THESIS

WATER CONSERVATION AND NUTRIENT, SEDIMENT, AND HERBICIDE

MOVEMENT IN FURROW-IRRIGATED TILLAGE SYSTEMS

Submitted by

Jordan A. Driscoll

Department of Soil and Crop Sciences

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2013

Master's Committee:

    Advisor: Neil C. Hansen

    Troy A. Bauder
    Philip Westra

ABSTRACT

WATER CONSERVATION AND NUTRIENT, SEDIMENT, AND HERBICIDE

MOVEMENT IN FURROW-IRRIGATED TILLAGE SYSTEMS

Due to an increase of population in the state of Colorado, as well as several years of receiving less than average precipitation, water allocation has become a state-wide concern. Agricultural, municipal, and recreational sectors demand ever-increasing volumes of water, which has caused the state to re-assess the amount and location of where water will be best economically and environmentally utilized. From an agricultural standpoint, furrow irrigation is a less effective method of irrigation than sprinkler or drip irrigation, however land suitability and socio-economic factors keep furrow irrigated acres high throughout Colorado. Therefore, there is a need to develop cropping systems that increase the irrigating efficiency of furrow irrigation in the state while decreasing sediment and nutrient contamination of water sources.

Adoption of conservation tillage in furrow-irrigated cropland is limited compared to rain-fed and sprinkler irrigated systems. Residue on the soil surface impeding furrow irrigation flow and establishing a quality seed bed are the primary concerns. A two year field-based study was conducted in Fort Collins, Colorado during 2011 and 2012 to compare (a) soil moisture and irrigation requirements, (b) water outflow, infiltration, and advance in furrows and (c) sediment and nutrients in runoff for minimum till (MT) and strip till (ST) systems to a conventional till, plow-based system (CT). The MT and ST systems included a modified row-cleaning operation to move residue from irrigated furrows to adjacent non-irrigated furrows. Crop residue was greater on the soil surface in MT and ST than in CT, which resulted in higher soil moisture content at planting yet still allowed for successful irrigation. Average advance of water through furrows in

2011 was faster in MT (79 min) than CT (101 min) and ST (108 min), and in the order of ST (109 min) > MT (99 min) > CT (88 min) during 2012. Penetration resistance measurements showed that CT (567 kPa) and ST (275 kPa) created good seedbeds, but hard soil on MT (848 kPa) beds caused poor seed placement. Within individual irrigation events, tillage practice had little effect on the concentrations of sediment or nutrients in runoff, except MT had higher concentration and load of nitrate (NO_3^-) than CT and ST. Sediment concentrations and loads were similar for all tillage systems and average annual sediment loss in irrigation runoff was 4.9 Mg ha^{-1}. Conservation tillage systems can be successfully modified for application to furrow irrigation systems and can decrease the dependence on irrigation at planting by maintaining crop residue at the soil surface, although high amounts of residue on the seedbed can be of concern for effective planting in MT ST was a better approach than MT because it created better seedbed conditions.

An additional concern for growers in regards to conservation tillage is decreased efficacy of herbicides due to interception of herbicides by residue on the soil surface. To address this concern, an herbicide dissipation study was included in this tillage study to compare the fate and movement of atrazine, *s*-metolachlor, and pyroxasulfone in the three tillage systems.

Pyroxasulfone is a newly released herbicide that is applied pre- or post-emergence to corn and has a similar weed control spectrum to atrazine and *s*-metolachlor, but with significantly lower application rates. The molecule has low water solubility and the potential for longer persistence in the soil than atrazine and *s*-metolachlor. More information is needed about the behavior of pyroxasulfone in the environment and about interaction with varying management systems. This field study was performed at the same site as the tillage study during 2011 and 2012 to 1) compare sorption of pyroxasulfone to that of atrazine and *s*-metolachlor for

an alkaline, loam soil, and 2) to evaluate and compare the persistence and movement of pyroxasulfone, atrazine, and *s*-metolachlor in conventional (CT), minimum (MT), and strip (ST) tillage systems under furrow irrigated grain corn. In each year, labeled rates of 0.28 kg ai ha^{-1} for pyroxasulfone, 0.74 kg ai ha^{-1} for atrazine, and 1.71 kg ai ha^{-1} for *s*-metolachlor were applied pre-emergence to corn. Four depth increments of soil samples were taken over the top 30 cm in each tillage system at five time intervals over 60 days. Herbicides were extracted and analyzed by GC/MS to determine the dissipation and movement in soil. All three herbicides had low to moderate sorption and the rank order of sorption coefficients (K_d) was *s*-metolachlor (0.96 L kg^{-1}) > pyroxasulfone (0.56 L kg^{-1}) > atrazine (0.45 L kg^{-1}). Pyroxasulfone had a much longer half life in all tillage systems when compared to atrazine and *s*-metolachlor. For pyroxasulfone, DT_{50} was longest in ST both years, and were not quantifiable because its persistence was longer than the 60 day sample period. Tillage practice affected DT_{50} of all herbicides, mainly due to residue coverage differences, with herbicides persisting longer in the conservation tillage systems than in conventional tillage.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: Water Conservation, and Nutrient and Sediment Movement

In Furrow-Irrigated Tillage Systems

INTRODUCTION

Furrow irrigation is practiced on nearly 4.5 million ha of cropland (11 million ac), or one fourth of irrigated cropland in the United States (USDA 2008). In the State of Colorado, furrow irrigation makes up 40% of irrigated land, representing 260,000 ha (650,000 ac). While furrow irrigation is a less efficient irrigation system than sprinkler or drip irrigation (Halvorson et al. 2008), it continues to be widely used. Among the factors limiting adoption of more efficient irrigation methods are concerns over profitability and feasibility of alternative irrigation systems, shape and size of irrigated fields, and water laws that protect return flows. There are a number of issues that raise concern about the sustainability of furrow irrigation. The systems are traditionally associated with extensive, plow-based tillage systems and annual land preparation that is expensive and energy demanding. High rates of soil loss can be induced by irrigation flow and carried off the field in tail water. Tail water returning to receiving waters can lead to sediment and nutrient contamination (Gates et al. 2006), while excessive percolation can also lead to nitrate losses to shallow groundwater (Ceplecha et al. 2004; Klocke et al. 1999). Managing furrow irrigation to minimize impacts on receiving waters is difficult because effective furrow irrigation depends on runoff to provide even irrigation of the upper and lower positions of irrigated fields (Bjorneberg et al. 2002).

Conservation tillage systems have gained acceptance throughout many parts of the country as an economical way to limit energy demand and costs associated with extensive tillage (Ashraf et al. 1999). Conservation tillage systems are designed to manage crop residues to

maintain a degree of protection of the soil surface. The USDA has classified conservation tillage systems as those that maintain a minimum of 30% of the soil surface covered by plant residue (USDA 2008). Several studies have shown that crop residues resulting from conservation tillage provide important soil benefits, including protection of the soil from erosion (Merrill et al. 2006), conserving soil moisture and promoting water storage (Tanaka and Anderson 1997), and reducing water runoff by promoting infiltration (Lal 1995). While there has been significant adoption of conservation tillage approaches in rain-fed and sprinkler irrigated systems (Evans et al. 2010), there has been very little adoption of conservation tillage in furrow irrigated cropland. The primary limitations to use of conservation tillage in furrow irrigation is concern over acceptable advance of irrigation water down furrows through high volumes of residue and the ability to create a suitable seedbeds for crops (Carter and Berg 1991). Development of a conservation tillage system that would address the concerns of furrow irrigators while gaining some of the advantages of crop residue and reduced tillage is needed.

The objectives of this study were to adapt two conservation tillage systems for use in furrow irrigation and to compare (a) soil moisture and irrigation requirements, (b) water outflow, infiltration, and advance in furrows and (c) sediment and nutrients in runoff from these systems to a conventional, plow-based system. A field based study was conducted for two cropping seasons near Fort Collins, Colorado.

MATERIALS AND METHODS

This study compares irrigation and water quality factors in furrow irrigation runoff under three tillage practices. The study was initiated in the fall of 2010 and data was obtained from the 2011 and 2012 growing seasons. The study site as managed in continuous grain corn.

2

Study Area

The 5.7 ha (14 ac) field site was located in Larimer County, Colorado, at Colorado State University's Agricultural Research, Development and Education Center, (40°67' N, 104°99' W, 1539 m) 19 km (12 mi) northeast of Fort Collins, Colorado. The soil type was mapped as a Garrett loam (fine-loamy, mixed, mesic Pachic Argiustolls) (Soil Survey Staff 2013) with 1.1 % organic matter (Table 1-1), having a pH of 7.8 in the surface horizon, sand, silt, and clay percentages of 52, 18, and 30, respectively, and a slope < 1%.

Tillage Systems

Three tillage systems, defined for this study as conventional till (CT), minimum till (MT), and strip till (ST) were replicated twice on field-scale plots of 320 m x 27 m (1050 ft x 90 ft), consisting of 36 rows (73 cm, 30 in) of corn in each plot. The intent of having such large plots was to replicate the dynamics of furrow irrigation with typical furrow length and production scale. These field-scale plots were considerably larger than experimental sites of similar studies (Bjorneberg et al. 2006; Lentz and Lehrsch 2010; Westermann et al. 2001). CT was used as a reference utilizing commonly practiced tillage operations in the region. The conservation tillage systems were based on local interest and potential utility of tested practices. Most field operations were performed with 6-row implements commonly used by commercial growers (Table 1-2). Following harvest, residue in all tillage systems was chopped using a 4.6 m (15 ft) flail chopper, windrowed and bailed. In 2010 following bailing operation, CT was deep ripped to a depth of 38 cm (15 in). Seven (2011) and six (2012) additional tillage operations were performed in CT in order to prepare the plots for planting (Table 1-2). Strip tillage was performed in ST plots prior to planting both years, using an Orthman 1tRIPr to prepare a 20 cm

(8 in) wide seedbed going 25 cm (10 in) deep. The strip tillage operation was performed on top of the previous year's beds, with a 10 cm (4 in) off-set from the prior year's crop row. The furrow cleaning operation in MT during 2011 and 2012, and ST during 2012 was performed using AcraPlant Trash Whippers consisting of 30 and 33 cm (12 and 13 in) offset disks. The purpose of this modified-row cleaning operation was to move corn residue from irrigated furrows to adjacent non-irrigated furrows to facilitate irrigation. A minimum driving speed of 5 mph was needed in order to throw the residue sufficiently to reach the non-irrigated furrows.

Corn (*Zea mays*) seed for both 2011 and 2012 growing seasons was acquired from Fontanelle Hybrids, and was 94 day Genuity® SmartStax® RIB Complete™ 4A098 RBC hybrid. Planting was performed by a Monosem NG Plus 6-row planter in 2011 and a John Deere MaxEmerge2 VacuMeter 7300 planter in 2012. Seeds were sown approximately 5 cm (2 in) deep at a spacing of 15 cm (6 in) on 75 cm (30 in) spaced rows for a target plant population of 83,950 seeds/ha (34,000 seeds/ac). Nutrient needs were determined by soil sample analysis and calculated to achieve an appropriate agronomic rate using Colorado State University Extension Corn Fertilizer Recommendations (Davis and Westfall 2009). At planting, a starter fertilizer was applied through Keeton Seed Firmers immediately adjacent to the seed at a rate of 6 kg ha^{-1} (5 lbs ac^{-1}) of nitrogen (N) and 22 kg ha^{-1} (20 lbs ac^{-1}) of phosphorus (P), and 1.7 kg ha^{-1} (1.5 lbs ac^{-1}) zinc (Zn) in all tillage systems during 2011 and 2012. Remaining fertility requirements were met by a side-dress operation where liquid fertilizer was band applied by injecting the fertilizer into the soil following a disc opener at a target depth of 5 cm (2 in). In 2011 total fertilizer applied was 157 kg ha^{-1} (140 lbs/ac) N, 22 kg ha^{-1} (20 lbs/ac) P, and 1.7 kg ha^{-1} (1.5 lbs ac^{-1}) Zn. In 2012, 134 kg ha^{-1} (120 lbs ac^{-1}) of N, 37 kg ha^{-1} (33 lbs ac^{-1}) of P, and 1.7 kg ha^{-1} (1.5 lbs ac^{-1}) of Zn were applied all three tillage systems. In 2011, the side-dress operation was performed on

the shoulder of non-irrigated furrows, and in 2012 it was performed on the shoulder of irrigated furrows. After side-dressing, a cultivation operation was then accomplished using an Orthman RowCrop Cultivator in each tillage system, which proved to be less effective in MT than CT and ST due to the hardness of the soil.

Soil Moisture

Soil moisture was monitored weekly by neutron attenuation (Troxler Electronic Labs, Research Triangle Park, NC). The neutron probe was calibrated against soil water content values obtained by performing gravimetric determinations by taking soil core samples of the top 15 cm (6 in) of the soil the same day access tubes were installed at the experimental site during the spring of 2011. The soil cores were dried at 105°C and then weighed. Galvanized steel access tubes were installed in north, middle, and south locations of each plot to a depth of 1.85 m (6 ft), which is the approximate maximum rooting depth of corn in the region. The neutron probe readings were taken at 0.30 m (1 ft) increments, beginning at 0.15 m (0.5 ft) below the soil surface. In both years, soil moisture data collection started three weeks after sowing and stopped three weeks before harvest.

Irrigations

Irrigation scheduling was determined by weekly moisture sensor readings as well as manual feel of the soil. There were a total of six irrigation events during the 2011 season, occurring on July 1, 19, 29, August 10, 19 and 29. For the 2012 season, there were ten irrigation events occurring on May 16, June 4, 12, 27, July 17, 25, August 1, 9, 20, and 31. Irrigation water came from a well and was delivered to every-other furrow from a concrete-lined ditch using 3.8 cm (1.5 in) diameter siphon tubes.

Crop Residue Measurements

The percentage of the soil surface covered by crop residues was measured in each tillage system during both growing seasons utilizing the line transect method (Laflen et al. 1981). Measurements were taken independently on top of beds, in non-irrigated furrows, and in irrigated furrows. Percent cover measurements were taken three weeks after planting, on May 23, 2011 and May 22, 2012. Residue mass was also determined from corresponding positions of each plot on June 14, 2011 and June 14, 2012. To gather the residue, metal frames 50 cm by 100 cm (20 in by 40 in) in 2011 and 20 cm by 50 cm (8 in by 20 in) during 2012 were used. The frame was placed in the center of the beds and furrows in north and south locations of each plot. Any reside inside the frame was collected, placed in paper bags, and dried for one week in ovens at 50°C (120°F) and weighed.

Soil Penetration Resistance

Soil penetration resistance in each tillage system was measured one week after planting in 2012, on May 9. A Field Scout SC 900 Soil Compaction Meter (Spectrum Technologies, Inc., Plainfield, IL) with a cone tip having a 1.3 cm (0.51 in) diameter was used to measure soil strength and to estimate soil compaction of the top 37.5 cm (14.8 in) of the soil profile. Readings were taken at 2.5 cm (1 in) depth increments to a depth of 40 cm (15 in) in bed, irrigated furrow, and non-irrigated furrow positions at 12 random locations for each plot. Soil moisture content was determined by taking soil core samples of the top 15 cm (6 in) of the soil the same day compaction readings were collected. The soil cores were dried at 105°C and then weighed. Prior to taking penetrometer readings, the field site had received 1.2 cm (0.5 in) of precipitation

between May 6 and 7, 2012, which created ideal field conditions in which to collect compaction readings.

<center>*Runoff Measurement and Sampling*</center>

One 60 degree V-notch trapezoidal furrow flume (Trout and Mackey 1988) was installed in the middle furrow of each plot, between beds 17 and 18 prior to irrigations in order to measure total outflow volume and rate for the three tillage systems. These flumes were installed within 6 m (20 ft) of the end of the field. Inflow rates from siphon tubes that irrigated the furrows with flumes were calculated by timing how long it took to fill a 1 or 7 L bucket. The time needed for irrigation water to advance from the beginning to the end of the furrows with flumes was measured and compared among tillage treatments. These furrows were driven furrows that were trafficked during field operations. Most of the other non-driven furrows had slower advance times due to less traffic. Flow stage was continuously measured in each flume by using pressure transducers (YSI Incorporated, Yellow Springs, OH and Geo-Met Instruments, New Minas, Nova Scotia, Canada) installed in stilling wells located on one side of each furrow flume. Transducers collected data at 5 or 15 minute intervals for the duration of the irrigation events, allowing for the calculation of total water outflow. In addition, a manual measurement of stage was taken at designated sample times to verify pressure transducer readings.

Runoff samples were collected from the furrow with an installed furrow flume in each plot at three time intervals. Time interval one (T1) was at initial water runoff from the measured furrow, time two (T2) was two hours after initial runoff, and time three (T3) was four hours after initial runoff. Small weirs were temporarily installed just prior to runoff sampling and then removed. The weir consisted of a steel plate which measured 30 cm (12 in) long and 15 cm tall

<center>7</center>

(6 in), having a 4 cm (2.5 in) diameter notch where runoff samples could be collected. When the water flowed over the notch in the weir, collection of the runoff sample occurred. The weirs allowed sample collection from the furrow with minimal disturbance of the soil and flowing water. Runoff samples were collected for determination of sediment concentration for all irrigations in both years. Runoff samples for analysis of nutrient concentrations were collected only for the first, second, and fourth irrigations after cultivation in both years. Samples were collected in nalgene bottles and were stored in a refrigerator at $\pm$ 2 °C (35 °F) until analysis.

Runoff Water Analysis

For total nitrogen analysis, samples were digested using the Kjeldahl method using a Tecator 2040 Digestion Block. The samples were then analyzed for ammonium using an OI Analytical Flow Solution 3000 according to US EPA Method 351.1 (Collins et al. 1996). Nitrate-nitrogen determination for the first irrigation of the study in 2011 was performed by ion chromatography based on US EPA Method 300.0 (Pfaff et al. 1993). Nitrate-nitrogen determination for every other irrigation for the duration of the study was performed by filtering the samples through a 0.45 μm membrane filter and analyzing them using cadmium reduction (OI Analytical Flow Solution 3000) according to US EPA Method 353.2 (Cook and Frum 2004).

Total phosphorus analysis was done by digesting the samples with nitric and perchloric acids using a Tecator 2040 Digestion Block. The samples were then analyzed for total P by inductively coupled plasma spectrometry (TJA Solutions IRIS Advantage) according to EPA Method 365.4, (Chen et al. 2006) and EPA Method 200.8, analysis by ICP (Wolf and Grosser 1997). Ortho-P analysis in was performed using the bi-carbonate method and reading with a

spectrophotometer after the samples were filtered through a 0.45 µm filter (Rodriguez et al. 1994). Calibrated imhoff cones were used to determine sediment concentration (Sojka et al. 1992), by measuring sediment settled at the bottom of the 1-L cones after 60 min after being hand-shaken for 30 sec. Imhoff cones were calibrated with a gravimetric filtration method to obtain a linear regression (y = 0.058x + 0.19, $R^2 = 0.94$) of sediment collected on a filter paper compared to the amount of settled sediment.

All reported concentration values for nutrient and sediment runoff concentrations are flow weighted mean concentrations. Cumulative loads were determined by multiplying the flow during the runoff time period associated with each sample by the concentration and expressing the product relative to the area of two furrows.

Statistical Analysis

Water runoff data was analyzed by analysis of variance (ANOVA) using SAS (Version 9.2) to compare concentrations of each runoff nutrient in each tillage system for both study years. The PROC Mixed model was used, using a repeated measures approach. Tillage, year, and irrigation were fixed effects in the model, with block as a random effect. All concentrations were transformed using a log of base 10 to stabilize variances and provide normality. Mean concentrations were reported in original units for table and figure presentations. Additionally, an ANOVA was performed on total loads of each nutrient, average inflow rates and advance times, outflow, and infiltration. The PROC Mixed model was used, with year and tillage being fixed effects for these analyses except inflow rates and advance times, in which irrigation was also a fixed effect. Block was a random effect in all analyses. Residue data was analyzed by the PROC

GLM model for each individual year and reside measurement method. Replication and tillage were fixed effects in the model. Statistical significance was determined at α=0.10.

RESULTS AND DISCUSSION

Surface Crop Residue Cover and Mass

A major focus of this study was to evaluate how crop residue affects the need and ability to irrigate with minimum (MT) and strip (ST) tillage systems under furrow irrigation compared to the conventional, plow-based tillage approach. The alternative tillage approaches (1-2) were selected with contrasting approaches to maintain crop residue cover at the soil surface while addressing the concern of growers about acceptable advance of irrigation water in the furrows (Carter and Berg 1991) and a suitable seedbed. In both MT and ST systems, corn stalks and stover from the previous year were managed by chopping, bailing, and moving the residue from irrigated furrows into an adjacent non-irrigated furrow using modified row-cleaners. For all three tillage systems after the harvest in 2010, corn stalks were chopped close to the soil surface and approximately 35% of the residue biomass was removed by bailing immediately after harvest. Bailing of corn stalks is common for irrigated corn in Colorado because of the value of the stalks as cattle feed supplement. Further, large amounts of residue from irrigated corn can hinder planting in reduced tillage systems. Heavy winds during the 2010-11 winter removed a significant amount of the remaining residue, leaving less residue than originally targeted in MT and ST and some of the residue being deposited in CT plots. As a result of this experience, less residue was removed by bailing after the 2011 harvest (~25%) and chopping was done in a way that left corn stalks standing about 45 cm above the bed. Consequently, there was substantially more residue mass on the field at planting in 2012 than in 2011 (Table 1-3).

The percentage of soil surface covered by crop residue (PR), in each tillage system was determined on the crop bed and in both irrigated and non-irrigated furrows in May of 2011 and 2012 (Table 1-3). During 2011, PR on crop beds was affected by tillage, with an average of 58, 31, and 15 % for MT, ST, and CT, respectively. Non-irrigated furrows in MT had significantly higher PR (84%) than did ST (38%) and CT (31%). For irrigated furrows, PR was not different among tillage practices in 2011, showing the effectiveness of the row cleaning operation in removing residue for the MT and ST systems. The mean PR in 2011 shows that CT had significantly less residue than MT, was not different than ST, and that both conservation tillage systems had more than 30% residue cover, the requirement to be classified as conservation tillage (Shelton et al. 1995).

In 2012, tillage affected PR on crop beds, with CT and ST having 10% and 28% and MT having 64%. For non-irrigated and irrigated furrows, CT had a lower PR than both MT and ST. These measurements were after a row cleaning event of the irrigated furrows in MT and ST. The mean PR for 2012 shows that CT (12%) had less residue than MT (67%) and ST (54%), while MT and ST were not different from each other.

While PR illustrated differences in residue amount and distribution among tillage systems, it did not illustrate the full extent of the differences. Residue mass (MR) was also assessed to better show tillage differences, with measurements made in June of 2011 and 2012 (Table 1-3). In 2011, MR was significantly affected by tillage on crop beds and non-irrigated furrows. CT had less MR than MT in both field positions, but ST was not statistically different from either of the other two tillage systems. MR from irrigated furrows shows that there was no significant difference among irrigated furrows during 2011. The mean MR shows that CT had significantly less residue than MT, and was not different than ST.

11

In 2012, CT again had significantly less MR than MT, with ST being similar to both. However, for non-irrigated furrows, all three tillage systems were significantly different ranking in the order of MT (40.2 Mg ha^{-1}) > ST (17.8 Mg ha^{-1}) > CT (1.0 Mg ha^{-1}). These numbers show more clearly than PR the relatively large amounts of residue biomass in the non-irrigated furrows of MT and ST. The heavy amounts of residue create a unique micro-environment of alternating furrows with heavy residue and furrows with little residue in ST and MT that can influence moisture retention and crop growth. As observed in 2011, MR did not differ among tillage system for the irrigated furrows in 2012, thus illustrating that the modified row-cleaning approach was effective.

The different handling of crop residues in the fall of 2010 and 2011 was more clearly observed with differences in MR than PR. The mean MR was 2.4 Mg ha^{-1} in 2011 and 9.4 Mg ha^{-1} in 2012, whereas the mean PR was 43% in 2011 and 44% in 2012. Thus, a 75% change in MR was only reflected as a 1% change in PR between the two years. MR measurements are a more sensitive indicator of management than PR because, even though there may be residue covering the soil surface, there might not be as much mass of residue on the soil as the PR measurement suggests. MR and PR measurements could also differ due to uneven distribution of residue. While MR was more telling of the quantity of residue on the soil surface, both methods revealed that CT had significantly less residue than MT and ST. The results show that leaving standing stalks when chopping in the fall was an important management decision that limited overwinter loss of residue to wind.

Several studies have shown that crop residues provide important soil benefits, including protection of the soil from erosion (Merrill et al. 2006), conserving soil moisture and promoting water storage (Tanaka and Anderson 1997). Crop residues on the soil surface can reduce water

runoff and promote infiltration (Lal 1995). These potential benefits have not been realized on most furrow irrigated farms because concern about effective irrigation and seed bed preparation has limited adoption (Carter and Berg 1991). However, not all effects from residues are beneficial. Studies have shown that residue on the soil surface in conservation tillage systems can slow the warming of soil and thus decrease the emergence and growth of corn compared to corn in conventional tillage systems (Kaspar et al. 1990; Gupta et al. 1983). This study shows that a modified row-cleaning operation can manage crop residues in irrigated furrows of conservation tillage systems with every-other furrow management to levels similar to CT. Residue levels in the seedbed were quite high for the MT system, which could be a concern for effective planting, but were moderate for ST.

Soil Moisture Dynamics

A key difference observed among tillage systems was the soil moisture content at planting (Figure 1-1). Soil moisture content at planting varied with tillage system in 2011, with MT (0.23 cm cm^{-1}) > ST (0.18 cm cm^{-1}) > CT (0.13 cm cm^{-1}). The 2012 year was very dry, but soil moisture content at planting was still greater for MT (0.15 cm cm^{-1}) and ST (0.14 cm cm^{-1}) than for CT (0.05 cm cm^{-1}). There is a pattern of increasing soil moisture content at planting among tillage systems with increasing amounts of crop residue on the soil surface and fewer tillage operations. The increased soil moisture in conservation tillage systems during the time between harvest and planting has also been observed by other researchers in Colorado (Nielsen and Vigil 2010) and other states in the Northern Plains (Tanaka and Anderson 1997). Increased soil moisture content at planting shows an increase in capture and storage of precipitation during the time between harvest and planting and is a benefit for the conservation tillage approaches,

13

because it may reduce the dependence on irrigation water to initiate seed germination and emergence.

Soil water content in a 1.8 m (6 feet) deep profile also varied with tillage practice during the 2011 and 2012 crop growing seasons. In 2011, CT had the lowest profile water content through the entire season when compared to the two conservation systems (Figure 1-2). The 2011 results clearly show the benefit of crop residues in conservation tillage relative to soil water content. The season long, 2012 water profile data was less instructive because of confounding irrigation management. Because soil water content was low at planting in 2012 for the CT treatment, it required an early irrigation for seed germination. MT had higher soil moisture at planting, but it also required an early irrigation due to shallow seed placement. The irrigation duration was 50-hrs for CT and 18-hrs for MT (Table 1-4). Favorable conditions for the ST system did not require the early irrigation. When neutron probe access tubes were later installed, CT had the highest water content and remained this way throughout the season. We attribute the high water content in CT to the extremely long duration of the first irrigation event of the season for that treatment. MT had the lowest average water content of the three tillage systems in 2012. This observation is attributed to poor infiltration (Table 1-4) caused by the soil compaction in MT.

The soil water content results illustrate that crop residue associated with the modified conservation tillage practices increases soil water content, with important differences noted at planting time. Results in 2011 showed the benefit of increasing soil moisture with conservation tillage throughout the growing season. In 2012, the results show that other factors, including irrigation timing, seed placement, and soil hardness can counter the benefits of water

14

conservation with crop residue. When considering the different conditions of the 2011 and 2012 years, the ST system had the greatest advantage from the perspective of soil moisture.

Penetration Resistance

Penetration resistance in each tillage system was determined on May 9, 2012 after planting (Table 1-5) and after a precipitation event of 1.5 cm (0.50 in) when soil conditions were ideal for measuring penetration resistance. Gravimetric soil samples were collected at the same time as penetrometer readings to determine if resistance values needed to be corrected for soil moisture content. Moisture content to a depth of 15 cm (6 in) was not different among tillage systems (Figure 1-1), so no moisture corrections were made to the penetration resistance measurements (Table 1-5).

In the 0-2.5 cm (0-1.0 in) layer of soil in irrigated furrows, penetration resistance followed the order CT (371 kPa) < ST (1056 kPa) < MT (1477 kPa). For this surface layer, the penetration resistance for MT was 75% greater than for CT and 29% greater than ST. Soil density at the surface layer of irrigated furrows is important because this is the interface for infiltration of irrigation water. The lower penetration resistance of CT was due to the full width tillage in that treatment. It is unclear why ST had lower penetration resistance than MT in the irrigated furrows, because furrows were not tilled at the time of measurement in either system. Penetration resistance in the bed positions is also important because this is where seed placement, germination, and root development occurs. Average penetration resistance for the top 0-5 cm (0-2 in) on the beds of MT (848 kPa) was higher than beds of CT (567 kPa) and ST (275 kPa) by 34% and 68%, respectively. While none of the penetration resistance observations in the beds are root limiting, the higher observations did affect mechanical seed placement in MT. Seed

placement was observed to be shallow, to the side of the bed, and inconsistent in MT. In addition to the penetration resistance, remaining stems and root systems also affected mechanical planting in MT. The high penetration resistance and interference by remaining roots and stems found in MT validates concerns producers have with about poor seedbed conditions with reduced tillage in furrow irrigated systems (Licht and Al-Kaisi 2005). Mean penetration resistance through the full measured depth in the bed position in ST (1066 kPa) was the lowest of all tillage systems, compared to MT (2050 kPa) and CT (1555 kPa). This confirms research claiming the benefits of an excellent seed bed created by strip tilling for unimpeded root growth (Licht and Al-Kaisi 2005; Tabatabaeekoloor 2011) and suggests that this approach may be well suited as a conservation tillage system for furrow irrigation.

Irrigation Dynamics

From January to July 2011, the field site received 18 cm (7.1 in) of precipitation, making it unnecessary to irrigate until July 1. For all three tillage systems, there were a total of six irrigation events during the 2011 season, all occurring after cultivation on July 1, 19, 29, August 10, 19 and 29 (Figure 1-2). The first irrigation had an 8-hr duration, and the remaining five irrigations had 12-hr durations for all tillage systems. The winter and spring of 2012 were extremely dry, with the field site receiving 3.7 cm (1.5 in) of moisture from January to July. There was only 2.0 cm (0.79 in) of precipitation from January to the middle of May, creating the need to irrigate plots much earlier than in 2011. CT had the driest soil at planting (Figure 1-1), and MT beds were very hard at the time of planting resulting in some seeds only being sown at a depth of 2.5 cm (1.0 in) or less, where soil moisture was limited. As a result, CT and MT were irrigated on May 16, 2012, but ST did not require irrigation on that day (Table 1-4). Due to the extreme dryness of the soil, the CT plots were irrigated for 50 continuous hours, but yet did not

16

advance to the end of the field or generate outflow. The surge technique (Bishop et al. 1981), was attempted to advance water to the end of the field in CT plots, which resulted in getting water further than continuous flow but there still was no outflow in CT during this first irrigation. For MT, this irrigation had a duration of 18-hr. As a result of the higher density of the irrigated furrows of MT, water did advance to the end of the rows, which shows an advantage of the reduced tillage system for dry years when irrigation is needed to induce germination.

The requirement for an early and long duration irrigation event illustrates a limitation of CT, a problem discussed in another furrow irrigation study. Researchers found that the first irrigations of conventionally tilled soil in semiarid Colorado can result in insufficient lateral movement of moisture from furrow to bed that is needed for seed germination and poor advancing of water in the furrow (Yoder and Duke 1990). The lack of lateral movement is due to the loss of water from deep percolation downward through the soil profile. By losing water through deep percolation, more irrigating is required and risk of nutrient leaching and groundwater contamination is elevated (Yoder and Duke 1990). Despite the very dry conditions, ST had adequate soil moisture at planting to avoid the early irrigation, showing the benefit of crop residues on the soil surface. MT also had adequate soil moisture and would not have needed irrigation if there were suitable seedbeds to allow deeper seed placement.

The second irrigation event of 2012 for CT was on June 4. On the same day, ST required the first irrigation of 2012. In this irrigation, there was some outflow in CT, but water did not make it to the end of the field in all furrows of ST after an 18-hr duration for both tillage systems. On June 12, 2012 the second irrigation for MT and ST took place. Both tillage systems had water reach the end of the furrows during this irrigation event with a12-hr duration. Cultivation and side-dressing of phosphorus and nitrogen occurred in the field on June 26, 2012,

after which the first simultaneous irrigation during 2012 for all three tillage systems took place. A total of seven irrigation events occurred after cultivation, including June 27, July 17, 25, August 1, 9, 20, and 31.

In order to more consistently compare advanced times, outflow, infiltration and water quality of tail water among tillage, these data were compared for the first, second, and fourth irrigations in 2011 and the first, second, and fourth irrigations after cultivation in 2012. In both years, the sampled irrigation events from each tillage system occurred directly after fertilization and cultivation and there was no further soil disturbance from cultivation during the time period of sampled irrigation events.

Inflow Rates

Inflow rates were measured during each irrigation during 2011 and 2012 (Table 1-4). For the 2011 season, ST (1.47 L s^{-1}) and MT (1.43 L s^{-1}) had higher average inflow rates than CT (1.24 L s^{-1}). The differences in inflow rates were caused mainly by an uneven erosion of soil below the irrigation ditch in ST and MT. Due to less soil on the ditch-bank in the ST and MT plots, the siphon tubes hung at steeper angles than those in CT, and thus resulted to higher inflow rates. In the spring of 2012, we deposited soil around the ditch in order to provide greater inflow normality. The average inflow rates during the 2012 season were statistically similar among tillage systems CT (1.14 L s^{-1}), MT (1.20 L s^{-1}), and ST (1.16 L s^{-1}) as a result of the soil placement around the ditch. These flow rates are comparable to flow rates used by local growers when utilizing 3.8 cm (1.5 in) diameter siphon tubes to furrow irrigate. However, many growers use 5 cm (2 in) diameter siphon tubes, which drastically increases flow rate well as nutrient and sediment in runoff.

Table 1-6 shows that only the first of the three post-cultivation irrigations during 2011 had a significant difference in flow rates when comparing individual irrigation events (P=0.013), with MT (1.36 L s^{-1}) and ST (1.24 L s^{-1}) having higher rates than CT (1.01 L s^{-1}). Similarly, in 2012 the first of the three post-cultivation irrigations had differing rates among tillage systems (P=0.022), with MT (1.34 L s^{-1}) having a higher inflow rate than CT (1.06 L s^{-1}) and ST (1.04 L s^{-1}).

Advance Times

Advance times were measured for all irrigation events (Table 1-4) and averaged 79 min., 101 min., and 108 min. for MT, CT, and ST in 2011. In 2012, average advance times were 88 min., 99 min., and 109 min. for CT, MT, and ST. The advance times for the average of all irrigation events could not be compared statistically because of the different dates and duration of irrigation among tillage systems in 2012. Statistical comparison of advance times was made for three, post-cultivation irrigation events in each study year (Table 1-7). For the July 01, 2011 irrigation, advance time was longest for ST (151 min) compared to CT (57 min.) and MT (57 min). For the July 19, 2011 irrigation event of 2011 CT (48 min.) and MT (39 min.) were similar, but ST (77 min) had a slower advance time than MT. There was no difference of advance times among the tillage systems for the August 10, 2011, or any of the irrigations during 2012. A comparison of average advance times for the common, post-cultivation irrigation events reveals that ST (116 min.) was significantly slower than CT (82 min.) and MT (71 min.) during the three sampled irrigations during 2011 but all tillage systems were similar in 2012 (Figure 1-3). While tillage affected advance times, it should be noted than none of these advance times are considered to be unacceptable for a management standpoint. In fact, the advance for the MT may be considered too fast for adequate infiltration.

It is important to note that there was statistically no difference in residue mass for any tillage system in the irrigated furrows (Table 1-3), yet in MT had faster advance times than CT and ST in 2011 and ST in 2012. The top 2.5 cm (1.0 in) of the soil surface in MT was more compacted than CT and ST (Table 1-5), to which we attribute the quick advance times. It appeared that soil compaction had more of an effect on advance time than did residue in this study. Also, when performing the strip tilling operation, loose soil was pushed from the beds into the furrows. This could be why ST consistently had slower advance times than CT, especially when considering that ST had a higher inflow rate than CT during the first irrigation of 2011. These results contrast findings others have reported (Yonts et al. 1991), where reduced tillage systems always increased advance times compared to CT. However, those studies did not utilize the modified row cleaning operation that was used in this study. The row cleaning approach is important because the ability to irrigate well with residue present can be very appealing to growers who are apprehensive about converting to conservation tillage due to concerns about residue creating dams in the irrigation furrows resulting in uneven irrigation of their fields (Carter et al. 1991).

Outflow

Total water outflow from a center furrow in each tillage system was measured for three irrigation events during both study years (Table 1-8). There was a significant difference in outflow between the two years (P=0.014), with 25% more outflow in 2011 than in 2012. No significant differences were found among tillage systems (P=0.214), however there was an interaction among tillage systems and year (P=0.075). When average outflow for the three sampled irrigations were compared in 2011, CT (193 mm) had less outflow than MT (328 mm) and ST (356 mm) (Figure 1-3). Other researchers have also found that CT may have less outflow

20

than conservation tillage systems (Zeimen 2007). Our result of a lower inflow rate in CT than in MT and ST (Figure1-3) could be the cause of less outflow in CT. There were no differences in cumulative outflow among tillage systems in 2012. Similar results were found when comparing average outflow for all irrigations during both study years (Table 1-4).These results show that conservation tillage systems can have either comparable or more outflow than CT when they are coupled with a row-cleaning operation. As with advance times, this is extremely valuable for growers looking for tillage systems that provide irrigation to the full length of their fields.

Infiltration

Infiltration of irrigation water into the soil was determined by subtracting total outflow from water applied to each tillage system (Table 1-9). Tillage system did not affect quantity of water infiltrating soil during the three, post-cultivation irrigations (P=0.468). There was also not an interaction among year and tillage (P=0.390). But year did have a significant effect on infiltration (P=0.091), with 14% more infiltration during 2011 than in 2012. A noticeable trend in cumulative infiltration can be seen as the inverse of the trend in cumulative outflow data (Figure 1-3). This trend has also been seen by other researchers (Lentz and Lehrsch 2010). This trend can be explained by the mild slope of our field, less inflow in CT, cracking of the soil caused by dry conditions in CT, and hardness of the soil in the conservation tillage systems with much less cracking of the soil than CT. While not statically compared, total infiltration for all irrigation events in 2011 (Table 1-4) showed values of MT (757 mm), CT (813 mm) and ST (839 mm). Total infiltration in 2012 showed values of MT (1197 mm), ST (1271 mm), and CT (1909 mm). These results suggest less infiltration in MT during both seasons, which can be explained by the more compacted soil in that system (Table 1-5). However, the apparently greater infiltration in CT during 2012 is due to no outflow from the first irrigation. There was extreme

21

infiltration and saturation of the soil in the top half of the CT plots, but due to the above

mentioned problems with water not reaching the end of the field, inflow and infiltration for CT

were very high, and likely led to significant deep percolation. This presents a limitation of CT

that was not expressed in MT and ST, mainly due to residue cover in the conservation tillage

systems that decreased reliance on irrigation for crop emergence.

<center>*Sediment and Nutrients in Outflow*</center>

Nutrient Concentrations

There were few differences for the flow weighted mean concentrations of soluble

phosphorus (SP), total phosphorus (TP), total nitrogen (TN), and nitrate (NO_3^-) in runoff water

for the three measured irrigations among tillage systems for the two study years (Table 1-10).

Soluble phosphorus (SP) concentrations ranged from 0.09 mg L^{-1} to 0.32 mg L^{-1}, and neither

tillage system (*P*=0.625) nor year (*P*=0.662) significantly affected SP concentration. Total

phosphorus (TP) concentrations in runoff ranged from 0.47 mg L^{-1} to 2.3 mg L^{-1}, having a

statistically significant tillage by year interaction (*P*=0.042). In 2011, CT had the highest average

TP concentration of runoff, with (2.3 mg L^{-1}), followed by MT at (1.1 mg L^{-1}) and then ST (0.94

mg L^{-1}). In 2012, MT had the highest TP concentration (2.2 mg L^{-1}), followed by ST at (1.8 mg

L^{-1}) and then CT (1.6 mg L^{-1}).Thus tillage did not have a consistent effect on TP concentration in

runoff in 2011 and 2012.

SP concentration has been reported to be higher in runoff from conservation tillage

systems than from conventional tillage due to phosphorus accumulation at the soil surface from

fertilizer and from crop residue, which is then transferred to runoff water (Hansen et al. 2002;

Sharpley et al. 1994). Additionally, conservation tillage generally has less runoff volume, and

<center>22</center>

thus usually results in a higher percentage of the TP loss as SP because there is less material available for which phosphorus can be sorbed (Sharpley et al. 1992). However, this study showed that MT and ST had similar SP concentrations to CT, and the outflow was comparable. In this study, P fertilizer was applied by banding rather than broadcast in hopes of limiting P runoff. A study concerning fertilizer placement showed that incorporation of phosphorus (P) fertilizer into the soil is a management method that can drastically decrease the loss of P in comparison to broadcast application of P fertilizer (Bundy et al. 2001). Our results show that banding prevented high SP and TP losses. Another reason for lack of differences observed among tillage practices in our study is that the levels of crop residue were similar among tillage practices within the irrigated furrows. The extractable plant available soil P determined from the ammonium bi-carbonate DTPA method (Soltanpour and Workman 1981) from soil at the site before planting in 2011 and 2012 was categorized as low to medium (Table 1-1). This led to applied P being tightly bound to the soil because it had the capacity to adsorb P, and was therefore less available for loss in runoff.

When freshwater sources such as streams have a concentration of 0.10 mg L^{-1} (or ppm) SP, there can be accelerated rate of eutrophication (Sharpley 1996) leading to increased algal growth and decreased oxygen content, which results in lowered water quality and fish kills. The average concentration of SP in this study was higher than this threshold, and thus provides an environmental concern about contaminating water sources. However, from an agronomic standpoint, losing an average of 0.35 kg ha^{-1} SP and would not be a significant concern when compared to the ~ 30 kg ha^{-1} of phosphorus applied to the field. It is important to note that the concentrations of SP were measured from water immediately leaving the field. Usually, concentrations will be diluted by the time the reach water sources.

Tillage system did not have a significant effect on total nitrogen (TN) concentration in runoff (P=0.913), nor did year have an effect (P=0.954), and there was no tillage by year interaction (P=0.826). Concentration of nitrate (NO_3^-) in runoff varied with tillage (P=0.023) and years (P=0.035), with no significant tillage by year interaction (P=0.248). The average NO_3^- concentration was highest in MT (0.74 mg L^{-1}), followed by ST (0.36 mg L^{-1}), and CT (0.19 mg L^{-1}). Dissolved nutrient concentrations, like NO_3^-, are products of reactions of runoff water with the soil surface and crop residues (Logan 1982). However, there was not a significant difference of residue mass in irrigated furrows (Table 1-3) eliminating the possibility that residue was the cause of higher NO_3^- concentrations in MT. We attribute the cause of higher NO_3^- to the compacted soil in that system (Table 1-5) making it more difficult to side-dress nitrogen into the beds of MT, which resulted in less fertilizer incorporation into the soil. Since the sampled irrigations occurred shortly after fertilization, we believe that more NO_3^- was carried off with runoff in MT than CT and ST during those irrigations because more nitrogen was on the soil surface.

The runoff nutrient concentration results are very interesting when considering the different field positions we fertilized during this study. In 2011, we side-dress fertilized (banded) nitrogen and phosphorus fertilizers in the non-irrigated furrows. Our intention of fertilizing the non-irrigated furrows during the first year was to prevent the loss of nutrients due to leaching through the soil profile as well as loss in runoff water in irrigation outflow (Benjamin et al. 1998; Lehrsch et al. 2001). But after receiving minimal precipitation during the second winter and spring of the study, we decided to fertilize the irrigated furrows in 2012 in order to provide needed moisture to ensure nutrient uptake by plant roots. We expected to see large differences of runoff nutrient concentrations between the two study years because of water flowing in the

furrows where fertilizer was placed in 2012 versus in furrows that were not fertilized. But our results show that only TP and NO_3^- runoff concentrations were statistically higher during 2012 than in 2011 (Table 1-10).

Irrigating every other furrow has been shown to be a reasonable method for minimizing the amount of irrigation water needed, and thus preventing over-irrigating and the loss of nutrients and sediment. Studies have demonstrated that when irrigating every other furrow instead of every furrow, there can be a water savings of up to 23% (Nelson and Al-Kaisi 2011). Also, by irrigating every other furrow, nitrate loss can be 11 to 26% less than when irrigating every furrow (Nelson and Al-Kaisi 2011). Irrigating every other furrow has been shown not to reduce corn yields when compared to irrigating every furrow (Fischbac and Mulliner 1974). Although we don't have data to show differences of nutrient runoff between irrigating every furrow versus every other furrow, the runoff concentrations we observed for every other furrow technique are relatively low, less than concentrations from fertilized, conventionally tilled furrows in a similar study (Lentz and Lehrsch 2010). Our average TP concentration in CT was 2.0 mg L^{-1} compared to the value of 2.8 mg L^{-1} reported by Lentz and Lehrsch and our average NO_3^- concentration in CT was 0.19 mg L^{-1} compared to their reported 0.26 mg L^{-1}.

Tillage did not have a significant effect on sediment runoff concentration (P=0.302), nor did year (P=0.440), and there was no tillage by year interaction (P=0.332). Sediment concentrations ranged from 574 mg L^{-1} to 1198 mg L^{-1}. The average sediment concentration in CT of our study was also lower than that of Lentz and Lehrsch (2010), where our average was 951 mg L^{-1} compared to 3100 mg L^{-1}. This result is significant with regard to the size of our study site. Our field site was considerably longer than those in other studies because we took a field-

scale approach in order to demonstrate actual losses that a grower will experience under these tillage systems.

Sediment concentrations were measured on samples collected at the outflow end of the field. However, most of the sediment detachment occurs at the inflow end of the field especially when there is a uniform slope (Trout 1996). As water travels down the furrow, flow and erosion rates decrease and deposition occurs. With our observation of no statistically significant variation of outflow among the three tillage systems (P=0.214), the lack of observed differences among tillage system for sediment loss is validated. It has also been shown that residue decreases sediment loss most in runoff from fields with relatively steep slopes (Ashraf et al. 1999). Nevertheless, since our field site had a slope of less than 1%, and there were no differences in residue mass in the irrigated furrows during 2011 or 2012 among tillage systems, it is not surprising that sediment concentrations were not statistically different.

An analysis of median concentrations for each runoff nutrient and sediment was also performed. Similar results were observed for all median values compared to means, except for NO_3^-. The median NO_3^- results showed that ST had the greatest concentration during 2012 whereas the mean showed that MT had the greatest concentration. This result can be attributed to the single high NO_3^- in runoff in the first interval of the first runoff event after cultivation in 2012, when we side-dressed N fertilizer in the irrigated furrows. After that one interval, MT had lower concentrations than ST. This presents a need to alter the side dress operation or timing of irrigation in MT in order to prevent substantial NO_3^- loss after fertilizing.

Cumulative Loads in Outflow

There were no significant differences among any of the three tillage systems during 2011 or 2012 for total load of SP, TP, TN during the three post-cultivation irrigations (Figure 1-4). However, there was a statistical difference in total load of NO_3^- in 2011, with MT having significantly higher NO_3^- load than CT. In 2012, NO_3^- load did not vary among tillage system, although the trend was similar to that of 2011. We consider this trend to be important because the high NO_3^- loads in 2011 and 2012 come from a single high NO_3^- load during the first irrigation in MT during both study years. As previously noted, this first irrigation closely followed fertilization. As with NO_3^- concentration, we hypothesize the high NO_3^- load in MT during 2012 was due to the hardness of the soil in tillage system. There was the least amount of nitrogen fertilizer incorporated into that tillage system compared to CT and ST. With less fertilizer being incorporated into the soil, more NO_3^- was carried off the field in the runoff water in MT than the other two systems. Soil hardness is one limitation of the MT system in this study.

Total sediment load for all irrigations during the both seasons was calculated (Table 1-4). Tillage did not affect total sediment load in 2011(P=0.158), with an average of 4.9 Mg ha^{-1} for the season. However, CT (6.4 Mg ha^{-1}) had a greater sediment load than MT (4.6 Mg ha^{-1}) and ST (3.6 Mg ha^{-1}) in 2012.

CONCLUSIONS

In this continuous corn study, conservation tillage in furrow irrigation was facilitated by after-harvest management of corn stalks by chopping and bailing, followed by use of a modified row-cleaner to move residues from irrigated furrows into adjacent non-irrigated furrows. Leaving the corn stalks standing about 45 cm above the beds was better than chopping near to the soil

surface. While the conservation tillage systems (MT and ST) had higher amounts of crop residue than CT on the beds and in non-irrigated furrows, the residue in irrigated furrows was uniformly low for all systems. Measuring residue mass was a better way to compare tillage practices than measuring percent residue cover. Conservation tillage systems had residue mass in the non-irrigated furrows as high as 40.2 Mg ha^{-1}, which created a unique microclimate of alternating clean irrigated furrows and furrows with concentrated amounts of crop residue. ST and CT were more effective at removing crop residue from beds than MT. The higher levels of residue in MT led to higher soil moisture content at planting, but this system was challenged by poor seed and fertilizer placement due to soil compaction. The ST system irrigated well, had a good seedbed, and had better soil moisture at planting than CT.

In 2012, a very dry study year, soil moisture at planting was limited in CT and required an early irrigation to promote germination. However, the loose, dry soil conditions limited good water movement from furrows to beds and irrigation water did not advance to the ends of the furrows, even after 50-hr of irrigation. Crop residue at the soil surface for both conservation tillage approaches (MT and ST) resulted in adequate soil water at planting and more effective water movement when they were irrigated. In general, advance of irrigation water in furrows was faster for conservation tillage systems, showing that the system of moving crop residues out of irrigated furrows with modified row-cleaners successfully avoided the concern of residue impeding irrigation.

Few variations in nutrient, sediment, and water outflow were observed among the CT, MT, and ST tillage systems. The large differences of crop residue among tillage practices were observed in the non-irrigated furrows, while residue was similar in irrigated furrows.

28

Comparing the three tillage systems between both study years, ST displays the best option for producers under furrow irrigation in order to conserve soil moisture, provide suitable seed beds, limit irrigation dependence at planting, and ensure even irrigating of crops. The apprehension of producers in adopting a conservation tillage system should be subdued when presented with the ability of irrigating ST by properly managing crop residue. Also, by providing producers an alternative tillage system that is less dependent on irrigation during crucial plant growth stages in a region where water is becoming scarcer each year, ST will appear as a clear substitution for CT. Applying fertilizers by band injection is recommended to minimize loss of nutrients in irrigation runoff.

Table 1-1. Analysis of top 0-20 cm (0-8 in) of the soil at field site performed before planting in 2011 and 2012.

Measurement	2011	2012
pH	7.9	7.8
EC (dS/m)	1.0	0.7
Lime Estimate	Very High	Very High
OM (%)	1.8	1.1
NO_3-N	12.2	30.8
P	7.8	6.4
K	242.5	244.8
Zn	1.1	1.2
Fe	5.0	4.9
Mn	2.3	2.2
Cu	2.1	1.9
Texture (%)	52 Sand, 18 Silt, 30 Clay	

Table 1-2. List of field operations in each tillage system for the 2011 and 2012 seasons.

Conventional Till			Minimum Till			Strip Till		
Operation	2011	2012	Operation	2011	2012	Operation	2011	2012
Chop/Windrow	12/1/2010	11/29/2011	Chop/Windrow	12/1/2010	11/29/2011	Chop/Windrow	12/1/2010	11/29/2011
Bail Residue	12/1/2010	11/29/2011	Bail Residue	12/1/2010	11/29/2011	Bail Residue	12/1/2010	11/29/2011
Deep Rip	12/7/2010	-	Plant/Fertilize	5/4/2011	5/3/2012	Clean Furrows	-	3/14/2012
Disk	-	11/30/2011	Clean Furrows	5/9/2012	5/1/2012	Strip till	12/3/2010	3/16/2012
Plow	12/8/2010	3/5/2012	Apply Herbicide	-	5/10/2012	Plant/Fertilize	5/4/2011	5/3/2012
Harrow (2x)	3/3/2011	3/8/2012	Clean Furrows	-	6/11/2012	Apply Herbicide	5/16/2011	5/10/2012
Level (2x)	3/15/2011	3/14/2012	Apply Herbicide	5/16/2011	6/20/2012	Pack Furrows	-	6/4/2012
Ditch	4/2/2011	4/13/2012	Fertilize	6/23/2011	6/26/2012	Clean Furrows	-	6/11/2012
Cultipack	4/5/2011	-	Cultivate	6/27/2011	6/26/2012	Apply Herbicide	-	6/20/2012
Pack Beds	-	4/13/2012	Harvest	11/15/2011	11/1/2012	Fertilize	6/23/2011	6/26/2012
Plant/Fertilize	5/4/2011	5/3/2012				Cultivate	6/27/2011	6/26/2012
Pack Furrows	-	5/10/2012				Harvest	11/15/2011	11/1/2012
Apply Herbicide	5/16/2011	5/10/2012						
Pack Furrows	-	6/4/2012						
Apply Herbicide	-	6/20/2012						
Fertilize	6/23/2011	6/26/2012						
Cultivate	6/27/2011	6/26/2012						
Harvest	11/15/2011	11/1/2012						

Table 1-3. Differences in percent residue cover and residue mass among tillage system on crop beds and in irrigated and non-irrigated furrows during 2011 and 2012. Means followed by a different letter indicate significant differences among tillage practices for the same field position and year (α=0.10). Residue cover measurements were collected three weeks after planting for both years, on May 23, 2011, and May 22, 2012. Mass measurements were collected on June 14, 2011 and June 14, 2012.

	Residue Cover (%)								
	2011					2012			
	Bed	Non-Irrigated Furrow	Irrigated Furrow	Mean		Bed	Non-Irrigated Furrow	Irrigated Furrow	Mean
Conventional Till	15 a	31 a	31 a	26 a		10 a	14 a	11 a	12 a
Minimum Till	58 b	84 b	65 a	69 b		64 b	87 b	51 b	67 b
Strip Till	31 c	38 a	37 a	35 ab		28 ab	85 b	49 b	54 b
Average	35	51	44	**43**		34	62	37	**44**
	Residue Mass (Mg ha^{-1})								
Conventional Till	0.6 a	0.2 a	0.2 a	0.3 a		0.9 a	1.0 a	1.0 a	1.0 a
Minimum Till	3.7 b	10.3 b	1.5 a	5.2 b		5.5 b	40.2 b	9.4 a	18.4 b
Strip Till	0.7 ab	2.1 ab	2.1 a	1.6 ab		3.6 ab	17.8 c	5 a	8.8 b
Average	1.7	4.2	1.5	**2.4**		3.3	19.7	7.2	**9.4**

Table 1-4. Effect of tillage on key indicators of irrigation management during the 2011 and 2012 seasons in conventional till (CT), minimum till (MT), and strip till (ST). Advance time is the average of all irrigations events during the reported year (6 in 2011; 9 in 2012). Inflow, outflow, infiltration and sediment load data are sums of the values for all of the individual irrigations during the reported year.

Measurement	Year	CT	MT	ST
Date of 1st Irrigation	2011	July 1	July 1	July 1
	2012	May 16	May 16	June 4
Hours of 1st Irrigation.	2011	8	8	8
	2012	50	18	18
Avg. Inflow Rate (L s^{-1})†	2011	1.24	1.43	1.47
	2012	1.14	1.20	1.16
Total Inflow (mm)†	2011	1266	1432	1515
	2012	2592	1978	1919
Avg. Advance Time (min)	2011	1266	1432	1515
	2012	2592	1978	1919
Total Outflow (mm)	2011	453	675	676
	2012	683	781	648
Total Infiltration (mm)	2011	813	757	839
	2012	1909	1197	1271
Total Sediment Load (Mg/ha)	2011	5.4	6.0	3.4
	2012	6.4	4.6	3.6

† Inflow differences are due to irrigation ditch variability, not as a result of tillage systems.

Table 1-5. Effect of tillage and field location on penetration resistance (kPa) on May 9, 2012 for conventional till (CT), minimum till (MT), and strip till (ST) in the top 40 cm (15.5 in) of the soil profile. Colors of quadrants are in a color scale in order of least to most penetration resistance with dark green signifying least resistance and dark red signifying increasing resistance.

Plot	CT			MT			ST		
Position	Non. Irr. Furrow	Bed	Irr. Furrow	Non. Irr. Furrow	Bed	Irr. Furrow	Non. Irr. Furrow	Bed	Irr. Furrow
Depth (cm)									
0-2.5	389	295	**371**	787	462	**1477**	860	234	**1056**
2.5-5	898	839	1079	1667	1234	2035	1664	316	2237
5-7.5	1664	1588	1848	2421	2380	1907	2044	488	2626
7.5-10	1863	1769	1915	2453	2719	1813	2032	459	2342
10-12.5	1775	1760	1749	2310	2608	1795	1921	489	1857
12.5-15	1705	1708	1632	2196	2348	1775	1778	567	1717
15-17.5	1819	1468	1611	2012	2120	1790	1746	687	1661
17.5-20	1889	1333	1760	1992	1942	1813	1743	968	1635
20-22.5	1968	1237	2015	2053	1869	1857	1722	1246	1705
22.5-25	1895	1196	2334	2065	1763	1956	1699	1331	1737
25-27.5	2129	1687	2395	2202	1880	1953	1743	1474	1661
27.5-30	2205	1921	2368	2193	1988	2067	1848	1535	1746
30-32.5	2252	2155	2319	2252	2176	2006	1872	1705	1784
32.5-35	2126	2103	2354	2222	2342	2076	1845	1825	1822
35-37.5	1994	1912	2208	2243	2407	1997	1810	1857	1804
37.5-40	1857	1901	2053	2029	2559	2032	1799	1871	1731
Avg.	1777	1555	1876	2069	2050	1897	1758	1066	1820

Table 1-6. Effect of tillage on inflow rate from individual irrigation events during the 2011 and 2012 seasons in conventional till (CT), minimum till (MT), and strip till (ST). Reported values represent the mean of two replications of each tillage system for every irrigation.

Irrigation Date	Inflow Rate (L s^{-1})			Anova
	CT	MT	ST	P value
2011				
July 1	1.01	1.36	1.24	0.013
July 19	1.36	1.39	1.47	0.628
August 10	1.36	1.40	1.52	0.392
2012				
June 27	1.06	1.34	1.04	0.022
July 17	1.20	1.20	1.23	0.949
August 1	1.16	1.25	1.12	0.542
Irrigation				0.012
Tillage				0.033
Irr x Till				0.072

Table 1-7. Effect of tillage on advance time from individual irrigation events during the 2011 and 2012 seasons in conventional till (CT), minimum till (MT), and strip till (ST). Reported values represent the mean of two replications of each tillage system for every irrigation.

Irrigation Date	Advance Time, (min)			Anova
	CT	MT	ST	P value
2011				
July 1	57	57	151	<0.001
July 19	48	39	77	0.201
August 10	143	116	119	0.412
2012				
June 27	67	78	69	0.856
July 17	70	69	75	0.965
August 1	68	77	75	0.899
Irrigation				0.003
Tillage				0.160
Irr x Till				0.164

Table 1-8. Effect of tillage on outflow from individual irrigation events during the 2011 and 2012 seasons in conventional till (CT), minimum till (MT), and strip till (ST). Reported values represent the mean of two replications of each tillage system for every irrigation.

Runoff Date	Outflow, (mm)			Anova
	CT	MT	ST	*P* value
2011				
July 1	19	37	41	0.295
July 19	43	69	55	0.221
August 10	34	58	82	0.012
Average	32	55	59	0.019
2012				
June 27	24	45	19	0.173
July 17	36	43	43	0.843
August 1	42	36	41	0.909
Average	34	41	34	0.536
Year				0.014
Tillage				0.214
Year x Till				0.075

Table 1-9. Effect of tillage on infiltration from individual irrigation events during the 2011 and 2012 seasons in conventional till (CT), minimum till (MT), and strip till (ST). Reported values represent the mean of two replications of each tillage system for every irrigation.

Irrigation Date	Infiltration, (mm)			Anova
	CT	MT	ST	*P* value
2011				
July 1	40	43	32	0.801
July 19	78	54	75	0.286
August 10	86	65	52	0.123
Average	68	54	53	0.033
2012				
June 27	70	74	73	0.967
July 17	71	63	66	0.896
August 1	61	74	58	0.556
Average	67	70	66	0.961
Year				0.091
Tillage				0.468
Year x Till				0.390

Table 1-10. Flow weighted mean concentrations of soluble phosphorus, total phosphorus, total nitrogen, nitrate, and sediment for conventional till (CT), minimum till (MT), and strip till (ST) for three individual irrigation events in 2011 and in 2012.

		Average Concentration † (mg L^{-1})				ANOVA Results	
	Year	CT	MT	ST	Avg.		*P* value
Soluble P	2011	0.197	0.062	0.092	0.117	Tillage	0.625
	2012	0.187	0.316	0.085	0.196	Year	0.662
	Avg.	0.192	0.189	0.089	0.157	Till by year	0.124
Total P	2011	2.289	1.121	0.937	1.449	Tillage	0.040
	2012	1.627	2.200	1.840	1.889	Year	0.028
	Avg.	1.958	1.661	1.389	1.669	Till by year	0.042
Total N	2011	1.712	1.061	1.335	1.369	Tillage	0.913
	2012	1.565	3.184	2.221	2.323	Year	0.954
	Avg.	1.639	2.123	1.778	1.846	Till by year	0.826
Nitrate	2011	0.266	0.425	0.258	0.316	Tillage	0.023
	2012	0.113	1.048	0.463	0.541	Year	0.035
	Avg.	0.190	0.737	0.361	0.429	Till by year	0.248
Sediment	2011	1198	878	688	921	Tillage	0.302
	2012	703	1059	574	779	Year	0.440
	Avg.	951	969	631	850	Till by year	0.332

† Average concentration over all tillage systems for three irrigation events during 2011 and three irrigation events during 2012, weighted by depth of runoff for each irrigation.
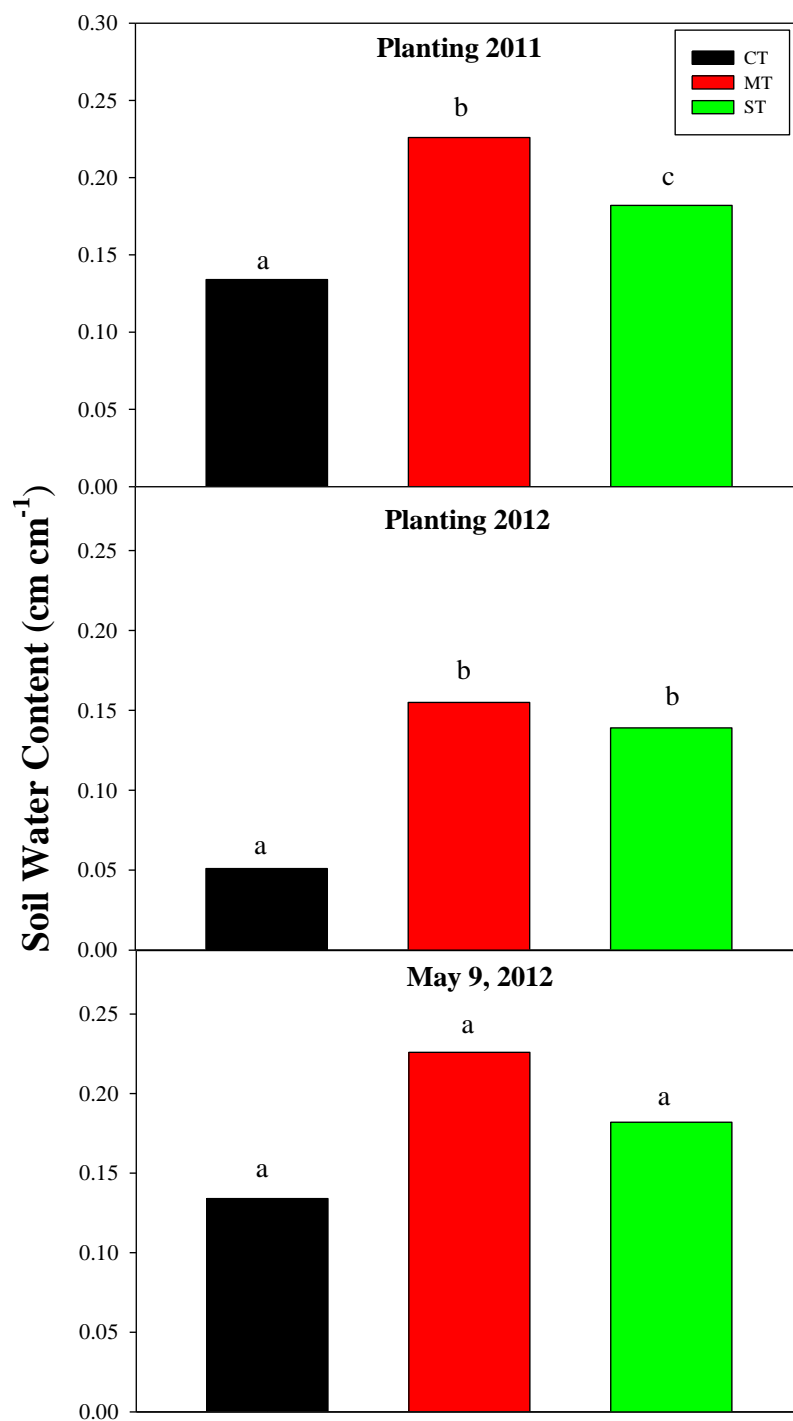
Figure 1-1. Average soil water content of top 15 cm (6 in) at planting in 2011 (top) and 2012 (middle), and May 9, 2012, the time of penetrometer readings (bottom). Tillage is compared within both years and bars with a different letter are significantly different (α=0.10).
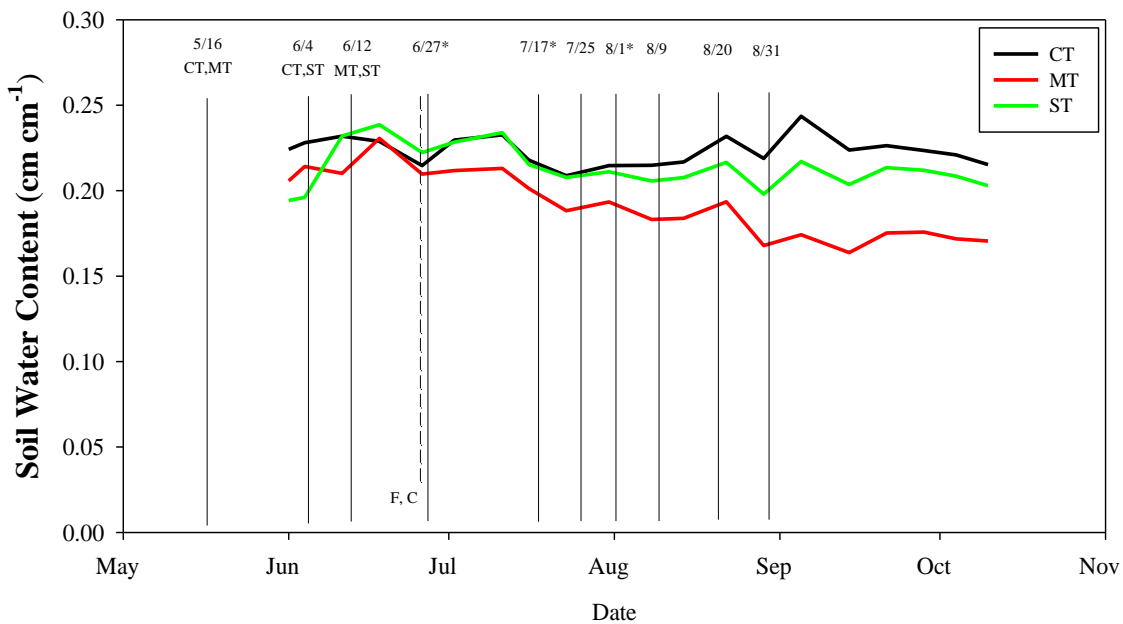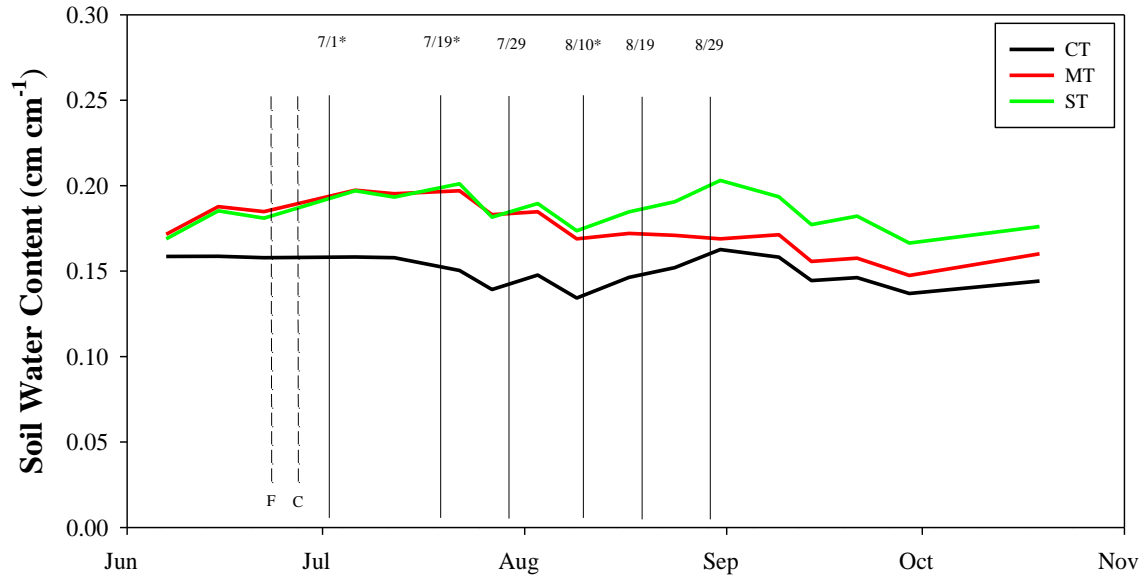
Figure 1-2. Average soil water content from neutron probe readings for the top 1.8 m (6 ft) of the soil profile during the 2011 (top) and 2012 (bottom) growing seasons, for conventional till (CT), minimum till (MT), and strip till (ST). Vertical lines with dates mark the irrigation events for each year. Dotted lines mark last field operations fertilization (F), and cultivation (C) before sample irrigations. * denotes the 1, 2, and 4 irrigations where runoff samples were collected.

41
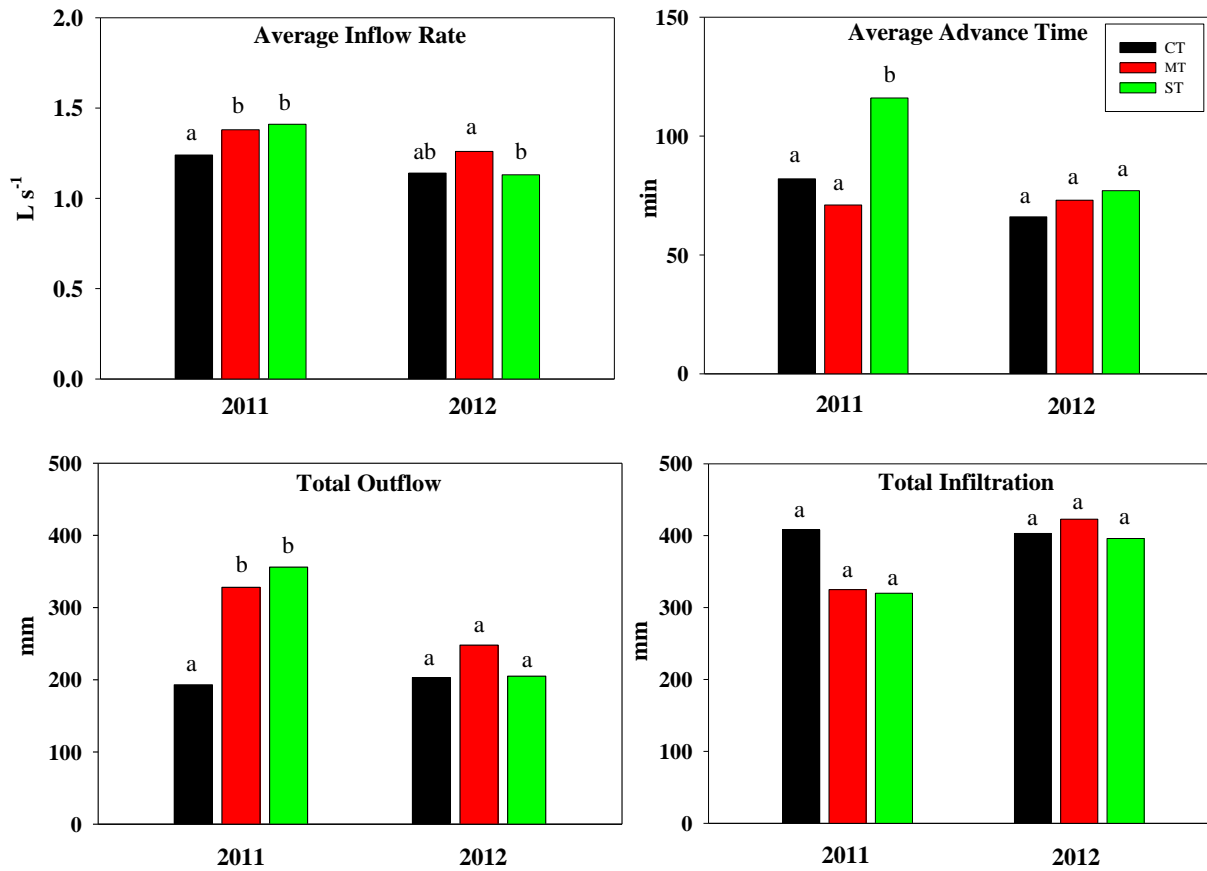
Figure 1-3. Average inflow rates and effect of tillage on advance time, and cumulative infiltration and outflow for three post- cultivation irrigations during 2011 and three post-cultivation irrigations in 2012. Tillage is compared within both seasons and bars with same letter are not significantly different (α=0.10).
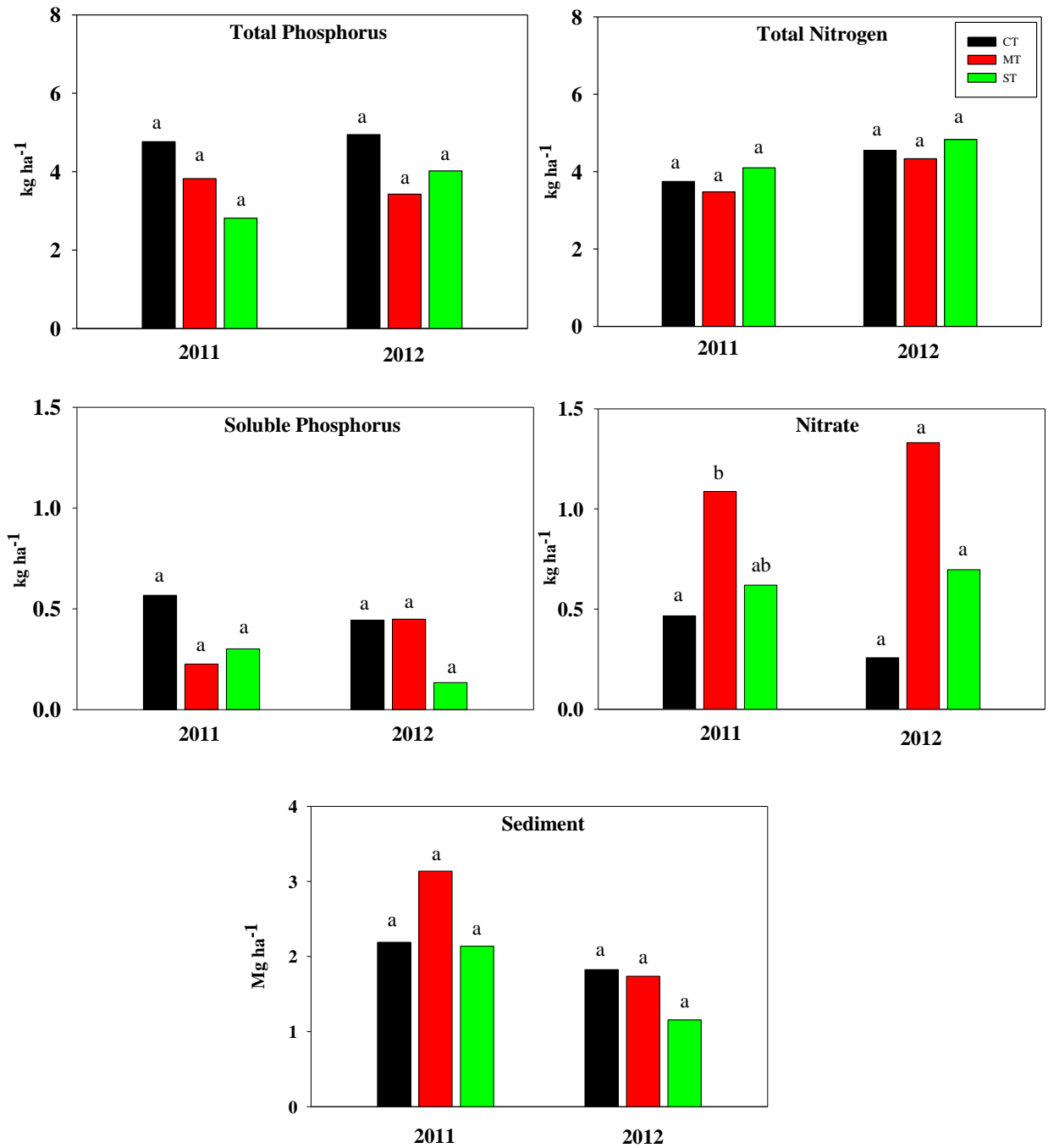
Figure 1-4. Effect of tillage on total load of four runoff nutrients and sediment for three post-cultivation irrigations during 2011 and three post-cultivation irrigations during 2012. Tillage is compared within both seasons and bars with same letter are not significantly different (α=0.10).

LITERATURE CITED

Ashraf, M., C.H. Pearson, D.G. Westfall, and R. Sharp. 1999. Effect of conservation tillage on crop yields, soil erosion, and soil properties under furrow irrigation in western Colorado. American Journal of Alternative Agriculture 14:85-92.

Benjamin, J.G., L.K. Porter, H.R. Duke, L.R. Ahuja, and G. Butters. 1998. Nitrogen movement with furrow irrigation method and fertilizer band placement. Soil Science Society of America Journal 62:1103-1108.

Bishop, A.A., W.R. Walker, N.L. Allen, and G.J. Poole. 1981. Furrow advance rates under surge flow systems. Journal of the Irrigation and Drainage Division- American Society of Agricultural Engineers 107:257-264.

Bjorneberg, D.L., D.T. Westermann, and J.K. Aase. 2002. Nutrient losses in surface irrigation runoff. Journal of Soil and Water Conservation 57:524-529.

Bjorneberg, D.L., D.T. Westermann, J.K. Aase, A.J. Clemmens, and T.S. Strelkoff. 2006. Sediment and phosphorus transport in irrigation furrows. Journal of Environmental Quality 35:786-794.

Bundy, L.G., T.W. Andraski, and J.M. Powell. 2001. Management practice effects on phosphorus losses in runoff in corn production systems. Journal of Environmental Quality 30:1822-1828.

Carter, D.L., and R.D. Berg. 1991. Crop sequenses and conservation tillage to control irrigation furrow erosion and increase farmer income. Journal of Soil and Water Conservation 46:139-142.

Carter, D.L., R.D. Berg, and B.J. Sanders. 1991 Producing no-till cereal or corn following alfalfa on furrow-irrigated land. Journal of Production Agriculture 4:174-179.

Ceplecha, Z.L., R.M. Waskom, T.A. Bauder, J.L. Sharkoff, R. Khosla. 2004. Vulnerability assessments of Colorado ground water to nitrate contamination. Journal of Water Air and Soil Pollution 159:373-394.

Chen, M., S.H. Daroub, and V. Nadal. 2006 Comparison of two digestion methods for determining total phosphorus in farm canal water. Communications in Soil Science and Plant Analysis 37:2351-2363.

Collins, L.W., S.J. Chalk, and H.M. Kingston. 1996 Atmospheric pressure microwave sample preparation procedure for the combined analysis of total phosphorus and Kjeldahl nitrogen. Analytical Chemistry 68:2610-2614.

Cook D.L., and H.L. Frum. 2004 Evaluation of total phosphorus and total nitrogen methods in pulp moll effluents. Water Science and Technology 50:79-86.

Davis, J.G., D.G. Westfall. 2009. Fertilizing Corn. Colorado State University Cooperative Extension Factsheet No. 0.538. Fort Collins, CO: Colorado State University

Evans R.G., W.B. Stevens, and W.M. Iversen. 2010 Development of strip tillage on sprinkler irrigated sugarbeet. Applied Engineering in Agriculture 26:59-69.

Fischbac, P., and H.R. Mulliner. 1974 Every other furrow irrigation of corn. Transactions of the American Society of Agricultural Engineers 17:426-428.

Gates, T.K., L.A. Garcia, A.H. Hemphill, E.D. Morway, and A. Elhaddad. 2006. Irrigation practices, water consumption, and return flows in Colorado's lower Arkansas River Valley. Colorado Water Institute Report 221. Fort Collins, CO: Colorado State University.

Gupta, S.C., W.E. Larson, and D.R. Linden. 1983. Tillage and surface residue effects on soil upper-boundary temperature. Soil Science Society of American Journal 47:1212-1248.

Halvorson, A.D., M.E. Bartolo, C.A. Reule, and A. Berrada. 2008. Nitrogen effects on onion yield under drip and furrow irrigation. Agronomy Journal 100:1062-1069.

Hansen, N.C., T.C. Daniel, A.N. Sharpley, and J.L. Lemunyon. 2002. The fate and transport of phosphorus in agricultural systems. Journal of Soil and Water Conservation 57:408-417.

Kaspar, T.C., D.C. Erbach, and R.M. Cruse. 1990. Corn response to seed-row residue removal. Soil Science Society of America Journal 54:1112-1117.

Klocke, N.L., D.G. Watts, J.P. Schneekloth, D.R. Davison, R.W. Todd, A.M. Parkhurst. 1999. Nitrate leaching in irrigated corn and soybean in a semi-arid climate. Transactions of the American Society of Agricultural Engineers 42:1621-1630.

Laflen, J.M., M. Amemiya, and E.A. Hintz. 1981. Measuring crop residue cover. Journal of Soil and Water Conservation 36:341-343.

Lal, R. 1995. The role of residues management in sustainable agricultural systems. Journal of Sustainable Agriculture 5:51-78.

Lehrsch, G.A., R.E. Sojka, and D.T. Westermann. 2001.Furrow irrigation and N management strategies to protect water quality. Communications in Soil Science and Plant Analysis 32:1029-1050.

Lentz, R.D., and G.A. Lehrsch. 2010. Nutrients in runoff from a rurrow-irrigated field after incorporating inorganic fertilizer or manure. Journal of Environmental Quality 39:1402-1415.

Licht M.A., and M. Al-Kaisi. 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil & Tillage Research 80:233-249.

Logan, T.J. 1982. Mechanisms for release of sediment-bound phosphate to water and the effects of agricultural land management on fluvial transport of particulate and dissolved phosphate. Hydrobiologia 91-92:519-530.

Merrill, S.D., J.M. Krupinsky, D.L.Tanaka, and R.L. Anderson. 2006. Soil coverage by residue as affected by ten crop species under no-till in the northern Great Plains. Journal of Soil and Water Conservation 61:7-13.

Nelson, D.J., and M.M. Al-Kaisi. 2011. Agronomic and economic evaluation of various furrow irrigation strategies for corn production under limited water supply. Journal of Soil and Water Conservation 66:114-121.

Nielsen, D.C., and M.F. Vigil. 2010. Precipiation storage efficiency during fallow in wheat-fallow systems. Agronomy Journal 102:537-543.

Rodriguez, J.B., J.R. Self, and P.N. Soltanpour. 1994. Optimal conditions for phosphorus analysis by the ascorbic-acid molybdenum blue method. Soil Science Society of America Journal 58:866-870.

Sharpley, A.N., S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman. 1992. The transport of bioavailable phosphorus in agricultural runoff. Journal of Environmental Quality 21:30-35.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters- issues and options. Journal of Environmental Quality 23:437-451.

Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. Journal of Soil and Water Conservation 51:160-166.

Shelton, D.P., E.C. Dickey, S.D. Kachman, and K.T. Fairbanks. 1995. Corn residue cover on the soil surface after planting for various tillage and planting systems. Journal of Soil and Water Conservation 50:399-404.

Sojka, R.E., D.L. Carter, and M.J. Brown. 1992. Imhoff cone determination of sediment in irrigation runoff. Soil Science Society of America Journal 56:884-890.

Soltanpour, P.N., and S.M. Workman. 1981. Soil-testing methods used at Colorado State University soil testing laboratory for the evaluation of fertility, salinity, and sodicity and trace-element toxicity. Colorado State University Experiement Station Technical Bulletin 142:1-22.

Tabatabaeekoloor, R. 2011. Soil characteristics at the in-row and inter-row zones after strip-tillage. African Journal of Agricultural Research 6:6598-6603.

Tanaka, D.L., and R.L. Anderson. 1997. Soil water storage and precipitation storage efficiency of conservation tillage systems. Journal of Soil and Water Conservation 52:363-367.

Trout, T.J. 1996. Furrow irrigation erosion and sedimentation: On-field distribution. Transactions of the American Society of Agricultural Engineers 39:1717-1723.

Trout, T.J., and B.E. Mackey. 1988. Furrow flow measurement accuracy. Journal of Irrigation and Drainage Engineering- American Society of Agricultural Engineers 114:244-255.

USDA. 2008. Farm and Ranch Irrigation Survey. Land Irrigated with Gravity Irrigation by Field Water Delievery System. Washington, DC: USDA. http://www.agcencus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.php.

Westermann, D.T., D.L. Bjorneberg, J.K. Aase, and C.W. Robbins. 2001. Phosphorus losses in furrow irrigation runoff. Journal of Environmental Quality 30:1009-1015.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. 2013. Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/.

Wolf, R.E., and Z.A. Grosser. 1997. Overview and comparison of ICP-MS methods for environmental analyses. Atomic Spectroscopy 18:145-151.

Yoder, R.E., and H.R. Duke. 1990. Non-darcy flow and drainage from irrigated furrows. Transactions of the American Society of Agricultural Engineers 33:1487-1491.

Yonts, C.D., J.A. Smith, and J.E. Bailie. 1991. Furrow irrigation performance in reduced-tillage systems. Transactions of the American Society of Agricultural Engineers 34:91-96.

Zeimen, M.B. 2007. Combining management practices to reduce sediment, nutrients, and herbicides in runoff. Journal of Soil and Water Conservation 62:6A-6A.

CHAPTER 2: Dissipation of Pyroxasulfone, Atrazine, and

s-Metolachlor Under Conservation Tillage

INTRODUCTION

The efficacy and environmental fate of agricultural herbicides are affected by chemical movement and persistence in the soil. Herbicide movement and persistence are influenced by both chemical and soil properties and also by management practices that influence environmental conditions (Fawcett et al. 1994). As new herbicides are developed, information is needed about their behavior under a wide set of environmental and management scenarios.

Atrazine and *s*-metolachlor are heavily used herbicides in the United States for pre-emergent weed control in corn fields (Whaley et al. 2009). Several facts justify a need to develop herbicide alternatives for these chemicals. Many weeds that have been controlled by atrazine have developed resistance to it (Nurse et al. 2011; Woodyard et al. 2009). Further, repeated use of atrazine in some soils has resulted in enhanced degradation of atrazine by soil organisms, which greatly reduces the time for effective weed control (Levanon et al. 1994; Shaner et al. 2009). Atrazine and *s*-metolachlor are two of the most commonly found herbicides in surface waters (Battaglin et al. 2003), and detection of these two herbicides in groundwater is a concern in many areas of the country. *S*-metolachlor has a relatively high risk of movement to groundwater because it is highly water soluble and only moderately sorbed to soil particles (Boyd 2000). Pyroxasulfone (KIH-485) is a new herbicide recently developed by Kumiai Chemical Industry (White Plains, NY) that is a potential alternative for traditionally used herbicides for corn (Sikkerna et al. 2008). It has comparable control of broadleaf and grasses with an application rate one-eighth that of *s*-metolachlor (Westra 2012; Penn State 2013) and

one-third that of atrazine (Nurse et al. 2011). Pyroxasulfone has a similar mode of action to that of s-metolachlor in that it inhibits very long chain fatty acid synthesis (Tanetani et al. 2009). However, pyroxasulfone's mode of action if differs from Atrazine, which controls weeds by the inhibiting photosynthesis as a result of disrupting electron transport in photosystem II (Hess 2000). Because it can be effective at very low rates, the environmental risk of pyroxasulfone is inherently lower than for atrazine or s-metolachlor. Pyroxasulfone has low water solubility and some reports show a low degree of sorption to the soil (Westra 2012). More information about the behavior of pyroxasulfone in agricultural environments is needed.

Efforts to promote best management practices (BMPs) have been made in the past few decades to try to minimize the amount of nutrient and herbicide contamination to receiving waters, including the adoption of reduce tillage systems (Mickelson et al. 2001). Studies evaluating herbicide loss in surface runoff from different tillage practices have had mixed results. Some studies show greater concentrations and greater losses of herbicides in runoff from conservation tillage systems than from conventional tillage approaches due to greater runoff volumes, greater herbicide concentrations, or both (Baker et al. 1978; Gaynor et al. 1995; Isensee and Sadeghi 1993). In other studies, herbicide losses are reduced for conservation tillage practices due to a reduced runoff volume and sediment loss (Felsot et al. 1990; Hall et al. 1991). Also, with reduced tillage systems, infiltration is usually increased, which raises the concern of leaching more herbicides below the root zone than in conventional tillage systems (Isensee et al. 1990). Herbicide efficacy is another concern for reduced tillage systems because in some cases crop residues intercept and bind applied herbicides. There has been little research done on the effect of residue on the dissipation of pyroxasulfone compared to atrazine and s-metolachlor in furrow irrigated systems.

The objectives of this study were 1) to compare sorption of pyroxasulfone to that of atrazine and *s*-metolachlor for an alkaline, loam soil, and 2) to evaluate and compare the persistence and movement of pyroxasulfone, atrazine, and *s*-metolachlor under conventional (CT), minimum (MT), and strip (ST) tillage systems. A field study was conducted under furrow irrigation for two crop growing seasons.

MATERIALS AND METHODS

Field Site

A 5.7 ha field site for this two year study (2011 and 2012) was established in Larimer County, Colorado, at Colorado State University's Agricultural Research, Development and Education Center, (40°67' N, 104°99' W) at 1535 km elevation,19 km north east of Fort Collins, Colorado. The soil type was a Garrett loam (fine-loamy, mixed, mesic Pachic Argiustolls) with 1.1% organic matter, pH of 7.8, and sand, silt, and clay percentages of 52, 18, and 30, respectively.

Three tillage systems, conventional till (CT), minimum till (MT), and strip till (ST) were replicated twice on large, production scale plots that consisted of 36 rows for a total of 72 rows of corn in each system. Corn rows were spaced 76 cm apart, and were 320 m long. The design for this experiment was a randomized block. Corn seed for both 2011 and 2012 growing seasons was acquired from Fontanelle Hybrids, and was 94 day Genuity® SmartStax® RIB Complete™ 4A098 RBC Brand.

Herbicide Application

Atrazine and *s*-metolachlor were applied simultaneously to the entire field at rates of 0.74 kg ai ha^{-1} and 1.7 kg ai ha^{-1}, respectfully. To broadcast apply atrazine and *s*-metolachlor, a

sprayer covering 12 rows (9 m) was used. Pyroxasulfone was applied at a rate of 0.28 kg ai ha^{-1}

on two sub-plots of four rows, (3 m) by 15.25 m. These sub-plots were 60 m from the end of the

field in 2011, and 90 m in 2012 (Figure 2-1). A CO_2 backpack sprayer with six equally spaced

tee-jet 8002 sprayer nozzles that covered the 3 m subsections was used to apply pyroxasulfone.

Atrazine and *s*-metolachlor were applied to the entire field to provide needed weed control,

whereas pyroxasulfone was only applied to sub-plots to provide small, controlled study areas.

Herbicide applications in 2011 occurred on May 16, 2011, 12 days after planting. In 2012,

herbicides were applied seven days after planting, on May 10, 2012. Applications of all three

herbicides were done both years on the same day as to provide consistent sampling.

Soil Sampling

For all three herbicides, soil samples were collected within the pyroxasulfone treated sub-

plots using a handheld sampler inserted with 30 cm long, zero-contamination plastic tubes with a

2.5 cm diameter. All sampling was done on the top of corn beds, and only taken from the center

two rows as to provide two buffer rows to decrease the chance for edge effect or drift. Samples

were taken at 1, 7, 16, 28, and 60 days after treatment (DAT) in 2011, and 1, 8, 15, 28, and 60

DAT in 2012. Three 30 cm samples were taken in each sub-plot on each sample day, which

resulted in six soil cores from each plot. Those samples were placed in a freezer at -20°C as soon

as possible after collection. Several weeks after collection, the six soil cores from each plot were

thawed for approximately one hour, and separated into 0-7.5 cm, 7.5-15 cm, 15-22.5 cm and

22.5-30 cm depths and aggregated by depth for each main plot which resulted in one sample per

depth for each day. After mixing, the samples were placed into plastic bags and put back into the

freezer until they were extracted and analyzed by gas chromatography-mass spectrometry

(GC/MS).

Sorption Coefficients

Sorption coefficient (Kd) values for pyroxasulfone, atrazine, and *s*-metolachlor were determined with soil from the field site. A stock solution with all three herbicides was prepared by combining 1 mg mL^{-1} of each herbicide with a 0.02M CaCl$_2$ solution. Batch equilibrium studies were conducted by adding 10 g of soil gathered from the field site with 10 mL of the stock solution in 50 mL glass centrifuge tubes. These tubes were shaken on an automated shaker for two hours. Control herbicide solutions that did not contain soil were also analyzed. The tubes were centrifuged at 1000 rpm for 10 minutes and 3.0 mL of the supernatant was added to 3.0 mL of toluene in a volumetric flask. We then spiked the solution in the flask with 500 ng L^{-1} butylate as an internal standard, after which we injected the samples in a GC/MS column in order to determine herbicide concentrations in the solution. The concentrations of pyroxasulfone, atrazine, and *s*-metolachlor in the solution were subtracted from the initial concentrations of the samples without soil to determine how much of each herbicide bound to the soil. Ratios of herbicides bound to the soil were calculated by dividing the concentration of bound herbicide by the concentration in the soil solution as shown in the following equation:

$$\text{Kd} = [\text{herbicide sorbed to soil (mg kg}^{-1})] / [\text{herbicide in solution (mg L}^{-1})] \qquad (1)$$

This procedure was performed twice, with three replications each time. A mean Kd for each herbicide was calculated by averaging the ratios of both runs and the three replications.

Soil Analysis

Analysis for pyroxasulfone, atrazine, and *s*-metolachlor residues in soil from the field experiment was performed on GC/MS (Shimadzu GC/MS-QP2012, Shimadzu Scientific Instruments, Inc., Columbia, MD). Standard curve concentrations of 2.0, 1.0, 0.75, 0.50, 0.25,

and 0.01 µg/mL were determined, with a detection limit of 0.005 µg/mL. Butylate served as an internal standard.

Depth aggregated soil samples were thawed for approximately one hour, mixed, and a10 g subsample placed into a 50 mL glass centrifuge tube. A 10.0 mL aliquot of deionized water and 5 mL of water saturated toluene were added to the tube with the soil, which was capped with a teflon-lined lid and shaken for 2 hours on an automated shaker. After shaking, the tubes were centrifuged for 20 minutes at approximately 900 rpm. A 2 mL aliquot of the supernatant was sampled and spiked with the 0.025 mg/mL butylate internal standard stock solution in a 2.5 mL volumetric flask. The flask was inverted to ensure proper mixture of the butylate and toluene supernatant. The contents were then poured into a GC vile, capped, and analyzed on the GC/MS. A column, DB-5 30 m by 0.25 mm (Restek, Bellefonte, PA) with a helium flow of 1 mL/min, was used in the GC/MS. Injector temperature was 200°C, interface at 260°C, and ion source at 200°C. Start temperature of the GC/MS was 100°C, was increased 10°C per minute until reached it 250°C, and then held constant at 250°C for two minutes. A separate 2.0 g subsample of soil was dried at 105°C do determine moisture content.

Bulk density was determined by taking soil samples with a bulk density soil sampler (Madera Probe, Precision Machine Company, Lincoln, NE, USA), which takes a fixed volume sample (3.5 by 6.3 cm) of undisturbed soil. Samples were weighed, dried and an average bulk density value for the field was determined. Herbicide concentrations in soil were calculated using measured values for GC/MS, bulk density, and a correction for moisture content.

Herbicide concentration data was analyzed by analysis of variance (ANOVA) using SAS (Version 9.2) to determine tillage system effects for each depth and sampling date. The PROC Mixed model was used, which included tillage, DAT, and year as fixed effects, with block as a random effect. All concentrations were transformed using a log of base 10 to stabilize variances and provide optimal normality. Concentrations were reported in original units for table and figure presentations. Sorption coefficients were analyzed by the PROC GLM model in SAS with tillage and replication being fixed effects. Statistical significance was considered at $\alpha = 0.10$ for all analyses.

RESULTS AND DISCUSSION

Sorption Coefficients

Sorption coefficients (K_d) were determined with a batch equilibrium approach for atrazine, *s*-metolachlor, and pyroxasulfone with the soil from the field site. The K_d is a ratio of the concentration of the herbicide sorbed by the soil to the concentration of that herbicide in soil solution (Weber et al. 2004). Herbicides with greater K_d values usually have to be applied at higher rates than those with low K_d values in order to provide comparable weed control and are less mobile in the soil. The K_d values of the herbicides evaluated indicate low to moderate sorption and ranked in the order of *s*-metolachlor (0.96 L kg^{-1}) > pyroxasulfone (0.56 L kg^{-1}) > (0.45 L kg^{-1}) atrazine (Table 2-1). The K_d values observed for atrazine and *s*-metolachlor are similar to those found in another study done on a similar Colorado soil, where values were 0.61 L kg^{-1} and 1.02 L kg^{-1}, respectively (Bridges et al. 2008). The K_d value for pyroxasulfone in this study is comparable to a value of 0.55 L kg^{-1} reported for a sandy loam soil in Colorado (Westra

54

2012). The ranking of K_d value of these herbicides is different than the ranking of water solubility, which follows the order *s*-metolachlor (530 mg L^{-1}) > atrazine (30 mg L^{-1}) > pyroxasulfone (3.49 mg L^{-1}). The K_d results do not explain why labeled application rates for pyroxasulfone are much lower than rates for atrazine.

Precipitation and Irrigations

During the 2011 study year, a total of 14.2 cm of precipitation was received at the field site during the 60 day sample collection period (Table 2-2). There was only one irrigation event during the 60 day sample collection period, which occurred 46 DAT and all tillage systems were irrigated for the same duration. The 2012 study year was much drier with only 3.1 cm of precipitation during the 60 day sample period (Table 2-2). In 2012, each tillage system was irrigated three times before DAT 60.

Herbicide Concentrations

Atrazine

Atrazine was found in the soil almost entirely in the 0-7.5 cm depth for both 2011 and 2012 (Table 2-3). The concentration of atrazine in the surface depth at 1 DAT of 2011 ranged from 0.31 to 0.51 kg ha^{-1}, which compared with a target application rate of 0.74 kg ha^{-1} (Figure 2-2). Some of the applied herbicide was likely intercepted by crop residues and had not yet moved into the soil. Other work has confirmed that applied atrazine has a propensity to adsorb to crop residue (Isensee and Sadeghi 1993; Selim et al. 2012). Tillage had some effect on the concentration of atrazine with depth and time. There were no differences in atrazine concentration for 1, 7, and 16 DAT among tillage systems for the 0-7.5 cm depth. At 28 DAT, the concentration of atrazine in the 0-7.5 cm depth was lower for CT (0.13 kg ha^{-1}), than MT

55

(0.42 kg ha^{-1}), indicating that tillage system affected herbicide dissipation, which is likely related to the effect of a higher amount of crop residue slowing degradation for MT and ST (Table 2-4). In the 7.5-15 cm depth, tillage affected atrazine concentration at DAT 7 (P=0.001), 16 (P=0.002), 28 (P=0.018), and 60 (P=<0.001). While concentrations of atrazine were low for all tillage systems at the deeper soil depths, the concentrations were higher for MT and ST than for CT. There was a rainfall event of 4.0 cm between DAT 1 and 7 that appears to have pushed more atrazine into the second depth for the reduced tillage systems. A study in Maryland, USA, showed that a similar event of 4.8 cm of rain caused substantial leaching of atrazine in CT and reduced tillage systems (Isensee et al. 1990). In this study, less downward movement of atrazine in CT may have been related to crusting at the soil surface while residues in the reduced tillage system allowed for greater infiltration and herbicide movement. Studies have shown that herbicides intercepted by residue can be washed off easily into the soil with small precipitation events (Baker and Mickelson 1994). This would explain why there was significantly less atrazine in the soil at DAT 1 than was applied, but supports the result of atrazine being pushed through the soil profile after a rainfall event. There were no tillage effects on atrazine concentrations at the 22.5 to 30 cm depth.

Observations of atrazine concentrations in the soil were similar in 2012, with concentration at 1 DAT ranging from 0.36 kg ha^{-1} to 0.62 kg ha^{-1} (Figure 2-3). As in 2011, the majority of the atrazine was detected in the 0-7.5 cm depth. The low amounts of rain in 2012 (Table 2-2) resulted in even lower detected concentrations at the deeper depths than in 2011. Tillage had a less pronounced effect on atrazine concentration in 2012. In the 0-7.5 cm depth on 28 DAT, CT (0.10 kg ha^{-1}) and ST (0.15 kg ha^{-1}) had lower concentrations than MT (0.046 kg ha^{-1}), which again was probably related to higher residue mass in MT.

s-Metolachlor

Concentrations of *s*-metolachlor during 2011 at DAT 1 ranged from 1.1 kg ha^{-1} to 1.6 kg ha^{-1} (Figure 2-2), compared to a target application rate of 1.7 kg ha^{-1}. There was no tillage effect on *s*-metolachlor concentrations for any of the five sample days in the 0-7.5 depth during 2011, where more than 90% of the extracted herbicide from the soil was found (Table 2-4). In the 7.5 to 15 cm depth at DAT 7, the concentration of *s*-metolachlor was highest in MT (0.15 kg ha^{-1}), and significantly lower in CT (0.014 kg ha^{-1}) and ST (0.019 kg ha^{-1}). This result correlates with the observation in atrazine for the same depth and year, where more herbicide leached into the second depth of MT than CT after a rain fall event. For the remaining combinations of sample day and depth, the reduced tillage systems had greater concentrations of *s*-metolachlor than CT, but all concentrations were very low. As discussed for atrazine, we attribute the greater downward movement of *s*-metolachlor to higher amounts of residue leading to more infiltration. Another possible reason there was more herbicidal movement in MT is the likely presence of macropores in that tillage system. In reduced tillage systems, macropores can be present due to previous years' crop roots and earth worm activity. Herbicides applied to soil where macropores are present from decaying roots and/or worm movement can be pushed through the soil profile after an irrigation or precipitation event (Shipitalo et al. 1990; Beven and Germann 1982).

Concentrations of *s*-metolachlor during 2012 ranged from 1.1 kg ha^{-1} to 2.0 kg ha^{-1} (Figure 2-3). As in 2011, tillage did not affect *s*-metolachlor concentrations at the 0-7.5 cm depth throughout the sample period, with 90% or more of the extracted herbicide coming from this depth. However, unlike 2011, in 2012 there was a higher concentration of *s*-metolachlor at the 15-22.5 cm depth in CT (0.032 kg ha^{-1}) than MT (0.013 kg ha^{-1}), with ST having a similar concentration to both (0.021 kg ha^{-1}). Since CT had less residue than MT, and likely less

microbial activity, we expected *s*-metolachlor to leach further in CT than MT during a drier year. It has been shown that the greatest degradation of *s*-metolachlor comes from microbial breakdown (Staddon et al. 2001). Therefore, with more residue in MT than CT, greater microbial activity would degrade *s*-metolachlor quicker in MT than in CT, and decrease leaching in MT.

Pyroxasulfone

As with atrazine and *s*-metolachlor, the majority of pyroxasulfone extracted from the soil came from the top 0-7.5 cm depth (Table 2-4). Our results are comparable to other studies in that the majority of all extracted herbicides from the soil were from the 0-7.5 cm depth (Sadeghi et al. 1998).

There was no tillage effect on pyroxasulfone concentrations for any of the sample days in the 0-7.5 depth during 2011 (Figure 2-2), with concentrations at DAT 1 ranging from 0.12 kg ha^{-1} to 0.16 kg ha^{-1}, relative to an application rate of 0.28 kg ha^{-1}. In the 7.5 to 15 cm depth, tillage affected pyroxasulfone concentrations for all sample times; 1 (P=0.008), 7 (P=<0.001), 16 (P=0.004), 28 (P=0.082), and 60 (P=0.025). Concentrations of pyroxasulfone were greater in MT and ST than in CT for all sample times, except at DAT 7 where only MT (0.033 kg ha^{-1}) had a higher concentration than CT (0.008 kg ha^{-1}). This result is the same as observations for atrazine and *s*-metolachlor, where MT had the greatest herbicide concentrations for depths below 7.5 cm. This finding allows us to conclude that with a rainfall event of at least 4 cm, atrazine, *s*-metolachlor, and pyroxasulfone will leach more into the 7.5-15 cm depth in MT than in CT or ST. There are no available studies in the literature with which to compare these results of pyroxasulfone in reduced tillage systems. However, when comparing the concentration of pyroxasulfone in the 0-7.5 cm depth at DAT 60, it is significantly higher in relation to the

concentration at DAT 1 than was observed for atrazine or *s*-metolachlor. This validates claims that pyroxasulfone will persist in the soil longer than traditionally used herbicides, and provide lasting weed control throughout the growing season (Mueller and Steckel 2011; Sikkerna et al. 2008). In the remaining two depths, pyroxasulfone concentrations were extremely low, but the reduced tillage systems had higher concentrations than CT.

Pyroxasulfone concentrations at DAT 1 in 2012 varied more than in 2011, with a range of 0.10 kg ha^{-1} to 0.23 kg ha^{-1}. Unlike the 2011 season, tillage affected the concentration of pyroxasulfone in the 0-7.5 cm depth. At DAT 8, CT (0.22 kg ha^{-1}) had a higher concentration than MT (0.09 kg ha^{-1}) and ST (0.14 kg ha^{-1}) (Figure 2-3). Also in this top depth, at DAT 28 ST (0.17 kg ha^{-1}) had a greater pyroxasulfone concentration than MT (0.06 kg ha^{-1}), and CT (0.10 kg ha^{-1}) was similar to both. In the remaining depths tillage only affected pyroxasulfone concentrations at DAT 8 in the 15 to 22.5 cm depth, where pyroxasulfone concentrations ranked in the order of ST (0.027 kg ha^{-1}) > CT (0.007 kg ha^{-1}) > MT (0.004 kg ha^{-1}). This is the only herbicide and year where ST had a higher concentration than MT at a depth other than 0-7.5 cm. Nevertheless, the same trend of pyroxasulfone persisting in the top layer of the soil profile longer than atrazine and *s*-metolachlor is followed in 2012. For both study years, pyroxasulfone persisted in the soil longer than the other two herbicides in CT, MT and ST.

Herbicide Dissipation and Half Life

Herbicide concentrations were averaged between two replications, and summed over all four sample depths from the 2011 and 2012 seasons and analyzed in SigmaPlot (Systat Software, San Jose, CA) to determine herbicide half life for each tillage system and year. A two parameter

regression of an exponential decay curve which used the following function provided the best fit for each herbicide:

$$f = a * \exp^{(-b * x)} \tag{2}$$

Where f = herbicide concentration (kg/ha), a = herbicide concentration at time zero (kg/ha), b = herbicide first-order rate constant (days), and x = time (DAT).

Half life (DT_{50}) values for all three herbicides were then calculated using the following equation:

$$DT_{50} = \ln 2 / b \tag{3}$$

Where b is the first- order rate constant (days) which was given in SigmaPlot upon selecting the regression for dissipation, and DT_{50} is the time in days needed for dissipation of half of a given herbicide (Krutz et al. 2007).

For the 2011 season, the DT_{50} of atrazine in CT was calculated to be 23.8 days. This was the shortest DT_{50} for atrazine among tillage systems in 2011 with DT_{50} values for MT and ST being 34.3 and 32.4 days, respectively (Figure 2-4). The observed DT_{50} values are shorter than published DT_{50} values of atrazine, which are as high as 60 days (Wackett et al. 2002). The DT_{50} of s-metolachlor in CT during 2011 was 18.8 days. MT had the next shortest DT_{50} for s-metolachlor of 27 days, followed by ST with a DT_{50} of 28 days. Wauchope et al. (1992) reported a DT_{50} of s-metolachlor of 56 days, again showing DT_{50}s from this study being shorter than reported values. DT_{50} of pyroxasulfone in CT was 89 days during 2011. In MT, pyroxasulfone dissipated slower than CT with the DT_{50} being 98 days. The DT_{50} was even longer for ST, but was not quantifiable with data collected for 60 days after herbicide application. Thus,

pyroxasulfone has much longer persistence in the soil than either atrazine or *s*-metolachlor. This property can provide an advantage of extended weed control period, but could also pose some management challenges for rotations with sensitive crops. The tillage systems in this study clearly influenced dissipation of all three herbicides. Research from a separate study showed that corn residue on the soil surface can significantly increase atrazine degradation (Moorman et al. 2001), but observations from the first year of this study suggest that residue decreases degradation of atrazine, *s*-metolachlor, and pyroxasulfone.

During 2012, atrazine had a DT_{50} of 17 days in CT, which was one week shorter than the DT_{50} of atrazine in 2011. Perhaps the most dramatic observation of the study was that the two conservation tillage systems had much shorter DT_{50} values for atrazine than in 2011, with MT having a DT_{50} of only 4.9 days and ST having a DT_{50} of 13 days (Figure 2-5). Large changes in the persistence of atrazine in the soil over multiple years has been reported by Bridges et al. (2008), who showed that soil never before exposed to atrazine had DT_{50} values ranging from 45 to 102 days, compared to soils that had been previously applied with atrazine had DT_{50} values ranging from 5 to 20 days. Others have reported enhanced degradation of atrazine when it was applied to soil that had a previously application history of atrazine, with reported DT_{50} values as short as 1 and 2 days (Shaner and Henry 2007) and 1.8 and 3.2 days (Bridges et al. 2008). The enhanced degradation was most pronounced in this study for MT. It is possible that limiting soil disturbance accelerated the biological processes that promote enhanced degradation (Levanon et al. 1994; Shaner et al. 2009) in the reduced tillage systems. Another possibility, as suggested by Moorman et al. (2001), is that reduced tillage increased atrazine degradation due to microbial metabolism associated with higher residue on the soil surface.

S-metolachlor had a DT_{50} of 21 days in CT during 2012 but was only 2.1 days in MT. As observed for atrazine, the DT_{50} of *s*-metolachlor was much lower in 2012 than in 2011 for MT. The DT_{50} in ST was 44 days, which was longer than in 2011. A study done on a Colorado soil found that *s*-metolachlor degradation was not enhanced by multiple years of exposure (Shaner and Henry 2007). However Moorman et al. (2001) reported that corn residue may also increase degradation of *s*-metolachlor, as previously discussed concerning atrazine. The increased degradation of *s*-metolachlor in MT during 2012 compared to 2011 may have been a result of significantly more crop residue mass on the soil surface in 2012 than in 2011 (Table 2-1). The breakdown of *s*-metolachlor has been shown to be attributed mostly to soil microbial activity (Staddon et al. 2001). Therefore, with the second year of our study having higher residue on the soil surface than in 2011, greater microbial activity may partially explain the shorter DT_{50} in 2012 because of the greater soil moisture provided by residue cover.

The only tillage system where the DT_{50} of pyroxasulfone was quantifiable within the 60-day study period in 2012 was CT, having a DT_{50} of 67 days. This DT_{50} was shorter than that of CT in 2011, but still demonstrates the ability of pyroxasulfone to persist in the soil considerably longer than atrazine and *s*-metolachlor. The model in SigmaPlot was unable to converge the data of ST in 2011 and 2012 and MT in 2012 due to long persistence of pyroxasulfone in those tillage systems. During the selection of decay curves of those respective data sets, there was no curve that provided an adequate fit with which to determine DT_{50}. The result of a shorter DT_{50} in CT during 2012, a drier year than 2011, differs from results from a Tennessee study done on the dissipation of pyroxasulfone (Mueller and Steckel 2011) where the DT_{50} was longer during a drier year versus a wetter year. A difference between the two studies is the soil texture, with the soil in Tennessee having much more clay than the soil in this study. Consistent among this study

and the study in Tennessee is longer persistence of pyroxasulfone than for *s*-metolachlor. The DT$_{50}$ of pyroxasulfone in MT was shorter in 2012 than in 2011, but both years show that there was minimal dissipation. Mueller and Steckel (2011) also report not being able to determine a DT$_{50}$ value for pyroxasulfone, as a result of a fairly linear and minimal dissipation for pyroxasulfone. The longer persistence of pyroxasulfone than atrazine or *s*-metolachlor increases its ability to provide control of weeds throughout the growing season. Future research will be needed to discover how pyroxasulfone will persist in the soil longer than the 60 days we monitored.

CONCLUSIONS

In this field study analyzing the dissipation and movement of atrazine, *s*-metolachlor, and pyroxasulfone, residue on the soil surface had a larger effect than tillage. Pyroxasulfone had a lower sorption coefficient than *s*-metolachlor, but a slightly higher one than atrazine, meaning that pyroxasulfone adsorbs to the soil less than *s*-metolachlor and more than atrazine. However, all three herbicides had low to moderate soil adsorption. Concentrations of all three herbicides extracted from the soil were found mostly in the 0-7.5 cm depth in all tillage systems. Atrazine, *s*-metolachlor, and pyroxasulfone leached into the 7.5-15 cm depth more in 2011 than in 2012 due to more precipitation during the 2011 season. Residue on the soil surface did not decrease the concentration of any of the herbicides, and our results show that herbicides intercepted by residue can be washed off and into the soil by precipitation.

Dissipation of atrazine and pyroxasulfone occurred more rapidly in CT during 2012, which was a drier year than 2011. Half life of atrazine was significantly less in 2012 than 2011 in the conservation tillage systems. This could be a result of rapid degradation caused by repeated

application of atrazine to the same, undisturbed soil and more soil microbial activity due to more residue mass in MT and ST than in CT. *s*-Metolachlor DT_{50} was also shorter in 2012 than 2011 in MT, supporting our claim that residue affected the degradation of herbicides more than tillage. Pyroxasulfone persisted in the soil much longer than atrazine and *s*-metolachlor in each tillage system, and would therefore provide longer control of weeds under furrow irrigation even with significant crop residue on the soil surface. Future research is needed to determine to length of pyroxasulfone persistence beyond 60 days in the soil in conservation tillage systems under furrow irrigation in order to prevent subsequent crop injury from residual pyroxasulfone.

Table 2-1. Mean sorption coefficients (K_d) from batch equilibrium reactions for atrazine, *s*-metolachlor, and pyroxasulfone with a Garrett loam soil from Fort Collins, CO. Means followed by a different letter are significantly different (α=0.10).

Herbicide	K_d
	(L kg^{-1})
Atrazine	0.45 a
Pyroxasulfone	0.56 b
s-Metolachlor	0.96 c

Table 2-2. Total precipitation during 2011 and 2012 sample collection periods. Precipitation values are total rainfall received since the time of the previous sample, represented as the number of days after herbicide treatment (DAT).

Precipitation			
2011		2012	
DAT	cm	DAT	cm
1	0.00	1	0.00
7	4.04	8	0.13
16	0.66	15	2.72
28	3.61	28	0.00
60	5.84	60	3.05
Total	14.15	Total	5.90

Table 2-3. Percent of total atrazine, *s*-metolachlor, and pyroxasulfone extracted from the soil during 2011 (top) and 2012 (bottom) at four sample depths for conventional till (CT), minimum till (MT), and strip till (ST).

	Percent of Herbicide Extracted from Soil 2011								
Depth (cm)	Atrazine			*s*-Metolachlor			Pyroxasulfone		
	CT	MT	ST	CT	MT	ST	CT	MT	ST
0-7.5	88.7	83.8	87.1	94.5	91.9	93.9	87.0	82.8	84.9
7.5-15	4.2	9.8	7.2	2.0	5.0	3.5	4.8	9.0	7.2
15-22.5	3.5	3.7	3.2	1.2	1.7	1.3	3.6	4.2	4.2
22.5-30	3.5	2.6	2.5	2.3	1.5	1.3	4.6	4.0	3.7
	Percent of Herbicide Extracted from Soil 2012								
Depth (cm)	Atrazine			*s*-Metolachlor			Pyroxasulfone		
	CT	MT	ST	CT	MT	ST	CT	MT	ST
0-7.5	92.6	90.6	89.2	94.6	95.4	95.1	87.8	88.8	87.3
7.5-15	2.8	3.5	3.8	1.3	1.2	1.2	5.3	5.2	5.2
15-22.5	3.0	4.4	3.4	2.6	2.1	1.7	4.8	4.2	4.9
22.5-30	1.7	1.5	3.6	1.5	1.3	1.9	2.1	1.9	2.6

Table 2-4. Mean residue mass for conventional till, minimum till, and strip till systems during 2011 and 2012. Means in the same year followed by a different letter indicate a significant tillage effect (α=0.10).

	Residue Mass (Mg ha^{-1})	
	2011	**2012**
Conventional Till	0.3 a	1.0 a
Minimum Till	5.2 b	18.4 b
Strip Till	1.6 ab	8.8 b
Average	2.4	9.4

CT1　MT1　ST1　MT2　ST2　CT2

Pyroxasulfone

1　2　3　4

Buffer　Sample Rows　Buffer
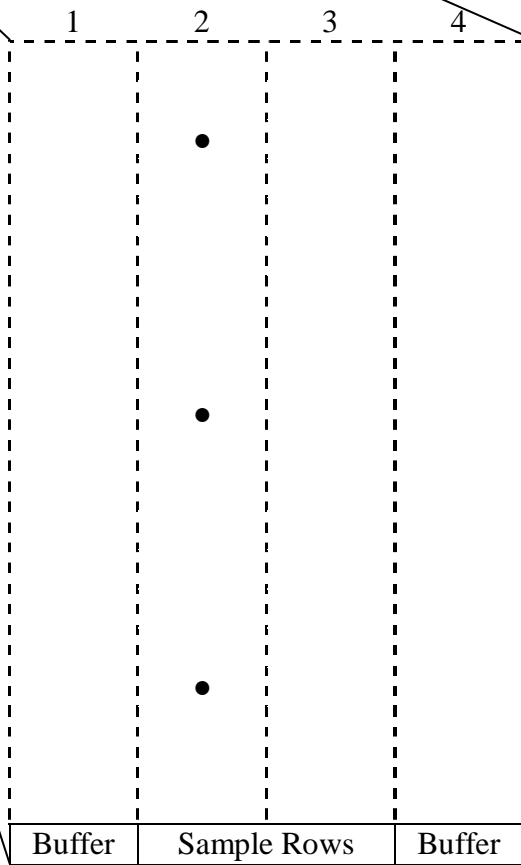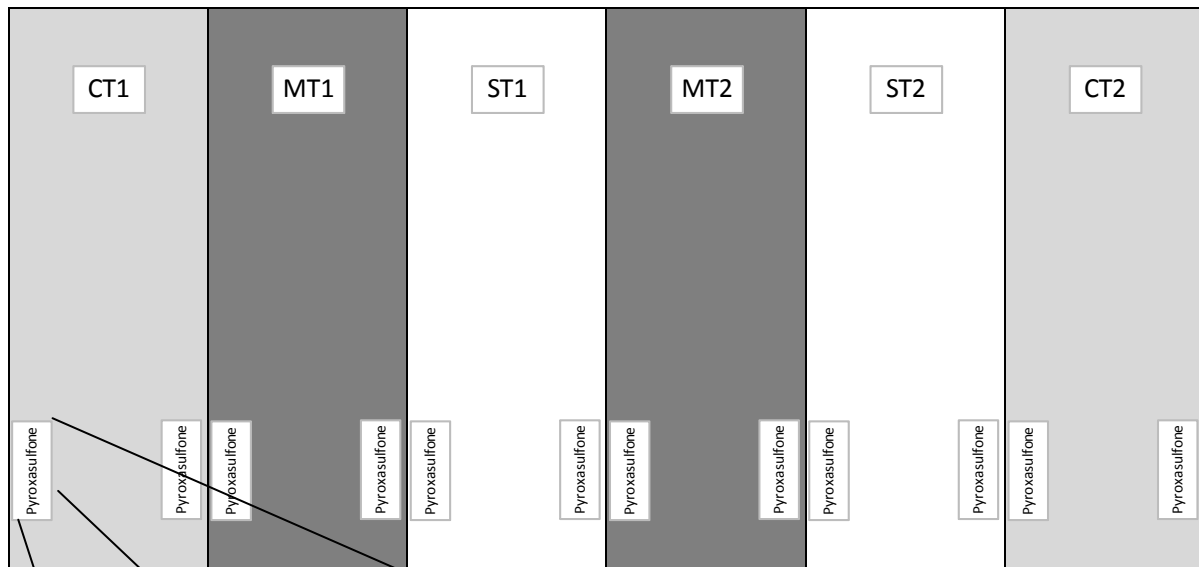
--- Subsection of pyroxasulfone-applied rows

● Sampling locations on corn bed

Figure 2-1. Map of field site.
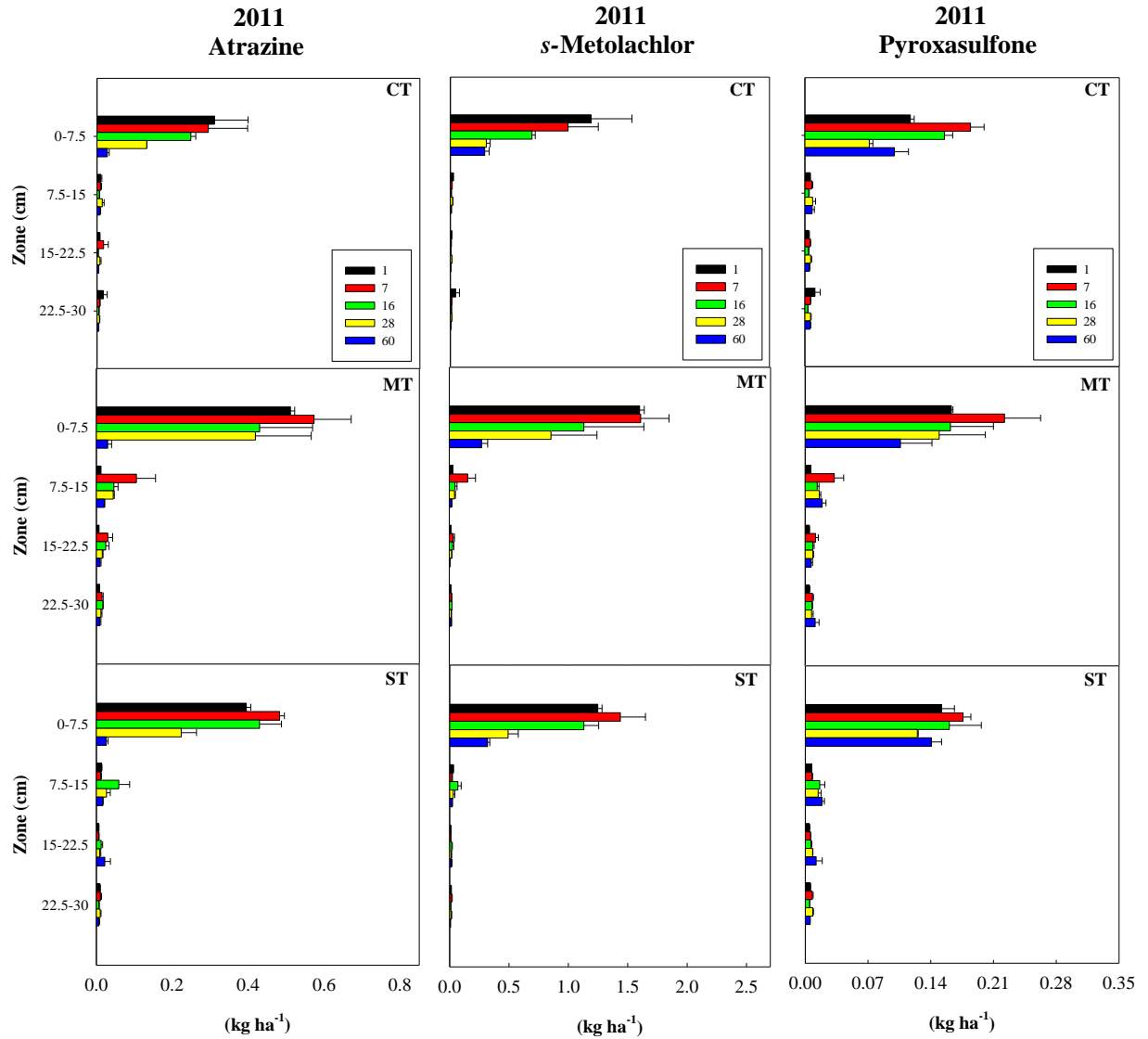
Figure 2-2. Concentrations of atrazine, *s*-metolachlor, and pyroxasulfone at each of the four sample depths and five sample dates for conventional till (CT), minimum till (MT), and strip till (ST) during 2011.
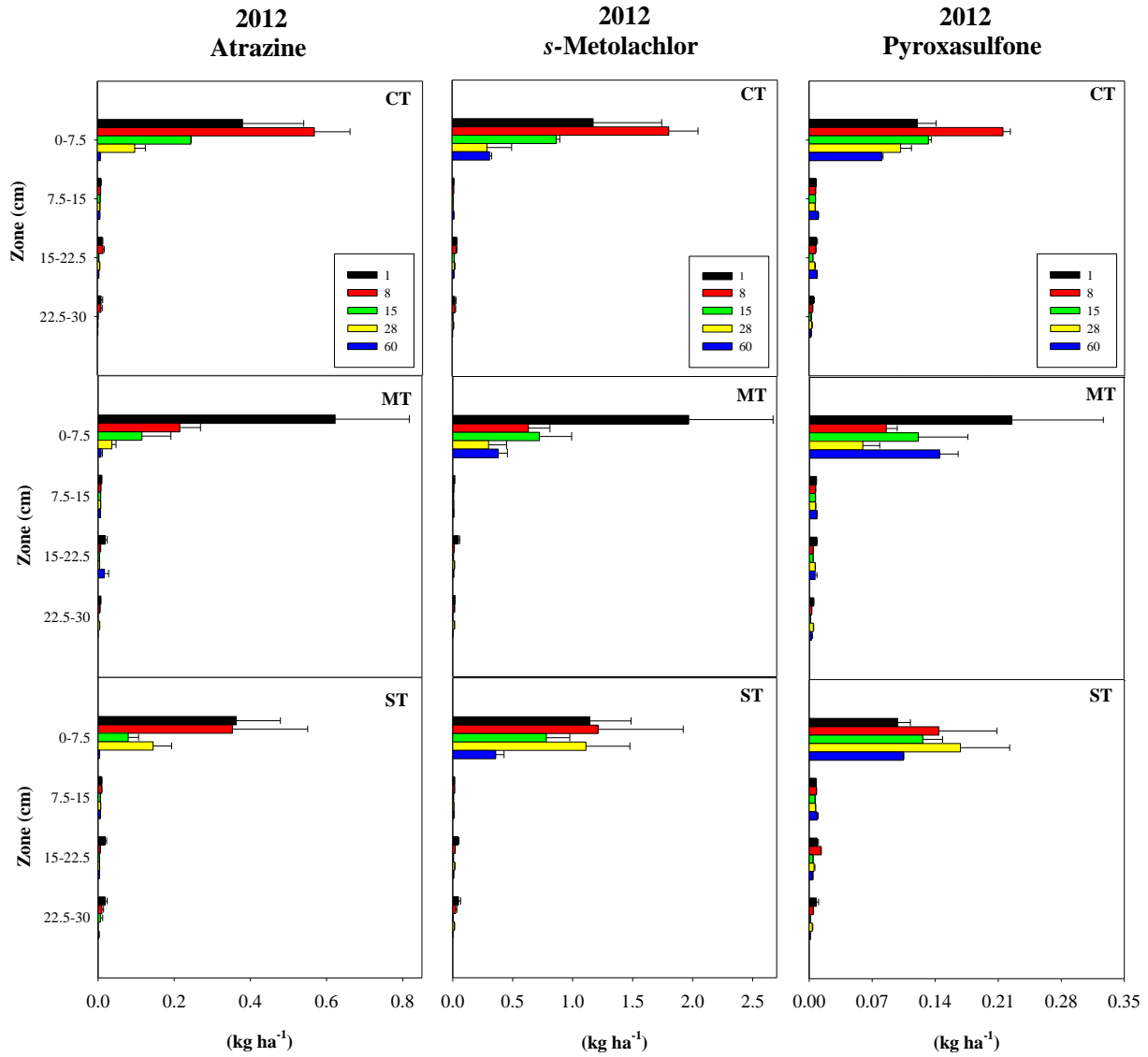
Figure 2-3. Concentrations of atrazine, *s*-metolachlor, and pyroxasulfone at each of the four sample depths and five sample dates for conventional till (CT), minimum till (MT), and strip till (ST) during 2012.
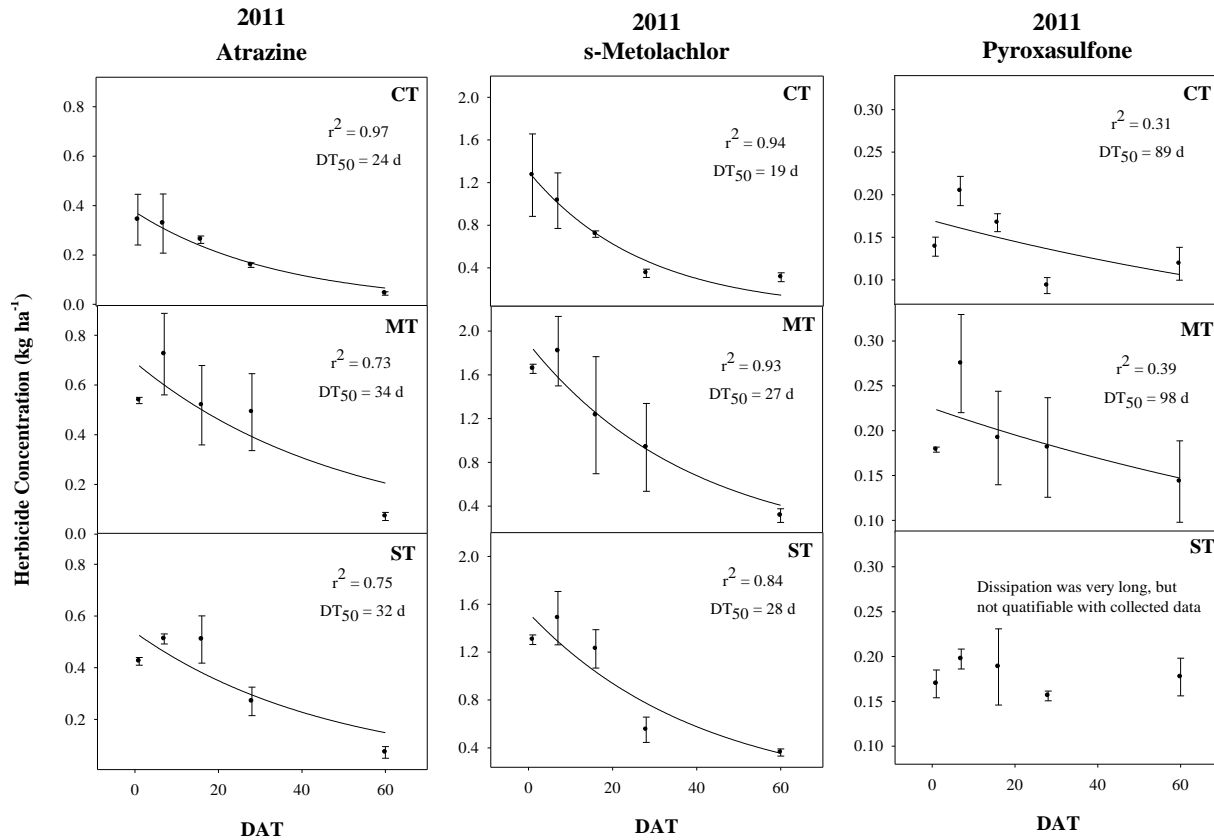
Figure 2-4. Change of concentration over time of atrazine, *s*-metolachlor, and pyroxasulfone in 2011 and the determined half life (DT_{50}) for conventional till (CT), minimum till (MT), and strip till (ST). All concentrations are averages of two replicates and sums for all four sample depths. Error bars represent standard error for dissipation averages.
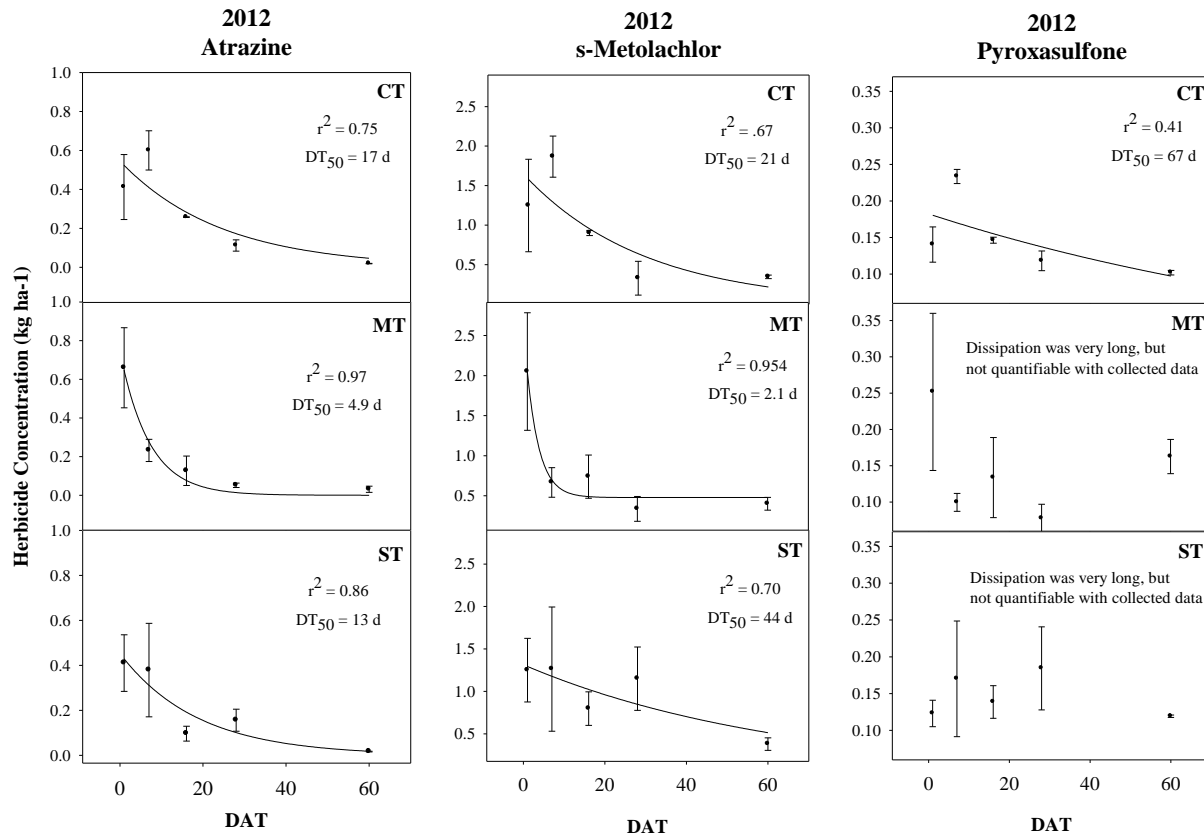
Figure 2-5. Change of concentration over time of atrazine, *s*-metolachlor, and pyroxasulfone in 2012 and the determined half life (DT$_{50}$) for conventional till (CT), minimum till (MT), and strip till (ST). All concentrations are averages of two replicates and sums of all four sample depths. Error bars represent standard error for dissipation averages.

LITERATURE CITED

Baker, J.L., and S.K. Mickelson. 1994. Application technology and best management-practices for minimizing herbicide runoff. Weed Technology 8:862-869.

Baker, J.L., J.M. Laflen, and H.P. Johnson. 1978. Effect of tillage systems on runoff losses of pesticides, a rainfall simulation study. Transactions of the American Society of Agricultural 21:886-892.

Battaglin, W.A., E.M. Thurman, S.J. Kalkhoff, and S.D. Porter. 2003. Herbicides and transformation products in surface waters of the Midwestern United States. Journal of the American Water Resources Association 39:743-756.

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resources Research 18:1311-1325.

Boyd, R.A. 2000. Herbicides and herbicide degradates in shallow groundwater and the Cedar River near a municipal well field, Cedar Rapids, Iowa. Science of the Total Environment 248:241-253.

Bridges, M., W.B. Henry, D.L. Shaner, R. Khosla, P. Westra, and R. Reich. 2008. Spatial Variability of Atrazine and Metolachlor Dissipation on Dryland No-tillage Crop Fields in Colorado. Journal of Environmental Quality 37:2212-2220.

Fawcett, R.S., B.R. Christensen, and D.P. Tierney. 1994. The impact of conservation tillage on pesticide runoff into surface-water: a review and analysis. Journal of Soil and Water Conservation 49:126-135.

Felsot, A.S., J.K. Mitchell, and A.L. Kenimer. 1990. Assesment of management-practices for reducing pesticide runoff from slopting cropland in Illinois. Journal of Environmental Quality 19:539-545.

Gaynor, J.D., D.C. Mactavish, and W.I. Findlay. 1995 Atrazine and metolachlor loss in surface and subsurface runoff from 3 tillage treatments in corn. Journal of Environmental Quality 24:246-256.

Hall, J.K., R.O. Mumma, and D.W. Watts. 1991. Leaching and runoff losses of herbicides in a tilled and untilled field. Agriculture Ecosystems & Environment 37:303-314.

Hess F.D. 2000. Light-dependent herbicides: an overview. Weed Science 48:160-170.

Isensee, A.R., and A.M. Sadeghi. 1993. Impact of tillage practice on runoff and pesticide transport. Journal of Soil and Water Conservation 48:523-527.

Isensee, A.R., R.G. Nash, and C.S. Helling. 1990. Effect of conventional vs no-tillage on pesticide leaching to shallow groundwater. Journal of Environmental Quality 19:434-440.

Krutz, L.J., R.M. Zablotowicz, K.N. Reddy, C.H. Koger, and M.A. Weaver. 2007. Enhanced degradation of atrazine under field conditions correlates with a loss of weed control in the glasshouse. Pest Management Science 63:23-31.

Levanon, D., J.J. Meisinger, E.E. Codling, and J.L Starr. 1994. Impact of tillage on soil microbial activity and the fate of pesticides in the upper soil. Water Air and Soil Pollution 72:179-189.

Mickelson, S.K., P. Boyd, J.L. Baker, and S.I. Ahmed 2001. Tillage and herbicide incorporation effects on residue cover, runoff, erosion, and herbicide loss. Soil & Tillage Research 60:55-66.

Moorman, T.B., J.K. Cowan, E.L. Arthur, and J.R. Coats. 2001. Organic amendments to enhance herbicide biodegradation in contaminated soils. Biology and Fertility of Soils 33:541-545.

Mueller, T.C., and L.E. Steckel. 2011. Efficacy and Dissipation of Pyroxasulfone and Three Chloroacetamides in a Tennessee Field Soil. Weed Science 59:574-579.

Nurse, R.E., P.H. Sikkema, and D.E. Robinson. 2011. Weed control and sweet maize (Zea mays L.) yield as affected by pyroxasulfone dose. Crop Protection 30:789-793.

Penn State Extension. 2013. Pyroxasulfone: The New Kid in The Neighborhood. University Park, PA: Pennsylvania State University. http://extension.psu.edu/plants/crops/news/2013/04/pyroxasulfone-the-new-kid-in-the-neighborhood.

Sadeghi, A.M., A.R. Isensee, and D.R. Shelton. 1998. Effect of tillage age on herbicide dissipation: A side-by-side comparison using microplots. Soil Science 163:883-890.

Selim, H.M., B.J. Naquin, and L.X. Liao. 2012. Adsorption and Desorption of Atrazine Retention by Sugarcane Residue and Soils. Soil Science 177:332-337.

Shaner, D.L., and W.B. Henry. 2007. Field history and dissipation of atrazine and metolachlor in Colorado. Journal of Environmental Quality 36:128-134.

Shaner, D.L., L. Wiles, and N.C. Hansen. 2009. Behavior of Atrazine in Limited Irrigation Cropping Systems in Colorado: Prior Use Is Important. Journal of Environmental Quality 38:1861-1869.

Shipitalo, M.J., W.M. Edwards, W.A. Dick, and L.B. Owens. 1990. Initial storm effects on macropore transport of surface-applied chamicals in no-till soil. Soil Science Society of America Journal 54:1530-1536.

Sikkerna, S.R., N. Soltani, P.H. Sikkema, and D.E. Robinson. 2008. Tolerance of eight sweet corn (Zea mays L.) hybrids to pyroxasulfone. Hortscience 43:170-172.

Staddon, W.J., M.A. Locke, and R.M. Zablotowicz. 2001. Microbiological characteristics of a vegetative buffer strip soil and degradation and sorption of metolachlor. Soil Science Society of America Journal 65:1136-1142.

Tanetani, Y., K. Kaku, K. Kawai, T. Fujioka, and T. Shimizu . 2009. Action mechanism of a novel herbicide, pyroxasulfone. Pesticide Biochemistry and Physiology 95:47-55.

Wackett, L.P., M.J. Sadowsky, B. Martinez, and N. Shapir. 2002. Biodegradation of atrazine and related s-triazine compounds: from enzymes to field studies. Applied Microbiology and Biotechnology 58:39-45.

Wauchope, R.D., T.M. Buttler, A.G. Hornsby, P.M. Augustijnbeckers, and J.P. Burt. 1992. The SCS ARS CES pesticide properties database for environmental decision-making. Reviews of Environmental Contamination and Toxicology 123:1-155.

Weber, J.B., G.G. Wilkerson, and C.F. Reinhardt. 2004. Calculating pesticide sorption coefficients (Kd) using selected soil properties. Chemosphere 55:157-166.

Westra, E.P. 2012. Adsorption, Leaching, and Dissipation of Pyroxasulfone and Two chloroacetamide Herbicides. Master's thesis, Colorado State University.

Whaley, C.M., G.R. Armel, H.P. Wilson, and T.E. Hines. 2009. Evaluation of *s*-metolachlor and *s*-metolachlor plus atrazine mixtures with mesotrione for broadleaf weed control in corn. Weed Technology 23:193-196.

Woodyard, A.J., J.A. Hugie, and D.E. Riechers. 2009. Interactions of mesotrione and atrazine in two weed species with different mechanisms for atrazine resistance. Weed Science 57:369-378.

APPENDIX A-I
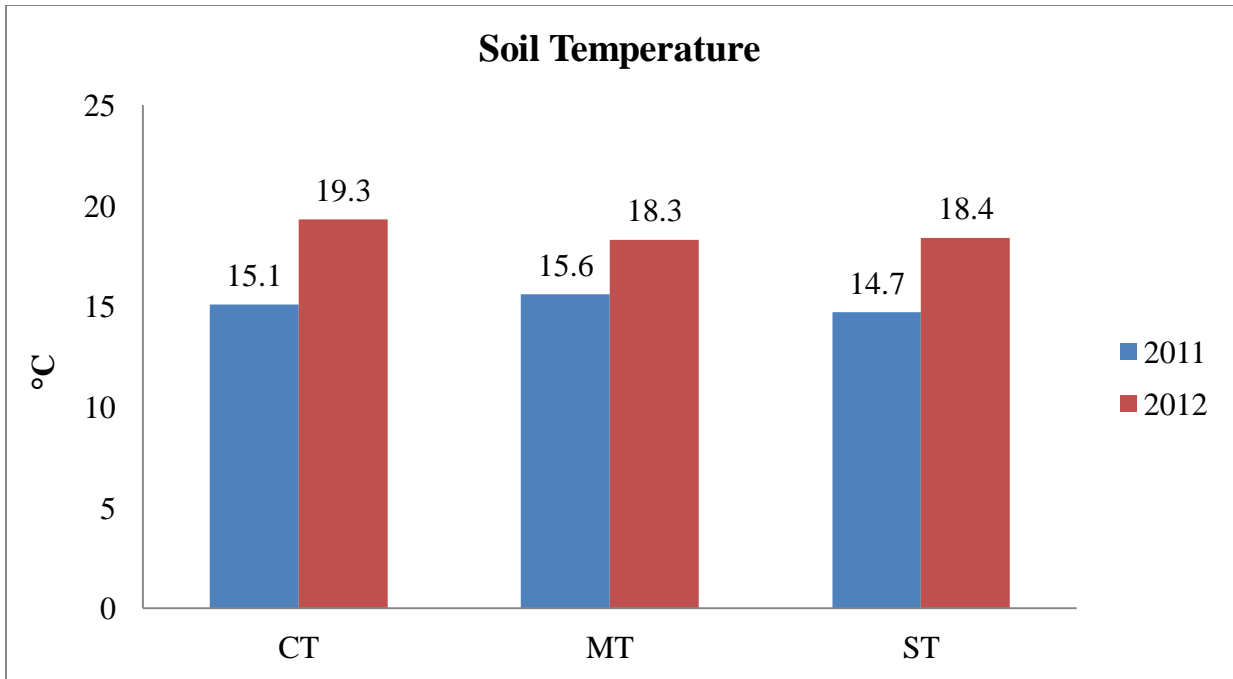
Figure A-1. Temperature of soil at time of planting (May 4, 2011 and May 3, 2012) in the top 5 cm (2 in) of soil for conventional till (CT), minimum till (MT) and strip till (ST) for the 2011 and 2012 seasons. Temperature was measured to determine whether tillage systems affected germination rate. Temperature sensors were installed at the same depth as seed placement on the top of beds at several locations of each plot and then averaged for the three tillage systems.
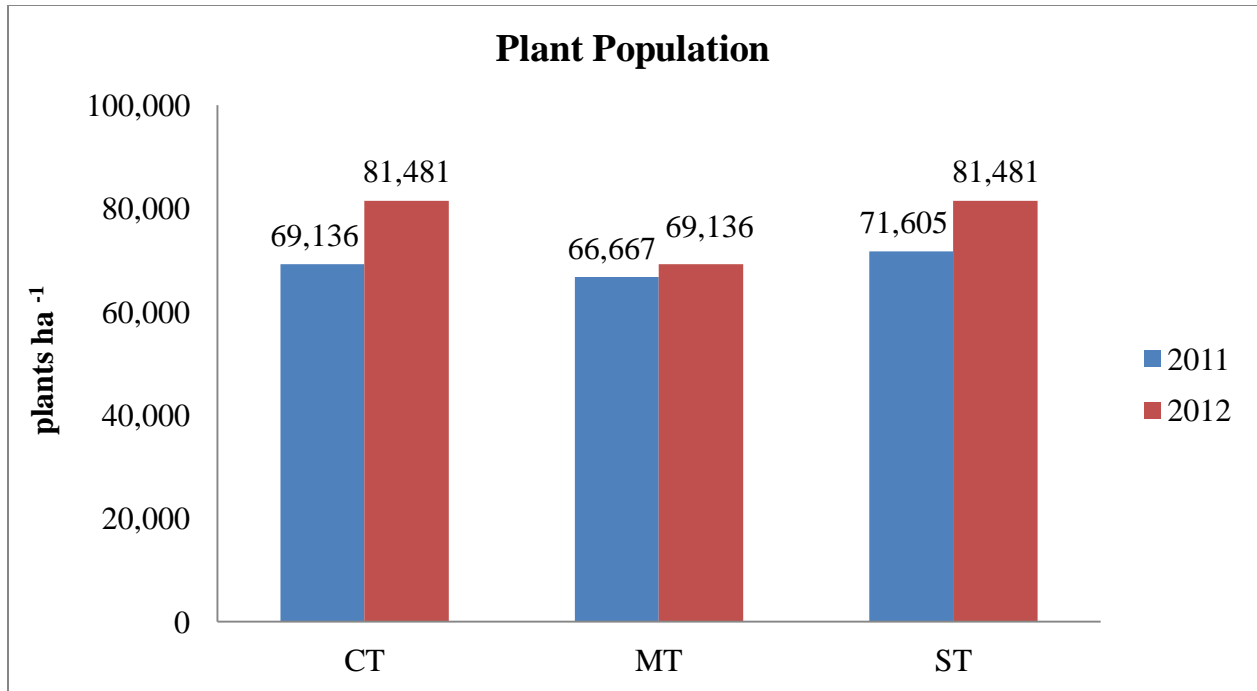
Plant Population

Figure A-2. Average plant population at ~ four weeks after planting in 2011 (June 1) and 2012 (May 29) for conventional till (CT), minimum till (MT) and strip till (ST). Populations were determined by counting every plant for 5.3 m (17.5 ft) in each plot, and then averaged for tillage system. Plant population measurements were made to determine if tillage systems affected the stand of corn due to planting, residue, and soil moisture differences.
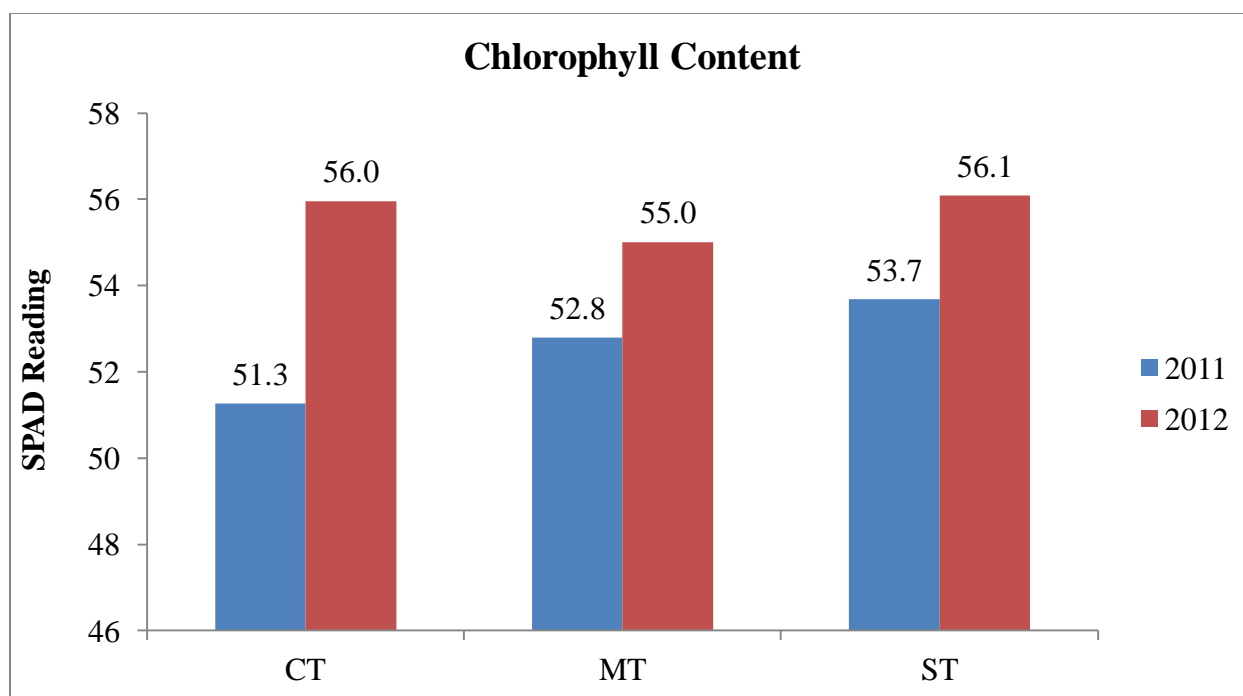
Figure A-3. Average chlorophyll content of corn plants (SPAD readings) on July 31, 2011 and August 10, 2012 of conventional till (CT), minimum till (MT) and strip till (ST). Readings were taken by starting at the north-west section of each plot and working diagonally to the south-east, recording an average reading of 30 consecutive leaves at five locations in each plot. Reported measurements are an average of all locations of the respective tillage systems. Readings were taken in the middle of the ear leaf.
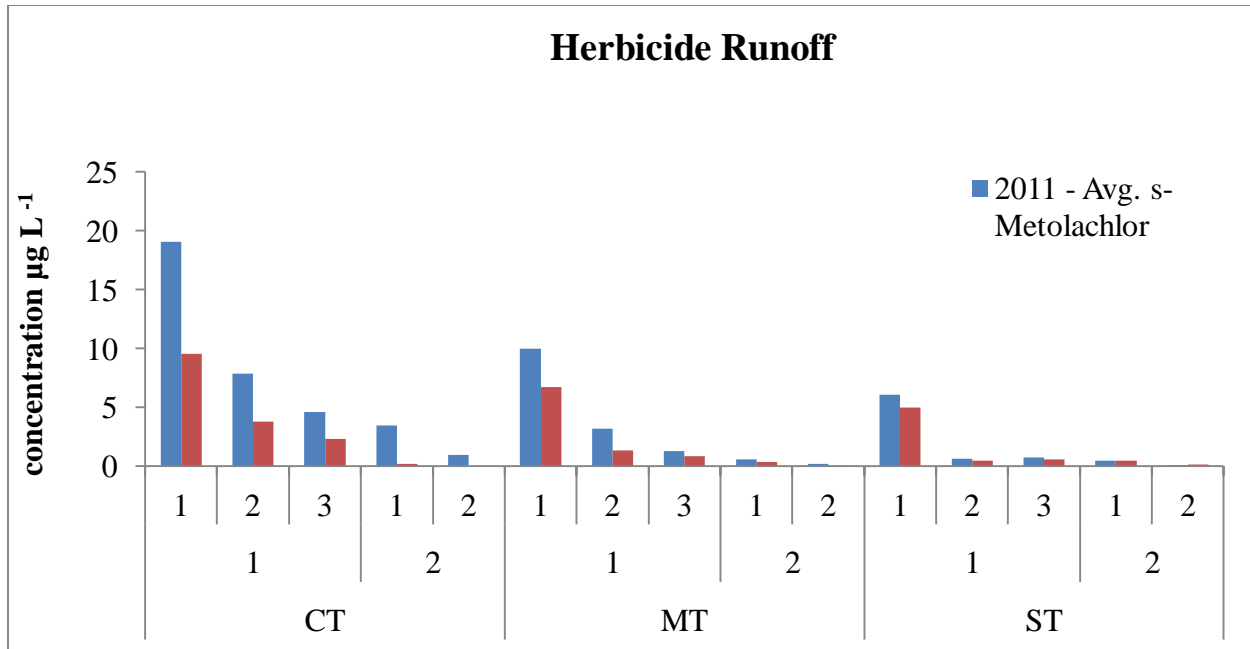
Figure A-4. Average concentration of s-metolachlor and atrazine in runoff water for conventional till (CT), minimum till (MT) and strip till (ST) during the first two irrigations of 2011. Samples were collected at three time intervals after initial water runoff from furrows (0, 120, and 240 min) during the first irrigation (July 1, 2011), and at two intervals (0 and 120 min) during the second irrigation (July 19, 2011). Herbicide runoff samples were collected to determine if surface residue differences affected the amount of herbicides lost during irrigation events.
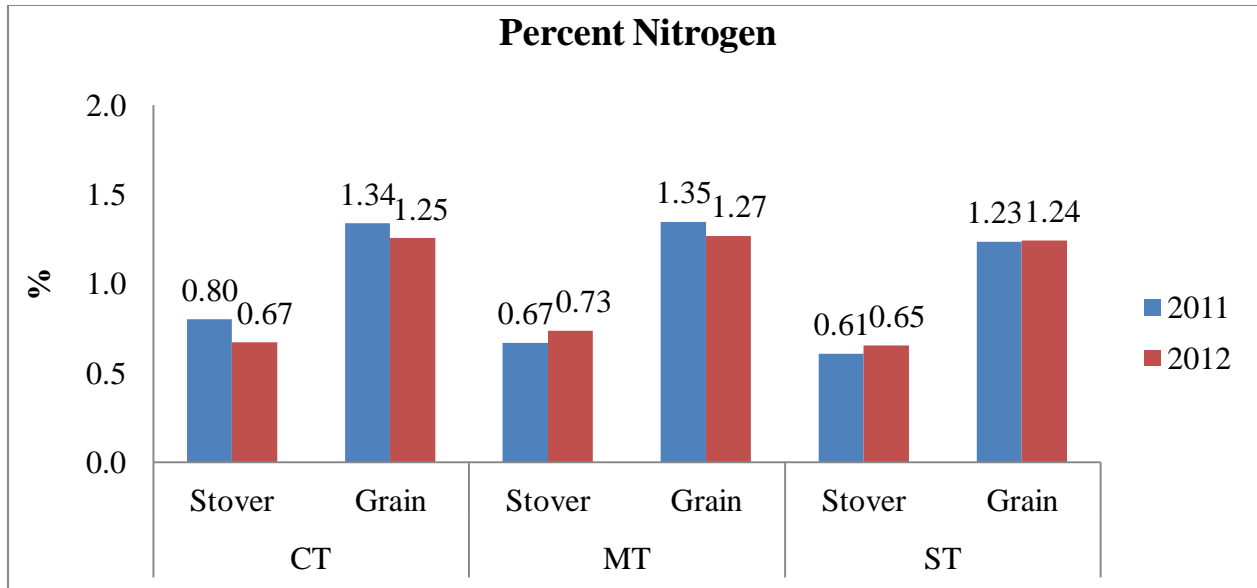
Figure A-5. Average percent nitrogen of corn stover and grain for conventional till (CT), minimum till (MT) and strip till (ST). Stover and grain samples were collected near the end of the growing season during both study years on October 7, 2011 and October 10, 2012. Samples were gathered by harvesting consecutive corn stalks in 5.3 m (17.5 ft) increments in the north, middle, and south locations of each plot. Corn ears were separated from the rest of the plant material, and both were dried and ground in order to determine percent nitrogen using LECO technology. Percent nitrogen of stover and grain were determined to establish the differences of plant uptake of applied nitrogen in each tillage system.
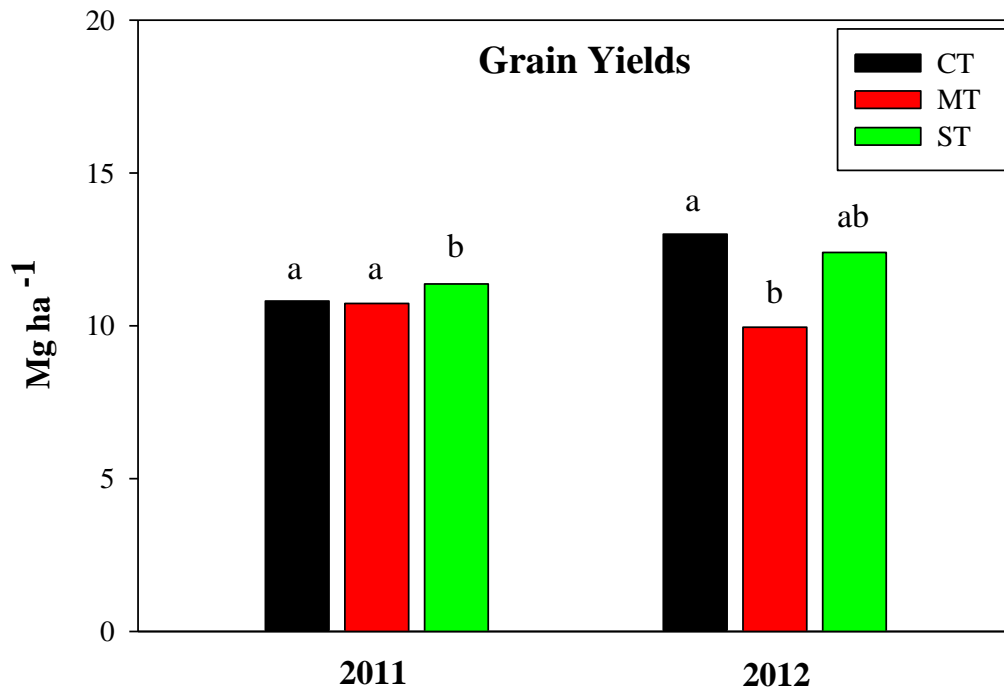
Figure A-6. Grain yields for conventional till (CT), minimum till (MT) and strip till (ST) for the 2011 and 2012 growing seasons. Tillage is compared within years and bars with different letters are significantly different $\alpha = (0.10)$. Yields were determined by total grain weight from the center 12 rows of each plot, which were corrected for 15.5% moisture. Reported values are the average of two replications of each tillage system. Grain yields were calculated to determine the economic value of each tillage system.
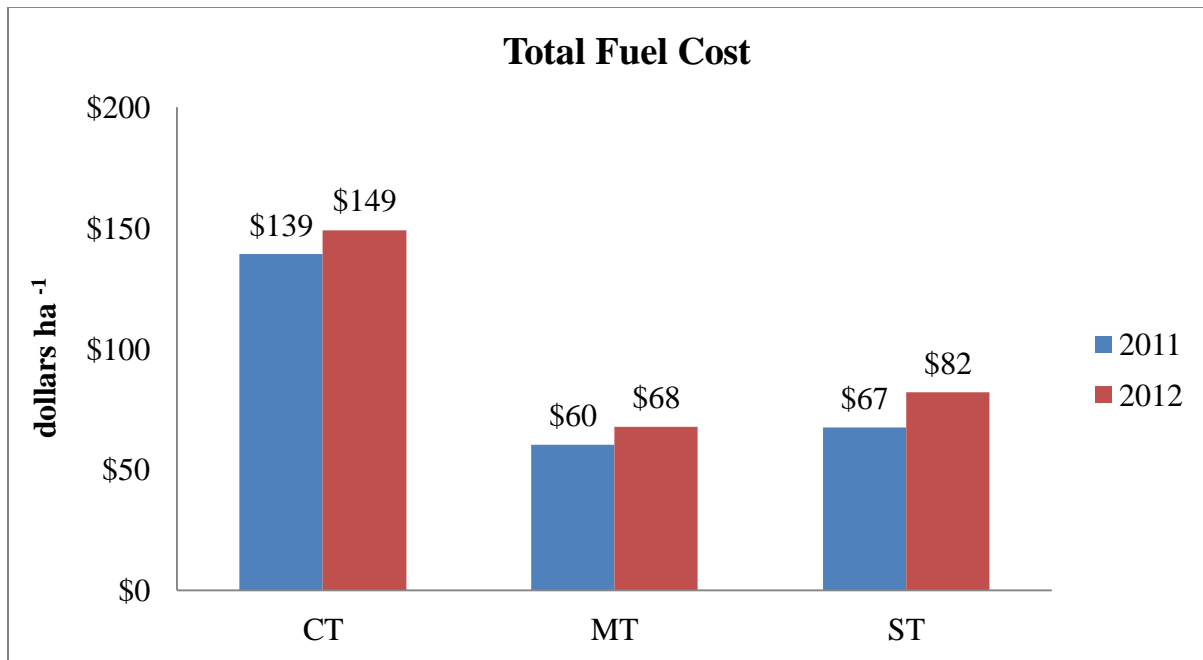
Figure A-7. Total fuel cost for conventional till (CT), minimum till (MT) and strip till (ST) during the 2011 and 2012 seasons. Fuel costs were calculated by measuring the actual amount of diesel used for each field operation, when possible. For operations where diesel was not able to be measured, published rates of fuel consumption for the respective operations in each tillage system were used. Fuel cost calculations allowed for a comparison of the economic vitality of each tillage system.
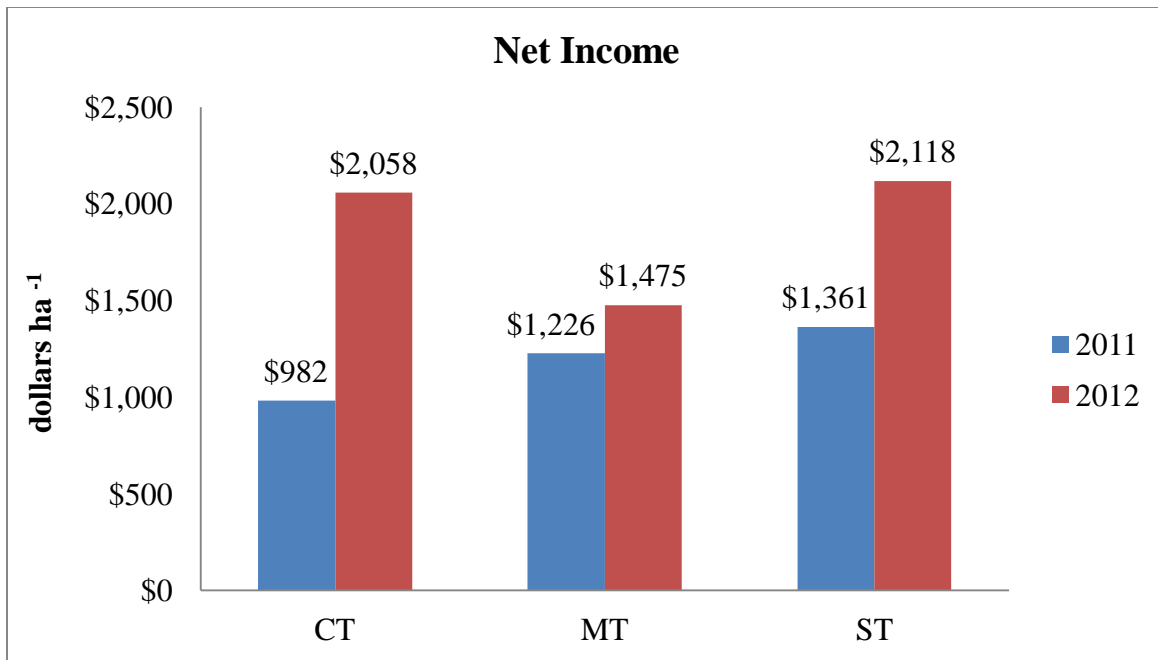
Net Income

Figure A-8. Net income for conventional till (CT), minimum till (MT) and strip till (ST) for the 2011 and 2012 seasons. Net income was based on corn sold for $5.50/bu in 2011 and $7.00/bu in 2012. Fixed and variable costs of each tillage system were accounted for in calculations, as well as the respective grain yields for each season. Net income was determined for each tillage system in order to provide an economic comparison for local growers to allow them make a wise management decision when considering different tillage systems.
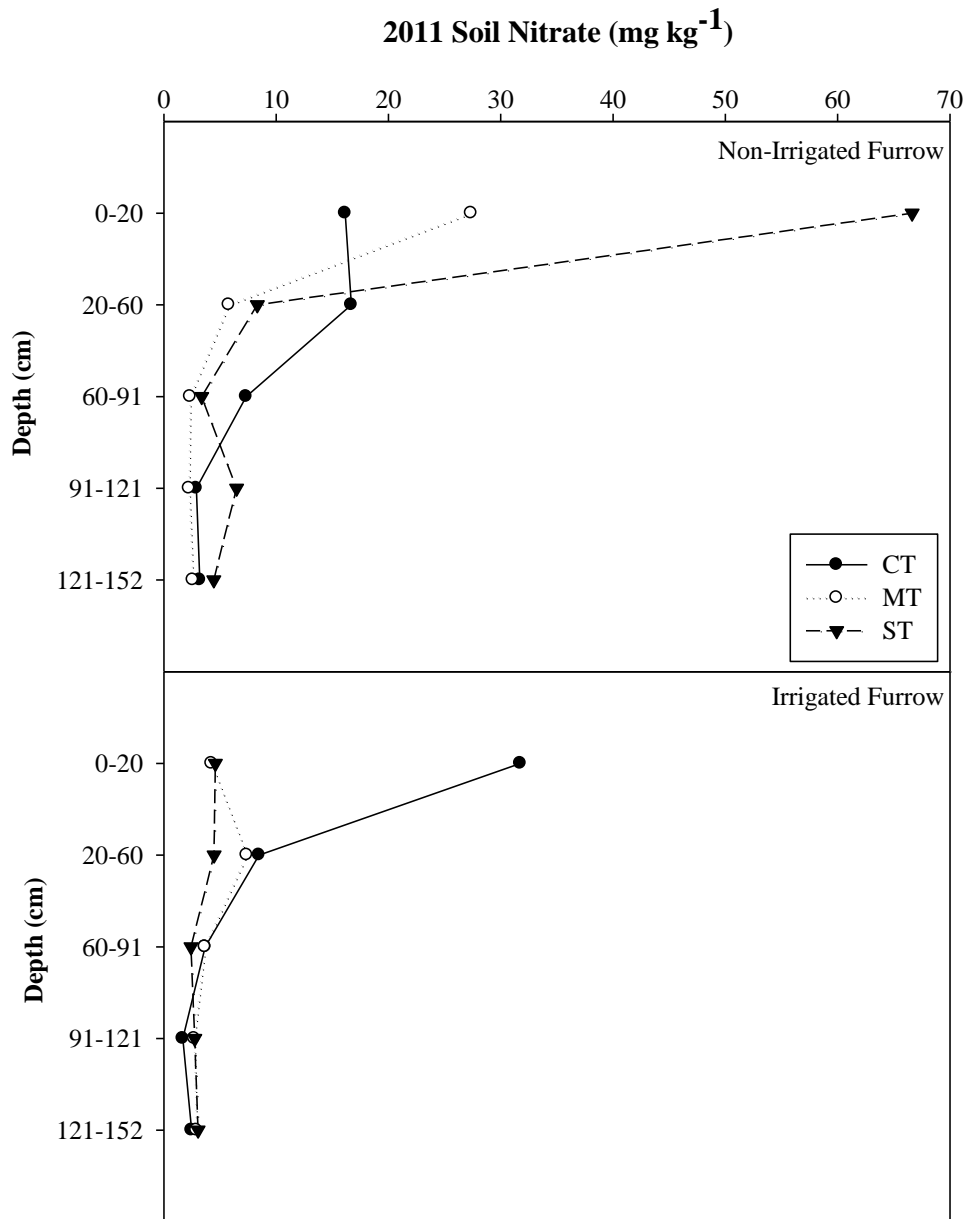
Figure A-9. Soil nitrate concentrations of five depths in the top 1.5 m (5 ft) of soil after the 2011 harvest on December 8, 2011 in the non-irrigated and irrigated furrows of conventional till (CT), minimum till (MT) and strip till (ST). Soil samples were collected using a Giddings Soil Sampler that provided a soil core from 0 to 152 cm (0-5 ft), which was divided into five depths for analysis. Samples were collected from north, middle, and south locations of each plot, and then dried and ground before being sent to a soil testing laboratory for soil analysis. Reported values are the average of all field locations and replications of each tillage system. Soil nitrate concentrations were determined to the movement of applied nitrogen in each tillage system in furrows that were non-irrigated as well as irrigated.

Figure A-10. Soil nitrate concentrations of five depths in the top 1.5 m (5 ft) of soil after the 2012 harvest on November 20, 2012 in the non-irrigated and irrigated furrows of conventional till (CT), minimum till (MT) and strip till (ST). Soil samples were collected using a Giddings Soil Sampler that provided a soil core from 0 to 152 cm (0-5 ft), which was divided into five depths for analysis. Samples were collected from north, middle, and south locations of each plot, and then dried and ground before being sent to a soil testing laboratory for soil analysis. Reported values are the average of all field locations and replications of each tillage system. Soil nitrate concentrations were determined to the movement of applied nitrogen in each tillage system in furrows that were non-irrigated as well as irrigated.

Table A-1. Median concentrations of soluble phosphorus, total phosphorus, total nitrogen, nitrate, and sediment for conventional till (CT), minimum till (MT), and strip till (ST) for three individual irrigation events in 2011 and in 2012. Median concentrations were derived from the same concentrations as average concentrations (Table 1-10), however the medians provide a different perspective on nutrient and sediment loss in runoff in each tillage system.

		Median Concentration † $(mg\ L^{-1})$			
	Year	CT	MT	ST	Avg.
Soluble P	2011	0.079	0.067	0.098	0.081
	2012	0.176	0.173	0.077	0.142
	Avg.	0.128	0.120	0.088	0.112
Total P	2011	2.180	1.245	0.535	1.320
	2012	1.772	1.691	1.540	1.668
	Avg.	1.976	1.468	1.038	1.494
Total N	2011	1.955	1.002	0.817	1.258
	2012	1.437	1.085	1.227	1.250
	Avg.	1.696	1.044	1.022	1.254
Nitrate	2011	0.184	0.295	0.216	0.232
	2012	0.027	0.076	0.351	0.151
	Avg.	0.106	0.186	0.284	0.192
Sediment	2011	923	608	465	665
	2012	601	943	536	693
	Avg.	762	776	501	679

† Average concentration over all tillage systems for three irrigation events during 2011 and three irrigation events during 2012.

Table A-2. Actual concentrations for atrazine, *s*-metolachlor, and pyroxasulfone determined by GC/MS for the 2011 and 2012 seasons at four depths (in the top 30 cm of soil) and five sample dates in conventional till (CT), minimum till (MT), and strip till (ST).

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha⁻¹)	*s*-Metolachlor (kg ha⁻¹)	Pyroxasulfone (kg ha⁻¹)
2011	5/17	1	101	CT	0-7.5	0.221	0.846	0.122
2011	5/17	1	102	MT	0-7.5	0.500	1.639	0.161
2011	5/17	1	103	ST	0-7.5	0.383	1.212	0.138
2011	5/17	1	201	MT	0-7.5	0.522	1.561	0.165
2011	5/17	1	202	ST	0-7.5	0.407	1.284	0.166
2011	5/17	1	203	CT	0-7.5	0.398	1.537	0.113
2011	5/23	7	101	CT	0-7.5	0.190	0.741	0.169
2011	5/23	7	102	MT	0-7.5	0.475	1.371	0.182
2011	5/23	7	103	ST	0-7.5	0.495	1.649	0.185
2011	5/23	7	201	MT	0-7.5	0.671	1.847	0.262
2011	5/23	7	202	ST	0-7.5	0.470	1.226	0.167
2011	5/23	7	203	CT	0-7.5	0.397	1.253	0.200
2011	6/1	16	101	CT	0-7.5	0.234	0.719	0.146
2011	6/1	16	102	MT	0-7.5	0.569	1.636	0.210
2011	6/1	16	103	ST	0-7.5	0.372	1.005	0.125
2011	6/1	16	201	MT	0-7.5	0.291	0.626	0.114
2011	6/1	16	202	ST	0-7.5	0.488	1.256	0.196
2011	6/1	16	203	CT	0-7.5	0.260	0.664	0.165
2011	6/13	28	101	CT	0-7.5	0.131	0.338	0.076
2011	6/13	28	102	MT	0-7.5	0.566	1.242	0.201
2011	6/13	28	103	ST	0-7.5	0.264	0.578	0.124
2011	6/13	28	201	MT	0-7.5	0.271	0.470	0.098
2011	6/13	28	202	ST	0-7.5	0.184	0.407	0.126
2011	6/13	28	203	CT	0-7.5	0.132	0.271	0.068
2011	7/15	60	101	CT	0-7.5	0.021	0.253	0.084
2011	7/15	60	102	MT	0-7.5	0.040	0.221	0.071
2011	7/15	60	103	ST	0-7.5	0.031	0.299	0.129
2011	7/15	60	201	MT	0-7.5	0.020	0.323	0.141
2011	7/15	60	202	ST	0-7.5	0.021	0.338	0.152
2011	7/15	60	203	CT	0-7.5	0.032	0.329	0.115

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha^{-1})	s-Metolachlor (kg ha^{-1})	Pyroxasulfone (kg ha^{-1})
2011	5/17	1	101	CT	7.5-15	0.007	0.014	0.006
2011	5/17	1	102	MT	7.5-15	0.012	0.029	0.006
2011	5/17	1	103	ST	7.5-15	0.012	0.029	0.007
2011	5/17	1	201	MT	7.5-15	0.011	0.031	0.006
2011	5/17	1	202	ST	7.5-15	0.015	0.034	0.007
2011	5/17	1	203	CT	7.5-15	0.013	0.028	0.006
2011	5/23	7	101	CT	7.5-15	0.012	0.016	0.009
2011	5/23	7	102	MT	7.5-15	0.055	0.088	0.022
2011	5/23	7	103	ST	7.5-15	0.014	0.024	0.008
2011	5/23	7	201	MT	7.5-15	0.156	0.220	0.043
2011	5/23	7	202	ST	7.5-15	0.009	0.013	0.007
2011	5/23	7	203	CT	7.5-15	0.007	0.011	0.007
2011	6/1	16	101	CT	7.5-15	0.007	0.010	0.005
2011	6/1	16	102	MT	7.5-15	0.057	0.066	0.016
2011	6/1	16	103	ST	7.5-15	0.030	0.041	0.010
2011	6/1	16	201	MT	7.5-15	0.035	0.032	0.012
2011	6/1	16	202	ST	7.5-15	0.088	0.098	0.022
2011	6/1	16	203	CT	7.5-15	0.006	0.010	0.004
2011	6/13	28	101	CT	7.5-15	0.019	0.023	0.012
2011	6/13	28	102	MT	7.5-15	0.047	0.052	0.018
2011	6/13	28	103	ST	7.5-15	0.037	0.045	0.018
2011	6/13	28	201	MT	7.5-15	0.041	0.036	0.014
2011	6/13	28	202	ST	7.5-15	0.017	0.017	0.011
2011	6/13	28	203	CT	7.5-15	0.009	0.016	0.005
2011	7/15	60	101	CT	7.5-15	0.010	0.010	0.011
2011	7/15	60	102	MT	7.5-15	0.020	0.014	0.015
2011	7/15	60	103	ST	7.5-15	0.017	0.024	0.021
2011	7/15	60	201	MT	7.5-15	0.022	0.024	0.023
2011	7/15	60	202	ST	7.5-15	0.018	0.020	0.016
2011	7/15	60	203	CT	7.5-15	0.007	0.007	0.006

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha⁻¹)	s-Metolachlor (kg ha⁻¹)	Pyroxasulfone (kg ha⁻¹)
2011	5/17	1	101	CT	15-22.5	0.005	0.009	0.004
2011	5/17	1	102	MT	15-22.5	0.007	0.014	0.005
2011	5/17	1	103	ST	15-22.5	0.007	0.013	0.005
2011	5/17	1	201	MT	15-22.5	0.006	0.011	0.004
2011	5/17	1	202	ST	15-22.5	0.006	0.009	0.004
2011	5/17	1	203	CT	15-22.5	0.008	0.014	0.005
2011	5/23	7	101	CT	15-22.5	0.030	0.008	0.006
2011	5/23	7	102	MT	15-22.5	0.018	0.023	0.009
2011	5/23	7	103	ST	15-22.5	0.008	0.012	0.006
2011	5/23	7	201	MT	15-22.5	0.043	0.044	0.015
2011	5/23	7	202	ST	15-22.5	0.005	0.009	0.006
2011	5/23	7	203	CT	15-22.5	0.005	0.008	0.006
2011	6/1	16	101	CT	15-22.5	0.003	0.007	0.005
2011	6/1	16	102	MT	15-22.5	0.033	0.039	0.010
2011	6/1	16	103	ST	15-22.5	0.017	0.024	0.007
2011	6/1	16	201	MT	15-22.5	0.016	0.017	0.007
2011	6/1	16	202	ST	15-22.5	0.009	0.011	0.005
2011	6/1	16	203	CT	15-22.5	0.004	0.006	0.004
2011	6/13	28	101	CT	15-22.5	0.011	0.015	0.008
2011	6/13	28	102	MT	15-22.5	0.018	0.024	0.009
2011	6/13	28	103	ST	15-22.5	0.012	0.018	0.009
2011	6/13	28	201	MT	15-22.5	0.013	0.016	0.008
2011	6/13	28	202	ST	15-22.5	0.007	0.009	0.008
2011	6/13	28	203	CT	15-22.5	0.005	0.011	0.005
2011	7/15	60	101	CT	15-22.5	0.005	0.007	0.005
2011	7/15	60	102	MT	15-22.5	0.008	0.007	0.005
2011	7/15	60	103	ST	15-22.5	0.037	0.021	0.019
2011	7/15	60	201	MT	15-22.5	0.012	0.008	0.008
2011	7/15	60	202	ST	15-22.5	0.007	0.007	0.005
2011	7/15	60	203	CT	15-22.5	0.005	0.006	0.006

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha⁻¹)	*s*-Metolachlor (kg ha⁻¹)	Pyroxasulfone (kg ha⁻¹)
2011	5/17	1	101	CT	22.5-30	0.007	0.005	0.013
2011	5/17	1	102	MT	22.5-30	0.008	0.004	0.012
2011	5/17	1	103	ST	22.5-30	0.009	0.006	0.014
2011	5/17	1	201	MT	22.5-30	0.009	0.005	0.013
2011	5/17	1	202	ST	22.5-30	0.011	0.006	0.014
2011	5/17	1	203	CT	22.5-30	0.027	0.017	0.078
2011	5/23	7	101	CT	22.5-30	0.009	0.007	0.014
2011	5/23	7	102	MT	22.5-30	0.012	0.007	0.017
2011	5/23	7	103	ST	22.5-30	0.014	0.009	0.022
2011	5/23	7	201	MT	22.5-30	0.018	0.009	0.022
2011	5/23	7	202	ST	22.5-30	0.007	0.007	0.013
2011	5/23	7	203	CT	22.5-30	0.005	0.006	0.009
2011	6/1	16	101	CT	22.5-30	0.006	0.004	0.011
2011	6/1	16	102	MT	22.5-30	0.018	0.007	0.021
2011	6/1	16	103	ST	22.5-30	0.008	0.005	0.011
2011	6/1	16	201	MT	22.5-30	0.017	0.008	0.025
2011	6/1	16	202	ST	22.5-30	0.006	0.005	0.010
2011	6/1	16	203	CT	22.5-30	0.003	0.003	0.006
2011	6/13	28	101	CT	22.5-30	0.005	0.007	0.012
2011	6/13	28	102	MT	22.5-30	0.015	0.009	0.020
2011	6/13	28	103	ST	22.5-30	0.013	0.009	0.017
2011	6/13	28	201	MT	22.5-30	0.010	0.005	0.013
2011	6/13	28	202	ST	22.5-30	0.008	0.008	0.012
2011	6/13	28	203	CT	22.5-30	0.008	0.005	0.013
2011	7/15	60	101	CT	22.5-30	0.005	0.005	0.006
2011	7/15	60	102	MT	22.5-30	0.006	0.016	0.021
2011	7/15	60	103	ST	22.5-30	0.009	0.005	0.007
2011	7/15	60	201	MT	22.5-30	0.012	0.007	0.008
2011	7/15	60	202	ST	22.5-30	0.005	0.006	0.006
2011	7/15	60	203	CT	22.5-30	0.005	0.007	0.008

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha⁻¹)	s-Metolachlor (kg ha⁻¹)	Pyroxasulfone (kg ha⁻¹)
2012	5/11	1	101	CT	0-7.5	0.540	1.740	0.141
2012	5/11	1	102	MT	0-7.5	0.817	2.671	0.327
2012	5/11	1	103	ST	0-7.5	0.247	0.798	0.085
2012	5/11	1	201	MT	0-7.5	0.428	1.265	0.124
2012	5/11	1	202	ST	0-7.5	0.479	1.487	0.112
2012	5/11	1	203	CT	0-7.5	0.220	0.603	0.099
2012	5/18	8	101	CT	0-7.5	0.661	2.042	0.223
2012	5/18	8	102	MT	0-7.5	0.269	0.811	0.098
2012	5/18	8	103	ST	0-7.5	0.156	0.503	0.079
2012	5/18	8	201	MT	0-7.5	0.161	0.451	0.073
2012	5/18	8	202	ST	0-7.5	0.550	1.921	0.209
2012	5/18	8	203	CT	0-7.5	0.474	1.557	0.207
2012	5/25	15	101	CT	0-7.5	0.244	0.895	0.136
2012	5/25	15	102	MT	0-7.5	0.191	0.992	0.176
2012	5/25	15	103	ST	0-7.5	0.053	0.585	0.104
2012	5/25	15	201	MT	0-7.5	0.040	0.453	0.066
2012	5/25	15	202	ST	0-7.5	0.106	0.977	0.148
2012	5/25	15	203	CT	0-7.5	0.245	0.836	0.129
2012	6/7	28	101	CT	0-7.5	0.126	0.086	0.114
2012	6/7	28	102	MT	0-7.5	0.026	0.149	0.041
2012	6/7	28	103	ST	0-7.5	0.096	0.743	0.113
2012	6/7	28	201	MT	0-7.5	0.047	0.450	0.078
2012	6/7	28	202	ST	0-7.5	0.194	1.477	0.223
2012	6/7	28	203	CT	0-7.5	0.069	0.494	0.090
2012	7/9	60	101	CT	0-7.5	0.008	0.329	0.082
2012	7/9	60	102	MT	0-7.5	0.011	0.457	0.166
2012	7/9	60	103	ST	0-7.5	0.004	0.428	0.105
2012	7/9	60	201	MT	0-7.5	0.004	0.303	0.125
2012	7/9	60	202	ST	0-7.5	0.004	0.290	0.105
2012	7/9	60	203	CT	0-7.5	0.007	0.296	0.079

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha^{-1})	s-Metolachlor (kg ha^{-1})	Pyroxasulfone (kg ha^{-1})
2012	5/11	1	101	CT	7.5-15	0.008	0.011	0.007
2012	5/11	1	102	MT	7.5-15	0.010	0.017	0.008
2012	5/11	1	103	ST	7.5-15	0.010	0.016	0.008
2012	5/11	1	201	MT	7.5-15	0.010	0.016	0.007
2012	5/11	1	202	ST	7.5-15	0.010	0.016	0.008
2012	5/11	1	203	CT	7.5-15	0.010	0.017	0.008
2012	5/18	8	101	CT	7.5-15	0.009	0.013	0.007
2012	5/18	8	102	MT	7.5-15	0.008	0.010	0.007
2012	5/18	8	103	ST	7.5-15	0.010	0.017	0.008
2012	5/18	8	201	MT	7.5-15	0.008	0.010	0.007
2012	5/18	8	202	ST	7.5-15	0.009	0.014	0.008
2012	5/18	8	203	CT	7.5-15	0.008	0.011	0.007
2012	5/25	15	101	CT	7.5-15	0.007	0.011	0.007
2012	5/25	15	102	MT	7.5-15	0.007	0.008	0.007
2012	5/25	15	103	ST	7.5-15	0.007	0.008	0.007
2012	5/25	15	201	MT	7.5-15	0.007	0.007	0.007
2012	5/25	15	202	ST	7.5-15	0.007	0.007	0.007
2012	5/25	15	203	CT	7.5-15	0.007	0.011	0.007
2012	6/7	28	101	CT	7.5-15	0.007	0.008	0.007
2012	6/7	28	102	MT	7.5-15	0.007	0.008	0.007
2012	6/7	28	103	ST	7.5-15	0.007	0.009	0.007
2012	6/7	28	201	MT	7.5-15	0.007	0.009	0.007
2012	6/7	28	202	ST	7.5-15	0.007	0.011	0.007
2012	6/7	28	203	CT	7.5-15	0.007	0.010	0.007
2012	7/9	60	101	CT	7.5-15	0.007	0.017	0.011
2012	7/9	60	102	MT	7.5-15	0.007	0.009	0.009
2012	7/9	60	103	ST	7.5-15	0.007	0.008	0.007
2012	7/9	60	201	MT	7.5-15	0.007	0.010	0.009
2012	7/9	60	202	ST	7.5-15	0.007	0.012	0.010
2012	7/9	60	203	CT	7.5-15	0.007	0.012	0.010

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha^{-1})	s-Metolachlor (kg ha^{-1})	Pyroxasulfone (kg ha^{-1})
2012	5/11	1	101	CT	15-22.5	0.011	0.035	0.007
2012	5/11	1	102	MT	15-22.5	0.014	0.037	0.008
2012	5/11	1	103	ST	15-22.5	0.023	0.055	0.010
2012	5/11	1	201	MT	15-22.5	0.024	0.058	0.009
2012	5/11	1	202	ST	15-22.5	0.014	0.030	0.007
2012	5/11	1	203	CT	15-22.5	0.015	0.043	0.009
2012	5/18	8	101	CT	15-22.5	0.018	0.042	0.008
2012	5/18	8	102	MT	15-22.5	0.007	0.014	0.004
2012	5/18	8	103	ST	15-22.5	0.000	0.000	0.000
2012	5/18	8	201	MT	15-22.5	0.004	0.011	0.004
2012	5/18	8	202	ST	15-22.5	0.011	0.021	0.027
2012	5/18	8	203	CT	15-22.5	0.011	0.023	0.007
2012	5/25	15	101	CT	15-22.5	0.004	0.018	0.004
2012	5/25	15	102	MT	15-22.5	0.004	0.007	0.004
2012	5/25	15	103	ST	15-22.5	0.004	0.007	0.004
2012	5/25	15	201	MT	15-22.5	0.004	0.006	0.004
2012	5/25	15	202	ST	15-22.5	0.004	0.005	0.004
2012	5/25	15	203	CT	15-22.5	0.004	0.017	0.004
2012	6/7	28	101	CT	15-22.5	0.007	0.025	0.007
2012	6/7	28	102	MT	15-22.5	0.004	0.013	0.007
2012	6/7	28	103	ST	15-22.5	0.004	0.014	0.004
2012	6/7	28	201	MT	15-22.5	0.004	0.016	0.006
2012	6/7	28	202	ST	15-22.5	0.004	0.019	0.006
2012	6/7	28	203	CT	15-22.5	0.006	0.015	0.006
2012	7/9	60	101	CT	15-22.5	0.004	0.018	0.009
2012	7/9	60	102	MT	15-22.5	0.004	0.006	0.004
2012	7/9	60	103	ST	15-22.5	0.004	0.006	0.004
2012	7/9	60	201	MT	15-22.5	0.028	0.009	0.008
2012	7/9	60	202	ST	15-22.5	0.004	0.009	0.004
2012	7/9	60	203	CT	15-22.5	0.004	0.012	0.009

Year	Date	DAT	Plot	Tillage	Depth (cm)	Atrazine (kg ha^{-1})	s-Metolachlor (kg ha^{-1})	Pyroxasulfone (kg ha^{-1})
2012	5/11	1	101	CT	22.5-30	0.006	0.015	0.003
2012	5/11	1	102	MT	22.5-30	0.000	0.000	0.016
2012	5/11	1	103	ST	22.5-30	0.024	0.067	0.011
2012	5/11	1	201	MT	22.5-30	0.015	0.038	0.005
2012	5/11	1	202	ST	22.5-30	0.012	0.030	0.005
2012	5/11	1	203	CT	22.5-30	0.014	0.033	0.006
2012	5/18	8	101	CT	22.5-30	0.006	0.016	0.003
2012	5/18	8	102	MT	22.5-30	0.006	0.017	0.003
2012	5/18	8	103	ST	22.5-30	0.015	0.035	0.005
2012	5/18	8	201	MT	22.5-30	0.003	0.010	0.003
2012	5/18	8	202	ST	22.5-30	0.006	0.014	0.004
2012	5/18	8	203	CT	22.5-30	0.013	0.031	0.004
2012	5/25	15	101	CT	22.5-30	0.000	0.004	0.001
2012	5/25	15	102	MT	22.5-30	0.000	0.003	0.001
2012	5/25	15	103	ST	22.5-30	0.012	0.003	0.001
2012	5/25	15	201	MT	22.5-30	0.000	0.003	0.001
2012	5/25	15	202	ST	22.5-30	0.000	0.004	0.001
2012	5/25	15	203	CT	22.5-30	0.003	0.009	0.003
2012	6/7	28	101	CT	22.5-30	0.000	0.015	0.004
2012	6/7	28	102	MT	22.5-30	0.005	0.017	0.005
2012	6/7	28	103	ST	22.5-30	0.000	0.011	0.003
2012	6/7	28	201	MT	22.5-30	0.004	0.012	0.004
2012	6/7	28	202	ST	22.5-30	0.000	0.016	0.004
2012	6/7	28	203	CT	22.5-30	0.002	0.006	0.002
2012	7/9	60	101	CT	22.5-30	0.000	0.005	0.003
2012	7/9	60	102	MT	22.5-30	0.000	0.002	0.001
2012	7/9	60	103	ST	22.5-30	0.000	0.003	0.001
2012	7/9	60	201	MT	22.5-30	0.000	0.004	0.004
2012	7/9	60	202	ST	22.5-30	0.004	0.003	0.001
2012	7/9	60	203	CT	22.5-30	0.002	0.003	0.001