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Influence of tillage on maize yield in soil with shallow fragipan

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ABSTRACT

A genuine concern for landowners and other stake holders is whether conservation tillage contaminates shallow groundwater even though it greatly reduces erosion. A six-year continuous maize (*Zea mays* L.) study that compared yields from no-tillage (NT), reduced-tillage (RT), and conventional-tillage (CT) was conducted in the upland hills of northern Mississippi on 4–6% sloping soils overlying a shallow fragipan. The objective was to test the hypothesis that neither no-tillage nor reduced-tillage has the same effect on maize crop as conventional-tillage on soils with a shallow water restricted layer. The study showed conservation tillage had fewer detrimental effects on the water quality in runoff and shallow groundwater and promoted more soil water for crop use during the growing season than conventional tillage. With adequate weed control, NT produced higher yields than CT on these silt loam soils due to soil water conservation. However, inadequate weed control occurred in several years of the study along with above normal rain resulting in lower NT maize yields than CT yields. Significant differences in maize yield were found for type of tillage, year, and tillage-year interaction. These differences were explained by a tillage system's ability to conserve soil water and control weeds. Other results included low sediment amounts lost from NT maize plots and insignificant free water quantities at the fragipan's surface during the cropping season for all tillage systems. Maximum groundwater movement across the surface of the fragipan occurred during the non-cropping season under soil profile saturation. Amount, timing, and distribution of rainfall rather than tillage system primarily influenced agrichemical movement from maize systems in this study. Some form of conservation tillage that decreases or prevents erosion will be required on sloping lands with shallow fragipan to sustain long term continuous corn production. Information from this study provides additional guidance for making tillage and pesticide management recommendations to farmers.

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1. Introduction

No-tillage crop production has been increasing in the United States for many years (CTIC, 2004; Lyon et al., 2004). The desire to reduce input costs, manage more hectares with the same or less labor and equipment, conserve valuable soil resources, and maintain compliance with government conservation programs has driven crop producer interest in conservation tillage practices (Uri, 2000). The potential for increased government and private sector incentives to practice no-till for carbon sequestration may cause additional adoption of high-residue no-till and strip-tillage crop production in the near future (Paustian et al., 2004; Lewandrowski et al., 2004).

There has been considerable debate over the relative merits of no-till as compared with conventional tillage over the years. Many tillage experiments have been conducted in the United States and Canada comparing yield and economic return between no-tillage and conventional tillage. The results of these research projects often appear to be contradictory. A general perception has arisen that no-tillage is more favorable in the southern United States, but does not perform as well in the northern United States or Canada (Manley et al., 2005; DeFelice et al., 2006).

Soil classification by soil water characteristics – especially drainage – has also been used to define areas that are suitable or unsuitable for no-tillage (Cosper, 1983). Farmers, crop advisors, extension agronomists, and seed breeders are all concerned about managing crop production to obtain optimum yield and economic returns.

Some form of conservation tillage is also needed in areas susceptible to high erosion rates, even if crop yield is reduced to protect soil losses. The Loring (*Typic Fragiudalfs*) soils at the Mississippi Agricultural and Forestry Experiment Station (MAFES) at Holly Springs are representative of the severely eroded loess soils and highly erosive climate of this region of the southeastern United States. Conservation tillage studies with several different row crops have shown that no-till and reduced-till cropping

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systems can dramatically reduce erosion in the southern United States (Greer et al., 1976; McGregor et al., 1996). With these systems, tillage operations are substituted with pesticides to control weeds. Pesticides move from agricultural fields to surface waters mainly in runoff (both in solution and sorbed to eroded sediment). The most commonly detected pesticides in surface waters are herbicides, including atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) and alachlor (2-chloro-2′,6′-diethyl-*N*-methoxymethylacetanilide) (Christensen et al., 1993). Many studies have shown that these herbicides are lost from fields primarily in surface runoff (Felsot et al., 1990; Hall et al., 1983; Thurman et al., 1991; Smith and Cullum, 1992; Smith, 1993). Wauchope (1978) reported that edge-of-field runoff losses for most commercial pesticides are 0.5% or less of that applied, except when intense rainfall occurs within 1–2 weeks after application. Goals to reduce soil erosion and associated pesticide losses to aquatic ecosystems surrounding agricultural lands have led to increased adoption of NT and other RT practices. However, NT and RT practices often require increased usage of herbicides to control weeds that are usually controlled with conventional-till practices. Also, increased infiltration associated with conservation tillage needs evaluation to determine the potential for increased contamination of the groundwater with agrichemicals.

Contamination of shallow groundwater and subsurface water movement under steady-state conditions is well documented (Smith, 1993; Smith et al., 1994). Information about the effect of chemical applications in various cropping systems on shallow groundwater quality is increasing (Cullum et al., 1995). Nevertheless, because of the complexity and interaction among different tillage practices, residue management scenarios, and regional environmental differences, very few guidelines for research planning exist. The available literature generally addresses the effects of residue management systems on surface runoff, with no indication of how water movement within the soil profile or water balance between surface and subsurface flow is affected (Dabney et al., 1992; McGregor et al., 1990). Limited information exists on water movement and water quality on and within the fragipan-type soils of southeast United States (Schreiber and Cullum, 1998; McGregor et al., 1999, 2000; Rhoton, 2000; Cullum et al., 2000, 2007).

This experiment was conducted to assess the tillage effects on maize (*Zea mays* L.) yields and to evaluate agrichemical losses in runoff and shallow groundwater from these different tillage practices. Information from this experiment is needed to assist in development of better conservation tillage systems and agrichemical application practices. An understanding of the impact of growing maize on soils possessing a shallow fragipan through conservation-till methods as compared with conventional-till methods will also help crop producers, crop advisors, and government policy makers to make better informed management and legislative decisions related to tillage options. Therefore, this study tests the hypothesis that neither no-tillage nor reduced-tillage has the same effect on maize crop as conventional-tillage on soils with a shallow water restricted layer.

2. Materials and methods

The study site in the upland hills of northern Mississippi at the Mississippi Agricultural and Forestry Experiment Station (MAFES) at Holly Springs consisted of sloping loess soils (4–6%) belonging to the Loring (Typic Fragiudalfs) series. The fragipan, a restrictive layer which prevents downward water movement and root penetration, was located approximately 45 to 50 cm below the soil surface. This restrictive layer also causes an intermittent perched water table during months of high rainfall. This fragipan is a naturally occurring subsurface horizon generally characterized by high bulk density, very low hydraulic conductivity, brittleness, and the absence of fine feeder roots in the brittle portion (Soil Survey Staff, 1975). The site had been planted with maize using conventional tillage for several years prior to 1990. In 1990, the plots were fallowed during construction of the sampling and data acquisition system (Cullum et al., 1992).

Plots with different tillage management practices were constructed with water measuring devices and planted in maize to determine yield and assess agrichemical movement and losses. Maize (Pioneer No. 3157) was planted mid-April at a rate of one seed per 18 cm or about 54,363 seeds/ha. Maize was harvested mid-September of each year of study. One 22-m row of maize from each plot was harvested by hand to determine maize yields. Moisture of maize was determined by standard procedures through oven drying. Maize weights were measured with a weighing scale and adjusted to 15% moisture to obtain maize yields.

The effect of tillage practice on maize yield was evaluated during the 1991 through 1996 growing seasons. Descriptions of the tillage practices were:

(1) NT – crop was slot-planted using bubble coulters and double-disk openers, no row cultivation, harvested, and stalks shredded,
(2) RT – plant crop with above planter, row cultivate twice during May, harvest, and shred stalks, and
(3) CT – plant crop following chisel/disk preparation to 15 cm depth, row cultivate twice during May, harvest, and shred stalks.

Fertilizer was applied at a rate of 563 kg/ha in the formulation of 13–13–13. Maize yield was analyzed as a two-factor randomized complete block design with type of tillage and year being the two factors.

Pesticides were evaluated in shallow ($\leq$3 m) groundwater and runoff from NT, RT, and CT maize plots during 1991 to 1994. Herbicides that included atrazine, alachor, cyanazine [2-(4-chloro-6-ethylamino-1,3,5-triazin-2-ylamino)-2-methylpropionitrile], and insecticides that included chlorpyrifos (O,O-diethyl O-3,5,6-trichloro-2-pyridyl phosphorothioate), and tefluthrin [2,3,5,6-tetrafluoro-4-methylbenzyl (1RS,3RS)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropanecarboxylate] were annually applied at 1.12, 2.24, 1.68, 1.12, and 0.11 kg/ha, respectively. Even though cyanazine has been off the U.S. market for a number of years, this chemical was in use in the U.S. during this study period and might still be prevalent in other countries.

Main components for shallow groundwater monitoring included six hydrologically isolated continuous maize plots (8.1-m wide by 38.1-m long) with subsurface drains (installed by horizontal drilling) placed just above the fragipan surface; drain outlets into sumps equipped with tipping buckets mounted in 18.9-L containers; composite wastewater samplers; dataloggers for data collection and control; and a series of observation wells ranging from 0.3 to 3-m depths positioned in one row of each main maize plot. Dataloggers recorded groundwater discharge during storm events and activated the wastewater samplers when the cumulative discharge equaled 0.250 mm. Groundwater incremental discharge and total discharge were recorded and the composite of the weighted-discharge samples was analyzed for specific chemicals introduced as pesticides. Following major storm events, water samples were collected from the observation wells for chemical analysis after depth measurements were made. Further description and methodology can be found in Cullum et al. (1992).

Main components for surface runoff from subplots (4-m wide by 22-m long) within the above maize plots included collectors, approaches, and H-flumes equipped with portable liquid-level

recorders and potentiometers, runoff splitters, dataloggers, and composite wastewater samplers (described by Cullum et al., 1992). The dataloggers recorded rainfall and runoff every minute during storm events. Wastewater samplers were activated by the dataloggers at each one mm of cumulative discharge. Incremental discharge rate, cumulative discharge, sediment loads, and water quality associated with surface runoff were obtained for each storm or group of storms.

Soil water contents were evaluated for each tillage system by using time domain reflectometry (TDR). Four sets of probes (buriable wave guides) were vertically inserted into the soil spaced 90 cm apart in one maize row of each of the six plots at depths of 0–10 cm, 10–20 cm, 20–40 cm and 40–60 cm. The 24 implanted soil probes were connected into the multiplex port of the TDR unit. The TDR unit was programmed to obtain dielectric constants and soil water contents from each probe on a 12-h interval each day during the 1993 water year (Oct 1, 1992 to Sept 30, 1993).

Shallow groundwater and runoff samples were collected after each major storm event and transported to the USDA-ARS National Sedimentation Laboratory and stored in walk-in cooler until analyzed. Chilled shallow groundwater and runoff samples were prepared for pesticide analysis by a method similar to that reported by Bennett et al. (2000) and modified by Smith and Cooper (2004). Runoff samples were separated into water and sediment phases by ultrafiltration. Sediment concentrations in shallow groundwater were negligible. Water processing involved extraction with pesticide-grade ethyl acetate, silica gel column chromatography cleanup, and concentration to 1 mL volume under high purity dry nitrogen. Pesticide recoveries based on fortified samples were >89% for all pesticides.

Two Hewlett Packard (now Agilent) model 6890 gas chromatographs each equipped with dual HP 7683 ALS autoinjectors, dual split-splitless inlets, dual capillary columns, an HP Kayak XA Chemstation were used to conduct all pesticide analyses (Smith and Cooper, 2004). One HP 6890 was equipped with two HP micro electron capture detectors (μECDs) and the other 6890, with one HP μECD, one HP nitrogen phosphorus detector (NPD), and an HP 5973 mass selective detector (MSD).

3. Results and discussion

Amount, timing, and distribution of rainfall were found to be the most common factors influencing agrichemical movement in the study. Illustrations of the pesticide losses attributed to tillage treatments are displayed for the 1993 crop year in Figs. 1 and 2. Results from the 1993 crop year (planting through harvest) showed that all five pesticides applied to the maize plots appeared in both the water and sediment phases of runoff. Total crop year runoff from NT and RT maize was 64 ± 9 and 75 ± 7 mm, respectively; whereas that from CT maize was about 3 times greater at 206 ± 13 mm. This likely resulted from higher crop residue levels on the surface in the NT and RT plots compared with the CT plots. The higher surface residue levels in NT and RT systems reduced impact of rainfall, velocity of overland flow, and consequently reducing the runoff. The surface residues as a barrier probably provided a restricted rate of infiltration which did not exceed the soil's infiltration capacity. Consequently, pesticide losses in the water phase of runoff from the three tillage treatments followed the order CT > RT > NT as displayed in Fig. 1. As a pesticide class, herbicide losses in the water phase of runoff were higher than insecticide losses, primarily due to the herbicides' higher water solubilities. Of the herbicides, however, atrazine losses were greater than those of alachlor. Even though atrazine's water solubility is less than that of alachlor, its half-life is about 4 times longer.

Herbicide losses in the water phase of runoff were independent of tillage practice. This result was true even though NT reduced sediment concentrations in runoff by about two orders of magnitude compared with CT. Herbicide losses in the sediment phase of runoff were low even with CT, where sediment concentrations in runoff reached 50,000 ppm or higher. In contrast, reductions in water phase runoff losses of the relatively water soluble herbicides of atrazine, alachlor, and cyanazine in NT and RT maize compared with CT maize were observed (Smith et al., 1994). These reductions in herbicide losses were attributed to reductions in runoff volumes in NT and RT maize. These same two tillage practices appeared to facilitate greater herbicide leaching into the soil profile in shallow groundwater, likely the result of the formation of conducting macropores and biochannels produced by soil faunal activity in these practices.

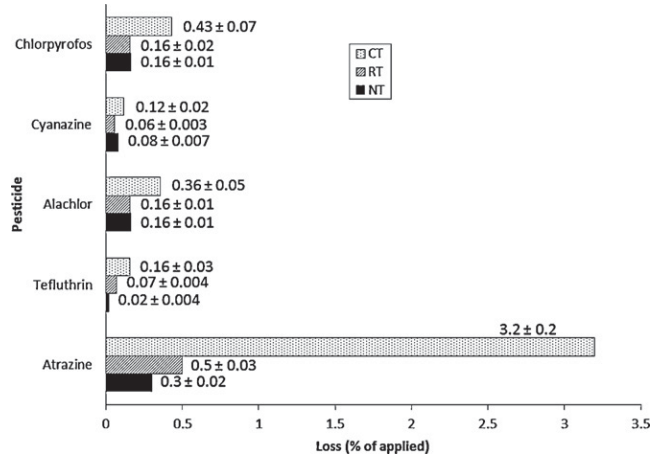

Fig. 1. Pesticide losses in the water phase of runoff from the three tillage systems.

Atrazine concentrations in the groundwater in the observation wells at the 3-m depth are shown in Fig. 2. During the crop year, five groundwater-producing rainfall events occurred after atrazine application (i.e., 2, 14, 21, 29, 167 days after application). During the first three weeks after application, atrazine concentrations for all three tillage treatments were about the same, averaging about 16, 18, and 20 $\mu g\,L^{-1}$ (ppb) for the NT, RT, and CT treatments, respectively. However, 29 days after application, atrazine concentrations reached their highest levels in the NT and RT treatments (94 and 54 ppb) and were about 6 and 3 times the concentration in the CT treatment (16 ppb), indicating increased infiltration in the NT and RT treatments. The last groundwater-producing rainfall event during the crop year (167 days after

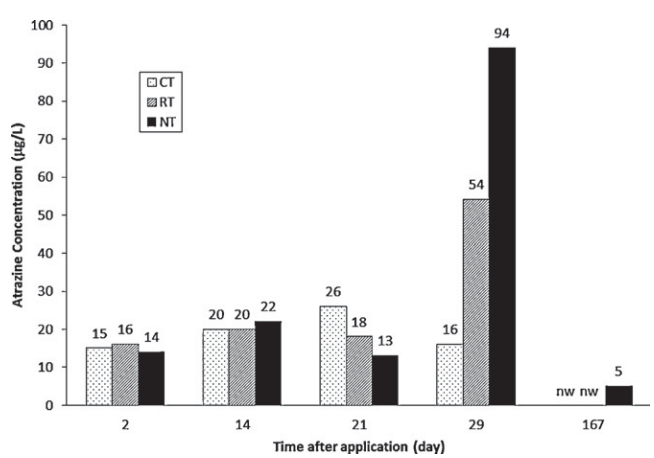

Fig. 2. Atrazine concentrations in groundwater in the observation wells at the 3-m depth.

Table 1
Average drainage volumes and percent of rainfall for each tillage system during three time periods for the calendar years of 1994 and 1995.

Yield (kg/ha)	Year					
	1991	1992	1993	1994	1995	1996
NT	6030	9375	8256	7935	6688	3344
RT	5470	7990	6454	5975	5827	2914
CT	4621	9185	6590	8265	7879	4937

		Year					
Rainfall (mm)	Norm	1991	1992	1993	1994	1995	1996
Water year rainfall	1391	2100	1660	1244	1514	1198	1318
April 15 to September 15	541	958	685	514	667	598	553
April 15 to April 30	72	261	51	77	55	71	54
May	139	330	42	77	98	121	146
June	83	173	229	57	273	35	118
July	109	67	215	107	116	189	84
Aug	90	88	133	156	100	175	33
September 1 to September 15	48	39	15	39	25	8	118

application) resulted in groundwater only in the NT treatment with atrazine at very low concentrations (5 ppb).

The effects of tillage practices on amounts of subsurface water flow on the fragipan surface were evaluated during 1994 and 1995. Rainfall patterns for these two years were slightly above and slightly below the normal, respectively. Tipping bucket data, summarized in Table 1, denoted the amount of subsurface water flow from the drains of each maize plot. The number of one-mm tips for each drain was averaged by tillage practice, converted to runoff volumes, and compared for before, during, and after the growing season with the growing season being from Julian date 107 (planting) to Julian date 229 (harvest). Rainfall for the area also was shown in Table 1. Since each tip represented 32 ml of water and the drainage area was 66 m^2, drainage could also be expressed as a percentage of rainfall (Table 1). The NT drainage was 1.65 and 5.1 times higher than the CT and RT drainage, respectively, for the before-the-growing-season periods. Lateral flow of water across the top surface of the fragipan was insignificant during each cropping season for all tillage systems. All tillage systems showed almost no drainage during the growing season for the two years. After harvest, the soil profile returned to near saturation during the two years with increase in drainage. Even though the numbers in Table 1 after the growing season were lower than before the growing season period, the NT drainage was 2.25 and 6.4 times greater than the CT and RT drainage, respectively. Free water often was perched above the fragipan intermittently from November through April during periods of soil profile saturation, and probably moved down-slope across the fragipan's surface.

Total runoff was evaluated for the 1991 through 1994 water years (Oct 1–Sept 30). These years provided a range in moisture conditions from drought to excessive rainfall during the crop growing seasons according to the monthly rainfall data for the area

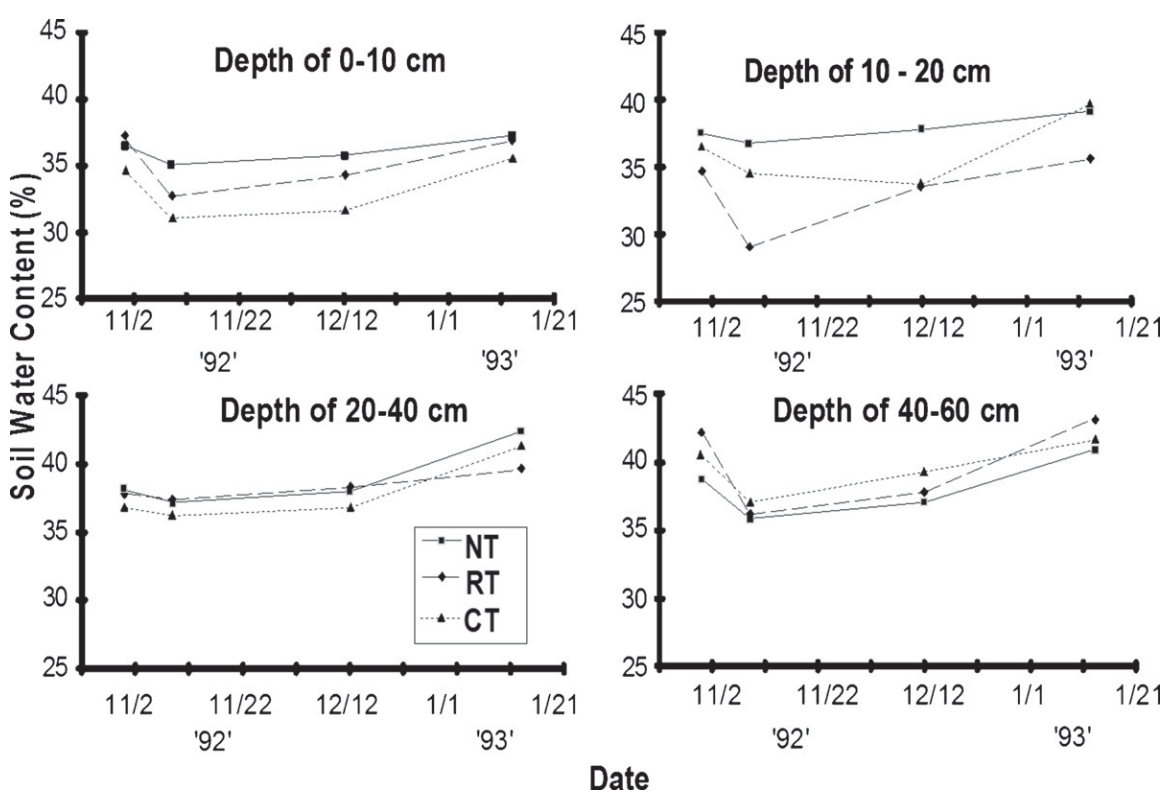

Fig. 3. Mean soil water content for the three tillage operations at four depths in the corn experiment during the winter of 1992.

Table 2
Analysis of variance and least significance differences of two-factor randomized complete block design on corn yield in tillage experiment.

Source	Analysis of variance on maize yield (kg/ha)			
	deg freedom	Mean square	*F*-value	Pr > F
Replication	1	2,461,656	8.67	0.1712
Tillage	2	4,470,353	15.74	0.0497
Error A	2	283,953		
Year	5	13,326,261	43.61	0.0001
Tillage × Year	10	1,005,794	3.29	0.0186
Error B	15	305,586		

Source	Least significant difference (LSD) analysis	
	Mean (kg/ha)	Groups[†]
Tillage		
NT	7179	A
CT	6906	AB
RT	6012	B
LSD = 936; mean square error = 283954; observations = 12		
Year		
1991	5374	C
1992	8850	A
1993	7100	B
1994	7392	B
1995	6798	B
1996	4682	D
LSD = 680.3; mean square error = 305,586; observations = 6		

[†] Items with same letter are not significantly different from each other tested at $\alpha = 0.05$.

from the National Oceanic and Atmospheric Administration. Total runoff as percentage of total rainfall for the NT, RT, and CT systems was 56, 27, and 62 for 1991; 14, 29, and 38 for 1992; 14, 19, and 38 for 1993; and 12, 16, and 56 for 1994. From this study, the 1992 water year produced approximately 30% greater sediment losses in the CT treatment than the NT treatment. Most differences occurred with the first rainfall events after planting when CT treatment was most vulnerable to erosion because of less surface residues. These trends were exhibited again in 1993 and 1994. Due to the establishment of the tillage plots in 1991, the differences in runoff for that year were not the result of the tillage treatment and were reported to show differences due to spatial variation in the plots.

Time domain reflectometry measurements were used to determine the mean soil water contents during the non-growing and growing seasons of water year 1993. During the non-growing season, the deeper probes were showing wetter soils for each date, probably due to the influence of the fragipan layer that underlies this area. The NT soil water contents generally were higher than CT at the 0 to 10 cm and 10 to 20 cm profiles (Fig. 3) because of the cooler soils resulting from the greater amounts of residue cover in the no-till. The relatively high readings of 35% to 40% for soil water content also showed that the soil profiles were near saturation. During the growing season before crop canopy closure, the NT soil water contents generally were 5% higher than CT at the 0–10 cm and 10–20 cm profiles attributed to the residue shading effect of the soil surface which would reduce evaporation losses. After closure of the crop canopy, little differences in soil water could be detected by the time domain reflectometry measurements.

An analysis of variance (ANOVA) on maize yield (Table 2) further showed tillage, year, and the tillage-year interaction to be significant factors on yield at the 95% probability level (alpha = 0.05). Least significant difference (LSD) was performed on the three means for tillage and six means for year. The LSD analysis for tillage indicated the yield average for both NT and CT were not statistically different. Both RT and CT were not statistically different, which possibly results from the tillage systems' available soil water and weed control. Interaction of tillage and year on average maize yields are presented in Table 3. The NT maize yields were 30%, 2%, and 25% greater than the CT maize yields in 1991, 1992, and 1993, respectively. The CT maize yields were 4%, 17% and 48% greater than the NT maize yields in 1994, 1995, and 1996 respectively. Also, the CT maize yields were slightly affected by drought conditions during 1992 and 1993. Rainfall from mid-April through May (maize planting and germination period) was 118 mm and 57 mm below normal for the respective year. In both years, the NT maize yields performed better than the CT maize yields. If proper weed control can be established, the NT would produce higher yields than the CT on these soil types due to soil water conservation. Inadequate weed control occurred in 1994 through 1996, as well as slightly above-normal rainfall during growing season, resulting in lower NT maize yields as compared with CT yields (Table 3). Lower yields from the RT system with time as compared with both CT and NT systems showed the response to both inadequate weed control and lack of conservation of soil water with row cultivation twice in May.

4. Conclusions

A six-year study with continuous maize was conducted that compared maize yields from NT, RT, and CT on 4–6% sloping soils overlying a shallow fragipan at the Mississippi Agricultural and Forestry Experiment Station at Holly Springs. Conservation tillage had less detrimental effects on the quality of runoff and shallow groundwater and promoted more soil water for crop use during the growing season than conventional tillage. With adequate weed

Table 3
Table of means for maize yields as affected by tillage along with annual and seasonal rainfall.

Yield (kg/ha)	Year					
	1991	1992	1993	1994	1995	1996
NT	6030	9375	8256	7935	6688	3344
RT	5470	7990	6454	5975	5827	2914
CT	4621	9185	6590	8265	7879	4937

Rainfall (mm)	Long-term Average (50 years)	Year					
		1991	1992	1993	1994	1995	1996
Water year rainfall	1391	2100	1660	1244	1514	1198	1318
April 15 to September 15	541	958	685	514	667	598	553
April 15 to April 30	72	261	51	77	55	71	54
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June	83	173	229	57	273	35	118
July	109	67	215	107	116	189	84
August	90	88	133	156	100	175	33
September 1 to September 15	48	39	15	39	25	8	118

control, NT produced higher yields than CT on these Loring soils due to soil water conservation. Significant differences in maize yield were found for type of tillage, year, and tillage-year interaction with these differences being explained by a tillage system's ability to conserve soil water and control weeds. Other results included low sediment concentrations found from NT maize plots and insignificant free water quantities at the fragipan's surface during the cropping season for all tillage systems with limited downward or lateral water movement and thus no agrichemical movement.

Amount and distribution of rainfall rather than tillage system were found to be the most common factors in influencing agrichemical movement from the maize systems for this study. Rainfall timing relative to agrichemical application was an important factor for agrichemical transport. Atrazine, alachor, cyanazine, chlorpyrifos, and tefluthrin were found in the first runoff events after application, and three herbicides appeared in the first shallow groundwater of the first major storm event after application.

Recommendations to attack the weed problem in the conservation tillage practice would be to rotate herbicides in future years and use Roundup Ready maize which could provide better weed control while using alachor and atrazine as a pre-emergence and Roundup as a post-emergence. Weed species will shift over time when a set herbicide program is followed in no-till practices. By addressing the weed problems in the no-till or reduced-till systems, higher maize yields would be achieved through better soil water management than in conventional-till systems. Also, ground cover in the no-till systems would aid in reducing erosion from these sloping fields thus enhancing the long-term productivity of these soils.

Some form of conservation tillage that decreases or prevents erosion will be required on sloping lands with shallow fragipan to sustain long term continuous corn production. Information from this study provides additional guidance for making tillage and pesticide management recommendations to farmers.

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All programs and services of the U. S. Department of Agriculture are offered on a nondiscriminatory basis without regard to race, color, national origin, religion, sex, marital status, or handicap. Mention of a pesticide in this paper does not constitute a recommendation for use by the U. S. Department of Agriculture nor does it imply registration under FIFRA as amended. Names of commercial products are included for the benefit of the reader and do not imply endorsement or preferential treatment by the U.S. Department of Agriculture.

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