Tillage effects on rainfall partitioning and sediment yield from an ultisol in central Alabama

C.C. Truman, J.N. Shaw, and D.W. Reeves

ABSTRACT: Coastal Plain soils in the Southeast have been intensively cropped, traditionally managed under conventional tillage practices, and are susceptible to erosion. Conservation tillage systems have significant potential as a management tool for row crop production, especially on sandy surface soils of the Coastal Plain because they reduce soil loss and conserve water. We quantified rainfall partitioning and sediment delivery from a Plinthic Paledudult-Typic Hapludult soil complex (loamy sand surface) located in the Coastal Plain region of Alabama managed under conventional- and no-till systems for 10 years. Conventional till and no-till treatments were evaluated with and without surface (Black Oat, *Avena strigosa* Schreb.) residue (0-9600 kg ha^{-1}) and with and without paratilling (non-inversion subsoiling to 40 cm). Field plots (~60 m^2) represented eight treatment combinations, two tillage treatments (conventional till, no-till), two residue management treatments, residue removed or left in place (+R), and two non-inversion, deep tillage treatments, paratilled, non-paratilled, with each treatment combination replicated four times. Two 1-m^2 rainfall simulator plots were established on one tillage-residue-deep tillage treatment replicate. Each 1-m^2 plot received 2 h of simulated rainfall (50 mm h^{-1}). Runoff and sediment delivery were continuously measured from each flat, level-sloping 1-m^2 plot (slope = 1 percent). No-till plots had at least two times less runoff and four times less sediment delivery compared to conventional till plots. Runoff was greatest for conventional till, residue removed, non-paratilled plots (58 percent of the rainfall amount), and lowest for no-till, residue left in place, paratilled plots (4 percent of the rainfall amount). About 42 percent of the rainfall infiltrated in the conventional till, residue removed, non-paratilled plots (worst-case scenario) compared to about 96 percent for the no-till, residue left in place, paratilled plots (best-case scenario), resulting in only 2.8 days of water for crop use in conventional till, residue removed, non-paratilled plots and 6.9 days of water for crop use in no-till, residue left in place, paratilled plots (2.5-fold difference). Removing residue resulted in 18 percent more runoff as a rainfall percentage (18 percent less infiltration) for no-till plots and 25 percent more runoff (25 percent less infiltration) for conventional till plots, and accounted for 38 to 76 percent of the differences in runoff and sediment transported from no-till and conventional till plots. For conventional till and no-till plots, removing surface residue increased sediment yields by 1.5 and 7 times. Paratilling resulted in 10 percent less runoff as a rainfall percentage (10 percent more infiltration) for no-till plots and 26 percent less runoff (26 percent more infiltration) for conventional till plots. Compared to non-paratilled conventional till and no-till plots, paratilling caused runoff rates to increase at a slower rate, and increased steady-state runoff rates by 40 percent and 400 percent, respectively. Paratilling reduced bulk density (0 to 12 cm) and soil strength 0 to 50 cm) by at least 15 percent compared to non-paratilled treatments. Combining residue management and paratilling through conservation tillage in row-crop agriculture in the Coastal Plain region of Alabama reduces runoff and soil loss for conventional till and no-till systems by improving soil properties and maintaining infiltration, resulting in increased estimates of plant available water.

Keywords: Infiltration, paratill, residue, runoff, simulated rainfall, water conservation

Coastal Plain soils in the Southeast have traditionally been intensively cropped under conventional (disk, chisel plow, in-row subsoiling, field cultivate) tillage systems. These highly-weathered soils have relatively sandy surfaces, tend to be drought-prone, and are susceptible to compaction/consolidation and erosion. Runoff from these soils reduces crop productivity and transports pollutants (sediments, nutrients, pesticides) to off-site areas.

Conservation tillage systems have significant potential as a management tool for row crop production in the Coastal Plain region because they reduce erosion and runoff, and increase infiltration and soil water holding capacity (Yoo and Touchton, 1988; Blevins et al., 1990; Seta et al., 1993; Edwards et al., 1993; Gaynor and Findlay, 1995; Potter et al., 1995). These benefits are attributed in large part to increased residue and organic matter accumulation at the soil surface (Edwards et al., 1992; Langdale et al., 1992; Reeves, 1997), which dissipates rainfall energy by raindrop interception, increases aggregate stability and soil resistance to raindrop impact, and decreases water dispersible clay (Blevins et al., 1990; McGregor et al., 1990; Shaw et al., 2002). However, some studies have shown that differences in runoff from conventional- and conservation-till systems were either negligible (McGregor et al., 1975; Siemens and Oschwald, 1976; Lindstrom et al., 1981; Laflen and Colvin, 1981) or that less runoff (more infiltration) occurs from conventional-till systems than from conservation-till systems (Moldenhauer et al., 1971; Lindstrom and Ontad, 1984; Mueller et al., 1984; Heard et al., 1988; Soileau et al., 1994; Cassel and Wagger, 1996), especially 1 to 3 years after reduced tillage adoption. These results have been attributed to increased soil density due to consolidation or compaction (NeSmith et al., 1987; Radcliffe et al., 1988). In the Southeastern United States, equipment traffic, implement action, and natural consolidation readily compact these weakly-structured surface soils and deep tillage is necessary

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to disrupt compacted zones (Campbell et al., 1974; Reeves and Touchton, 1986; Vepraskas et al., 1987; Reeves and Mullins, 1995).

A non-inversion, deep tillage technique often used in the Southeast is paratilling. Paratilling reduces bulk density and cone index (20 to 40 cm depth) (Bicki and Guo, 1991; Pierce and Burpee, 1995; Truman et al., 2003), and increases infiltration and decreases erosion (Sojka et al., 1993; Rawitz et al., 1994; Truman et al., 2003). However, in the Piedmont region of Georgia, Clark et al. (1993) found that paratilling effects on infiltration and runoff decreased with time, lasting only 12 months. Similarly, in the Tennessee Valley region of Alabama, Truman et al. (2003) found that paratilling reduced runoff by 60 percent 13 months after paratilling and by 200 percent eight months after paratilling.

Our goal was to quantify differences in soil properties and hydraulic properties associated with adoption of conservation tillage systems in the Coastal Plain region of the Southeast, thus quantifying enhanced soil quality and conservation of soil and water resources. Our hypothesis was that differences in runoff, infiltration, and sediment delivery, resulting from tillage-residue-deep tillage management, would be largely due to the effects these management systems have on soil organic carbon, aggregate stability, residue cover, density, etc. of the near-surface soil. Therefore, we quantified the effect of tillage (conventional-till, no-till, and paratill) and residue management systems on runoff and soil loss from a Plinthic Paleudult-Typic Hapludult soil complex. Runoff and soil loss were measured from 1-m^2 field plots exposed to 2 hr of simulated rainfall (50 mm h^{-1}).

Materials and methods

Experimental site. The research site was located in the Coastal Plain region of central Alabama at the Alabama Agricultural Experiment Station's E.V. Smith Research center near Shorter, Alabama (N 32° 25', W 85° 54'). The soil complex is classified as coarse-loamy, siliceous, thermic, Plinthic Paleudult-Typic Hapludult. The Ap horizon (0 to 20 cm) had a sand (2 to 0.05 mm) content of 805 g kg^{-1} and clay (<0.002 mm) content of 42 g kg^{-1}.

Prior to this rainfall simulation study, the research site had been in long-term traffic and tillage studies (1988 to present). Details of past studies are given in Reeves et al. (1992; 2000). From 1988 to 1995, the site was a traffic and tillage study using a corn (*Zea mays* L.)—soybean [*Glycine max L.* (Merr.)] rotation, along with a winter cover crop of crimson clover (*Trifolium incarnatum* L.). During that period (1988 to 1995), tillage treatments consisted of disking, chisel plowing, in-row subsoiling, disking, and field cultivating for conventional tillage (conducted in spring), and strip-tillage, i.e., no-tillage with subsoiling (15-cm wide and 40-cm depth) under the row (row spacing = 76 cm). In the fall of 1995, all plots were paratilled to a depth of 40 cm and subsequently cropped to ultra-narrow row cotton (19 cm rows) in 1996 to 1997. Surface tillage-residue management treatments remained unchanged, thus maintaining the integrity of the conventional and conservation tillage treatments initiated in 1988 throughout the various cropping systems imposed on the site. White lupin (*Lupinus albus* L.) was grown in the winter of 1996 to 97 and black oat (*Avena strigosa* Schreb.) was grown during the winter of 1997 and 98. In the summer of 1998, the area was planted to sorghum-sudangrass [*Sorghum x drummondii* (Nees ex Steud.) Millsp. & Chase]. On 12 November 1998, the site was planted to black oat for seed production, and harvested on 2 June 1999. Black oat residue was mowed and evenly distributed with a flail mower following black oat seed harvest. For the rainfall simulation study, black oat residue was mowed and evenly distributed on four plots, and was removed from four plots just prior to simulating rainfall, thus long-term surface tillage treatments were maintained.

Eight plots (3-m wide by 21-m long) representing eight treatment combinations were chosen for the simulated rainfall study. The factorial arrangement making up the eight treatment combinations consisted of two long-term surface tillage treatments (conventional or no-tillage), two residue management treatments (residue removed or left in place), and two non-inversion, deep tillage treatments (paratilled or non-paratilled), with each treatment combination replicated four times. Residue was removed on four plots with a hay rake to simulate a grower baling oat straw after harvest. Conventional tillage was established on 7 July, 1999 by chisel plowing to a depth of 15-18 cm. Half the plots were then paratilled equipped with a smooth roller. The paratill® (Bigham Brothers, Inc., Lubbock, Texas) was equipped with six shanks on 61-cm spacings, and disrupted soil to about 40-cm. Therefore, the eight treatment combinations evaluated in this study with simulated rainfall were 1) conventional-till with residue and without paratilling (conventional till, residue left in place, non-paratilled), 2) conventional-till without residue and without paratilling (conventional till, residue removed, non-paratilled), 3) conventional-till with residue and with paratilling (conventional till, residue left in place, paratilled), 4) conventional-till without residue and with paratilling (conventional till, residue removed, paratilled), 5) no-till with residue and without paratilling (no-till, residue left in place, non-paratilled), 6) no-till without residue and without paratilling (no-till, residue removed, non-paratilled), 7) no-till with residue and with paratilling (no-till, residue left in place, paratilled), and 8) no-till without residue and with paratilling (no-till, residue removed, paratilled).

Soil sampling and measurements. Soil samples were taken at selected depths from random locations within each replication of each tillage-residue treatment. When possible, samples were collected in the immediate vicinity of areas designated for simulated rainfall subplots. Soil properties were determined with the following methods: particle size distributions measured by the pipette method (Kilmer and Alexander, 1949); soil organic carbon measured by the combustion method (Yeomans and Bremmer, 1991); aggregate stability measured by the water stable aggregate method (Kemper and Rosenau, 1986); and bulk density measured by the core method (Blake and Hartge, 1986).

For particle size distributions, samples were air-dried, crushed, and coarse fragments (> 2 mm) removed. Sand grains were separated into size fractions by sieving.

Soil organic carbon was determined from ten composite samples (20-mm diameter core) taken immediately adjacent to rainfall simulation subplots. Samples were divided into depth increments of 0-1, 1-3, 3-6, 6-12, and 12-18 cm depths. Samples were cleaned of recognizable organic debris and subsamples were finely ground on a roller mill (Kelly, 1994). Subsamples were analyzed for C by automated combustion using a NA 1500 NCS analyzer (Fisons Intruments Inc., Beverly, Massachusetts). Each ground subsample was subjected to four determinations for C analysis.

Percentage water stable aggregates from the 0 to 3 cm depth were determined from a composite sample taken from five locations immediately adjacent to areas designated for rainfall simulations using a modification of the procedure described by Kemper and Rosenau (1986). Due to the large sand content of this soil, 8-g samples of 1-2 mm air-dried aggregates were used rather than the 4-g sample size proposed by Kemper and Rosenau. Mean water stable aggregates (%) were determined from eight lab determinations from each composite sample per plot.

Bulk density was determined from samples (5.4-cm diameter cores) taken from three locations within each treatment combination plot immediately adjacent to areas designated for rainfall simulations. Densities were determined at the 0-15 15-30, and 30-45 cm depth intervals and were used to calculate porosity values.

Soil water content was determined gravimetrically (Gardner, 1986) from eight 20-mm diameter cores taken in the immediate vicinity around rainfall simulation plots. This border area received the same distribution of simulated rainfall as the test areas. Gravimetric soil water samples were taken immediately before and after each simulated rainfall event and were separated into 0-1, 1-3, 3-6, 6-9, 9-12, 12-18, and 18-24 cm depth increments.

Prior to simulating rainfall, a Remik CP 20 recording cone penetrometer (Agridry Rimik Pty Ltd, Toowoomba, Queensland, Australia, 4350) was used to record soil strengths from all plots. Twenty insertions, at 1.5-cm intervals to a depth of 50 cm, were randomly made within each plot, immediately outside areas designated for rainfall simulations. The soil profile was at about field capacity as a result of a 295 mm of natural rainfall occurring from black oat harvest to time of rainfall simulations, with 197 mm of this occurring during the 17 d period immediately prior to data collection.

Rainfall simulations. Duplicate (two) 1-m^2 plots were somewhat randomly established on one replicate of each tillage-residue-deep tillage treatment combination (eight plots) (13-17 July, 1999), given the limitation associated with border effects of each tillage-residue treatment, and were considered replicates. Rainfall simulations were not conducted on all tillage-residue-deep tillage treatment replicates because of the time-consuming and destructive nature of the simulations. Plots (1-m^2) were defined by aluminum framing 1-m wide by 1-m long by 10-cm tall. Each 1-m^2 plot had an aluminum collection trough on the down-slope end of each plot to collect runoff and soil loss. Each 1-m^2 plot had similar slopes (~1 percent). An area surrounding each 1-m^2 plot was treated like the test area to allow soil material to be splashed in all directions. Simulated rainfall was applied to each 1-m^2 plot at a target intensity (I) of 50 mm h^{-1} for 1 h. One hour after the end of the first simulated rainfall event, each 1-m^2 plot received an additional simulated rainfall event (50 mm h^{-1} for 1 h). Rainfall was applied with an oscillating nozzle rainfall simulator (Foster et al., 1982). The simulator uses 80100 Veejet nozzles that produce drops with a median drop size of about 2.3-mm. The rainfall simulator was placed 3 m above each 1-m^2 plot. Deep well water was used in all simulations, and had an average pH of 7.7 (cv = 0.6 percent) and EC of 0.002 S m^{-1} (cv = 1.4 percent).

Runoff water (R) and sediment yields (E) from each 1-m^2 plot were measured continuously at 5-min intervals during each simulated rainfall event. Runoff and E were collected in tared, 1-L Nalgene (autoclaveable) bottles, with time required to fill each bottle recorded. Bottles were weighed (bottle+water+sediment), dried at 105° C for 24 hr, then weighed again (bottle+sediment). Runoff and E were determined gravimetrically, and infiltration (INF) was calculated by difference (rainfall-runoff).

After simulating rainfall, all identifiable non-decomposed residue from each 1-m^2 plot was collected, dried at 80° C for 72 hr, cleaned of soil particles, and weighed. conventional till, residue left in place, paratilled plots had no identifiable residue on the soil surface following rainfall simulations.

Statistics. Unpaired t-tests were performed, and the probability level used in evaluating the test statistics was P = 0.05. Regression analysis was used to determine relationships between dependent and independent variables. Means and coefficient of variations (cv, percent) are given for measured data. All data analysis were conducted with corresponding functions in Corel WordPerfect Office 2000 QUATTRO Pro 9.

Results and Discussion

Runoff. Runoff, infiltration, and sediment yields for treatments and simulated rainfall events studied are presented in Table 1. Compared to conventional till plots, no-till plots had on average two times less total runoff for the first (0-60 min, R_{60}) and four times less total runoff for the second (60-120 min, R_{120}) simulated rainfall events, even though the target intensity was relatively constant (ave. I = 49 mm h^{-1}, cv = 8 percent for conventional till plots; ave. I = 53 mm h^{-1}, cv = 7 percent for no-till plots, NS) and gravimetric water content differences existed. Soil water (w, 0-1 cm) was 1.4-4.3 times greater for no-till plots compared to conventional till plots (P = 0.0009-0.0013). Runoff amounts were greatest for conventional till, residue removed, non-paratilled plots (R_{60} = 26 mm h^{-1}; R_{120} = 32 mm h^{-1}), and lowest for no-till, residue left in place plots (2 mm h^{-1} for R_{60} & R_{120}). The conventional till, residue removed, non-paratilled treatment is the "standard practice" for farmers in the Coastal Plain region of central Alabama, yet represents the greatest potential for runoff and soil losses (discussed below).

For conventional till plots, incorporating surface residue (~6000 kg ha^{-1}) in the top 18 cm and paratilling to ~ 40 cm (conventional till, residue left in place, paratilled) decreased runoff 8-fold during the first event (R_{60}, 3 vs. 26 mm h^{-1}) (P = 0.0042) and 2.6-fold during the second event (R_{120}, 12 vs. 32 mm h^{-1}) (P = 0.0022) compared to conventional till, residue removed, non-paratilled plots. Thus, corresponding differences between runoff as a percent of rainfall for the first (R_{60}, percent) and second (R_{120}, percent) events for conventional till, residue removed, non-paratilled and conventional till, residue left in place, paratilled plots were 54 and 47 percent, respectively. Similar results were obtained for R_{60} (2 vs. 10 mm h^{-1}, P = 0.0179) and R_{120} (2 vs. 25 mm h^{-1}, P = 0.0018) values from no-till plots, with corresponding differences between R_{60} and R_{120} (percent) values for no-till, residue removed, non-paratilled and no-till, residue left in place, paratilled plots equaling 15 and 42 percent respectively. Runoff (R_{60} and R_{120}, percent) increased in order: conventional till, residue left in place, paratilled < conventional till, residue removed, paratilled < conventional till, residue left in place, non-paratilled < conventional till, residue removed, non-paratilled, with similar results obtained for no-till plots. For paratilled and non-paratilled conventional till and no-till plots, removing surface residue increased R_{60} and R_{120} (mm h^{-1}) values by 1.5 and 10.6 times (P = 0.0022, P = 0.0476). Removing surface residue from non-paratilled conventional till plots had the greatest impact on R_{60} values (6 vs. 26 mm

Table 1. Runoff (R), infiltration (INF), and sediment (E) losses for the first (0-60 min) and second (60-120 min) simulated rainfall events.

Treatment[a]	R_{60}[b]	R_{60}	R_{max}	INF_{60}	INF_{min}	INF_{60}	E_{60}	w
	mm h^{-1}	%	mm h^{-1}	mm h^{-1}	mm h^{-1}	%	g	%
NT-R-P	10.9 (11)[c]	19		45.8 (03)	40.1 (11)	81	78 (12)	14.5 [67.4]
NT-R+P	4.7 (01)	9		45.1 (00)	42.4 (00)	91	84 (00)	16.6 [66.8]
NT+R-P	1.6 (13)	3		47.3 (00)	47.1 (01)	97	8 (04)	13.8 [67.5]
NT+R+P	2.0 (06)	4		53.6 (00)	53.5 (00)	97	12 (22)	13.3 [44.4]
CT-R-P	26.5 (06)	61		17.0 (09)	11.8 (15)	39	194 (14)	8.4 [29.7]
CT-R+P	6.0 (18)	11		48.8 (02)	43.1 (04)	89	96 (02)	0.3 [1.3]
CT+R-P	6.0 (38)	13		40.1 (06)	32.9 (25)	87	104 (11)	0.9 [3.9]
CT+R+P	3.3 (05)	7		45.5 (00)	44.1 (00)	93	78 (05)	3.9 [15.5]
Treatment	R_{120}	R_{120}	R_{max}	INF_{120}	INF_{min}	INF_{120}	E_{120}	w
	mm h^{-1}	%	mm h^{-1}	mm h^{-1}	mm h^{-1}	%	g	%
NT-R-P	25.5 (04)	45	35.0 (9)	31.0 (03)	22.9 (23)	55	71 (30)	24.3 [80.8]
NT-R+P	7.3 (16)	15	9.4 (17)	41.8 (03)	39.8 (06)	85	75 (07)	21.1 [85.0]
NT+R-P	2.4 (33)	7	7.1 (56)	46.1 (02)	42.5 (13)	93	11 (39)	24.2 [96.3]
NT+R+P	2.0 (06)	3	2.6 (15)	56.0 (01)	55.9 (01)	96	14 (01)	22.0 [73.8]
CT-R-P	32.3 (03)	72	35.1 (03)	12.4 (07)	9.6 (17)	28	181 (06)	15.2 [53.7]
CT-R+P	22.8 (18)	42	27.6 (15)	32.1 (13)	27.2 (21)	59	127 (12)	16.9 [63.9]
CT+R-P	20.7 (12)	42	26.4 (10)	28.5 (08)	22.9 (17)	58	131 (07)	24.2 [96.3]
CT+R+P	12.2 (00)	25	18.2 (02)	33.7 (08)	27.7 (13)	69	86 (11)	18.2 [72.2]

[a] NT = no surface tillage; CT=conventional-till; R=residue; P=paratill.

[b] Rainfall intensity = 50 mm h^{-1}. R_{60}, INF_{60}, (mm h^{-1}), and E_{60} (g) are runoff, infiltration, and sediment losses for the 0-60 min time period, respectively. R_{120}, INF_{120} (mm h^{-1}), and E_{120} (g) are runoff, infiltration, and sediment losses for the 60-120 min time period, respectively. R_{60}, INF_{60} (%) and R_{120} and INF_{120} (%) are percentages of rainfall that was runoff and infiltration for the 0-60 min and 60-120 min time periods, respectively. R_{max} (mm h^{-1}) values and maximum runoff rates (all occurred in the 60-120 min time period. INF_{min} (mm h^{-1}) values are minimum infiltration rates for each simulated rainfall event. Gravimetric water content (w) is given for the 0-1 cm depth prior to simulating rainfall. Values in brackets, [ ], are water contents expressed as a percent of porosity.

[c] Values in parenthesis are coefficients of variations (%).

h^{-1}) (P = 0.0172), whereas removing residue from paratilled and non-paratilled no-till plots significantly impacted both R_{60} and R_{120} values (P = 0.0022-0.0444). The greatest impact of residue removal on runoff was for non-paratilled no-till plots R_{120} values (2 vs. 25 mm h^{-1}, P = 0.0033). Impact of residue removal was greater on no-till plots than on conventional till plots.

In general, paratilling numerically decreased R_{60} and R_{120} values for conventional till and no-till plots with and without surface residue, with a trend toward a greater impact on conventional till plots compared to no-till plots. Also, paratilling tended to have a greater impact on conventional till and no-till plots without residue compared to corresponding plots with residue. Paratilling, conventional till, residue removed plots had the greatest impact on R_{60} values (6 vs. 26 mm h^{-1}, 4-fold difference, P = 0.0080), whereas paratilling, no-till, residue removed plots had the greatest impact on R_{120} values (7 vs. 25 mm h^{-1}, 3.5-fold difference, P = 0.0069).

Runoff rates generally increased through the first simulated rainfall event (0-60 min), then reached steady-state runoff rates during the second (60-120 min) simulated rainfall event (Figure 1). Residue management and paratilling significantly reduced runoff rates for conventional till and no-till plots. Steady-state runoff rates for conventional till, residue removed, non-paratilled plots (worst case scenario) were greatest (33 mm h^{-1}), while steady-state runoff rates for no-till, +R, paratilled (best case scenario) were the lowest (~ 3 mm h^{-1}) (Figure 1A). Also, maximum runoff rates (R_{max}) for conventional till, residue removed, non-paratilled (35 mm h^{-1}) and no-till, residue removed, non-paratilled (35 mm h^{-1}) plots were ~2 and 13 times greater than those for conventional till, residue left in place, paratilled (18 mm h^{-1}) (P = 0.0048) and no-till, residue left in place, paratilled (2 mm h^{-1}) (P = 0.0090), respectively (Figure 1A, Table 1). Because residue effects were more pronounced for non-paratilled conventional till and no-till plots, we used conventional till, residue left in place, non-paratilled; conventional till, residue removed, non-paratilled; no-till, residue left in place, non-paratilled; and no-till, residue removed, non-paratilled plots to illustrate residue effects on runoff rates (Figure 1B). Removing residue caused runoff rate curves to increase at a faster rate than those from plots where residue remained in place, and increased steady-state runoff rates by ~25 mm h^{-1} for no-till plots and by ~10 mm h^{-1} for conventional till plots. Also, R_{max} values for conventional till, residue removed, non-paratilled (35 mm h^{-1}) and no-till, residue removed, non-paratilled (35 mm h^{-1}) plots were 1.3 (32 percent) and 4.9 times greater than those for conventional till, residue left in place, non-paratilled (26 mm h^{-1}) (P = 0.1006) and no-till, residue left in place, non-paratilled (7 mm h^{-1}) (P = 0.0313), respectively (Figure 1B, Table 1).

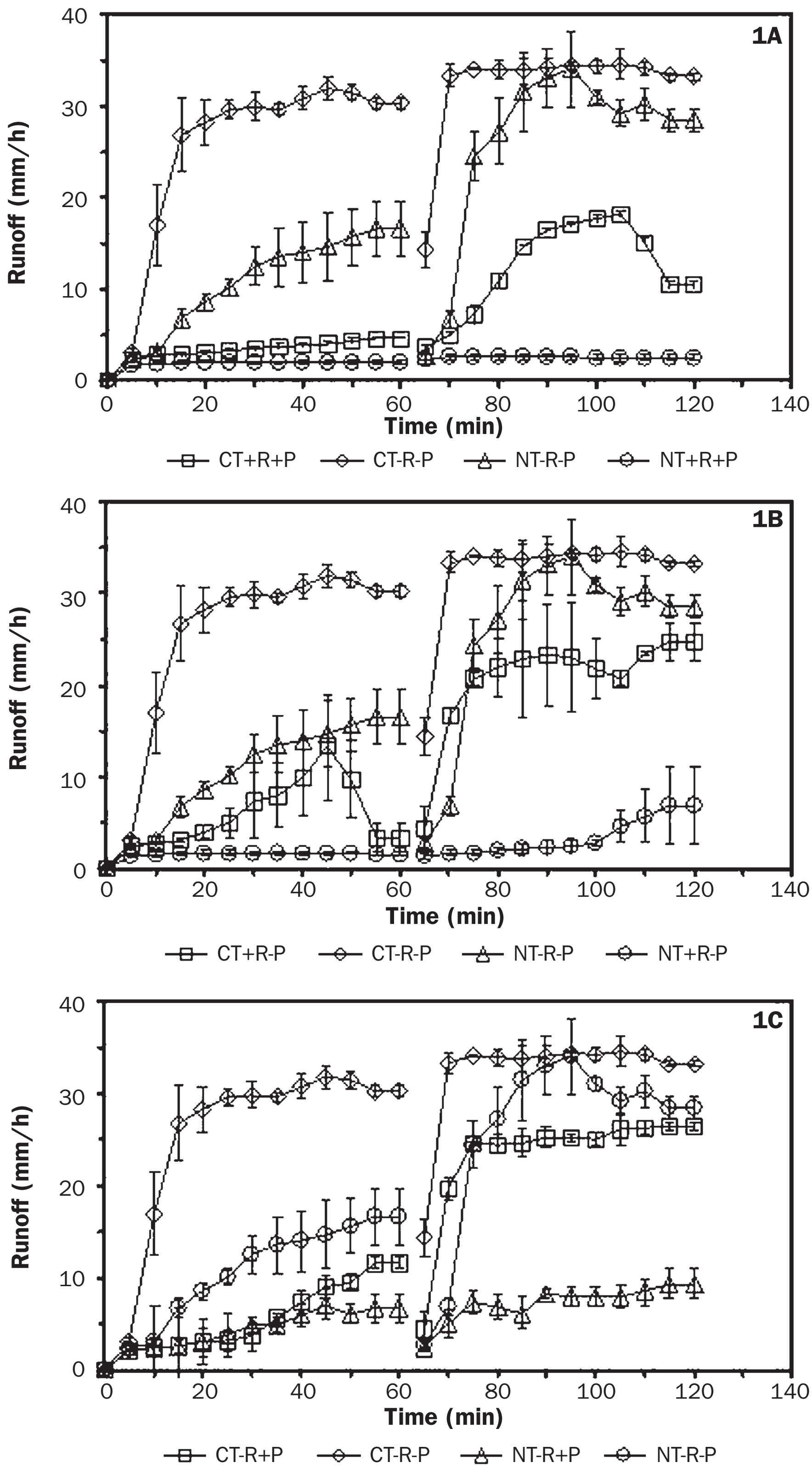
Because paratilling effects were more pronounced for conventional till and no-till plots without residue, we used conventional till, residue removed, paratilled, conventional till, residue removed, non-paratilled; no-till, residue removed, paratilled; and no-till, residue removed, non-paratilled plots to illustrate paratilling effects on runoff rates (Figure 1C). Paratilling caused runoff rate curves to increase at a slower rate than those from non-paratilled plots. Steady-state runoff rates for non-paratilled plots without residue increased by ~20 mm h^{-1} for no-till plots and by ~10 mm h^{-1} for conventional till plots. Also, R_{max} values for no-till, residue removed, non-paratilled (35 mm h^{-1}) plots were 3.7 times greater than those for no-till, residue left in place, non-paratilled (9 mm h^{-1}) (P = 0.0177) (Figure 1C, Table 1). However, even though paratilling numerically reduced R_{max} values for conventional till plots shown, no significant differences were found between R_{max} values for conventional till, residue removed, non-paratilled (35 mm h^{-1}) and conventional till, +R, non-paratilled (27 mm h^{-1}) (P = 0.2171).

Sediment delivery. Compared to conventional till plots, no-till plots had on average about five times less soil loss for the first (0-60 min, E_{60}) and about four times less soil loss for the second (60-120 min, E_{120}) simulated rainfall events (Table 1), despite no-till plots having significantly greater antecedent soil water contents. In general, an increase in antecedent water content increases runoff and soil loss, however, contrasting results have been reported (Truman and Bradford, 1990). Increased antecedent water contents can increase or decrease runoff and soil loss because it influences rate of wetting of a soil's surface, aggregate stability, rate of surface seal development, and runoff initiation, which in turn affects soil detachment and sediment transport processes during a rainfall event. Soil loss amounts were greatest for conventional till, residue removed, non-paratilled plots (E_{60} = 194 g and E_{120} = 181 g), and lowest for no-till, residue left in place plots (E_{60} = 8 g for no-till, residue left in place, non-paratilled plots; E_{120} = 14 g for no-till, residue left in place, non-paratilled and no-till, residue left in place, paratilled plots). Again, the most common tillage practice used by farmers (conventional till, residue removed, non-paratilled) results in a "worst-case" scenario among treatments studied.

For conventional till plots, residue incorporation and paratilling (conventional till, residue left in place, paratilled) decreased soil loss by at least two times during the first (E_{60}, 78 vs. 194 g) (P = 0.0551) and second event (E_{120}, 86 vs. 181 g) (P = 0.0.0231). Soil loss from conventional till plots (E_{60} and E_{120}, g)

Figure 1

Runoff (mm h^{-1}) from conventional- (CT) and no-till (NT) plots with (+R) and without (-R) surface residue and with (+P) and without (-P) paratilling during the 2 hr of simulated rainfall (I = 50 mm h^{-1}). Bars = standard error.



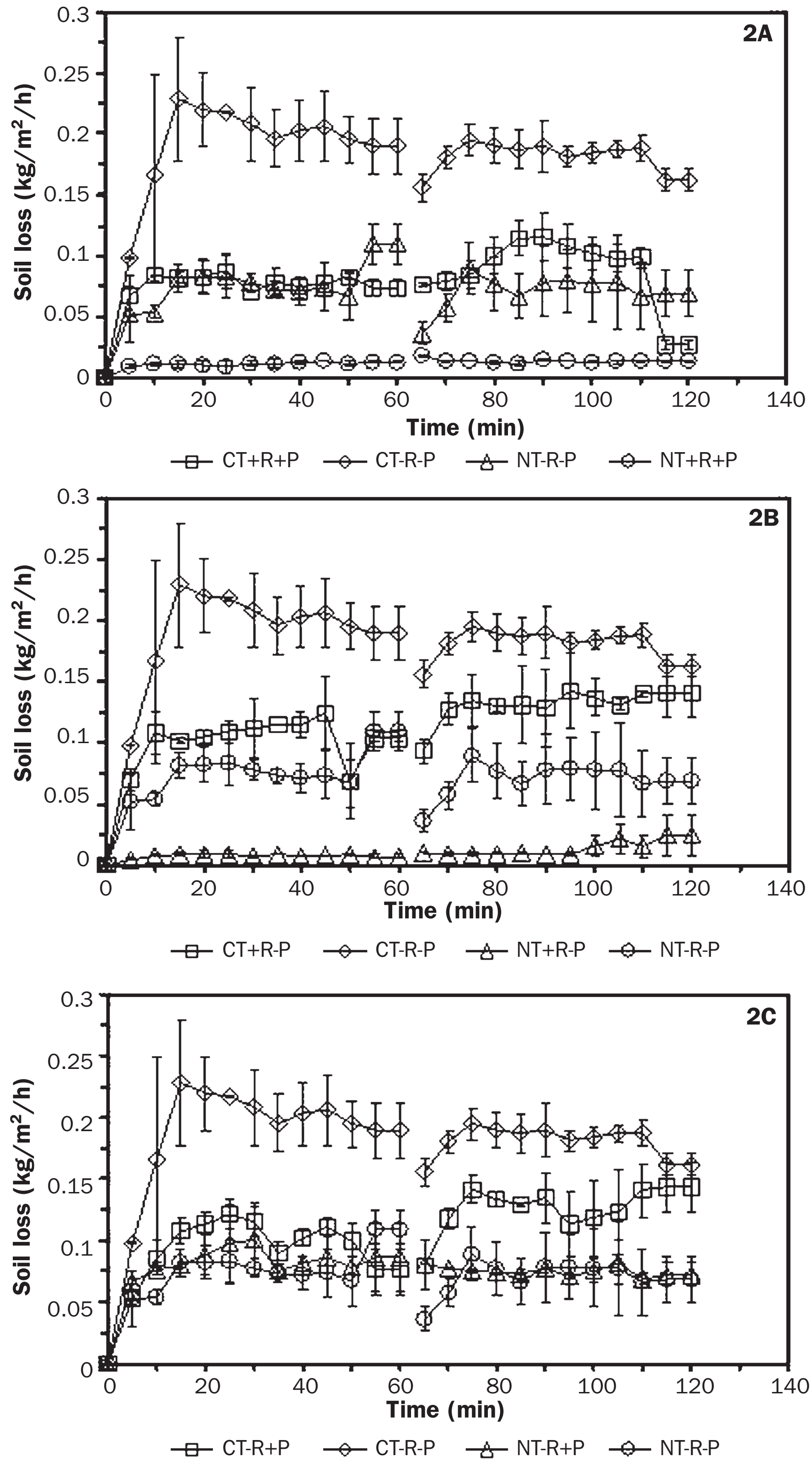
increased in order: conventional till, residue left in place, paratilled < conventional till, residue removed, paratilled < conventional till, residue left in place, non-paratilled < conventional till, residue removed, non-paratilled. Removing surface residue from paratilled and non-paratilled conventional till plots increased E60 and E120 values by at least 23 and 38 percent. For no-till plots, removing surface residue increased soil loss by at least 7-fold during the first (E_{60}, 12 vs. 84 g) ($P = 0.0012$) and by at least 5-fold during the second event (E_{120}, 14 vs. 75 g) ($P = 0.0068$). Removing surface residue from non-paratilled no-till plots had the greatest impact on sediment delivery for both events. Impact of residue removal on sediment delivery was greater on no-till plots than on conventional till plots.

In general, paratillling numerically decreased E_{60} and E_{120} values for conventional till plots with and without surface residue; conversely, paratilling numerically increased E_{60} and E_{120} values for no-till plots with and without surface residue. For conventional till plots, the greatest impact of paratilling was on E_{60} values from plots without surface residue (96 vs. 194 g) ($P = 0.0733$). The non-significant, numerical increase in soil loss due to paratilling from no-till plots with and without was caused by paratill disturbance. For the Coastal Plain region of central Alabama, presence or absence of surface residue dominated soil loss. Soil loss from no-till plots (E_{60} and E_{120}, g) increased in order (total soil loss from both events): no-till, residue left in place, non-paratilled (19 g) < no-till, residue left in place, paratilled (26 g) < no-till, residue removed, non-paratilled (149 g) < no-till, residue removed, paratilled (159 g).

Sediment yield rates generally increased rapidly and reached steady-state rates during the first 30-min of the first simulated rainfall event (0-60 min) (Figure 2). Similar to runoff, residue management and paratilling reduced soil loss rates for conventional till and no-till plots. Steady-state soil loss rates for conventional till, residue removed, non-paratilled plots (worst case scenario) were greatest (~0.20 kg/m^2/h), while steady-state soil loss rates for no-till, residue left in place, paratilled plots (best case scenario) were the lowest (~0.02 kg/m^2/h) (Figure 2A). In terms of soil loss rates, no-till without residue and without parartilling had similar soil loss rates as those for conventional till with residue and with paratilling (Figure 2A). We

Figure 2

Sediment yields (kg m^{-2} h^{-1}) from conventional- (CT) and no-till (NT) plots with (+R) and without (-R) surface residue and with (+P) and without (-P) paratilling during the 2 hr of simulated rainfall (I = 50 mm h^{-1}). Bars = standard error.



used conventional till, residue left in place, non-paratilled, conventional till, residue removed, non-paratilled; no-till, residue left in place, non-paratilled; and no-till, residue removed, non-paratilled plots to illustrate residue effects on soil loss rates (Figure 2B). Removing residue increased steady-state soil loss rates by ~0.050 kg/m^2/h for both conventional till and no-till plots, representing a 40 and 200 percent increase respectively. We used conventional till, residue removed, paratilled; conventional till, residue removed, non-paratilled; no-till, residue removed, paratilled; and no-till, residue removed, non-paratilled plots to illustrate paratilling effects on soil loss rates (Figure 2C). Paratilling reduced soil loss rates for conventional till plots. Paratilling decreased steady-state soil loss rates by ~0.075 kg/m^2/h (60 percent) for conventional till plots. Paratilling had little effect on soil loss rates for no-till plots.

Based on our data, no-till, residue left in place, paratilled plots represented the best-case scenario and conventional till, residue removed, non-paratilled plots represented the worst-case scenario, thus defining the range of infiltration, runoff, and sediment losses for any given experimental condition studied. A purpose of this paper was to evaluate the individual effects of surface residue cover, paratilling, and fundamental soil property differences among conventional till and no-till plots on differences in infiltration, runoff, and sediment yields from those respective plots.

Residue. Differences in infiltration, runoff, and sediment delivery among tillage treatments were assumed to be due to differences in surface residue cover and/or changes in intrinsic soil properties. Removing surface residue from conventional till and no-till plots decreased infiltration, and increased runoff and sediment yields. Surface residue protects the soil surface from raindrop impact, thus maintaining infiltration by limiting surface seal development and reducing runoff, soil detachment, and sediment transport. On average, no-till plots had more surface residue than conventional till plots (6148 vs. 210 kg ha^{-1}) (P = 0.0322). Removing surface residue, to simulate a haying operation, from no-till plots resulted in a 2- to 3-fold decrease in surface residue cover (P = 0.0121). For non-paratilled conventional till plots, removing residue decreased surface residue by 330 kg ha^{-1}, a 4 fold decrease. Similar differences were noticed for paratilled conventional till plots. After removing residue, average residue cover remaining was 3230 and 90 kg ha^{-1} for no-till and conventional till plots, respectively. Note that on average, 6420 kg ha^{-1} of surface residue was present before conducting rainfall simulations (residue incorporated 5-d before rainfall simulations), and that over 90 percent of that residue was incorporated into the 18-cm depth of conventional till, residue left in place plots.

Surface residue effects on seal development and rainfall partitioning can be quantified by examining INF_{min} values (Table 1). These minimum values (or steady-state) values were calculated by difference (rainfall-runoff), and can be used to calculate the change in infiltration (ΔINF) throughout each simulated rainfall event. Values of ΔINF (rainfall intensity-INF_{min}) have been used as an indicator of surface sealing, resulting in alterations of the soil surface by raindrop impact (Truman and Bradford, 1990; Truman and Bradford, 1993). The greater the ΔINF value (smaller INF_{min}), the larger the effect of raindrop impact on the soil surface. The largest ΔINF values are for no-till and conventional till plots without surface residue, thus leaving the soil surface exposed to kinetic energy associated with raindrop impact. Conversely, maintaining and incorporating residue into conventional till plots resulted in the greatest decrease in ΔINF (greatest increase in INF_{min}), indicating that incorporated residue reduced the overall effect of raindrop impact.

Removing surface residue increased runoff, and accounted for 38 percent (first simulated rainfall event, 0-60 min) and 76 percent (second simulated rainfall event, 60-120 min) of the overall change in runoff obtained from no-till and conventional till plots without surface residue. As a result, changes in intrinsic soil properties accounted for the remaining 62 percent (first simulated rainfall event, 0-60 min) and 24 percent (second simulated rainfall event, 60-120 min) of the overall change in runoff obtained from no-till and conventional till plots without surface residue.

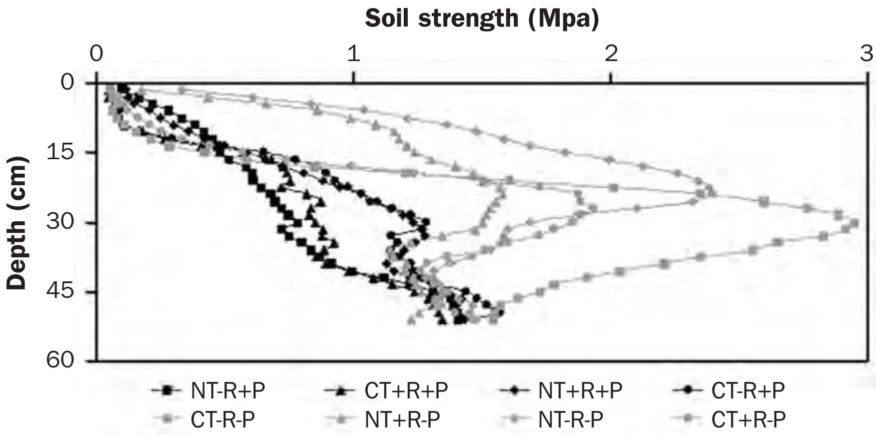
Removing residue increased sediment delivery, and accounted for 34-38 percent (both simulated rainfall events) of the overall change in sediment transported from no-till and conventional till plots without surface residue. Changes in intrinsic soil properties accounted for the remaining 62-66 percent of the change in sediment transported between the two plots. Increased surface residue cover reduced the impact of the raindrop kinetic energy reaching the soil surface, thus decreased soil detachment and sediment delivery.

As for soil property differences, no-till was relatively effective in building up soil organic carbon in the surface soil (top 3-cm), with little differences occurring below 3 cm for both conventional till and no-till treatments. Overall, no-till plots had about 53 percent more soil organic carbon (0.86 g kg^{-1}) than conventional till plots (0.56 g kg^{-1}) (P = 0.0012). Soil organic carbon values for the 0-1 cm soil layer averaged 1.09 g kg^{-1} for no-till plots, whereas soil organic carbon values for conventional till plots averaged 0.54 g kg^{-1} (a 2-fold difference, P = 0.0101). Also, water stable aggregate (0-3 cm) percentage for no-till plots was 21 percent greater than that for conventional till plots (58 vs. 37 percent) (P = 0.0001). Furthermore, soil strength values (0-1.5 cm) for no-till plots (0.18 MPa) were on average 3.5 times greater (P = 0.0522) than those for conventional till plots (0.05 MPa). Increased aggregate stability and soil strength contributed to decreased soil detachment and sediment transportability, thus an overall decrease in sediment delivery.

Because surface residue influenced infiltration and runoff amounts, sediment yield was correlated with surface residue cover for all plots (R^2 = 0.77). The R^2 value for sediment yield vs. surface residue cover for no-till plots was 0.97. Also, by reducing runoff, surface residue diminished sediment transport capacity. Sediment delivery from this soil complex is dependent upon the transportability of surface soil particles, which are dominated by sand-sized particles from the plot. Therefore, sediment transport from the plots should be related to runoff (transport capacity). Sediment yields were correlated with runoff amounts for all plots (R^2 = 0.76). Furthermore, the R^2 value for the same correlation for conventional till residue removed plots alone was 0.98. Residue management and improved soil properties associated with no-till systems reduced runoff and sediment yields.

Paratilling. Paratilling is a management technique that prevents compaction or consolidation. Paratilling reduced runoff and runoff rates by as much as 32 percent compared to non-paratilled conventional till and no-till plots. In soils where the soil surface does not limit infiltration, very often subsurface layers limit vertical water movement, especially those closer to the soil surface. Paratilling breaks up these layers, thus it maintains vertical water movement including infil-

Figure 3
Soil strength values (MPa) by depth for conventional- (CT) and no-till (NT) plots, with (+R) and without (-R) surface residue and with (+P) and without (-P) paratilling. Strength values determined by a cone penetrometer.



tration, and subsequently reduces runoff. This effect can be seen by examining bulk density (porosity) and soil strength values with depth. Overall, we found increased bulk density values in the top 30-cm of no-till plots compared to conventional till plots, and that paratilling was effective in reducing bulk density values in the top 30-cm of soil, especially for no-till plots. Bulk density values (0-15 cm) were on average 4 percent greater for no-till plots (1.51 g cm^{-3}) than those for conventional till plots (1.45 g cm^{-3}) ($P = 0.0142$). For no-till plots, paratilling on average reduced bulk density by 15 percent (1.62 vs. 1.40 g cm^{-3}) for the 0-15 cm depth and by 9 percent (1.75 vs. 1.60 g cm^{-3}) ($P = 0.0022$) for the 15-30 cm depth compared to non-paratilled no-till plots. Bulk density values from the 0-15 and 15-30 cm depths for non-paratilled no-till plots were 8-15 percent greater ($P = 0.0142$) than those for conventional till plots and paratilled no-till plots. Porosity in the 0-1, 1-3, and 3-6 cm depths of no-till plots (61.5, 52.3, 48.3 percent) were at least 50 percent greater than corresponding values from conventional till plots (12.6, 25.0, 30.8 percent) ($P = 0.0012$-0.0438).

Soil strength curves, as measured by a cone penetrometer, are given in Figure 3. Within the 0-15 cm depth, soil strength curves were similar, except for non-paratilled no-till and no-till without surface residue plots, which had increased soil strength values. For the 0-45 cm depth, magnitude and depth of maximum soil strength for conventional till and no-till plots varied depending on paratilling. Non-paratilled treatments generally had numerically greater soil strength curves compared to corresponding paratilled treatments. For example, maximum soil strengths measured for paratilled plots (1.25-1.50 MPa) occurred at 48.5-50 cm, whereas maximum soil strengths measured for non-paratilled plots (1.60-2.90 MPa) occurred at 22-29 cm. Differences between maximum and minimum soil strength values were 70 and 32 percent greater for non-paratilled conventional till and no-till plots compared to paratilled conventional till and no-till plots. At the surface (0-1.5 cm), paratilling reduced soil strength (0-1.5 cm) by as much as 27 percent ($P = 0.0578$) for conventional till plots and by as much as 3-fold ($P = 0.0024$) for no-till plots.

Because surface residue and paratilling maintain infiltration, one would expect differences in soil water content throughout the soil profile. We did not find, nor expect, statistical differences in gravimetric water content as a function of surface residue or paratilling alone on soil samples (01-, 1-3, 3-6, 6-9, 9-12 cm) taken just prior to simulating rainfall. However, if one averages gravimetric water contents by tillage (no-till vs. conventional till), significant differences were found. Gravimetric water content from the 0-1, 1-3, and 3-6 cm depths of no-till plots (14.5, 12.2, 11.3 percent) were at least 40 percent greater than corresponding values from conventional till plots (3.4, 6.5, 8.0 percent) ($P = 0.0013$-0.0420). No-till plots had more infiltration and less runoff than conventional till plots even though no-till plots had higher gravimetric water contents.

From a practical standpoint, producers want to know how a particular tillage system will affect how much rainfall infiltrates into the soil surface, thus becoming available for plant uptake. Over the 2 hr simulated rainfall duration, 21 percent more of the total rainfall ran off conventional till plots (34 percent) than for no-till plots (13 percent) (Table 1). This translates into 22 percent more of the total rainfall infiltrated no-till plots (87 percent) compared to conventional till plots (65 percent). Also, about 42 percent of the rainfall infiltrated in the conventional till plots without surface residue (the normal practice in the Coastal Plain region of central Alabama, USA) compared to about 96 percent for the no-till plots. Given the rainfall intensity (50 mm h^{-1}) and assuming that evapotranspiration (ET) was 7 mm d^{-1}, then 17 mm of water infiltrated for conventional till plots without surface residue and 47 mm of water infiltrated no-till plots. This would result in 2.8 days of water for crop use in conventional till plots without surface residue and 6.9 days of water for crop use in no-till plots. This difference (2.5 times) is extremely important for the low water holding capacity soils of the Coastal Plain during drought conditions. Removing residue (simulating a harvesting of straw activity) resulted in about 18 percent more runoff as a percentage of rainfall (18 percent less infiltration) for no-till plots and 25 percent more runoff (25 percent less infiltration) for conventional till plots. Paratilling resulted in about 10 percent less runoff as a percentage of rainfall (10 percent more infiltration) for no-till plots and 26 percent less runoff (26 percent more infiltration) for conventional till plots.

As for sediment, about 2.8 times more sediment loss occurred from conventional till plots (124 g) than for no-till plots (44 g), with a sediment yield of 187 g for the "normal" practice of conventional tillage with surface residue removed and not incorporated. Removing residue yielded ~7 times more sediment from no-till plots and ~1.5 times more sediment in conventional till plots. Paratilling increased sediment losses by as much as 1.4 times for no-till plots, but decreased sediment yields by as much as 2 times for conventional till plots.

Summary and Conclusion

We quantified the effect of long-term tillage and residue management systems on rainfall partitioning into infiltration and runoff, and sediment yields from a Plinthic Paledudult-

Typic Hapludult soil complex with a loamy sand surface. Based on our results, the following conclusions can be made:

Compared to conventional till plots, no-till plots had two times less runoff and five times less soil loss for the first simulation (0-60 min) and four times less runoff and four times less soil loss for the second simulation (60-120 min), even though rainfall intensity was constant and soil water content (0-1 cm) was as much as 4.3 times greater for no-till plots compared to conventional till plots.

No-till, residue left in place, paratilled plots represented the best-case scenario and conventional till, residue removed, non-paratilled plots, the "standard practice" for farmers in the region, represented the worst-case scenario. Runoff was greatest for conventional till, residue removed, non-paratilled plots (runoff = 58 percent of the rainfall amount), and lowest for no-till, residue left in place, paratilled plots (runoff = 4 percent of the rainfall amount). Maximum runoff rates for conventional till, residue removed, non-paratilled plots (35 mm h^{-1}) were 13 times greater than those for no-till, residue left in place, paratilled plots (2 mm h^{-1}). Steady-state runoff rates for conventional till, residue removed, non-paratilled plots were greatest (33 mm h^{-1}), while steady-state runoff rates for no-till, residue left in place, paratilled were the lowest (~3 mm h^{-1}). Soil loss amounts and steady-state rates were greatest for conventional till, residue removed, non-paratilled plots (375 g, 0.20 kg/m^2/h), and lowest for no-till, residue left in place, paratilled plots (22 g, 0.02 kg/m^2/h).

Surface residue had more influenced on runoff and soil loss than did paratilling. Removing surface residue increased runoff and sediment delivery, and accounted for 38 percent (first simulation, 0-60 min) and 34 to 76 percent (second simulation, 60-120 min) of the differences in runoff and sediment transported from no-till and conventional till plots. Impact of surface residue removal was greater on no-till plots (6148 kg ha^{-1} surface residue) than on conventional till plots (210 kg ha^{-1} surface residue). For conventional till and no-till plots, removing surface residue increased steady-state runoff rates by 50 percent and 500 percent, increased sediment yields by 1.5 and 7 times, and increased steady-state soil loss rates by 40 percent and 200 percent.

Consolidation occurred in the top 50 cm of no-till plots and lower (< 30 cm) depths of conventional till plots. Paratilling reduced consolidation, and improved rainfall partitioning conditions for conventional till and no-till plots. Bulk density values (0-30 cm) for non-paratilled no-till plots were up to 15 percent greater than corresponding values for conventional till and paratilled no-till plots. Paratilling reduced surface soil strength (0-1.5 cm) by as much as 27 percent for conventional till plots and by as much as 3-fold for no-till plots. Maximum soil strengths measured for paratilled plots (1.25-1.50 MPa) occurred at 48.5-50 cm, whereas maximum soil strengths measured for non-paratilled plots (1.60-2.90 MPa) occurred at 22-29 cm. Paratilling had the greatest impact on runoff from conventional till, residue removed, and no-till, residue removed plots (3.5-4-fold difference). Compared to non-paratilled conventional till and no-till plots, paratilling reduced runoff by as much as 32 percent, caused runoff rates to increase at a slower rate, and increased steady-state runoff rates by 40 percent and 400 percent, respectively.

Improvement in soil properties resulting from conservation tillage contributed to differences in rainfall partitioning and soil losses. Soil organic carbon values (0-1 cm) for no-till plots (1 g kg^{-1}) were two times greater than corresponding values for conventional till plots (0.5 g kg^{-1}). Water stable aggregate (0-3 cm) percentage for no-till plots was 21 percent greater than that for conventional till plots (58 vs. 37 percent). Soil strength values (0-1.5 cm) for no-till plots (0.18 MPa) were 3.5 times greater than those for conventional till plots (0.05 MPa). Porosity values (0-1, 1-3, 3-6 cm) for no-till plots (61, 52, 48 percent) were at least 50 percent greater than corresponding values from conventional till plots (12, 25, 30 percent). Increased surface residue, soil organic carbon, aggregate stability and soil strength decreased soil detachment, sediment transportability, and resulting sediment delivery.

For this study, 21 percent more of the total rainfall ran off conventional till plots (34 percent) than for no-till plots (13 percent), translating into 22 percent more of the total rainfall infiltrated no-till plots (87 percent) compared to conventional till plots (65 percent). Also, about 42 percent of the rainfall infiltrated in the conventional till, residue removed, non-paratilled plots (worst-case scenario) compared to about 96 percent for the no-till, residue left in place, paratilled plots (best-case scenario), resulting in only 2.8 days of water for crop use in conventional till, residue removed, non-paratilled plots and 6.9 days of water for crop use in no-till, residue left in place, paratilled plots (2.5-fold difference). Removing residue, to simulate a straw harvesting activity, resulted in 18 percent more runoff as a rainfall percentage (18 percent less infiltration) for no-till plots and 25 percent more runoff (25 percent less infiltration) for conventional till plots, thus yielding less water available for crop use. Paratilling resulted in 10 percent less runoff as a rainfall percentage (10 percent more infiltration) for no-till plots and 26 percent less runoff (26 percent more infiltration) for conventional till plots, again affecting amount of water available for crop uptake.

Combining residue management and paratilling through conservation tillage in row-crop agriculture in the Coastal Plain region of Alabama reduces runoff and soil loss for conventional till and no-till systems by improving soil properties and maintaining infiltration, resulting in increased estimates of plant available water.

Endnote

Mention of trade names, commercial products, or companies in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by U.S. Department of Agriculture nor Auburn University over others not mentioned.

References Cited

Bicki, T.J. and L. Guo. 1991. Tillage and simulated rainfall intensity effect on bromide movement in an Agriudoll. Soil Science Society of American Journal 55:794-799.

Blake, G.R. and K.H. Hartge. 1986. Bulk density. Pp. 363-376. *In:* Methods of Soil Analysis. Part 1, Physical and Mineralogical Methods, A. Klute (ed.) Agronomy Monograph No. 9 (2nd Edition). Agronomy Society of America-Soil Science Society of America Madison, Wisconsin.

Blevins, R.L., W.W. Frye, P.L. Baldwin, and S.D. Robertson. 1990. Tillage effects on sediment and solute nutrient losses from a Maury silt loam soil. Journal of Environmental Quality 19:683-686.

Campbell, R.B., D.C. Reicosky, and C.W. Doty. 1974. Physical properties and tillage of Paleudults in the southeastern Coastal Plains. Journal Soil and Water Conservation 29(5):220-224.

Cassel, D.K. and M.G. Wagger. 1996. Residue management for irrigated maize grain and silage production. Soil and Tillage Research 39:101-114.

Clark, R.L., D.E. Radcliffe, G.W. Langdale, and R.R. Bruce. 1993. Soil strength and water infiltration as affected by paratillage frequency. Transaction of the American Society of Agricultural Engineers 36:1301-1305.

Edwards, J.H., C.W. Woods, D.L. Thurow, and M.E. Ruf. 1992. Tillage and crop rotation effects on fertility status of a Hapludult soil. Soil Science Society of America Journal 56:1577-1582.

Edwards, W.M., G.B. Triplett, D.M. Van Doren, L.B. Owens, C.E. Redmond, and W.A. Dick. 1993. Tillage studies with a corn-soybean rotation: Hydrology and sediment loss. Soil Science Society of America Journal 57:1051-1055.

Foster, G.R., W.H. Neibling, and R.A. Natterman. 1982. A programmable rainfall simulator. American Society of Agricultural Engineer Paper No. 82-2570.

Gardner, W.H. 1986. Water content. Pp. 493-594. *In:* Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, A. Klute (ed.) Agronomy Monograph No. 9 (2nd Edition). Agronomy Society of America-Soil Science Society of America Madison, Wisconsin.

Gaynor, J.D. and W.I. Findlay. 1995. Soil and phosphorus loss from conservation and conventional tillage in corn production. Journal of Environmental Quality 24:734-741.

Heard, J.R., E.J. Kladivko, and J.V. Mannering. 1988. Soil macroporosity, hydraulic conductivity, and air permeability of silty soils under long-term conservation tillage in Indiana. Soil Tillage Research 11:1-18.

Kelley, K.R. 1994. Conveyor-belt apparatus for fine grinding of soil and plant materials. Soil Science Society of America Journal 58:144-146.

Kemper, W.D. and R.C. Rosenau. 1986. Aggregate stability and size distribution. Pp. 425-442. *In:* Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, A. Klute (ed.) Agronomy Monograph. No. 9 (2nd Edition). Agronomy Society of America-Soil Science Society of America, Madison, Wisconsin.

Kilmer, V.J. and L.T. Alexander. 1949. Methods of making mechanical analysis of soils. Soil Science 68:15-24.

Laflen, J.N. and T.S. Colvin. 1981. Effect of crop residue on soil loss from continuous row cropping. Transactions of the American Society of Agricultural Engineers 24:605-609.

Langdale, G.W., L.T. West, R.R. Bruce, W.P. Miller, and A.W. Thomas. 1992. Restoration of eroded soil with conservation tillage. Soil Technology 5:81-90.

Lindstrom, M.J., W.B. Voorhees, and G.W. Randall. 1981. Long-term tillage effects on interrow runoff and infiltration. Soil Science Society of America Journal 45:945-948.

Lindstrom, M.J. and C.A. Ontad. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. Journal Soil and Water Conservation 39(2):149-152.

McGregor, K.C., J.D. Greer, and G.E. Garley. 1975. Erosion control with no-till cropping practice. Transactions of the American Society of Agricultural Engineers 18:918-920.

McGregor, K.C., C.K. Mutchler, and M.J.M. Romkens. 1990. Effects of tillage with different crop residues on runoff and soil loss. Transactions of the American Society of Agricultural Engineers 33:1551-1556.

Moldenhauer, W.C., W.G. Lovely, N.P. Swanson, and H.D. Currence. 1971. Effect of row grades and tillage systems on soil and water losses. Journal Soil and Water Conservation 26(5):193-195.

Mueller, D.H., D.H. Wendt, and T.C. Daniel. 1984. Soil and water losses as affected by tillage and manure application. Soil Science Society of America Journal 48:896-900.

Nesmith, D.S., D.E. Radcliffe, W.L. Hargrove, R.L. Clark, and E.W. Tollner. 1987. Soil compaction in double-cropped wheat and soybeans on an Ultisol. Soil Science Society of America Journal 51:183-186.

Pierce, F.J. and C.G. Burpee. 1995. Zone tillage effects on soil properties and yield and quality of potatoes (*Solanum tuberosum* L.). Soil and Tillage Research 35:135-146.

Potter, K.N., H.A. Torbert, and J.E. Morrison. 1995. Tillage and residue effects on infiltration and sediment. Transactions of the American Society of Agricultural Engineers 38:1413-1419.

Radcliffe, D.E., E.W. Tollner, W.L. Hargrove, R.L. Clark, and M.H. Golabi. 1988. Effect of tillage practices on infiltration and soil strength of a Typic Hapludult soil after ten years. Soil Science Society of America Journal 52:798-804.

Rawitz, E., A. Hadas, H. Etkin, and M. Margolin. 1994. The effect of various residue mulch-tillage combinations on soil physical conditions and performance of irrigated cotton. Soil and Tillage Research 32:347-366.

Reeves, D.W. 1997. The role of organic matter in maintaining soil quality in continuous cropping systems. Soil and Tillage Research 43:131-167.

Reeves, D.W., D.P. Delaney, and R.M. Durbin. 2000. Farming systems for the ultra-narrow row cotton. Beltwide Cotton Conference, Jan. 4-8, 2000. San Antonio, Texas. Vol. 2. Pp. 1415-1416. National Cotton Council.

Reeves, D.W., H.H. Rogers, J.A. Droppers, S.A. Prior, and J.B. Powell. 1992. Wheel traffic effects on corn as influenced by tillage system. Soil and Tillage Research 23:117-192.

Reeves, D.W. and G.L. Mullins. 1995. Subsoiling and potassium placement effects on water relations and yield of cotton. Agronomy Journal 87:847-852.

Reeves, D.W. and J.T. Touchton. 1986. Subsoiling for nitrogen applications to corn grown in a conservation tillage system. Agronomy Journal 78:921-926.

Seta, A.K., R.L. Blevins, W.W. Frye, and B.J. Barfield. 1993. Reducing soil erosion and agricultural chemical losses with conservation tillage. Journal of Environmental Quality 22:661-665.

Shaw, J.N., C.C. Truman, and D.W. Reeves. 2002. Mineralogy of eroded sediments derived from highly weathered soils. Soil Science 168:209-217.

Siemens, J.C. and W.R. Oschwald. 1976. Erosion for corn tillage systems. Transaction of the American Society of Agricultural Engineers 19:69-72.

Soileau, J.M., J.T. Touchton, F.F. Hajek, and K.H. Yoo. 1994. Sediment, nitrogen, and phosphorus runoff with conventional- and conservation-tillage cotton in a small watershed. Journal of Soil and Water Conservation 49(1):82-89.

Sojka, R.E., D.T. Westerman, M.J. Brown, and B.D. Meek. 1993. Zone-subsoiling effects on infiltration, runoff, erosion, and yields of furrow-irrigated potatoes. Soil and Tillage Research 25:351-368.

Truman, C.C. and J.M. Bradford. 1990. Effect of antecedent soil moisture on splash detachment under simulated rainfall. Soil Science 150:787-798.

Truman, C.C. and J.M. Bradford. 1993. Relationships between rainfall intensity and the interrill soil loss-slope steepness ratio as affected by antecedent water content. Soil Science 156:405-413.

Truman, C.C., D.W. Reeves, J.N. Shaw, A.C. Motta, C.H. Burmester, R.L. Raper, and E.B. Schwab. 2003. Tillage impacts on soil property, runoff, and soil loss variations from a Rhodic Paleudult under simulated rainfall. Journal of Soil and Water Conservation 58(5):258-267.

Vepraskas, M.J., G.S. Miner, and G.F. Peedin. 1987. Relationships of soil properties and rainfall to effects of subsoiling on tobacco yield. Agronomy Journal 79:141-146.

Yeomans, J.C. and J.M. Bremmer. 1991. Carbon and nitrogen analysis of soils by automated combustion techniques. Communication of Soil Science Plant Analysis 22:843-850.

Yoo, K.H. and J.T. Touchton. 1988. Surface runoff and sediment yield from various tillage systems of cotton. Transaction of the American Society of Agricultural Engineers 31:1154-1158.