacting water quality.

In contrast to TKN, reducing soil disturbance and maintaining surface residue cover failed to decrease TNa concentrations in irrigation runoff, as TNa loads were similar among the tillage treatments. Residue can improve sediment-bound N, but has a smaller effect on the soluble fraction that is carried in runoff (Mostaghimi, 1992). Increased infiltration in the conservation tillage treatments did reduce the overall runoff volume therefore minimizing the impact of higher TNa loads in the conservation treatments. This result provides additional evidence for the abatement of nutrients by controlling runoff. In 2016, TNa concentrations and loads for all three treatments were negligible. The two irrigations took place when plant uptake was at its highest, thus it appears that this minimized available N to be carried in runoff.

For 2015 and 2016, nitrate concentrations were not significantly different between the treatments, but values for the conservation plots were higher than the control. For perspective, in 2015 the highest N concentration in runoff total nitrogen (TKN + NO_3+NO_2) in CT (1.47 mg L^{-1}), MT (0.65 mg L^{-1}), and ST (1.04 mg L^{-1}) did not exceed the interim numeric value of 2.01 mg L^{-1} for warm surface water set by Colorado Department of Public Health and Environment (CDPHE, 2012). Runoff volume was much lower in the conservation plots which resulted in no statistical differences in loads between the treatments since conservation practices in MT and ST did not mitigate NO_3 concentration directly but indirectly by reducing overall runoff volume and accredited to surface residue. Ammonium in runoff did not significantly contribute to N losses because concentrations were frequently below the detection limit.

PHOSPHORUS

Conservation tillage treatments had a large impact on TP concentration and annual loads (Table 1.7). But for both growing seasons, TP concentration for all three treatments still exceed the interim value of 0.17 mg L^{-1} for warm surface water set by Colorado Department of Public

Health and Environment (CDPHE. 2012). Results show a TP load reduction of 87% in conservation tillage treatments compared to the control. Avalos et al. (2009) had similar reductions for TP loads when comparing a system with four times as much residue as the control. Smaller reductions of TP loading were seen in a conventional tillage system that utilized straw mulching (Wang et al., 2015). These results show that residue cover could have a larger impact on reducing TP in runoff. It's important to note that TP losses in years 2015 and 2016 were proportional to TSS losses as seen in other studies (Berg and Carter, 1980). The majority of TP was bound to sediment, making field scale sediment control crucial in controlling TP. This further supported by a strong correlation between TSS and TP concentrations (Figure 1.3a).

Average annual DRP concentrations were higher, though not significantly, in the conservation tillage treatments, but the overall load was lower compared to CT. The controlling factor that reduced DRP load was the reduction in runoff volume. Annual DRP load for the entire field was only about 4% of total phosphorus, but was about 8% of TP in the conservation plots. Results from the surface soil test P levels show that our soils have a medium risk potential for phosphorus transport by the Colorado Phosphorus Index Risk Assessment (Sharkoff et al., 2012). The relatively low levels of DRP are also attributed to the high $CaCO_3$ content (69%) in the soils at this site that reduces P solubility available for runoff (Schierer et al., 2006). Higher concentration of DRP observed in the conservation plots could be attributed to the increase in residue on the surface. Decomposition of residue on the surface could have increased soluble P available to be carried in runoff. A similar study looking at the effects of crop residue on nutrient loss found that an increase in surface residue lead to an increase of soluble P loss (Avalos, 2009). Dissolved reactive P is soluble in solution making it difficult for residue to impede its flow down the furrow and off the field. In both years, the magnitude of TSP loss was so low to make it insignificant in runoff.

When considering the differences between treatments it is important to keep in mind that in 2016 the sample size (n=12) was small, because of only two irrigation events; this reduced the power of the statistical results. The result of significant differences between the treatment in 2016 were seen in some of the water quality parameters, however, additional irrigations would have provided a stronger power in the statistical model in detecting the differences. In 2015, three treatments with two replications and six irrigations resulted in a much larger sample size (n = 36).

Conservation tillage was successful in reducing sediment and nutrients leaving the field in runoff and these constitutions have monetary value. Irrigation-induced erosion includes the on-site cost of reduced soil productivity and the cost of off-site impacts that include, but are not limited to, the negative externalities of water quality, recreation, and social costs (Hansen and Ribaudo, 2008). Using their approach, Hansen and Ribaudo (2008) developed a hydrologic unit code (HUC) level water quality value benefit for water-based categories (e.g. reservoir services, navigation, and water-based recreation). The value of soil loss (ignoring water quality effects) from furrow irrigation in CT, MT, and ST was approximately \$10, \$0.81, and \$0.24 ha^{-1} in 2015 and \$4.68, \$0.09 and \$0.60 ha^{-1} in 2016.

STORM WATER RUNOFF

Reduced tillage and residue cover had a significant impact on sediment and nutrient loads, but had no effect on concentrations. During a storm event, the kinetic energy of raindrops has the potential to exacerbate the detachment and transport of sediment and nutrients in bare unprotected soils. Rainfall intensity is an important factor when looking at sediment and nutrient concentration in runoff. In 2015, the first event had a lower rainfall intensity, while the second event had high rainfall intensity resulting in higher concentrations. Accordingly, storms with low rainfall intensity produced much lower concentrations (Table 1.8) when compared to the storm with high rainfall intensity. With the presence of residue cover, the soil is shielded from rainfall impact reducing erosive force (Trout, 1993) as well as increasing infiltration and minimizing overall runoff (Tesfuhuney et al., 2013).

We saw no measurable runoff in the MT treatment and very little in the ST treatment for all storm events in 2015 and 2016. Comparing irrigation and storm water concentrations, we found that storms produced higher concentrations across all measured parameters than irrigation events. For example, one storm event in 2015 produced 30% of total annual TP loading from six irrigation events. In 2016, TP loads in CT was 0.5 kg ha^{-1} greater from just one storm event when compared to total annual TP load from all 2016 irrigations (two irrigations). In the same year, TSS total storm load in CT produced about 60% of total annual irrigation loads in CT. Rainfall will generally effect the entire fields while irrigation effects on sediment and nutrient loss are localized in the furrows. The potential for higher rainfall intensity in northern Colorado increases the likelihood of greater detachment and transport of sediment and nutrients. Residue cover in the conservation tillage treatments did reduce sediment, nitrogen and phosphorus loading in runoff in cases where higher rainfall intensity was present. More research comparing runoff from irrigation induced and losses from precipitation within the same season is needed to further assess how conservation tillage impacts water quality in semi-arid environments. Most research looks at one or another, ours looked at both of these drivers of sediment and nutrient losses and found that precipitation can significantly contribute to loads during intensive storm events.

RELATIONSHIP BETWEEN TOTAL SUSPENDED SOLIDS AND NUTRIENT LOADS

Exploring TSS and nutrient concentration relationships can help infer, with a certain degree of certainty, nutrient loss by determining TSS concentration, which is an inexpensive analytical method. Our study shows a strong correlation between TSS and TP and other studies have reported similar result with R^2 values ranging from 0.44 - 0.85 (Bjorneberg et al., 2015). Dissolved reactive P is soluble and is not bound to sediment, resulting in a weak relationship with TSS loss as found by other researchers (Bjorneberg, 2006; Lentz and Lehrsch, 2010; Westermann, 2001). Dissolved reactive phosphorus concentrations were much lower than TP, indicating that most of the phosphorus in runoff was sediment-bound P which is consistent with past studies (Westermann, 2001). While it is true that conservation tillage can reduce TP concentrations in runoff by reducing TSS concentration, it had no effect on DRP. Total P is bound to sediment but DRP is dissolved in solution making it difficult to limit its transport. Therefore, DRP load leaving the field is a function of runoff volume and can reduce loads by reducing runoff. These findings suggest that controlling irrigation-induced erosion and runoff volume is key for controlling P loss in furrow irrigation systems.

CONCLUSION

Runoff from furrow irrigation can contribute to excessive sediment and nutrients into downstream water bodies, leading to water quality degradation. These findings support the hypothesis that adoption of conservation tillage under furrow irrigation can have beneficial impacts on sediment and nutrient abatement in irrigation runoff. Widespread adoption of these practices has the potential to substantially mitigate many of the environmental problems caused by furrow irrigated agriculture. Our finding supports the utilization of conservation tillage practices such as MT and ST under furrow irrigation systems when compared to the CT. Strip-till outperformed MT in a few parameters (TSS and TKN) but both treatments provided beneficial impacts on water quality and irrigation parameters.

Irrigation quality parameters such as runoff, advance time, and infiltration all saw improvements from surface residue cover caused by reduced tillage in the conservation plots. Maintaining surface residue in furrows through reduced tillage in the conservation tillage treatments was crucial for the abatement of sediment and sediment bound nutrients. Sediment and sediment-bound nutrients, such as TKN and TP, were the water quality parameters most impacted by conservation tillage treatments. A strong correlation was observed between TSS and TP concentrations, suggesting that most of the phosphorus was sediment bound, this further supports the need for BMPs that control sediment loss. Considerable reductions in runoff volume in the conservation treatments had significant remediation of soluble nutrient loads in runoff water. Proper surface residue management was the main factor in achieving high reductions of sediment, nitrogen, and phosphorus contaminates in surface runoff.

Farmers' apprehension for adopting conservation tillage practices for furrow irrigation could be moderated through education on water quality and soil benefits and demonstration of proper residue management. Continued assessments of conservation tillage under furrow irrigation is vital in understanding the impacts of irrigation-induced sediment and nutrient loss on water quality. Developing region wide edge of field monitoring on a farm level would be ideal to track annual water quality changes when implementing conservation tillage. With additional unambiguous evidence of the feasibility of conservation tillage on furrow irrigation systems, we could provide farmers' and other stakeholders with the information needed to make a significant change in farm management which could have considerable impacts on sediment and nutrient abatement in irrigation runoff.

TABLES AND FIGURES

Table 1.1. Selected pre-planting soil characteristics for Conventional (CT), Minimum (MT), Strip (ST) tillage treatments. (0 – 15 cm).

Treatment	pH	OM (%)	NO_3-N (mg kg^{-1})	Extractable-P* (mg kg^{-1})	$CaCO_3$ (%)
			2015		
CT	8.1	1.8	11.3	10	69
MT	8.1	1.9	11.2	11.5	69
ST	8.1	1.9	10.5	9.5	69
			2016		
CT	8.1	1.7	6.15	9.5	69
MT	8.1	1.8	8	12.3	69
ST	8.1	1.9	5.4	10.5	69

*$NaHCO_3$ extractable P

Table 1.2. Field operations for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments for the 2015 and 2016 seasons.

2015					
Conventional Till		Minimum Till		Strip Till	
Date	Operation	Date	Operation	Date	Operation
3/23/15	Disk	3/23/15	Verti-Till	4/13/15	Strip Till
3/23/15	Plow	4/13/15	Strip Till	4/13/15	Fertilize
3/27/15	Mulch	4/13/15	Fertilize	4/30/15	Planting
4/14/15	Fertilize	4/30/15	Planting	6/24/15	Cultivate
4/14/15	Bed	6/24/15	Cultivate	6/24/15	Fertilize
4/14/14	Cultipack	6/24/15	Fertilize	11/16/16	Harvest
4/30/15	Planting	11/16/15	Harvest		
6/24/15	Cultivate				
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	12/11/15	Verti-Till (2x)	12/11/15	Verti-Till
12/11/15	Disk	3/01/16	Strip Till	3/01/16	Strip Till
12/11/15	Plow	3/01/16	Fertilize	3/01/16	Fertilize
2/22/16	Mulch	3/03/16	Planting	3/03/16	Planting
3/01/16	Fertilize	3/03/16	Cultivate	3/03/16	Cultivate
3/02/16	Bed	7/25/16	Harvest	7/25/16	Harvest
3/02/16	Cultipack				
3/03/16	Planting				
3/03/16	Cultivate				
7/25/16	Harvest				
# of Field Operations	10	7		6	

Table 1.3. Fertility requirements for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments for the 2015 and 2016 seasons.

	CT	MT	ST
Method	Broadcast	Side Dress	
		(kg ha^{-1})	
Fertilizer		2015	
N	180	180	180
P_2O_5	68	34	34
Zn	5.6	1.5	1.5
		2016	
N	78	78	78
P_2O_5	90	45	45

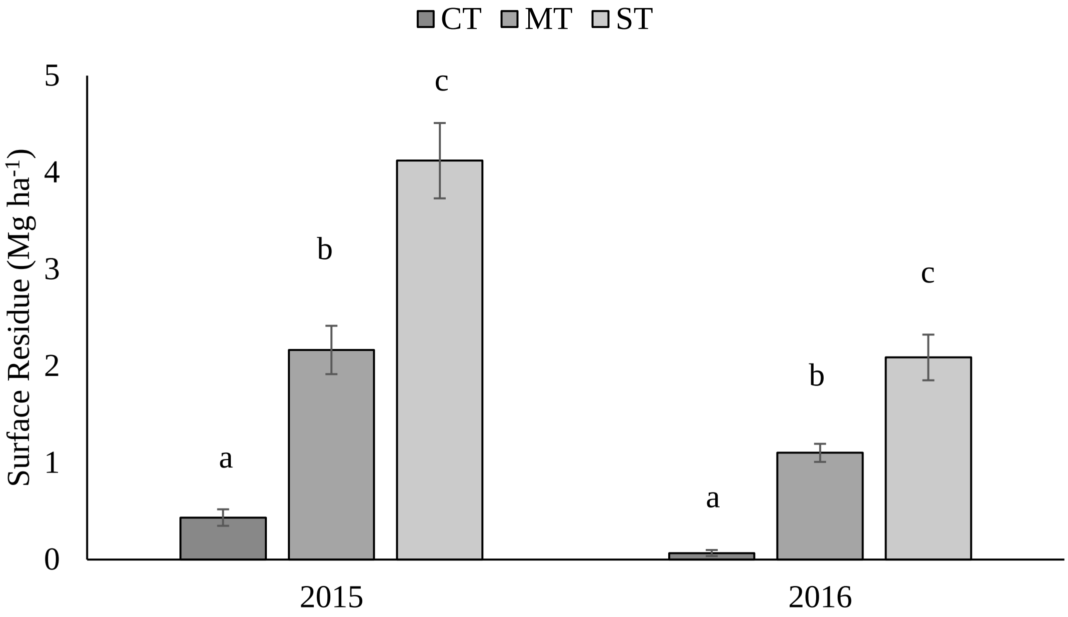

Figure 1.1. 2015 and 2016 surface residue in mass for the Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments. Values within the same year followed by the same letter are not significant at α = 0.05

Table 1.4. Tillage impacts on flow characteristics for Conventional, Minimum, and Strip tillage treatments for 2015 and 2016 irrigation seasons.

	Annual Flow Parameters		
Tillage Treatment	Runoff	Infiltration	Advance time
	$m^3\ ha^{-1}$		*minutes*
	2015		
Conventional	1785 a	2948 a	171 a
Minimal	1258 a	3294 a	200 a
Strip-Till	558 a	3742 a	350 b
P – Value*	0.07	0.18	<0.001
	2016		
Conventional	1092 a	1645 a	60 a
Minimal	147 b	2548 a	510 b
Strip-Till	564 b	2215 a	412 b
P – Value*	0.006	0.06	0.002

*Values within the same year followed by the same letter are not significant at $\alpha = 0.05$

Table 1.5. Average annual concentration and total loads for total suspended solids for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments for the 2015 and 2016 irrigation seasons.

Total Suspended Solids (TSS)

Year	CT		MT		ST		P value	
	g L^{-1}	*Mg ha^{-1}*	*g L^{-1}*	*Mg ha^{-1}*	*g L^{-1}*	*Mg ha^{-1}*	*g L^{-1}*	*Mg ha^{-1}*
2015	1.54 a	3.27 a	0.24 b	0.27 b	0.09 b	0.08 b	<0.001*	0.004*
2016	1.18 a	1.56 a	0.19 a	0.03 b	0.55 a	0.20 a	0.30	0.25

*Concentrations and loads within the same year followed by the same letter are not significant at $\alpha = 0.05$. P values marked with (*) have significant ($\alpha = 0.05$) interaction with irrigation events.

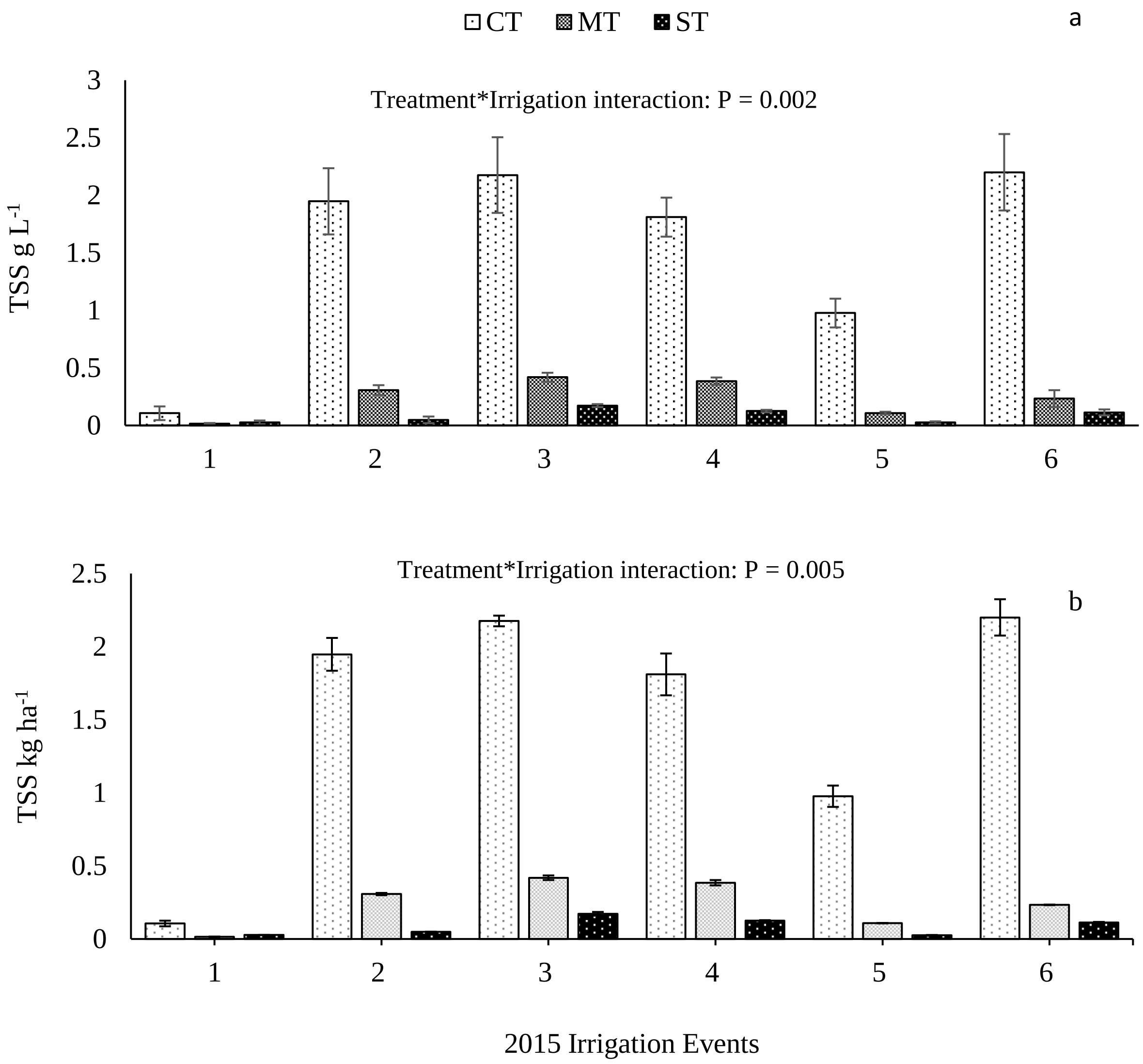

Figure 1.2. 2015 total suspended solid concentrations (a) and loads (b) for the Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments per irrigation event.

Table 1.6. Average annual concentration and total loads for Nitrogen compounds for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments for the 2015 and 2016 irrigation seasons.

Total Kjeldahl Nitrogen

Year	CT		MT		ST		P value	
	mg L^{-1}	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$
2015	1.37 a	2.39 a	0.48 b	0.47 b	0.72 c	0.34 b	<0.001	0.03
2016	0.14 a	0.18 a	0.09 a	0.01 a	0.10 a	0.06 a	0.65	0.23

Total Nitrogen - aqueous

Year	CT		MT		ST		P value	
	mg L^{-1}	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$
2015	0.25 a	0.32 a	0.52 a	0.31 a	0.74 b	0.27 a	0.001	0.93
2016	0.10 a	0.10 a	0.10 a	0.01 a	0.10 a	0.06a	0.99	0.31

Nitrate-N

Year	CT		MT		ST		P value	
	mg L^{-1}	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$
2015	0.10 a	0.09 a	0.17 a	0.11 a	0.32 a	0.13 a	0.56	0.87
2016	0.24 a	0.37 a	0.28 a	0.06 a	0.35 a	0.25 a	0.75	0.49

Ammonium-N

Year	CT		MT		ST		P value	
	mg L^{-1}	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$	*mg L*$^{-1}$	*kg ha*$^{-1}$
2015	0.005 a	0.01 a	0.009 a	0.006 a	0.04 b	0.013 a	<0.001	0.72
2016	0.09 a	0.08 a	0.003 a	0.001 a	0 a	0.00 a	0.46	0.46

*Concentrations and loads within the same year followed by the same letter are not significant at $\alpha = 0.05$.
P values marked with (*) have significant ($\alpha = 0.05$) interaction with irrigation events.

Table 1.7. Average annual concentration and total loads for Phosphorus compounds for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments for the 2015 and 2016 seasons.

Total Phosphorus (TP)

Year	CT		MT		ST		P value	
	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$
2015	1.25 a	2.72 a	0.33 b	0.35 b	0.24 b	0.36 b	<0.001*	0.02*
2016	1.01 a	1.07 a	0.98 a	0.16 b	0.98 a	1.01 a	0.99	0.002

Dissolved Reactive Phosphorus (DRP)

Year	CT		MT		ST		P value	
	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$
2015	0.049 a	0.080 a	0.040 a	0.025 a	0.059 a	0.029 a	0.39	0.15*
2016	0.053 a	0.059 a	0.017 b	0.002 a	0.021 b	0.008 a	0.002*	0.08

Total Soluble Phosphorous (TSP)

Year	CT		MT		ST		P value	
	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$	$mg\ L^{-1}$	$kg\ ha^{-1}$
2015	0.17 a	0.31 a	0.085 b	0.057 b	0.011 c	0.007 b	<0.001*	0.007*
2016	0.019 a	0.02 a	0.014 a	0.003 a	0.025 a	0.013 a	0.32	0.15

*Concentrations and loads within the same year followed by the same letter are not significant at $\alpha = 0.05$. P values marked with (*) have significant ($\alpha = 0.05$) interaction with irrigation events.

Table 1.8. Storm water sediment and nutrient concentrations and loads for Conventional (CT), and Strip (ST) tillage treatments in the 2015 and 2016 seasons.

9 May 2015

Treatment	Total P	DRP	TKN	NO_3-N	TSP	TSS
	Concentration (mg L^{-1})					g L^{-1}
CT	2.29	0.12	2.64	1.80	0.25	1.23
ST	2.24	0.15	3.40	0.10	0.26	1.04

11 June 2015

Treatment	Total P	DRP	TKN	Total N aq	NO_3-N	NH_4-N	TSS
	Concentration (mg L^{-1})						g L^{-1}
CT	8.56	0.25	15.23	1.40	1.00	0.47	8.61
ST	8.48	0.58	22.07	1.85	0.80	0.44	4.58
	Load (kg ha^{-1})						Mg ha^{-1}
CT	0.75	0.02	1.33	0.12	0.08	0.04	0.77
ST	0.02	<0.01	0.06	<0.01	<0.01	<0.01	0.01

7 May 2016

Treatment	Total P	DRP	TKN	Total N aq	NO_3-N	NH_4-N	TSS
	Concentration (mg L^{-1})						g L^{-1}
CT	5.32	0.27	0.02	1.12	0.38	0.32	2.50
ST	3.40	0.23	BDL	1.18	0.42	0.32	3.16
	Load (kg ha^{-1})						Mg ha^{-1}
CT	1.5	0.10	0.01	0.32	0.11	0.10	0.70
ST	0.03	<0.01	BDL	<0.01	<0.01	<0.01	0.02

*The minimum (MT) tillage treatment had no measurable runoff. No statistical analysis due runoff in only one rep of ST.

BDL = below detection levels

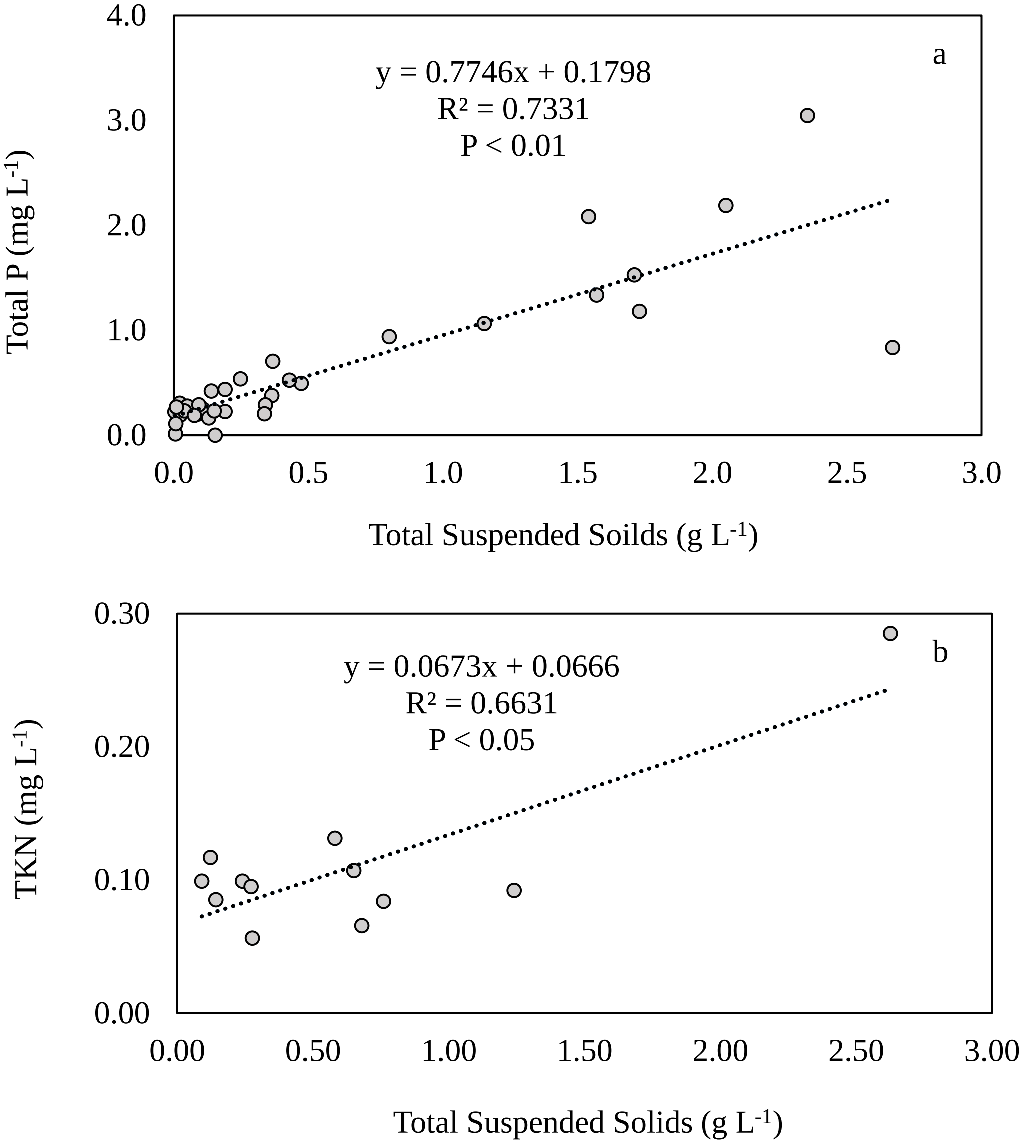

Figure 1.3. Relationships between a) total suspended solid and total phosphorus concentrations in runoff in 2015 and b) total suspended solid and total Kjeldahl nitrogen in runoff in 2016. The significant linear regression with significant coefficients (significance level at $\alpha = 0.05$) are shown.

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CHAPTER 2: IMPACTS OF CONSERVATION TILLAGE ON SOIL BIOLOGICAL, PHYSICAL, AND CHEMICAL PARAMETERS

INTRODUCTION

As a fundamental component of agriculture and ecosystem productivity, soil is one of our most important natural resources. Soil is comprised of an array of living and dead organisms within a complex network of pores and aggregates and is governed by key chemical factors such as soil carbon content and pH. Soil quality, or the ability of the soil to perform multiple functions, takes into account this complex relationship between soil biological, physical, and chemical parameters. Critical functions provided by the soil include being a medium for plant growth, nutrient cycling, water regulation, C sequestration, and providing substrate and suitable habitat for biota (Lewandowski, 1999). Given the fundamental role that soil plays in maintaining agroecosystem productivity and the threats that improper management pose to soil quality, there is great interest in understanding how management impacts on soils and to develop more sustainable farming practices.

Soil degradation is a widespread issue around the globe and has long lasting implications on soil productivity and future food security. Intensive tillage and residue removal are widespread agricultural practices that can accelerate soil degradation by reducing soil biological activity, soil organic matter, and aggregation, as well as increasing the susceptibly of soil to erosion, ultimately leading to a decline of soil productivity (Carter et al., 1985; Kemper and Koch, 1966; Lal, 1993; Reicosky et al., 2011). Growing concern over soil degradation in conventionally tilled systems has sparked the interest in the use of conservation tillage. Conservation tillage is any tillage practice that leaves at least 30% of the soil surface covered with residue from the previous year(s) (Conservation Tillage Information Center, 2004). It can range from no-till to reduced tillage operations with considerable less soil disturbance.

In furrow-irrigated agriculture, conventional tillage that inverts the soil and buries residue, leaving the surface unprotected from environmental factors, is commonly applied to ensure unobstructed (clean) furrows that allow uniform flow and infiltration as water moves down the furrow. The need to maintain clean furrows, complicates management under conservation tillage management and slows its adoption. However, in recent years, new tillage strategies and greater recognition of the potential for conservation tillage to improve soil quality as well as reduce operational costs has made it an attractive best management practice (BMP).

Conservation tillage can offer several benefits to the biological component of soils. Maintaining biological diversity and activity improves nutrient cycling, plant growth, the formation of soil aggregates, and can contribute to biocontrol of pests in agricultural system (Barrios, 2007; Lewandowski, 1999). Soil biota facilitate the conversion of plant residue (organic matter source) into plant available nutrients and aid in the early detection of compromised systems. The composition of soil biological communities can also serve as valuable diagnostic tools for assessing soil quality and overall ecosystem health (Rousseau et al., 2013).

Increased surface residue from reduced tillage has shown to increase abundance and diversity of soil macrofauna (i.e., earthworms, beetles, ants, etc.) compared to conventional systems by reducing soil disturbance. This can lead to improved soil structure and nutrient cycling by soil macrofauna activity (Lewandowski 1999, Mutema, 2013). Other studies have found positive effects of reduced tillage on macrofauna abundance (Chan, 2001; House and Parmelee, 1985) and accredited it to both the reduction of soil disturbance and management of surface residue cover. Due to the interconnectivity of soil parameters, soil macrofauna have great influence on soil physical parameters. These properties determine how water and air move through the soil, and facilitate the transfer of nutrients to microorganisms and plant roots. The physical manipulation of the soil surface, or lack thereof, can impact the quality of the soil's physical properties. Higher infiltration rates in a reduced tillage system were reported in a study comparing conventional tillage and no-till systems, and this was attributed to increased earthworm activity and/or higher surface residue in the reduced tillage system (Savabi et al., 2007). Earthworms can also improve aggregation and SOM stabilization in newly formed soil macroaggregates (Fonte et al., 2007). Soil aggregation promotes a balance between air and water that is critical to root development and microbial activity. When soil aggregates become unstable and fall apart during the wetting processes, soil pores will become clogged with loose clay particles, greatly reducing water infiltration. Studies have shown that reduced tillage and maintaining crop residue promotes larger and more stable aggregates in the surface layer (Hajabbasi and Hemmat, 2000; Hontoria et al., 2016; Karlen et al., 1994).

The biological processes carried out by a range of soil organisms have a direct impact on the soil's chemical properties. Understanding the relationship between the biological and chemical soil parameters is important in assessing soil health of a field. Permanganate oxidizable carbon (POXC) has been identified as the prominent labile (or recently active) soil organic fraction, having a relatively rapid turnover rate, and responds quickly to land management changes (Blair et al., 1995; Hurisso and Culman, 2016). POXC is thought to be readily available food for soil biological activity and when present in high amounts, can be an indicator of good soil health. Reduced tillage has shown to increase accumulation of labile C (Melero et al., 2009).

In order to better understand the potential of conservation tillage to improve soil quality and long-term farm sustainably, this research used replicated field-scale plots to examine soil parameters four years after the implementation of two conservation tillage practices vs. conventional tillage 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 parameters associated with soil quality, (2) explore relationships between key soil biological, chemical and physical parameters, and (3) understand the potential economic benefits of conservation vs. conventional tillage practices under furrow irrigation.

MATERIALS AND METHODS

SITE DESCRIPTION

Research was conducted at the Colorado State University Agricultural Research, Development and Education Center (ARDEC) (40°67' N, -104°99' W). With an elevation of 1570 meters, this area experiences an annual precipitation of 407 mm, annual maximum temperature of 17.6 C, minimum of 2.7 C, and average of 10 C. The site is dominated by the Garrett soil series, a fine-loamy, mixed, mesic type of Pachic Argiustoll (Soil Survey Staff, 2017). The soil is comprised of 1.8% of organic matter and a texture profile of 52 % sand, 18 % silt, and 30 % clay, pH 7.8 and a slope of 0.75%.

EXPERIMENTAL DESIGN AND MANAGEMENT

In 2011, a field scale experiment was established to compare two conservational tillage treatments, minimum till (MT) and strip till (ST) to a conventional tillage treatment (CT). The experiment was arranged in a randomized complete block design with two blocks and each of the three treatments randomly assigned to each block. To better mimic the dynamics of commercial production fields using furrow irrigation in Colorado large field plots, (320 m long x 27 m wide), were used. Conventional tillage continues to be utilized by most farmers in the region with furrow irrigation. Conservation practices applied in the study were selected with a group of advising farmers interested in the feasibility of conservation tillage for furrow-irrigated systems. Each plot was oriented in a North-South direction, 36 furrows wide in which every other row were irrigated.

All operations were performed by a six row implements. After harvest, residue in all tillage systems was chopped using a 4.6 m flail chopper, windrowed, and bailed. Flailing and baling operation were performed to remove less than 50% of the pervious crop residue. Following the residue management, CT, MT, and ST received nine, seven, and six field operations in 2015 and eight, six, and five in 2016 (Table 1). Conventional tillage is a plow-based treatment that inverts the soil, thus burying residues. The conservation tillage, MT and ST use a vertical and strip till operations respectively that leaves most of the residue on the soil surface.

In 2015, a hybrid Mycogen 2V357 corn (*Z. mays* ssp. *Mexicana* **x** *T. dactyloidies)* (Zea mays) variety with a 90 to 95-day maturity was planted on April 30. Seed was sown approximately five cm deep at an in-row spacing of 15 cm and 75 cm row spacing for a target plant population of 83,950 seed ha^{-1} (34,000 seed ac^{-1}). On March 3, 2016, a Foundation seed drill was used to plant barley (*Hordeum vulgare* L.) at a target seeding rate of 112 kg ha^{-1} (100 lbs ac^{-1}). In the CT plots fertilizer was applied by broadcasting and uniformly distributing fertilizer on the soil surface. In the conservation plots, liquid fertilizer was applied by side-dressing techniques, fertilizer was applied in the subsurface bands along the side of the plant row. In 2015 180 kg N ha^{-1} was applied to the corn in all treatments, while in 2016 78 kg N ha^{-1} was applied to the barley. Side-dressing allowed us to reduce P application for the conservation tillage treatments, such that the CT plots received 68 kg P_2O_5 ha^{-1} in 2015 and 90 kg P_2O_5 ha^{-1} in 2016, and the MT and ST plots half of this rate for both years.

SURFACE RESIDUE SAMPLING

Percent residue cover was measured in all plots at the beginning of the growing season, in early May of 2015 (corn) and in March 2016 (barley) using a line transect method outlined by Laflen et al. (1981). Measurements were taken on the north and south of each plot, laying out a 15-m line across 6 beds at each end of the field, then once again perpendicular to the already measured transects. For each transect the presence or absences of residue cover was noted every 61 cm. Residue mass was also measured using a plastic 1 m^2 quadrat covering both bed and furrow components of the row. All residue within the quadrat at each location was collected, oven dried at 65°C and weighed.

SOIL BIOLOGICAL PARAMETERS

Soil macrofauna were evaluated on June 22 (only earthworms) and September 11, 2015 and on May 31, 2016. Samples were taken in the bed and furrow in two locations of each plot. A soil monolith (25 x 25cm with a depth of 25cm) was excavated from a bed and furrow location at both the north and south end of each plot. The entirety of the excavated soil was hand-sorted for all visible macrofauna (Anderson and Ingram, 1993) and all collected specimens were stored in a 70% ethanol solution. Macrofauna were identified to the level of order or family and diversity was assessed using overall taxonomic richness (S) as well as with the Shannon diversity index (Shannon, 1963) using he following formula,

$$\mathbf{H = -\Sigma\ [pi) * ln(pi)]}$$

where Σ = Summation, pi= number of individuals of species (i) divided by the total number of individuals in a sample (from all taxonomic groups).

SOIL CHEMICAL PARAMETERS

In 2015, composite soil samples at 15 cm depth were taken from the north end of the plot. In 2016 soil samples were taken in beds and furrow from two locations of each plot. To provide information about labile or recently active carbon (C) pools, permanganate oxidizable carbon (POXC) was assessed according to Weil et al. (2003).

In 2016 subsamples were collected from two locations (north and south) and two positions (bed and furrow) of each plot. The samples were air dried and passed through a 2mm sieve and made into a soil paste (1:1 soil to water mixture). Using a Hach IntelliCAL pH probe, soil pH was measured for each plot. The soil was then passed through a 0.25 μm filter and collected the liquid to measure soil electrical conductivity. Soil electric conductivity was measured using a Hach IntelliCAL EC probe (Dellavalle, 1992).

PHYSICAL PARAMETERS

Bulk density was measured in beds and furrows at the north and south end of each plot using a Madera probe (Allen et al., 1993). Samples were collected from 0 to 12.7 cm, 12.7 to 25.4 cm, and 25.4 to 38.0 cm, returned to the lab, weighed moist, dried at 105°C and then reweighed. To better understand tillage impacts on soil compaction, a Field Scout SC 900 Soil Cone Penetrometer (SCP) (Spectrum Technologies, Inc., Plainfield, IL) with a cone tip (1.3 cm dia.) was used to measure soil resistance (kPa) in 2.5 cm increments to a 45 cm depth in the beds, non-irrigated furrows, and irrigated furrows (ASAE S313.3, 1999). Measurements were taken in two randomly selected locations in each plot. Soil samples for gravimetric moisture content were taken in conjunction with the SCP samples. Only 2015 results for bulk density and soil resistance will be presented as we experienced difficultly in sampling in the 2016 season due to cracking and dry soils.

Wet aggregate stability was measured on air-dried soil using an aggregates size fraction of 0.25mm- 2mm (small macroaggregates). Soil aggregate stability was measured using the Cornell sprinkle infiltrometer using a rainfall simulation method that delivers a steady rate of water droplets on to a 0.025 mm sieve containing a known weight (20 to 30 g) of oven-dried soil. Water is delivered at a rate of 0.25 cm mm^{-1} for 5 minutes from a height of 50 cm and aggregate stability is determined by the proportion of soil remaining on the sieve (Moebius et al., 2007; Schindelbeck et al., 2016). Soil passing though the sieve was collected on a filter paper and was then oven dried at 40° C for 48 hours. The soil remaining on the sieve was determined by difference (starting – soil collected on the filter paper), after correcting for large sand and rocks.

On August 6 and October 20, 2015 and June 15, 2016, two infiltration measurements were conducted 15 m apart within three meters of sampling for the other soil parameters for each of the six plots. Given that the field receives much of its water from irrigation, infiltration measurements were taken in the furrows that convey irrigation water. Infiltration was assessed using a Cornell Sprinkler Infiltrometer. In brief, a metal ring (24 cm diameter) was inserted into the soil to a depth of 7.5 cm and the infiltrometer delivered water at a controlled steady rate of 350 mm h^{-1} to the soil surface 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 applied to determine infiltration rate (Ogden et al., 1997; Schindelbeck, 2016).

ENTERPRISE BUDGET ANALYSIS

During harvest, the grain yield was evaluated for each plot by weighing grain from the center six rows (6.1 cm) that was harvested with a combine. Cost analysis was performed on all three treatments by assessing gross revenue, fixed and variable costs. Fixed costs included the price of purchase and maintenance for equipment. Variable costs are production expense such as labor, seed, irrigation water, and other expenses directly related to farm operations which change from year to year. The variable costs were done using enterprise budgets as developed by Colorado State University's Agriculture and Business Management(ABM) website (http://www.wr.colostate.edu/ABM/cropbudgets.shtml) (ABM, 2016). Gross revenue was generated by annual commodity (crop) price for corn in 2015 and malting barley in 2016 multiplied by yields for each treatment. Net income was compared over the two years of the study to evaluate the economic feasibility on conservation tillage under furrow irrigation.

STATISTICAL ANALYSIS

Analysis of variance (ANOVA) was used to compare soil quality characteristics between the treatments separately for 2015 and 2016 in the R software environment. ANOVA test assumptions were evaluated for all models and log transformations used as necessary to meet these assumptions. The best fit model was constructed using lm() function from the CAR package. Tillage treatment, block, position (bed and furrow), and plot location was used as a categorical predictor. A least squares mean using the lsmean() function was performed on statistically significant soil quality results to better understand treatment differences. Simple linear regression was performed to examine possible relationships between the measured variables.

RESULTS

SURFACE RESIDUES

In 2015, residue cover was significantly different between the treatments, with higher surface cover in MT (43%) and ST (47%) compared to CT (4%) ($P < 0.001$). The mass of residues followed a similar pattern with ST (4.1 Mg ha^{-1}) and MT (2.2 Mg ha^{-1}) have significantly higher residue mass compared to CT (0.43 Mg ha^{-1}) ($P = 0.03$). In 2016, percent residue cover was 53% and 55% cover for MT and ST, respectively, and 22% cover under CT ($P = 0.0001$). Residue mass in 2016 was significantly different between treatments, with 2.1, 1.1, and 0.07 Mg ha^{-1} under ST, MT and CT, respectively ($P = 0.03$).

SOIL MACROFAUNA

Macrofauna and earthworms are shown in Figure 2.2 (averaged across position and location). In the 2015 season, there was a significant difference for macrofauna and earthworm abundance between the treatments ($P = 0.002$, Fig 2). The ST treatments had the largest macrofuana population 486 (no. m^{-2}) followed by MT with 210 (ind m^{-2}) and CT 178 (ind m^{-2}). In 2016, macrofauna abundance was greatest in the MT treatment with 278 (ind m^{-2}) followed by ST 212 (ind m^{-2}) CT 78 (ind m^{-2}), but means were not significantly different. A range of macrofauna types were collected, with earthworms being the most abundant group in 2015 and 2016 (87% of total and 54% of total, respectively) followed by beetles (Coleoptera; 7% of total) in 2015, Diptera (24% of total) in 2016 (Table 2.2). When examining macrofauna diversity, the conservation tillage treatments were generally highest in terms of overall richness and Shannon index, but differences were not statistically significant. In 2016, taxonomic richness was not significantly different between the treatments with CT, MT and ST having a taxonomic richness of 2.0, 4.1, and 3.4, respectively (data not shown).

In the 2015 season, earthworm abundance was significantly different among the treatments ($P < 0.001$) as well as position ($P = 0.001$). Earthworms were most active in the conservation tillage plots with ST having the greatest numbers (362 ind m^{-2}) and MT (138 ind m^{-2}) compared to CT (107 ind m^{-2}). Further examination of position showed a higher number of earthworms in the furrow compared to beds. In 2016, earthworm population density was not significantly different between the treatments ($P = 0.36$). Nevertheless, earthworms were present in greater number in the MT and ST treatments with an earthworm population of 134 ind.m^{-2} and 124 ind.m^{-2} respectively compared to CT (48 ind.m^{-2}; Fig 2.3).

CHEMICAL PROPERTIES

In the 2015 season, POXC was significantly different between the treatments ($P = 0.001$), such that the conservation tillage treatments (MT and ST; 265 mg kg^{-1} and 213mg kg^{-1}, respectively) were significantly higher than CT (126 mg kg^{-1}). In 2016, there was no significant difference between the treatments ($P = 0.13$). However, there was a similar trend to 2015, with higher POXC in the conservation tillage treatments than in CT (Fig. 2.4). Soil pH and EC were not significantly different between the treatments (data not shown).

PHYSICAL PROPERTIES

In 2015, bulk density in the top 38 cm (15in) did not differ between the treatments and had an average value of 1.52 g cm^{-1} (Fig. 2.5). Beds had the lowest bulk density with an average of 1.45 g cm^3 in the top 38 cm. Further investigation of bulk density in the seeding beds demonstrated a marginal difference between the treatments ($P = 0.07$). In 2016, bulk density was not significantly different between the treatments in the top 38 cm with values of 1.55, 1.58, and 1.52 g cm^{-3} for CT, MT, and ST respectively ($P = 0.06$) but was the lowest in the strip-till treatment in all positions compared to CT and MT.

Soil penetrometer data were collected and analyzed separately by position, bed, dry furrow, and wet furrow (irrigated). In 2015, tillage treatments were not different between the treatments. In the top 20 cm of beds, CT showed higher soil resistance compared to the conservation treatments. Nevertheless, beds in all treatments were below the 2000 kPa threshold that is stated to impede root growth. In the dry furrow, there were no significant differences between the treatments. There was a significant interaction with depth (Treatment by Depth, $P < 0.001$). At a depth ranging from 12 to 15 cm, CT had significantly less soil resistance when compared to the conservation treatments (Figure 2.6). Only 2015 data is present because in 2016 we experienced dry and cracking soils that resulted in sampling error.

In the 2015 season, CT had significantly lower aggregate stability (11.8 %) than MT (20.2 %) or ST (25.2 %). There were no significant differences between the treatments in 2016 (Figure 2.7).

Infiltration measurements were significantly different between the treatments in the 2015 season ($P = 0.038$). Furrows from the ST treatments had the highest infiltration rate of 200 mm hr^{-1} (Figure 2.8) while there was no significant difference between CT and MT (164 mm hr^{-1} and 167 mm hr^{-1}; respectively). Though not significant, there was a similar trend in the 2016 season, such that ST had the highest infiltration rate with 275 mm hr^{-1} followed by MT with a rate of 243 mm hr^{-1} and CT with 232 mm hr^{-1}.

RELATIONSHIPS BETWEEN SOIL QUALITY PARAMETERS

Several relevant correlations between soil parameters are depicted in Figure 2.9 for the 2015 season. Earthworm abundance was highly correlated with surface residue mass ($R^2 = 0.77$, $P < 0.001$; Fig 2.9a). The increase of earthworm activity was positively associated with infiltration rate ($R^2 = 0.42$, $P = 0.02$; Fig 2.9b) as well as aggregate stability ($R^2 = 0.75$, $P <$

0.001; Fig 2.9c). Aggregate stability had a positive relationship with infiltration rate ($R^2 = 0.84$, P = 0.01; Fig 2.9d) and POXC ($R^2 = 0.40$, P = 0.03; Fig 2.9e). In 2016, there were no significant relationships between soil quality parameters, except that residue mass was positively correlated with POXC ($R^2 = 0.40$, P = 0.02; data not shown) in 2016.

ENTERPRISE BUDGET ANALYSIS

Corn grain yields for 2015 were significantly different (P = 0.02) but relatively small between the treatments with CT, MT, and ST having 12.8, 12.4, and 12.3 Mg ha^{-1} yeilds; respectively. Barley grain yield for 2016 was not significantly different between the treatments with CT, MT, and ST producing 5.4, 5.0, and 5.2 Mg ha^{-1}, respectively. Gross revenue for treatments CT, MT and ST for a 2-year average (2015-2016) was \$266, \$251, and \$257 ha^{-1}, respectively. Total fixed and variable cost for CT, MT, and ST was \$215, \$184, and \$187 ha^{-1}, respectively. Fixed cost and operational variable cost such as fuel, machinery operation, machinery repair, and machinery labor were reduced in MT and ST by 13% and 15% when compared to CT. Considering gross revenue and total cost, treatments MT and ST had an average profit increase of 32% and 39% when compared to CT tillage treatment (Table 2.3).

DISCUSSION

SURFACE RESIDUE COVER

By design, the conservation plots maintained a residue cover of over 40% for both years. Crop residues have been shown to aid in reducing irrigation-induced soil erosion (Berg, 1984; Carter and Berg, 1991) and protect the soil from water drop impact (Lehrsch et al., 2014), improving soil-nutrient-water relationships (Allmaras, 1985; Mostaghimi et al., 1992) and improving soil biological, physical, and chemical characteristics (Karlen, 1994). Fields with higher residue cover typically have higher infiltration rates and lower runoff (Papendick, 1988).

However, there have been studies stating that too much residue can generate adverse effects. For example, surface residue slows soil warming in the early spring, especially in higher-altitude climates like Colorado (Logan et al., 1991). Having cold, wet soil can impede germination resulting in late seed emergence that could decrease yields (Licht and Al-Kaisi, 2005; Midwest Plan Service., 1992; United States Department of Agriculture, 1999). A healthy balance needs to be met accounting for regional climatic norms to achieve the optimal residue application. The longer a field is under conservation practices, the benefits of improvement of soil properties, erosion control, and productivity, become more noticeable (Lafond et al., 2008).

IMPACTS OF CONSERVATION TILLAGE ON SOIL QUALITY

Our findings suggest that conservation tillage supports various aspects of improved soil quality. Perhaps the greatest impact was observed on soil biological parameters, specifically earthworm abundance and macrofauna diversity (i.e., richness). Many of the macrofauna groups encountered, particularly earthworms, subsist on residues which provides a season long food source. For example, during surface residue sampling, a greater number of macrofauna were observed in the ST furrows where most of the residue accumulated. Tillage practice has a significant impact on macrofauna communities, with continuous reduced tillage promoting the concentration of organic matter and nutrients that benefit biological activity (Doran, 1980). In contrast, conventional tillage inverts and mixes residues on the soil surface and reduces soil fauna’s influence on the rate of decomposition and nutrient release (House, 1985). In this study, we saw a direct positive relationship between surface residue mass and macrofauna abundance ($R^2 = 0.54$ in 2015; data not shown), corroborating others who have found similar trends (e.g., Mutema et al. 2013). In this study, the least soil-disturbing tillage operation (ST) presented the highest macrofauna population density, thus indicating that reduced tillage can improve soil biological activity. Macrofauna population density can thus be a good soil health indicator due to their sensitivity and rapid response to land management practices (Rousseau, 2013).

Results from this study indicate that the macrofauna most affected by reduced tillage are earthworms (Table 2.2 and Fig. 2.3). Earthworms can play a major role in the maintenance of soil physical conditions and often provide a of beneficial effects on soil fertility (Edwards and Bohlen, 1996; Valckx et al., 2011). Earthworms are sensitive to a range of environmental factors such as temperature, soil moisture content, nutrient availability and salinity (Lee, 1985). Earthworms' ability to respond to changes in land management makes them a good indicator of soil health (Linden et al., 1994). Studies have documented higher earthworm populations under no-till and reduced tillage systems when compared with conventional tillage systems (Fonte et al., 2009; Rovira et al., 1987; Yahyaabadi and Asadi, 2010). It's also important to note that earthworm cocoons were only observed in the ST treatments (data not shown). Earthworm cocoons are sensitive to environmental factors and tend to be present only when optimal soil moisture and temperature conditions exist (Chan, 2001). Barley is a cool season crop, thus macrofauna was measured in less than optimal soil temperature conditions, which could have resulted in lower overall abundance for the 2016 season. It is also possible that the extra tillage operation post 2015 season could have had adverse effects on soil macrofauna.

During the 2015 season, infiltration rates were significantly higher in the ST treatment while MT and CT had similar results. The Cornell Sprinkler Infiltrometer (CSI) measures bare soil infiltration which eliminated the immediate influence of surface residue on infiltration in furrows. However, preserved crop residue adds to soil organic matter and protect the soil surface from surface sealing (Sojka et al., 2007), which increases infiltration indirectly. The CSI confines flow to a small area as opposed to flow across the entire field. Other studies have shown infiltration rates are three times greater under reduced tillage operation compared to a chisel or plow-based systems (Wuest, 2001). Low infiltration rates in the CT treatment could be due to surface sealing due to clay particle deposition on the furrow surface. During irrigation events, clay particles were removed from the top of the field and deposited in the bottom of the field by irrigation water and settle into open pores decreasing infiltrate rate. In our research, the detachment, transport, and deposition of sediment was reduced dramatically with the increases of residue cover in the conservation treatments.

Minimal soil disturbance promotes the creation of macroaggregates, these can be destroyed when plow-based tillage is introduced (Kasper et al., 2009). Maintaining surface residue has shown to improve the formation of stable soil aggregates (Al-Kaisi et al., 2014). In our research, reducing soil disturbance and maintaining surface cover had similar results, in that higher aggregate stability was observed in the conservation treatments. Kasper (2009) noted a decrease in SOC and soil total N in a conventional tillage treatment when compared to no-till and minimum tillage treatments. Such degradation in soil structure over time can have adverse impacts on soil health and productivity.

Conservation tillage treatments consistently showed higher POXC concentration compared to the conventional tillage treatments for both growing seasons, though not significant in 2016. An explanation for higher labile C in the conservation plots is the reduction of tillage operations. Continuous plow-based tillage reduces labile C by destroying soil aggregates, exposing protected organic matter to microbial degradation (Chen et al., 2007). Another explanation for higher POXC levels in the conservation plots is that surface residue has a slower decomposition rate because residue is not incorporated into the soil profile. Eliminating the inversion of soil reduced the decomposition rate of residue which promotes soil organic matter accumulation in semi-arid regions (Rasmussen et al., 1998). The results obtained agree with earlier studies on the impacts of conservation tillage on POXC concentration due to the protection of soil aggregated reducing the oxidation of POXC (Awale et al., 2013; Chen et al., 2009; Melero, 2009). The literature further reports that the POXC fraction is more sensitive to management variation compared to all C fractions in soil and can be used to assist in selecting management practices that promotes long term C sequestration (Culman et al., 2012).

RELATIONSHIPS BETWEEN SOIL QUALITY PARAMETERS

Residue had a positive impact on earthworm abundance; as residue on the surface increased, earthworm abundance increased. All earthworms found were identified as A. trapezoids, an endogeic species that feed primarily on soil and associated organic matter (geophages). Earthworms consume soil and crop residue then excreted, forming stable soil aggregates (Chaney and Haydock, 2011). Recent studies support that there is a significant influence of earthworm activity and residue application on stable aggregate formation (Bossuyt et al., 2006) the positive relationship between earthworm abundance and aggregate stability (Fig 2.9c) in our study supports these findings. The earthworm population was higher in the conservation plots with ST having the largest population and higher aggregate stability when compared to CT during the 2015 season. Increased earthworm activity could have assisted in promoting the positive relationship between POXC and soil aggregate stability. Supporting results from Fonte et al. (2009), who observed an increase of particulate organic matter in macroaggregates from a mulched system that contained higher earthworm activity when compared to bare fallow (and heavily tilled) systems.

In our study, earthworms appeared to have a positive influence on soil infiltration rates (Fig 2.9b). This is likely due to burrowing, creating micro- and macro- pore networks and improved soil structure and soil aggregation (Andriuzzi et al., 2015). Under a furrow irrigated study, infiltration increased 30% and was attributed to earthworms penetrating the wetted furrow perimeter during irrigation events (Trout and Johnson, 1989). Many studies have shown the beneficial impact of high earthworm abundance on infiltration by increasing preferential flow paths (Hallaire and Curmi, 1993; Kribaa et al., 2001; Lamandé et al., 2003). Finding a strong positive relationship between aggregate stability and infiltration rate strengthens our resolve that earthworm activities, increased by reduced tillage and surface residue, likely mediated the beneficial impact of reduced till and surface residues on infiltration. The majority of these correlations were only found to be significant in the 2015 field season. This could be due to the extra tillage operation done to the field that likely had adverse impacts to many of the soil quality parameters measured in the conservation tillage treatments in the second year of the study.

ECONOMIC AND MANAGEMENT IMPLICATIONS

Yields showed only small differences between the treatments, hence, gross revenue was the similar between the treatments. Comparing the cost of establishment, production, and maintenance of the treatments is where major differences in cost reductions are seen in the conservation treatments. The principal impacts of conservation tillage were seen in the reduction of machinery operation, fuel, machinery repair, and machinery labor costs and is seen in other cost analysis studies of conservation tillage (Zhou et al., 2009). The conservation treatments use less equipment and fewer operations that convert to savings in fixed and variable costs when compared to the conventional tillage treatment. Even though yields, therefore gross income was slightly lower (but not significantly) in the conservation tillage treatments, they had larger profits when considering the fixed and variable cost. Reducing fuel and labor by decreasing the amount of tillage operation has shown to improve profits when yields are normalized (Smart et al., 1998). Despite the benefits of conservation tillage methods, the initial costs of converting to conservation practices can present a barrier of entry on an already established farm. Increased profits by reducing cost and maintaining comparable yields can negate the initial cost over time, though long-term research would need to be conducted to better understand this relationship and to better inform farmers.

There is evidence that crop yields are initially reduced when converting to conservation tillage, but yields tend to stabilize after the transition period (3-5 years) (Logan, 1991). The 6-year cost-benefit analysis for the minimum tillage treatment did result in a 7% loss in profit when compared to CT. Originally the MT treatment was a no-till, but because of soil compaction, yields were drastically reduced. When no-till was converted to MT in the third year of the study, profits for MT improved when compared to CT.

The comparisons of net income (profit) for these systems is one way to identify the most efficient conservation tillage treatment, but it should not be the sole criteria. In many ways, the reduction in soil and nutrient loss is where the most important long-term savings could be realized and societal benefits achieved. Irrigation-induced erosion includes the on-site cost of reduced soil productivity and offsite costs that include but are not limited to, the negative externalities of water quality, recreation, and social costs.

Despite the ever-mounting evidence of soil degradation from conventional management practices, conservation best management practices, such as reduced tillage and residue cover, remain underutilized. Based on our observations we believe that region wide implementation of conservation tillage on furrow irrigated land can improve soil health and increase profits on the farm scale, as well as reduce environmental impacts. Some of the environmental damages reported today are directly connected to intensive tillage used in agriculture. Many environmental issues such as sedimentation, “dead zones”, and water quality degradation can be mitigated by large scale education, demonstration, and adoption of conservation practices. Uri (1999) identified that capital cost of conversion and the degree of risk which comes in the form of yields, as some of the biggest factors deterring the adoption of conservation tillage. Thus, identifying and addressing these social, economic, geographic, and policy factors that impede the adoption of conservation tillage is crucial in making large-scale change.

CONCLUSION

Diminishing soil quality under conventional tillage remains to be a serious problem. For the years 2015 and 2016, assessment of the soil health from two conservation tillage systems converted in 2011 showed a positive influence in the soil’s biological, physical, and chemical parameters. Furthermore, results from an enterprise budget analysis from the conservation tillage systems showed increased profits over time when compared to the control.

Beneficial impacts from reduced tillage and residue cover were seen in soil macrofauna activity, specifically earthworm abundance. Both MT and ST saw large increases in population density and species diversity, which is attributed to the increased food sources and crop residue. Strong positive relationships were seen between earthworms and soil physical attributes, such as aggregate stability and infiltration, which highlight the importance of understanding the interaction between soil parameters needed for improved soil health.

Our research indicates that conservation tillage improves soil health and increases farmers’ income, however; large-scale adoption of conservation will require addressing multiple social and economic factors. The need for education and demonstration of conservation tillage on soil health and economic viability is crucial to increase the rate of adoption and to curtail adverse environmental impacts from conventional practices.

TABLES AND FIGURES

Table 2.1. Field operations for Conventional, Minimum, and Strip tillage treatments for the 2015 and 2016 seasons.

2015					
Conventional Till		Minimum Till		Strip Till	
Date	Operation	Date	Operation	Date	Operation
3/23/15	Disk	3/23/15	Verti-Till	4/13/15	Strip Till
3/23/15	Plow	4/13/15	Strip Till	4/13/15	Fertilize
3/27/15	Mulch	4/13/15	Fertilize	4/30/15	Planting
4/14/15	Fertilize	4/30/15	Planting	6/24/15	Cultivate
4/14/15	Bed	6/24/15	Cultivate	6/24/15	Fertilize
4/14/14	Cultipack	6/24/15	Fertilize	11/16/16	Harvest
4/30/15	Planting	11/16/15	Harvest		
6/24/15	Cultivate				
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	12/11/15	Verti-Till (2x)	12/11/15	Verti-Till
12/11/15	Disk	3/01/16	Strip Till	3/01/16	Strip Till
12/11/15	Plow	3/01/16	Fertilize	3/01/16	Fertilize
2/22/16	Mulch	3/03/16	Planting	3/03/16	Planting
3/01/16	Fertilize	3/03/16	Cultivate	3/03/16	Cultivate
3/02/16	Bed	7/25/16	Harvest	7/25/16	Harvest
3/02/16	Cultipack				
3/03/16	Planting				
3/03/16	Cultivate				
7/25/16	Harvest				
# of Field Operations	10	7		6	

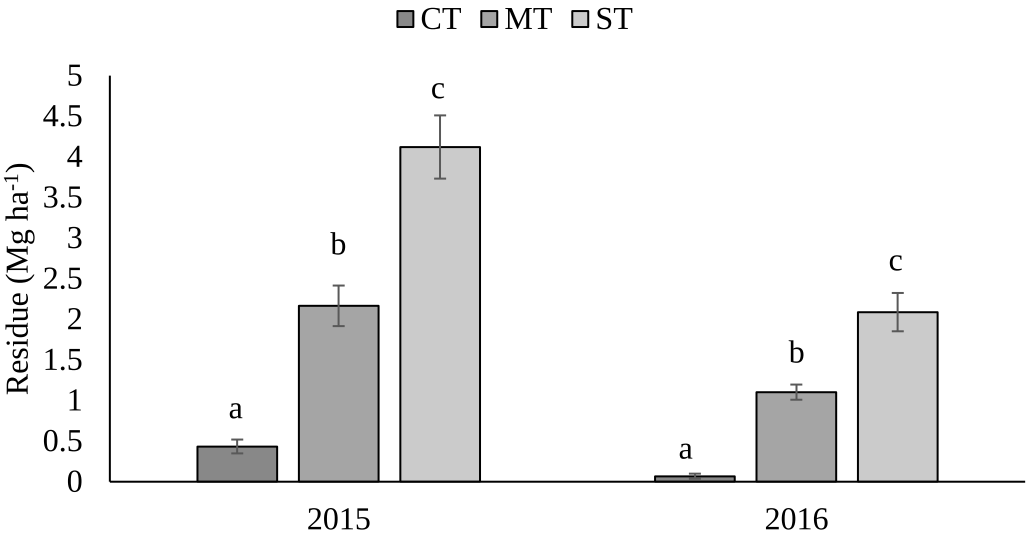

Figure 2.1. 2015 and 2016 surface residue mass for the Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments. Means within the same year followed by the same letter are not significant at α = 0.05.

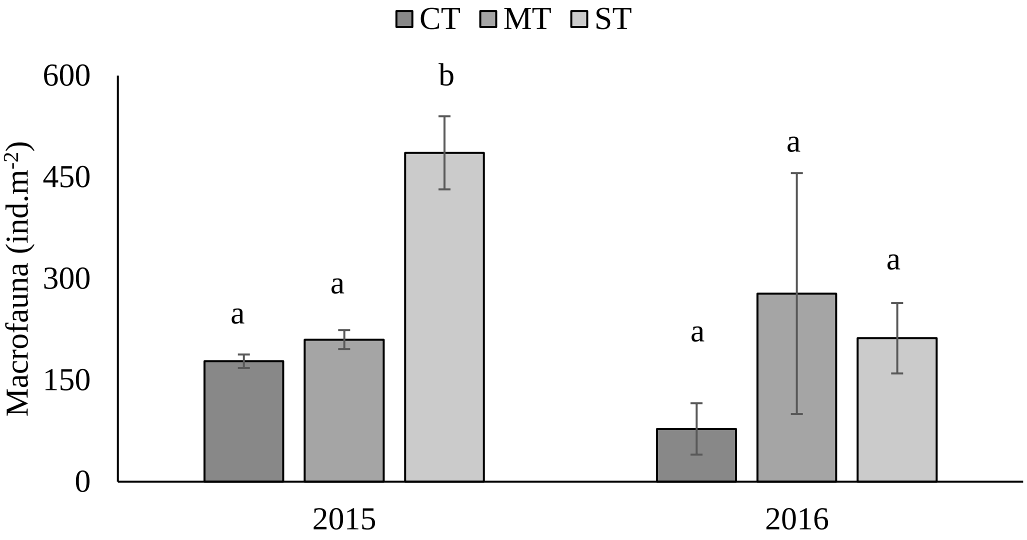

Figure 2.2. 2015 and 2016 total macrofauna abundance for the Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments. Means within the same year followed by the same letter are not significant at α = 0.05.

Table 2.2. Mean abundance for the most common macrofauna orders in Conventional (CT), Minimum (MT), and Strip (ST) for the 2015 and 2016 seasons.

Order	2015			2016		
	CT	MT	ST	CT	MT	ST
	Ind.m^{-2}					
Annelida	158	182	422	48	134	124
Coleoptera	12	18	30	8	48	32
Rhabdura	0	16	0	0	16	16
Hemiptera	4	0	4	0	6	0
Centipede	0	6	28	0	6	14
Diptera	0	0	0	20	78	36
Hymenoptera	16	16	0	0	16	0

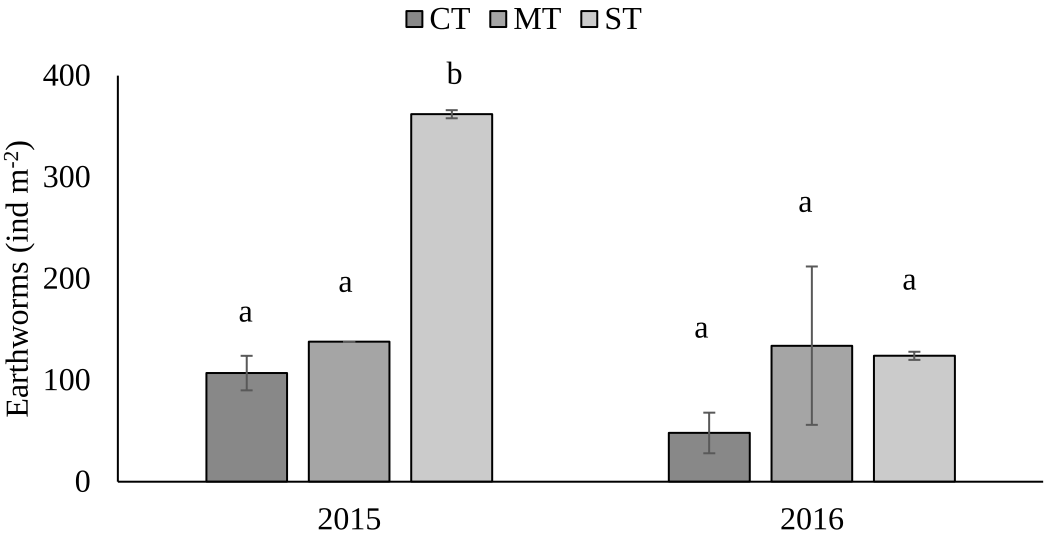

Figure 2.3. 2015 and 2016 earthworm abundance for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments. Means within the same year followed by the same letter are not significant at α = 0.05

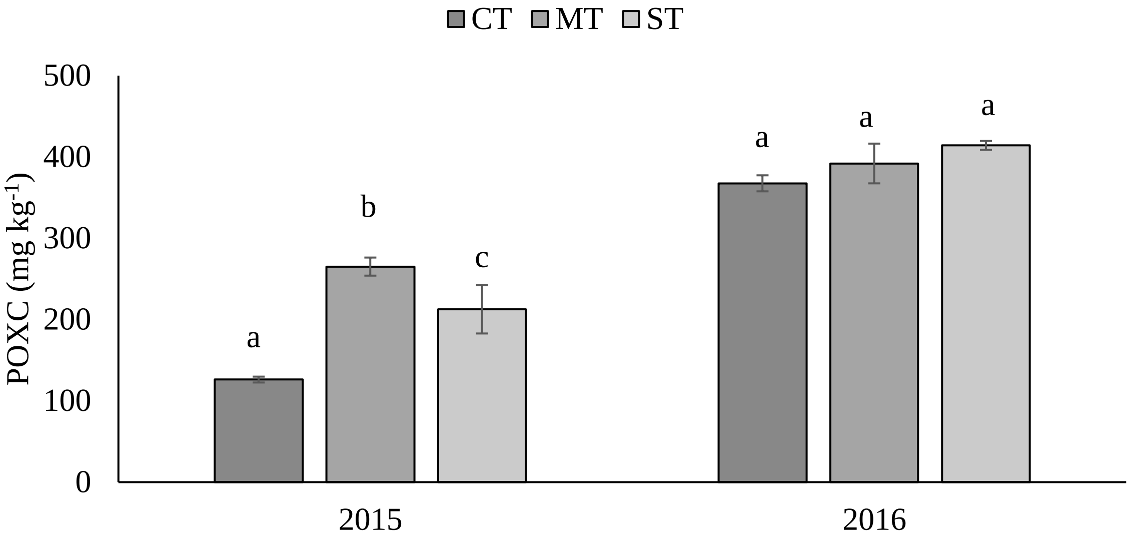

Figure 2.4. 2015 and 2016 permanganate oxidizable carbon (POXC) for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments. Means within the same year followed by the same letter are not significant at α = 0.05

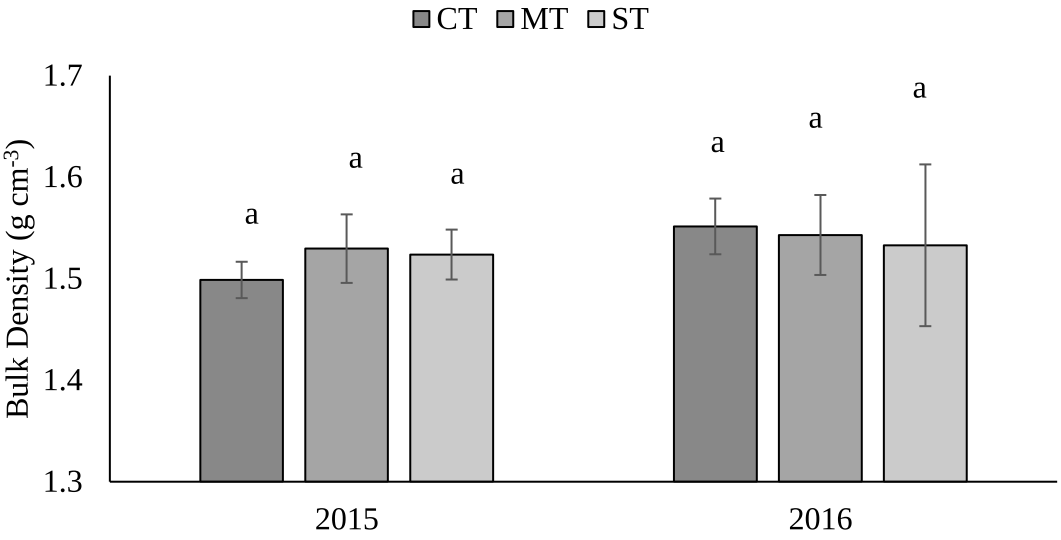

Figure 2.5. Bulk Density for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments at 38 cm for the 2015 and 2016 growing seasons. Means within the same year followed by the same letter are not significant at α = 0.05

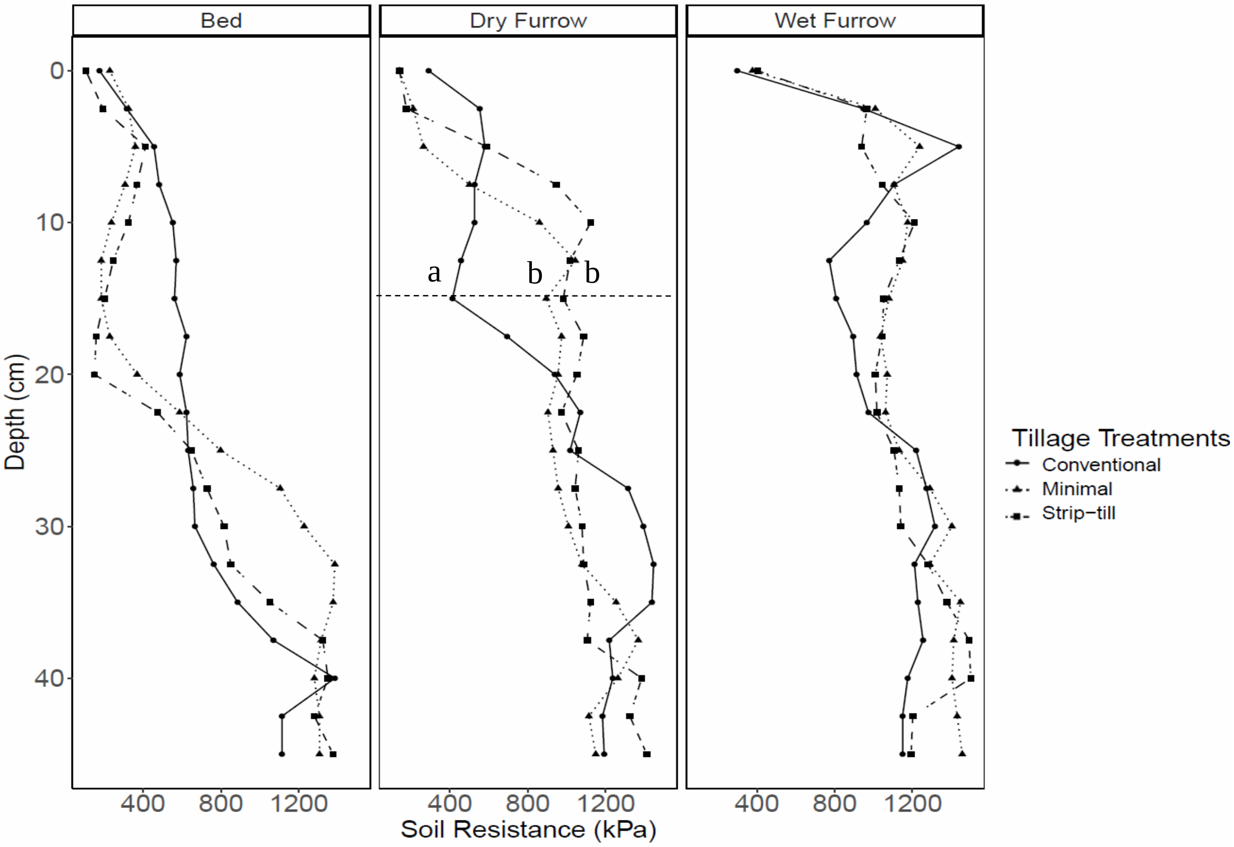

Figure 2.6. Soil resistance for the bed, non-irrigated (dry) and irrigated furrows (wet) from 0 – 45 cm for the Conventional (CT), minimum (MT), and Strip (ST) tillage treatments for the 2015 season. Means followed by the same letter are not significant at α = 0.05

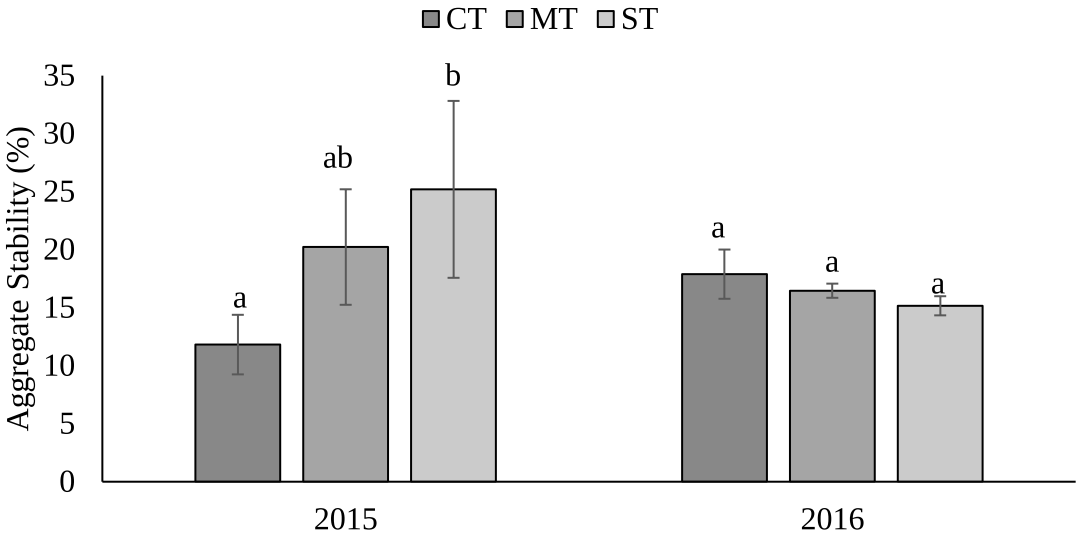

Figure 2.7. 2015 and 2016 aggregate stability for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments. Means within the same year followed by the same letter are not significant at α = 0.05

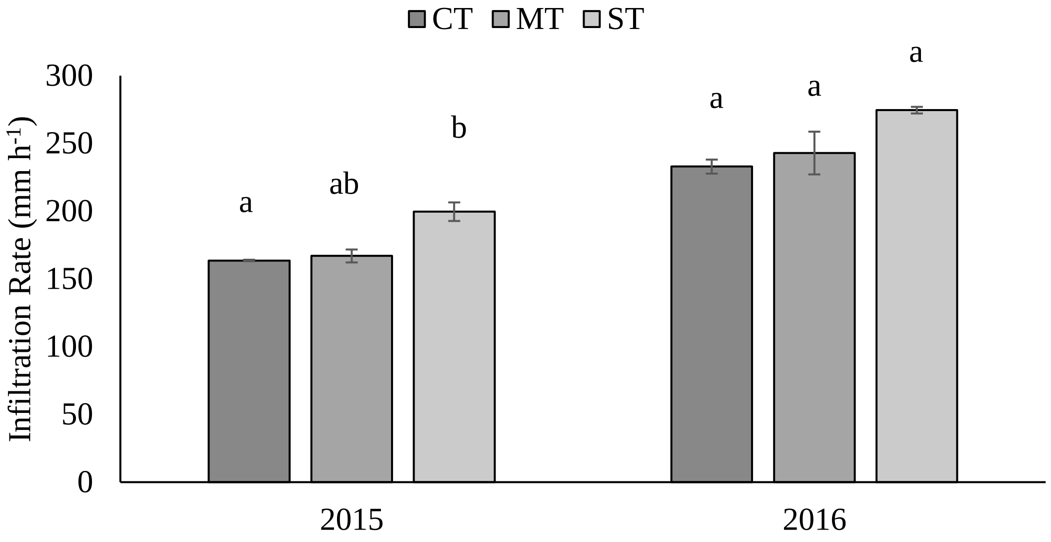

Figure 2.8. Average infiltration rate for Conventional (CT), Minimum (MT), and Strip (ST) tillage treatments for 2015 and 2016. Means within the same year followed by the same letter are not significant at $\alpha = 0.05$

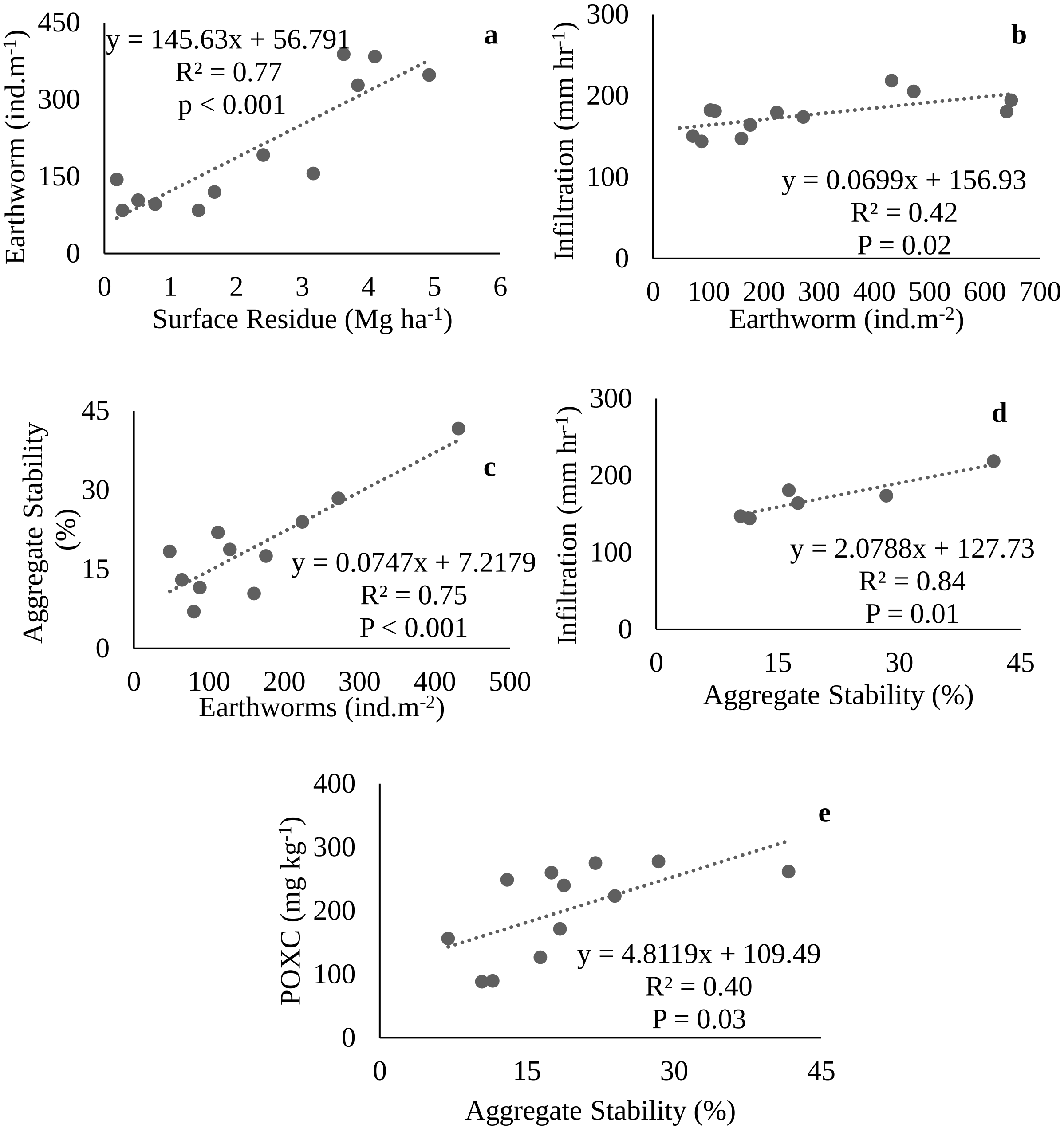

Figure 2.9. Soil quality parameter relationships for 2015. The significant linear regression with significant coefficients (significance level at $\alpha = 0.05$) are shown. a) Residue abundance vs. Earthworm abundance, b) Earthworms abundance vs. Infiltration rate, c) Earthworm abundance vs. Aggregate stability, d) Aggregate stability vs. Infiltration rate, and e) Aggregate stability vs. Permanganate oxidizable carbon (POXC).

Table 2.3. Two-year average enterprise budget for Conventional, Minimum, Strip tillage treatments.

	Conventional Tillage	**Minimum Tillage**	**Strip Tillage**
		2 Year Average	
Gross Revenues		**$ ha^{-1}**	
Returns per Hectare	$ 266	$ 251	$ 257
Key Variable Cost	CT	MT	ST
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 Cost	$ 196	$ 176	$ 178
Fixed Costs			
Machinery Ownership	$ 19.42	$ 7.58	$ 8.74
Total Fixed Cost	$ 19.42	$ 7.58	$ 8.74
Total Cost	**$ 216**	**$ 184**	**$ 187**
Return to Land and Management	**$ 50**	**$ 67**	**$ 70**

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