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Runoff and nutrient losses from conventional and conservation tillage systems during fixed and variable rate rainfall simulation

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Abstract:. Tillage systems and fertilizer sources impact soil health and ecosystem services. Rainfall simulations can be used to evaluate tillage and fertilizer management effects on ecosystem services associated with runoff amount and quality. Fixed rate (FR; 57 mm h^{-1} for 60 minutes) and variable rate (VR; based on the pattern of the most frequent spring rain) simulations were conducted on corn (*Zea mays* L.) plots supplied with conventional fertilizer (CF; ammonium nitrate [NH_4NO_3]) or poultry litter (PL) and managed with conventional tillage (CT) or no-tillage (NT) on a Cecil soil (Ultisol) near Watkinsville, Georgia. Simulations were conducted in separate years (FR in 2004 and VR in 2005). Tillage and tillage × fertilizer interactions had significant effects on total runoff and sediment loss under FR but not VR. Under FR, 55.8% of the simulated rainfall was partitioned into runoff from CT compared with 9.7% from NT. Under VR, 42% to 60% was partitioned into runoff with no difference among treatments. Sediment loss was 11-fold greater from CT compared with NT under FR (919 g versus 82 g). Under VR, sediment loss varied between 755 g and 2,174 g with no difference among treatments. Tillage and tillage × fertilizer interactions had significant effects on total load for ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N) in both methods and dissolved reactive and total phosphorus (DRP and TP) under VR. Fertilizer source affected loads of NH_4-N under VR and NO_3-N and TP under both methods. Our results confirm that 12 years of continuous NT on a Cecil soil, representative of much of the Southern Piedmont, is far superior to CT for reducing runoff and sediment loss. Larger and more intense storms predicted in future climate projections warrant greater adoption of reduced tillage systems to counteract potential runoff and sediment losses from CT systems.

Key words: organic nutrients—phosphorus—poultry litter—soil erosion—tillage

Numerous studies have demonstrated that conservation tillage systems have the potential to substantially reduce runoff, erosion, and sediment loss, particularly in the US Southeast (Langdale et al. 1992; Bruce and Langdale 1996; Reeves 1997; Allmaras et al. 2000; Endale et al. 2000; Schomberg et al. 2003). A 43% decrease in soil erosion on US croplands between 1982 and 2007 has been attributed to adoption of conservation tillage practices that prevented close to 0.7 billion Mg of soil erosion (USDA NRCS 2010). The US Southeast is dominated by Ultisols and Alfisols, which are inherently erodible due to their relatively low organic matter content, weak structure, low permeability, low water holding capacity, and a tendency to form surface crusts and develop hard pans (West et al. 1997). Much of the region has a long history of CT cultivation (e.g., moldboard plowing, disking, chiseling, and harrowing), which has resulted in extensive soil erosion (Trimble 2008; Langdale et al. 1992). Without application of sound conservation practices, soil erosion continues to be a serious problem (Bruce and Langdale 1996; Reeves 1997; Schnepf and Cox 2006; Towery and Werblow 2010).

The 2017 US Census of Agriculture (USDA NASS 2019) found that conservation tillage practices increased from 2012 and comprised 51% of all US cropland (~81.7 million ha), of which ~51% (~41.7 million ha) was in no-tillage (NT). Similarly, the 2008 crop residue management survey by the Conservation Technology Information Center (CTIC 2009) found that approximately 49%, 34%, 48%, and 43% of the total planted cropland was under conservation tillage in Alabama, Georgia, South Carolina, and North Carolina, respectively. Thus, more intensive CT management continues to be practiced in close to 50% of the cropland in these states.

Ultisols and Alfisols respond favorably to organic matter additions. Increased carbon (C) inputs enhance soil physical, chemical, and biological properties and influence water and nutrient availability and subsequently crop productivity (Bruce and Langdale 1996; West et al. 1997; Allmaras et al. 2000; Endale et al. 2002, 2008; Terra et al. 2005). In addition to cover crops, poultry litter (PL), a mixture of manure and organic bedding material such as pine (*Pinus* sp.) shavings, is a regionally available C and plant nutrient source (nitrogen [N], phosphorus [P], and potassium [K] along with calcium [Ca], magnesium [Mg], sulfur [S], copper [Cu], manganese [Mn], and zinc [Zn]) applied to both row crop and pasture systems in the US Southeast (Moore et al. 1995; Dunkley et al. 2011). The region contributes 60% of the United States' annual 8.6 billion broiler

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Table 1

Summary of cropping history from 1991 to 2005.

	Treatment*		Cropping‡		Fertilizer				
					Spring		Fall		
Year	Main plot†	Subplot	Spring and summer	Fall and winter	CF (kg N ha^{-1})	PL (Mg ha^{-1})	CF (kg N ha^{-1})	PL (Mg ha^{-1})	Remark
1991	CT	Rye and fallow	Corn	Rye and fallow	168	0	0	0	CT all plots
1992 to 1994	CT and NT	Rye and fallow	Corn	Rye and fallow	168	0	0	0	1992 year 1 for tillage treatment
1995 to 2000	CT and NT	CF and PL	Cotton	Rye	67	4.5	56	Same as CF§	1995 year 1 for fertilizer treatment
2001 to 2002	CT and NT	CF and PL	Corn	Rye	168	11.2	67	4.5	
2003	CT and NT	CF and PL	Corn	Rye	336	22.4	67	4.5	2003 hormone study
2004 to 2005	CT and NT	CT and PL	Corn	Rye	168	11.2	67	Same as CF	

*CT = conventional tillage. NT = no-tillage. CF = conventional fertilizer. PL = poultry litter.

†CT was used in all plots during 1991, after which NT and CT were established as main plots in the split plot design.

‡Corn cv. Pioneer 3223, Cotton cv. Stoneville 474, Rye cv. Hy Gainer.

§"Same as CF" means CF was applied in place of PL.

production, which results in nearly 10 million Mg y^{-1} of byproduct PL (USDA NASS 2014). Repeated PL applications can lead to excessive levels of P and other nutrients in soils (Kingery et al. 1994; Sharpley et al. 2003; He et al. 2009; Schomberg et al. 2009), which can result in their losses in runoff contributing to nonpoint-source pollution (Scholefield et al. 1991; Barlow et al. 2007). Of the nutrients present in PL, N, P, and C are implicated in eutrophication of surface waters (Sharpley et al. 1994; Carpenter et al. 1998; Goolsby 2000; Showstack 2000; USEPA 2002).

El Niño-Southern Oscillation (ENSO) has a strong influence on the seasonal to interannual scale climate of the US Southeast with winter precipitation increasing during El Niño and decreasing during La Niña years (Bolson et al. 2013). These climate pattern oscillations result in extreme weather such as floods and droughts (Mishra et al. 2017; Groisman et al. 2001; Todd et al. 2006; Ingram et al. 2013). Climate change presents additional uncertainty about rainfall amount and intensity. Mirhosseini et al. (2013), for example, in evaluating six climate models for Alabama found that for short duration (≤4 h) events precipitation patterns would be less intense. Four of the six models suggested greater intensity for longer (>4 h) duration storms. Ingram et al. (2013) suggest annual rainfall in the Southeast will increase up to 6% through the mid-21st century. They predict precipitation increases of 5% to 20% in fall, spring, and winter, and decreases of 5% to 20% in summer for most of the region. For days with precipitation greater than 25 mm, annual increases of up to 10% are expected in most of the region and up to 20% in some areas such as southern Georgia.

Rainfall simulators have proven useful tools to extensively evaluate rainfall effects on runoff, erosion, and pesticide transport (Sumner et al. 1996; Truman et al. 2005, 2007; Strickland et al. 2005; Potter et al. 2006). Intense and constant fixed rates of simulated rainfall over a short period (±1 h, for example) have typically been used based on the precept that a few (extreme) rain storms generally account for large amounts of offsite pollutant loads. However, changes in rainfall intensity within a storm affect how rainfall is partitioned between infiltration and runoff and subsequent soil loss, which points to the need for evaluating runoff and erosion using variable rate rainfall based on local storms (Meyer 1988; Flanagan et al. 1988; Paige et al. 2003; Frauenfeld and Truman 2004; Strickland et al. 2005; Potter et al. 2006; Franklin et al. 2007).

Understanding how long-term tillage (CT and NT) and nutrient source applications (conventional fertilizer [CF] or PL) interact to affect runoff amounts and quality is needed to provide insight for policies aimed at optimizing ecosystem services. Information about how systems respond to constant and variable rate rainfall simulations can help improve models for predicting runoff and water quality since many of these models were developed using data from constant rate rainfall simulations. The hypotheses explored in this study were the following: (1) a history of conservation tillage significantly reduces runoff and sediment loss in Cecil soil; (2) following repeated PL applications, P levels in runoff from both CT and NT will be above levels of concern for water quality; and (3) system response to runoff nutrient concentrations and load from fixed and variable simulation rates will be different with more runoff and sediment loss in variable rate simulations due to short periods of high rainfall intensity. Implications of the outcomes will be related to agricultural management improvements needed for sustainable intensification of agriculture.

Materials and Methods

Study Site and Management. This research was conducted at the former USDA Agricultural Research Service (ARS) J. Phil Campbell, Sr., Natural Resource Conservation Center, Watkinsville, Georgia (33°54’ N, 83°24’ W) during 2004 and 2005. The site consists of 12 0.03 ha plots (10 × 30.5 m) on a Cecil sandy loam soil (Fine, kaolinitic, thermic, Typic Kanhapludults) with 2% slope. The soil consists of a 20 cm thick brown sandy loam Ap horizon (75% sand and 6% clay), 5 to 10 cm red sandy clay loam to clay loam BA horizon, 100 cm thick red clay Bt horizon, 30 cm thick red loam to clay loam BC horizon, and a loamy saprolitic C horizon (Bruce et al. 1983).

Cropping. Details of the cropping history from 1991 through 2009 are given in Endale et al. (2010), He et al. (2009), and Schomberg et al. (2009), and are presented briefly in table 1 for 1991 to 2005. Crops included corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), winter rye cover (*Secale cereale* L.), and fallow in 1991 to 1994. Beginning in spring of 1995, treatments were applied as a split-plot design with tillage (CT and NT) as main plot and fertilizer (CF and PL) as subplots, resulting in a factorial combination of treatments as CTCF, CTPL, NTCF, and NTPL. There were three replicate blocks of the treatments.

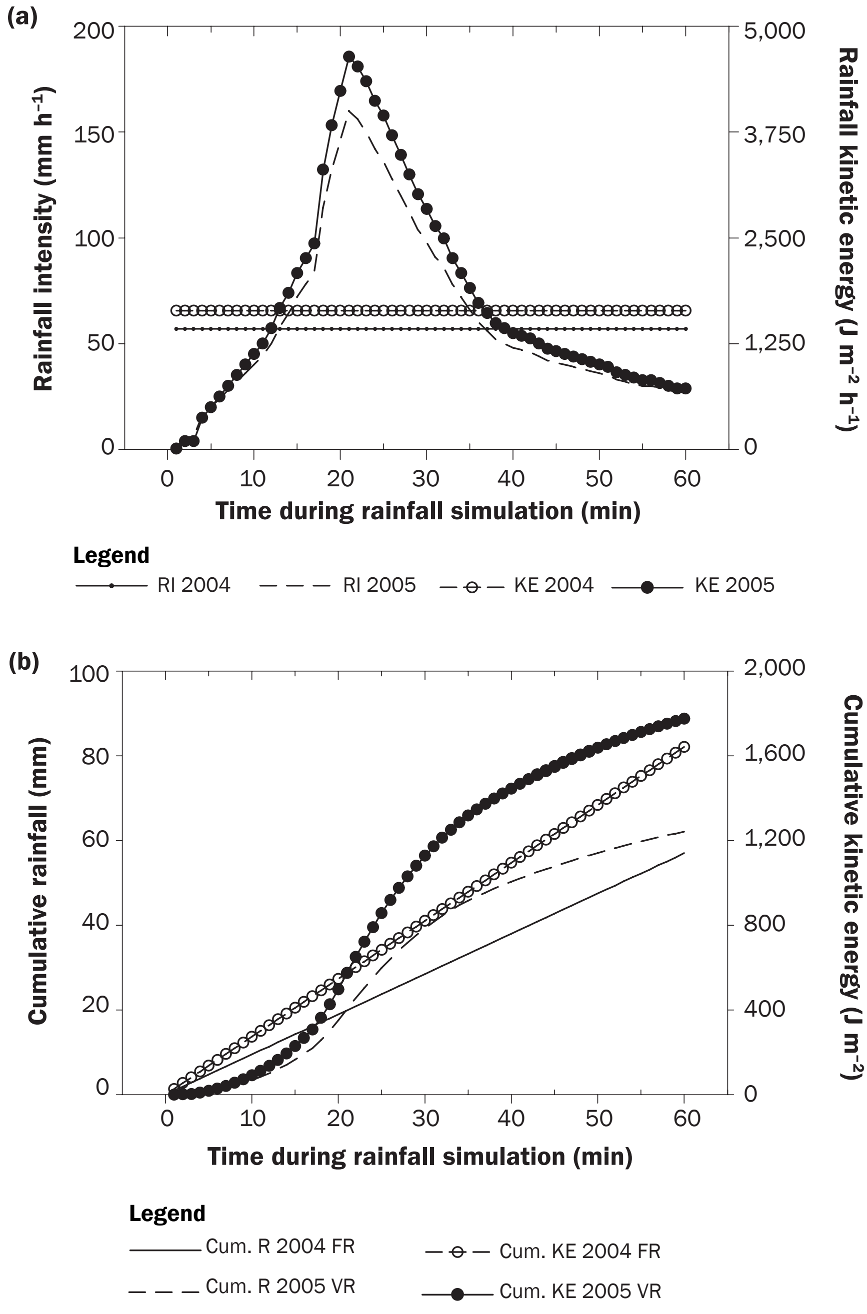
Plots were mowed with a rotary mower prior to planting each crop, and residues were incorporated in the CT treatment only. Spring N fertilization was as ammonium nitrate (NH_4NO_3) for CF treatments and an equivalent quantity of N to PL plots, assuming N mineralization from PL was 50% over the growing season (Vest et al. 1994). Nutrient analysis of PL in 2004 and 2005 (first and second year of rainfall simulation), respectively, indicated in grams per kilogram, 34.7 and 36.2 total N, 1.34 and 3.11 NH_4-N, 0.36 and 0.12 NO_3-N, and 13.4 and 12.1 total P (TP). In the spring of 2003, CF and PL rates were doubled to evaluate losses of estradiol and testosterone from PL. Rye fertilization used ammonium sulfate ($[NH_4]_2SO_4$) in all CF treatments and in PL treatments some years (CF replacing PL) as shown in table 1.

Spring and fall tillage operations in CT consisted of 30 cm deep chisel plowing, heavy-duty disc harrowing to 20 cm, and seed bed preparation with a light disc-harrow. Soil disturbance in NT was limited to the coulter and double disc opener on the no-tillage planter. Glyphosate was applied to kill the rye cover crop three weeks before rainfall simulations were scheduled to begin. Two weeks later, CT plots were chisel plowed and disked. One day before rainfall simulations, mineral fertilizer and PL were applied by hand, after which CT plots were lightly disked.

Rainfall Simulations. Stainless steel plates 15 cm high were pushed 5 cm into the soil to create a 2 by 3 m border for runoff collection. A 2 m long aluminum (Al) trough was installed at the down-slope end of the frame to facilitate runoff collection. The enclosed rainfall simulation plot contained two previous year corn rows, one wheel tracked area between the two rows, and one-half of a nonwheel tracked area on the outsides of the two rows. Rainfall was applied over a 3 by 5 m area around each runoff plot to allow soil and water to be splashed in all directions. Antecedent soil water content (SWC) was determined gravimetrically from 0 to 15 cm depth soil samples collected at four locations just outside the runoff borders.

Figure 1

The 1-minute targeted (a) simulated hourly rainfall intensity (RI) and hourly kinetic energy (KE) and (b) simulated cumulative rainfall depth (Cum. R) and cumulative kinetic energy (Cum. KE) under constant fixed (FR) rate in 2004 and variable rate (VR) in 2005.



Fixed rate (FR) and variable rate (VR) rainfall simulation patterns were programmed into the computer controller on a 1-minute basis (figure 1). The VR pattern represented the pattern of the most frequent spring (row-crop planting season) storm based on measured 1- and 5-minute rainfall data from the past 30 years (Frauenfeld and Truman 2004; Truman et al. 2007; Jenkins et al. 2008). The FR simulation rainfall rate of 57 mm h^{-1} was the statistical mean of the

VR pattern. Kinetic energy (1-minute basis) of the FR and VR simulated rainfall was estimated as in the Revised Universal Soil Loss Equation 2 (RUSLE 2) erosion model (USDA ARS 2013). Ramon et al. (2017) found this approach gave similar results to those measured for 3,656 different intensities >1 mm h^{-1} identified from 81 storms in southern Brazil. The equation has the form

$$KEv = 29 \times [1 - 0.7 \times EXP(-0.082 \times I)] , \quad (1)$$

where KEv is volume-specific kinetic energy (J m^{-2} mm^{-1}) and I is storm intensity (mm h^{-1}). Salles et al. (2002) argued for time-specific kinetic energy KEt (J m^{-2} h^{-1}) as a preferred expression. Multiplying KEv by intensity produces KEt. Subsequent use of the term "kinetic energy" in this paper implies KEt. This approach allowed us to estimate total kinetic energy for each 5-minute period as J m^{-2} and examine its possible impact on some of the other variables based on 5-minute time periods.

In equation 1, 29 denotes the maximum attainable KEv, the coefficient 0.7 along with this maximum determines the minimum KEv attained at very low rainfall intensity, and the coefficient 0.082 defines the general shape of the curve (USDA ARS 2013). Estimation of kinetic energy was done for comparative purposes only, recognizing that differences between natural and simulated rainfall characteristics are present due to the many factors that influence it (van Dijk et al. 2002; Meshesha et al. 2016). The rainfall simulator (described below) was designed to minimize such differences and has been used for many runoff studies (Truman and Bradford 1993; Truman et al. 2007).

Rainfall simulations were conducted for 60 minutes at FR in 2004 (April 1 through April 13) and at VR in 2005 (April 19 through May 3) with a pressurized rainfall simulator with 80150 VeeJet oscillating-nozzles (Spraying Systems Co., Glendale Heights, Illinois) (Frauenfeld and Truman 2004; Truman et al. 2005) placed 3 m above each plot. The simulator produces median drop size of 2.3 mm, attaining terminal velocity. Catch cans, 15 cm diameter and 15 cm tall, were placed on three sides of the plot to monitor and verify variability in rainfall amount and distribution. Franklin et al. (2007) reported a coefficient of uniformity between 66 and 73 for the rain simulator. Water from the municipal water supply was passed through reverse osmosis filters and held in a 2,000 L polyethylene tank for each simulation. Logistical constraints prevented both simulation patterns from being carried out in the same year.

Runoff was collected continuously in one to five 9 L stainless steel buckets at 5-minute intervals through each simulation. Two subsamples of 50 mL or 100 mL (depending on runoff volume) were removed from each bucket for nutrient analysis while the contents were being mixed with an electric stirrer. Subsamples from all buckets within a 5-minute interval were combined and placed in a cooler on ice. The remaining contents of each bucket were transferred into preweighed 1 L wide mouth Nalgene polypropylene bottles (Nalge Nunc International Corporation, Rochester, New York) for determination of sediment. These bottles were weighed (bottle + water + sediment) and treated with 10 drops of concentrated hydrogen chloride (HCl) to flocculate sediments. After 24 hours, most of the water was decanted and bottles were placed in an oven to dry overnight at 105°C. Final weights (bottle + sediment) were used to determine sediment load. Runoff and sediment were summed for 5-minute intervals and corrected for nutrient analysis subsamples. Infiltration was calculated as the difference between applied rainfall and measured runoff.

Runoff Nutrient Processing and Analyses. A 50 mL portion of composited 5-minute subsamples was filtered through a 0.45 μm cellulose NO_3 membrane and analyzed for NH_4-N by the salicylate–hypochlorite method (Crooke and Simpson 1971), nitrate plus nitrite (NO_3^- + NO_2^-) by Griess–Ilosvay method (Keeney and Nelson 1982) after reduction of NO_3^- with a cadmium (Cd) column, and for dissolved reactive P (DRP; PO_4^{3-}) by the molybdate blue method (Murphy and Riley 1962). Total P was determined colorimetrically on unfiltered samples after Kjeldahl digestion (USEPA 1979). Total N was not determined because digested samples were stored for analysis in a freezer that failed. Nutrient load for a 5-minute interval was calculated as nutrient concentration multiplied by runoff volume. Total load for the 60-minute simulation is the sum of 5-minute loads. Flow weighted mean concentration (FWMC) was calculated as total load divided by total runoff volume for each 5-minute period and for the whole 60-minute period.

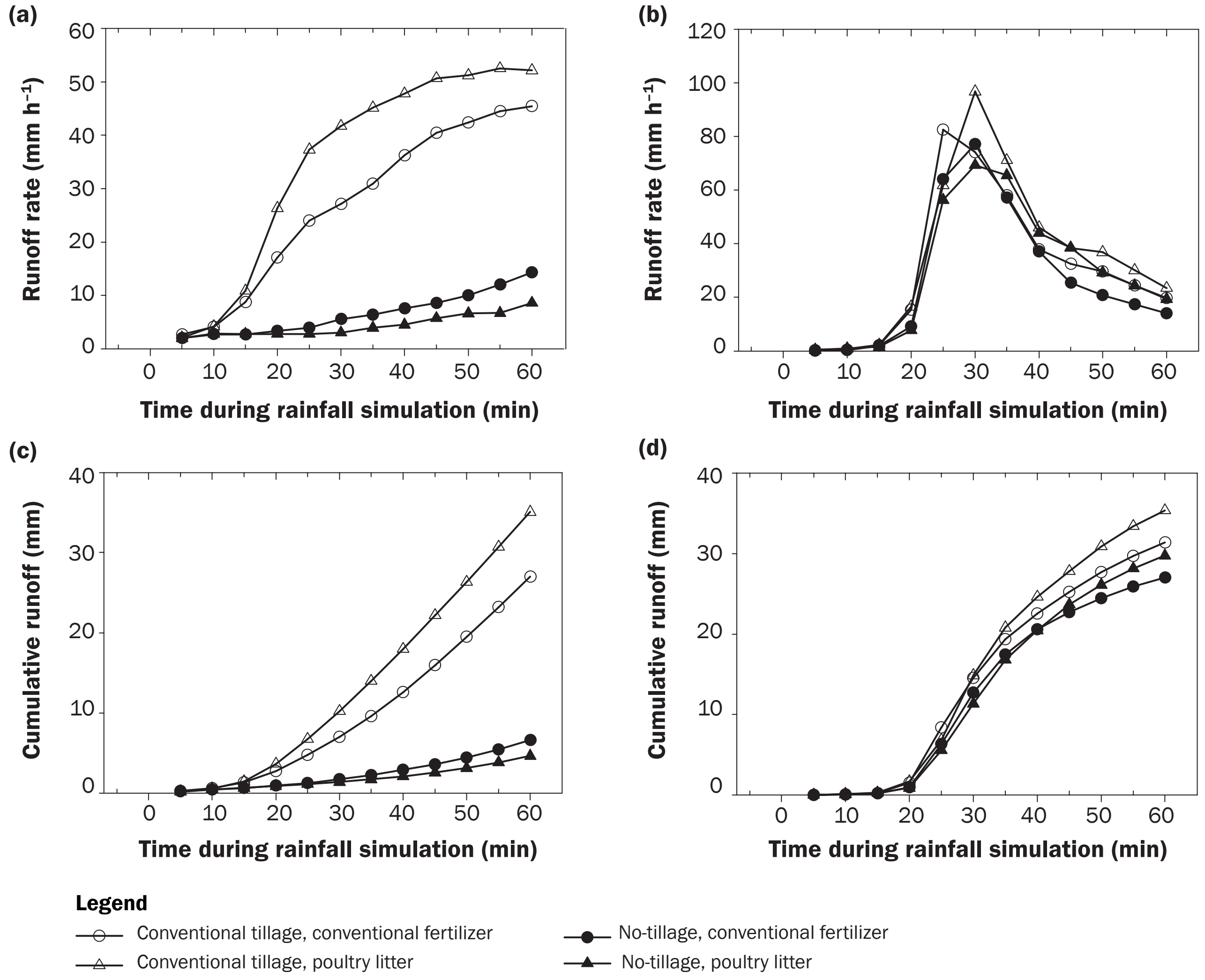
Statistical Analyses. Direct statistical comparisons between FR and VR simulations are not possible because they were conducted in different years. Data analyses were conducted independently for FR and VR simulations. Factors known to affect runoff, such as antecedent moisture and surface residue, were different between the two years and thus further confound direct statistical comparisons.

Runoff, infiltration, sediment load, and concentration and load of NH_4-N, NO_3-N, DRP, and TP data were evaluated over the 5-minute periods and for the total rainfall event. The GLIMMIX procedure (SAS Institute Inc. 2017) was used for analysis of variance of the 5-minute data. Time was designated as a repeated factor with a RANDOM statement and a first-order autoregressive (AR[1]) variance, and covariance structure was determined to best fit the data. Block (replication), block by tillage, and block by tillage by fertilizer were designated random effects in a second RANDOM statement (G-side variance). Tillage, nutrient source, time, and their interactions were the independent fixed effects included as class variables in the model statement. Antecedent SWC for the 0 to 15 cm depth was evaluated as a covariate in the model (see below), but was removed because it was not significant. When significant interactions were present among fixed effects, an analysis of simple effects was performed using the SLICEDIFF option of the LSMEANS statement. Confidence limits and *p*-values for multiple comparisons of interaction effects were adjusted using the Tukey option.

Cumulative data over the 60-minute period were analyzed using Proc Mixed (SAS Institute Inc. 2017) in a similar manner as described above, but without time in the model. As with the 5-minute data, antecedent SWC for the 0 to 15 cm depth was evaluated as a covariate by including SWC, SWC-squared, and SWC-cubed effects in the model as a continuous variable. Covariate effects not significant were removed from the final model. When a significant interaction between tillage and fertilizer was present, an analysis of simple effects was performed using the SLICE option in the mixed models LSMEANS statement to evaluate differences among NTPL, NTCF, CTPL, and CTCF. Unless otherwise indicated, differences among treatments were considered significant at $p \leq 0.05$.

Figure 2

The 5-minute treatment average of (a and b) runoff rate, and (c and d) cumulative runoff depth through the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for runoff rate.



Results and Discussion

Figures 2 to 7 show response of dependent variables over time, whereas figures 8 to 10 show data as functions of cumulative kinetic energy, which gives an indication of the physical intensity of rainfall. Tables 2 and 3 provide results of the analysis of variance for the 5-minute data. Tables 4, 5, 6, and 7 show analysis of variance for the total 60-minute period.

Simulated Rainfall and Soil Water Content. Rainfall intensity (mm h^{-1}) and cumulative rainfall (mm) for the FR and VR simulations in 2004 and 2005, respectively, are given in figure 1, which also shows the hourly and cumulative rainfall kinetic energy. At peak rainfall intensity of the VR simulation, the hourly kinetic energy was 2.83 times greater than any point in the FR simulation (figure 1a). Although total cumulative rainfall and cumulative kinetic energy are similar for the VR and FR simulations, figure 1b illustrates the contrast between the two over time. For both simulations, total rainfall volume among management treatments were similar. The FR volumes (±se) were 1,011 ± 19, 1,020 ± 25, 1,005 ± 18, and 1,068 ± 32 mL for CTCF, CTPL, NTCF, and NTPL, respectively. Corresponding values for VR simulations were 1,078 ± 32, 1,074 ± 35, 1,051 ± 4, and 1,090 ± 33, respectively. Overall average rainfall volume was 1,026 ± 13 mL for FR and 1,073 ± 3 mL for VR simulations.

In 2004, antecedent SWC for the 0 to 15 cm soil depth was lower in CT (0.08 g g^{-1}) compared with NT (0.13 g g^{-1}), while in 2005 SWC was not different among treatments (0.20 g g^{-1}). Fertilizer source resulted in a SWC difference in 2005 (0.19 g g^{-1} for CF and 0.22 g g^{-1} for PL) but not in 2004 (0.10 and 0.11 g g^{-1}, respectively). The SWC data indicate the soils were dryer in 2004 compared to 2005. Average weekly rainfall in the four weeks prior to simulation was 6.3 mm in 2004 (range 1 to 16 mm) and 61.0 mm in 2005 (range 20 to 97 mm). During the two weeks of simulations, average weekly values were 10.0 mm for 2004 and 12.3 for 2005.

Table 2

Analysis of variance evaluating tillage, fertilizer, and time effects on runoff, infiltration, and sediment loss for the fixed rate (FR) and variable rate (VR) simulations in 2004 and 2005, respectively.

	Runoff (mm)	Runoff (%)	Infiltration (mm)	Infiltration (%)	Sediment (g)
Year/effect	***p*-value > *F*-value**				
FR 2004					
Tillage (T)	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0319**
Fertilizer (F)	0.3916	0.4186	0.7498	0.3978	0.5222
T × F	0.1728	0.1391	0.0922	0.1483	0.4749
Time	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
T × time	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
F × time	0.8460	0.8109	0.8720	0.8545	0.9051
T × F × time	0.6764	0.6494	0.6888	0.6796	0.9041
95% confidence interval (±)	T × time; 0.7	T × time; 15.2	T × time; 0.7	T × time; 15.3	T × time; 46.3
VR 2005					
T	0.1999	0.2034	0.2758	0.2028	0.1650
F	0.0987	**0.0367**	0.1599	**0.0366**	0.5062
T × F	0.7470	0.8577	0.9782	0.8590	0.8277
Time	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
T × time	0.9219	0.1557	0.9645	0.1564	**0.0001**
F × time	0.2775	**0.0021**	**0.0468**	**0.0022**	0.9587
T × F × time	0.5980	0.6812	0.9449	0.6760	0.4854
95% confidence interval (±)		F × time; 11.8	F × time; 1.0	F × time; 11.8	T × time; 29.8

Note: Values bolded to indicate significant effects where $p < 0.05$.

Runoff, Infiltration, and Sediment. The 5-minute runoff rates and cumulative runoff for FR and VR simulations are shown in figure 2 (notice that *y*-axis scales for runoff rate are different between the two years). For the FR simulation, CT resulted in much greater total runoff compared with NT (figures 2a and 2c). The difference between CT and NT was significant from the 20-minute period to the end of the simulation (tables 2 and 3; repeated measures analysis). Significant interactions were present for total runoff and rainfall partitioned to runoff (mean runoff percentage) with CTCF and CTPL being different while NTCF and NTPL were not (tables 4 and 5). A 4-fold difference in runoff and rainfall partitioned to runoff was observed between CTCF and NTCF and an 8.5-fold difference between CTPL and NTPL. Overall, nearly six times more rainfall was partitioned into runoff under CT (55.8%) compared with NT (9.7%).

Infiltration was estimated as the difference between rain applied and runoff, which results in the values being a near reverse image of runoff. At the end of the rainfall

Table 3

Analysis of variance evaluating tillage, fertilizer, and time effects on flow weighted mean concentration (FWMC) and total load of nutrients in runoff for the fixed rate (FR) and variable rate (VR) simulations in 2004 and 2005, respectively.

	FWMC (mg L^{-1})				Total load (mg)			
	NH_4-N	NO_3-N	DRP	TP	NH_4-N	NO_3-N	DRP	TP
Year/effect	***p*-value > *F*-value**							
FR 2004								
Tillage (T)	**0.0005**	**0.0035**	**0.0026**	0.1985	0.2447	**0.0131**	0.7716	**0.0012**
Fertilizer (F)	**0.0190**	**0.0036**	0.1608	0.6450	0.6406	**0.0084**	0.7319	**0.0275**
T × F	**0.0081**	**0.0038**	**0.0215**	**0.0189**	0.2174	**0.0096**	0.2065	**0.0098**
Time	**0.0025**	**0.0307**	**0.0001**	**0.0041**	**0.0066**	**0.0238**	**0.0003**	**0.0001**
T × time	**0.0021**	**0.0288**	**0.0001**	**0.0011**	**0.0350**	**0.0343**	0.0651	**0.0017**
F × time	**0.0015**	**0.0305**	**0.0001**	**0.0156**	0.1484	**0.0347**	0.3220	0.4877
T × F × time	**0.0014**	**0.0281**	**0.0001**	**0.0131**	**0.0257**	**0.0280**	**0.0142**	0.3293
95% confidence interval (±)	T × F × time; 10.4	T × F × time; 12.2	T × F × time; 4.8	T × F × time; 6.0	T × F × time; 78.1	T × F × time; 38.7	T × F × time; 57.4	T × time; 34.9
VR 2005								
T	**0.0029**	0.0780	0.0522	**0.0001**	**0.0001**	**0.0046**	**0.0405**	**0.0060**
F	**0.0032**	**0.0214**	0.1479	**0.0001**	**0.0001**	**0.0005**	0.1124	**0.0022**
T × F	**0.0034**	**0.0402**	0.1479	**0.0021**	**0.0001**	**0.0007**	0.1125	0.0655
Time	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
T × time	**0.0001**	**0.0449**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
F × time	**0.0001**	0.2084	0.1332	**0.0001**	**0.0001**	**0.0001**	0.2124	**0.0001**
T × F × time	**0.0001**	0.1361	0.1255	**0.0001**	**0.0001**	**0.0001**	0.2141	**0.0365**
95% confidence interval (±)	T × F × time; 18.6	T × time; 7.7	T × time; 6.3	T × F × time; 9.7	T × F × time; 300.8	T × F × time; 165.4	T × time; 111.2	T × F × time; 483.2

Notes: NH_4-N = ammonium-nitrogen. NO_3-N = nitrate-nitrogen. DRP = dissolved reactive phosphorus. TP = total phosphorus. Values bolded to indicate significant effects where $p < 0.05$.

Table 4

Means and standard errors (se) for runoff, infiltration, sediment, and time to peak (max) sediment loss for the fixed rate (FR) and variable rate (VR) simulations in 2004 and 2005, respectively.

Year/effect	Total runoff (mm)		Mean runoff (%)		Max 5-min runoff rate (mm h^{-1})		Time to max 5-min runoff (min)		Total infiltration (mm)		Mean infiltration (%)		Total sediment (g)		Max 5-min sediment (g)		Time to max 5-min sediment (min)	
	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se
FR 2004																		
CT	31.0	3.9	55.8	7.1	49.4	3.7	53.3	2.1	24.7	3.8	44.5	7.0	918.7	158.0	122.3	19.0	43.3	6.0
NT	5.6	3.9	9.7	7.1	11.5	3.7	60.0	2.1	51.2	3.8	90.1	7.0	81.6	158.0	12.5	19.0	50.8	6.0
CF	16.8	3.4	30.3	6.1	30.0	3.7	57.5	1.6	38.5	3.2	69.9	6.1	459.5	132.7	62.1	16.6	45.8	5.7
PL	19.8	3.4	35.2	6.1	30.9	3.7	55.8	1.6	37.4	3.2	64.7	6.1	540.8	132.7	72.7	16.6	48.3	5.7
CTCF	27.0	4.4	48.5	8.0	45.8	4.3	55.0	2.2	28.6	4.3	51.7	7.9	832.4	181.8	113.5	21.5	43.3	8.1
CTPL	35.1	4.4	63.0	8.0	53.1	4.3	51.7	2.2	20.9	4.3	37.2	7.9	1,005.0	181.8	131.0	21.5	43.3	8.1
NTCF	6.6	4.4	12.0	8.0	14.3	4.3	60.0	2.2	48.5	4.3	88.0	7.9	86.5	181.8	10.7	21.5	48.3	8.1
NTPL	4.6	4.4	7.4	8.0	8.6	4.3	60.0	2.2	53.9	4.3	92.1	7.9	76.6	181.8	14.3	21.5	53.3	8.1
VR 2005																		
CT	33.4	2.4	55.2	3.8	92.5	4.9	27.5	1.2	29.0	2.5	44.8	3.8	2,080.2	515.1	643.3	114.2	26.7	1.3
NT	28.4	2.4	47.4	3.8	82.5	4.9	29.2	1.2	33.3	2.5	52.7	3.8	936.5	515.1	222.7	114.2	29.2	1.3
CF	29.2	1.9	46.4	3.2	81.9	4.6	27.5	1.2	33.2	2.2	53.7	3.2	1,370.9	420.4	383.3	112.4	25.8	1.2
PL	32.6	1.9	56.2	3.2	93.1	4.6	29.2	1.2	29.1	2.2	43.8	3.2	1,645.8	420.4	482.7	112.4	30.0	1.2
CTCF	31.4	2.7	50.6	4.5	85.2	6.6	26.7	1.4	31.0	3.1	49.4	4.5	1,986.6	594.6	606.2	158.9	25.0	1.4
CTPL	35.4	2.7	59.8	4.5	99.8	6.6	28.3	1.4	27.0	3.1	40.2	4.5	2,173.8	594.6	680.3	158.9	28.3	1.4
NTCF	27.0	2.7	42.1	4.5	78.7	6.6	28.3	1.4	35.3	3.1	57.9	4.5	755.2	594.6	160.4	158.9	26.7	1.4
NTPL	29.8	2.7	52.6	4.5	86.4	6.6	30.0	1.4	31.2	3.1	47.4	4.5	1,117.7	594.6	285.1	158.9	31.7	1.4

Notes: CT = conventional tillage. NT = no-tillage. CF = conventional fertilizer. PL = poultry litter.

Table 5

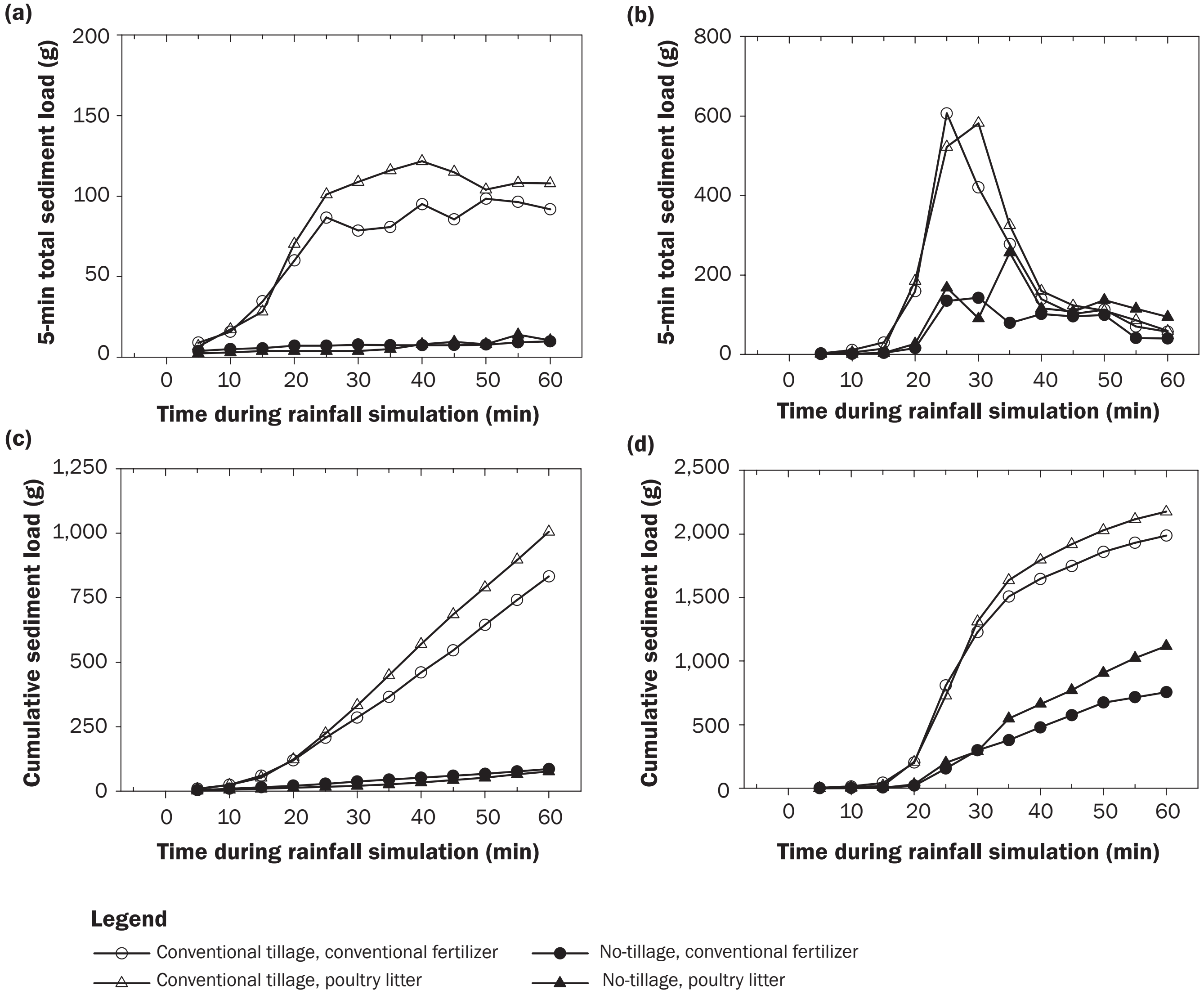
Analysis of variance and simple effects evaluating tillage and fertilizer effects on runoff, infiltration, sediment, and time to peak (max) sediment loss for the fixed (FR) and variable rate (VR) simulations in 2004 and 2005, respectively.

Year/effect	Total runoff (mm)	Mean runoff (%)	Max 5-min runoff rate (mm h^{-1})	Time to max 5-min runoff (min)	Total infiltration (mm)	Mean infiltration (%)	Total sediment (g)	Max 5-min sediment (g)	Time to max 5-min sediment (min)
	Pr > *F*-value								
FR 2004									
Tillage (T)	**0.0002**	**0.0001**	**0.0022**	0.0637	**0.0003**	**0.0001**	**0.0001**	**0.0068**	0.058
Fertilizer (F)	0.9914	0.8329	0.3165	0.7732	0.4623	0.9474	0.4314	0.4124	0.2728
T × F	**0.0139**	**0.0074**	0.2144	**0.0085**	**0.0102**	**0.0094**	**0.0258**	0.7546	0.2696
SWC	**0.0154**	**0.0081**	**0.0213**	**0.0271**	**0.0215**	**0.0111**	**0.0041**	**0.0226**	0.0886
SWC × SWC	.	.	**0.0184**	.	.	.	.	**0.0331**	.
T × F slices									
CT	**0.0357**	**0.0249**	0.0703	**0.0075**	0.0567	**0.0272**	0.1398	0.2346	0.9926
NT	0.0589	**0.0296**	0.8307	**0.0455**	**0.0249**	**0.0406**	**0.0464**	0.7907	0.1683
CF	**0.0006**	**0.0003**	**0.0015**	0.1168	**0.0009**	**0.0004**	**0.0003**	0.0042	0.1197
PL	**0.0003**	**0.0001**	**0.0033**	**0.0345**	**0.0003**	**0.0002**	**0.0002**	0.0122	0.061
VR 2005									
T	0.2102	0.2152	0.2199	0.1723	0.3021	0.2143	0.0574	0.0598	0.2254
F	0.1594	**0.0429**	0.1469	0.1723	0.1866	**0.0429**	0.263	0.5591	**0.0075**
T × F	0.759	0.8632	0.6076	1.000	0.9798	0.8644	0.8403	0.8791	0.3739
SWC	.	.	.		.	.	0.1301	.	.
SWC × SWC	.	.	.		.	.	.	.	.
T × F slices									
CT	0.22	0.1248	0.1715	0.3153	0.3299	0.1244	0.4698	0.7542	**0.0474**
NT	0.3791	0.093	0.4301	0.3153	0.3156	0.0929	0.3354	0.6025	**0.0132**
CF	0.3017	0.2227	0.5015	0.3153	0.3584	0.2222	0.0566	0.0825	0.3836
PL	0.193	0.2905	0.1853	0.3153	0.3729	0.2893	0.0748	0.1167	0.1292

Notes: SWC = soil water content. CT = conventional tillage. NT = no-tillage. CF = conventional fertilizer. PL = poultry litter. Dots mean SWC or SWC × SWC was not included in model—not significant as covariate. Values bolded to indicate significant effects where $p < 0.05$

Figure 3

The 5-minute treatment average of (a and b) sediment load, and (c and d) cumulative sediment load through the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for concentration and cumulative load.



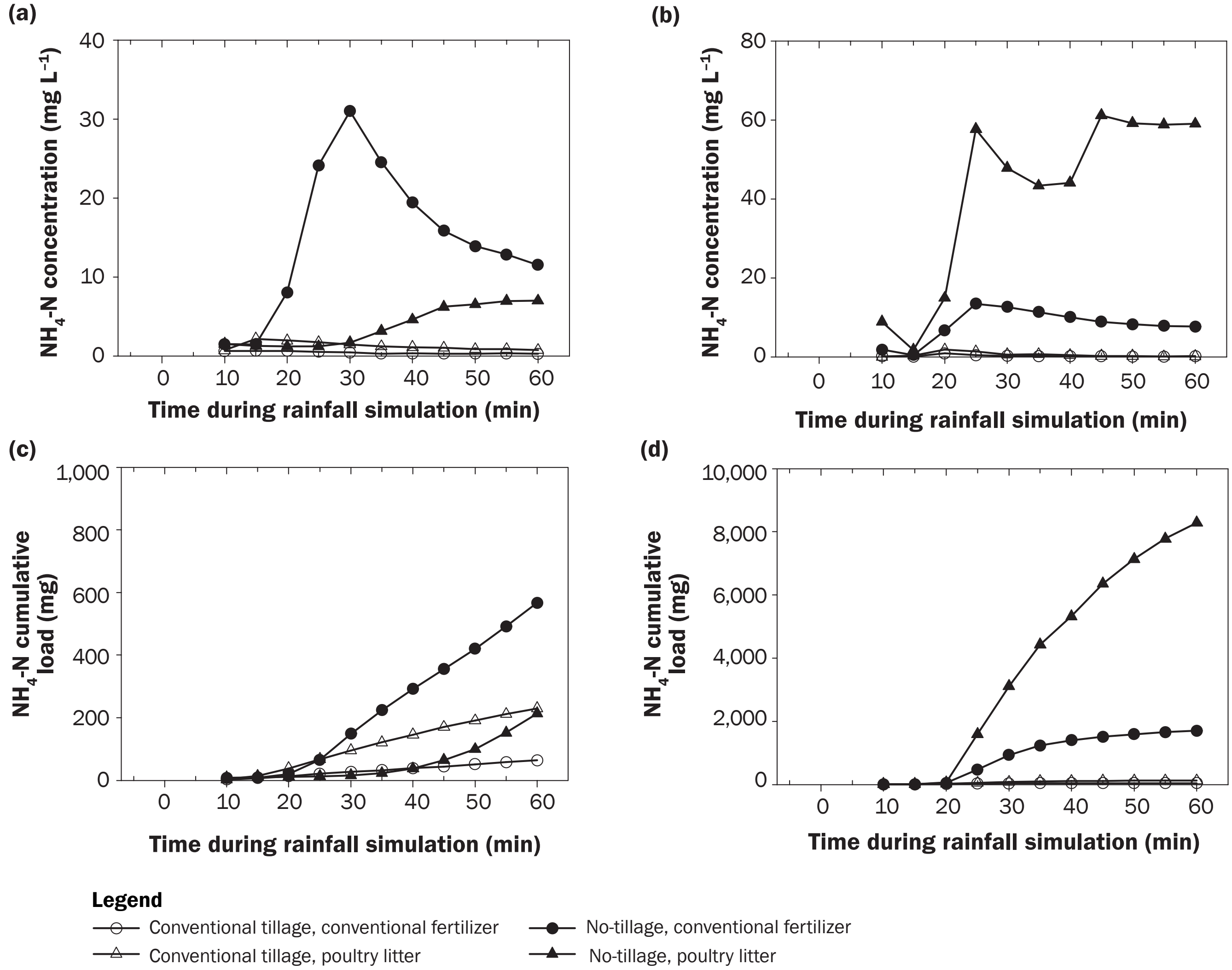
simulation, infiltration rates in millimeters per hour were 10.3 in CTCF, 4.1 in CTPL, 40.8 in NTCF, and 48.7 in NTPL. Like the runoff results, the tillage by fertilizer interaction was significant with differences in infiltration between NTCF and CTCF (1.7-fold) smaller than between NTPL and CTPL (2.6-fold) (tables 4 and 5). Overall, infiltration was 2.1 times greater in NT compared with CT.

In contrast to the FR simulation, runoff rates for the VR simulation were not different among treatments and reflect 5-minute variable rate intensities over the course of the simulation (compare figure 2a and 2b). The similarity of runoff among treatments reflects the wetter condition of the soil in 2005 and appears to indicate that the average 5-minute rainfall rates between 15 and 35 minutes in 2005 (64.4, 127.1, 142.2, 105.0, and 72.4 mm h^{-1}) are near or above the infiltration capacity of this soil even under NT management. Radcliffe et al. (1990) recorded infiltration rates of 61.9, 6.7, 32.9, 21.2, and 27.8 mm h^{-1} for Cecil soils at five locations near the site of our study. Rainfall partitioned to runoff diverged over time depending on the fertilizer treatment. Significantly more rainfall was partitioned to runoff for PL compared to CF starting at the 30-minute period and continued to the end of the simulation (figure 2d). Rainfall partitioned to runoff varied between 42% and 60% for the four treatments, with no difference between CT (55.2%) and NT (47.4%), while there was significantly more runoff with PL (56.2%) compared to CF (46.4%). During the VR simulation, total infiltration for the treatments varied between 27.0 mm and 35.3 mm with no significant differences.

Although we cannot compare FR and VR simulation results statistically, both showed a period of high infiltration early in the simulation, which transitioned to runoff as the simulation continued. Transition to runoff was earlier for CT compared to NT in the

Figure 4

The 5-minute (a and b) treatment average concentration, and (c and d) cumulative load for ammonium-nitrogen (NH_4-N) through the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for concentration and cumulative load.



FR simulation but occurred at the same time in the VR simulation. The low rate of rainfall initially in the VR simulation allowed the upper 5 to 10 cm of pore space to become filled with water, and as the rainfall intensity increased, caused infiltration to slow due to slow movement of water to deeper layers. A contributing factor to the difference in response between years was that SWC was greater in 2005 compared to 2004. The greater water content would result in more similar responses for CT and NT. The divergence of NT and CT in 2004 may also reflect soil surface sealing in the CT plots because of the absence of surface residue cover compared to NT (figures 2a and 2c).

The 5-minute sediment load and cumulative sediment load for both FR and VR simulations had significant tillage × time interactions, with greater rates of sediment loss from CT compared with NT (figure 3; table 2 for RM ANOVA). Losses in the FR simulation were greater from 20 minutes to the end of the simulation for CT compared with NT (figure 3a). Total sediment loss for CT was 11.2-fold greater than for NT (919 g versus 82 g; equivalent to 1,532 kg ha^{-1} h^{-1} versus 137 kg ha^{-1} h^{-1}) (tables 4 and 5). The tillage × fertilizer interaction for total sediment loss reflected the larger difference between CTCF and CTPL compared with NTCF and NTPL (figures 3a and3b; tables 4 and 5).

In the VR simulation, sediment loss, like runoff, followed the VR rainfall pattern (figure 3b). Sediment loss differences between tillage treatments were significant only for the 25- and 30-minute segments, where losses were nearly 4 times greater from CT than NT (figure 3b). Total sediment losses were 2.2-fold greater from CT compared with NT. Sediment loss was similar for CF and PL in the two tillage treatments (figure 3d). For both FR and VR, sediment loss was greater from CT than NT (figures 3c and 3d). Some of the differences between response to tillage may have been related to

Table 6

Flow-weighted mean nutrient concentration (FWMC) (mg L^{-1}) and total load (mg) means and standard errors (se) in runoff from fixed rate (FR) and variable rate (VR) rainfall simulations in 2004 and 2005, respectively.

	FWMC (mg L^{-1})								Total load (mg)							
Year/effect	NH_4-N	se	NO_3-N	se	DRP	se	TP	se	NH_4-N	se	NO_3-N	se	DRP	se	TP	se
FR 2004																
CT	0.8	1.7	0.12	1.83	1.00	0.90	4.84	1.08	146.7	79.6	22.2	69.5	187.1	48.8	880.0	97.5
NT	10.4	1.7	7.33	1.83	6.16	0.90	7.15	1.08	390.2	79.6	268.2	69.5	230.6	48.8	258.0	97.5
CF	7.9	1.7	7.30	1.83	4.35	0.90	5.61	1.08	315.4	79.6	278.0	69.5	183.1	48.8	395.1	97.5
PL	3.3	1.7	0.15	1.83	2.81	0.90	6.38	1.08	221.6	79.6	12.5	69.5	234.5	48.8	742.8	97.5
CTCF	0.4	2.4	0.14	2.59	0.40	1.27	3.15	1.52	63.7	112.6	25.2	98.3	61.4	68.3	494.6	126.7
CTPL	1.2	2.4	0.10	2.59	1.60	1.27	6.53	1.52	229.7	112.6	19.3	98.3	312.8	68.3	1,265.3	126.7
NTCF	15.4	2.4	14.46	2.59	8.30	1.27	8.06	1.52	567.0	112.6	530.7	98.3	304.9	68.3	295.6	126.7
NTPL	5.4	2.4	0.20	2.59	4.01	1.27	6.24	1.52	213.4	112.6	5.7	98.3	156.2	68.3	220.3	126.7
VR 2005																
CT	0.5	1.5	1.62	1.39	0.13	2.39	4.80	1.24	81.9	268.7	301.5	226.8	24.2	363.0	958.0	356.9
NT	30.7	1.5	7.79	1.39	10.76	2.39	17.77	1.24	4,993.8	268.7	1,182.6	226.8	1,651.2	363.0	2,921.8	356.9
CF	5.7	1.4	8.59	1.39	3.38	2.16	5.04	1.24	871.1	268.7	1,327.6	226.8	514.8	319.0	790.6	356.9
PL	25.5	1.4	0.82	1.39	7.50	2.16	17.53	1.24	4,204.7	268.7	156.4	226.8	1,160.7	319.0	3,089.2	356.9
CTCF	0.3	1.9	1.84	1.90	0.13	3.02	2.09	1.75	43.8	379.9	327.3	305.8	24.1	445.2	367.6	504.7
CTPL	0.7	1.9	1.40	1.90	0.12	3.02	7.51	1.75	120.0	379.9	275.7	305.8	24.3	445.2	1,548.4	504.7
NTCF	11.2	1.9	15.34	1.90	6.64	3.02	7.99	1.75	1,698.4	379.9	2,328.0	305.8	1,005.4	445.2	1,213.6	504.7
NTPL	50.3	1.9	0.24	1.90	14.87	3.02	27.56	1.75	8,289.3	379.9	37.2	305.8	2,297.1	445.2	4,630.0	504.7

Notes: NH_4-N = ammonium-nitrogen. NO_3-N = nitrate-nitrogen. DRP = dissolved reactive phosphorus. TP = total phosphorus. CT = conventional tillage. NT = no-tillage. CF = conventional fertilizer. PL = poultry litter.

Table 7

Analysis of variance and simple effects evaluating tillage and fertilizer effects on flow weighted mean concentration (FWMC) and total load of nutrients in runoff for the fixed rate (FR) and variable rate (VR) simulations in 2004 and 2005, respectively.

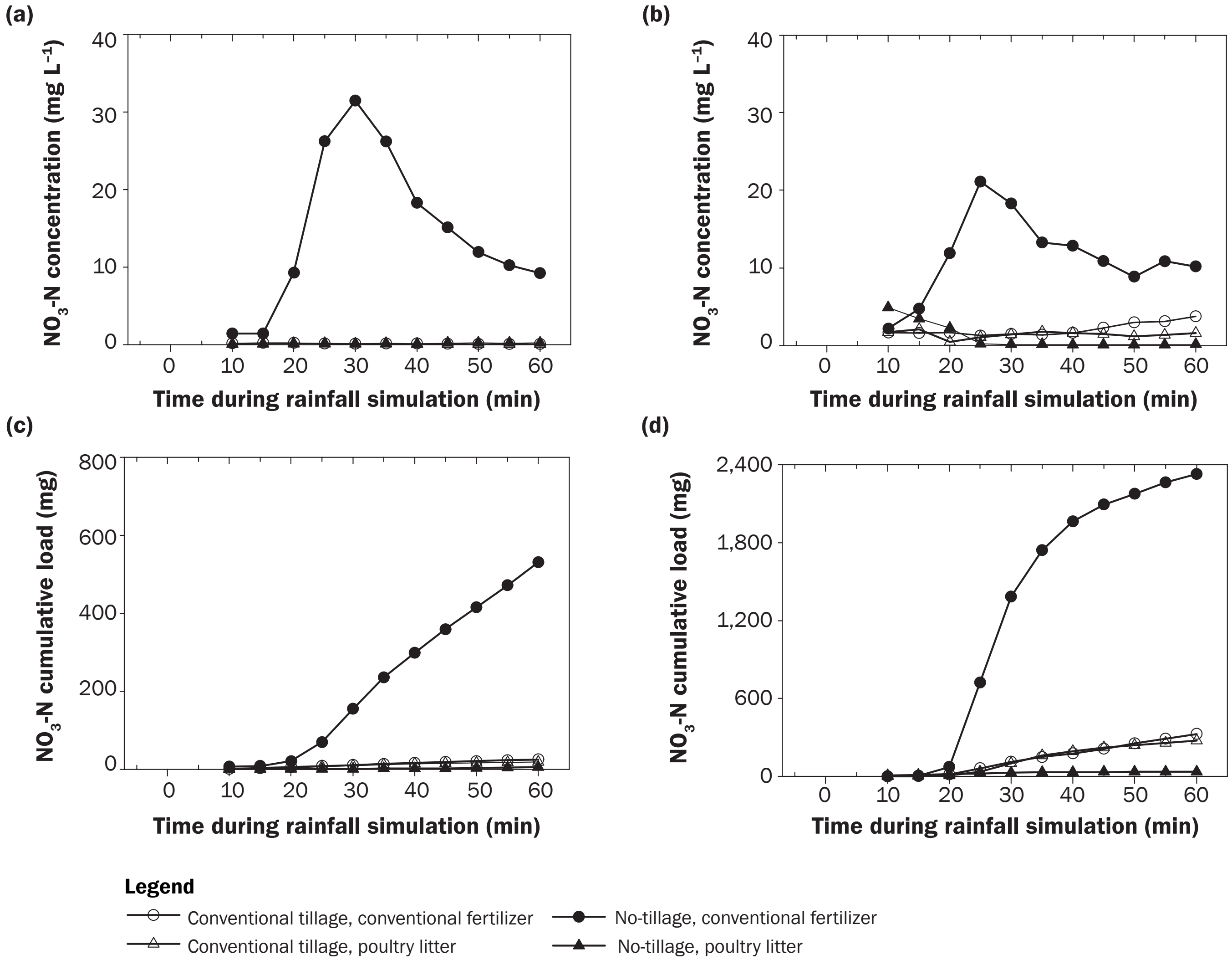
	FWMC (mg L^{-1})				Total load (mg)			
	NH_4-N	NO_3-N	DRP	TP	NH_4-N	NO_3-N	DRP	TP
Year/effect	Pr > *F*-value							
FR 2004								
Tillage (T)	**0.004**	**0.0237**	**0.0037**	0.1679	0.0625	**0.0369**	0.5447	0.1082
Fertilizer (F)	0.0942	**0.0246**	0.2601	0.6263	0.4288	**0.0271**	0.4771	**0.0256**
T × F	0.0564	**0.0253**	0.0633	0.1264	**0.0499**	**0.0297**	**0.0257**	0.0937
SWC	.*	.	.	.	.	.	.	0.0559
SWC × SWC	.	.	.	.	.	.	.	**0.0455**
T × F slices								
CT	0.8211	0.9903	0.5237	0.1564	0.3277	0.9668	**0.039**	**0.031**
NT	**0.0193**	**0.0046**	**0.0445**	0.4209	0.0571	**0.0054**	0.1706	0.2519
CF	**0.0023**	**0.0045**	**0.0023**	0.0522	**0.0134**	**0.0066**	**0.0436**	0.2612
PL	0.2501	0.9778	0.218	0.8966	0.921	0.9245	0.1523	0.0576
VR 2005								
T	**0.0001**	**0.0151**	0.0854	**0.0001**	**0.0001**	**0.0229**	0.0837	**0.0046**
F	**0.0004**	**0.0054**	0.1921	**0.0001**	**0.0001**	**0.0068**	0.1511	**0.0019**
T × F	**0.0004**	**0.0071**	0.1908	**0.0037**	**0.0001**	**0.0084**	0.1512	0.0576
SWC	.	.	.	.	.	.	.	.
SWC × SWC	.	.	.	.	.	.	.	.
T × F slices								
CT	0.8832	0.8711	0.9969	0.0601	0.8906	0.904	0.9997	0.1367
NT	**0.0001**	**0.0011**	0.0903	**0.0001**	**0.0001**	**0.0014**	0.0664	**0.0014**
CF	**0.0043**	**0.0020**	0.1938	**0.0443**	**0.0151**	**0.0028**	0.1878	0.2699
PL	**0.0001**	0.6693	**0.0218**	**0.0001**	**0.0001**	0.5823	**0.0208**	**0.0026**

Notes: NH_4-N = ammonium-nitrogen. NO_3-N = nitrate-nitrogen. DRP = dissolved reactive phosphorus. TP = total phosphorus. SWC = soil water content. CT = conventional tillage. NT = no-tillage. CF = conventional fertilizer. PL = poultry litter. Values bolded to indicate significant effects where $p < 0.05$.

*Dots mean SWC or SWC × SWC was not included in model—not significant as covariate.

Figure 5

The 5-minute (a and b) treatment average concentration, and (c and d) cumulative load for nitrate-nitrogen (NO_3-N) through the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for cumulative load.



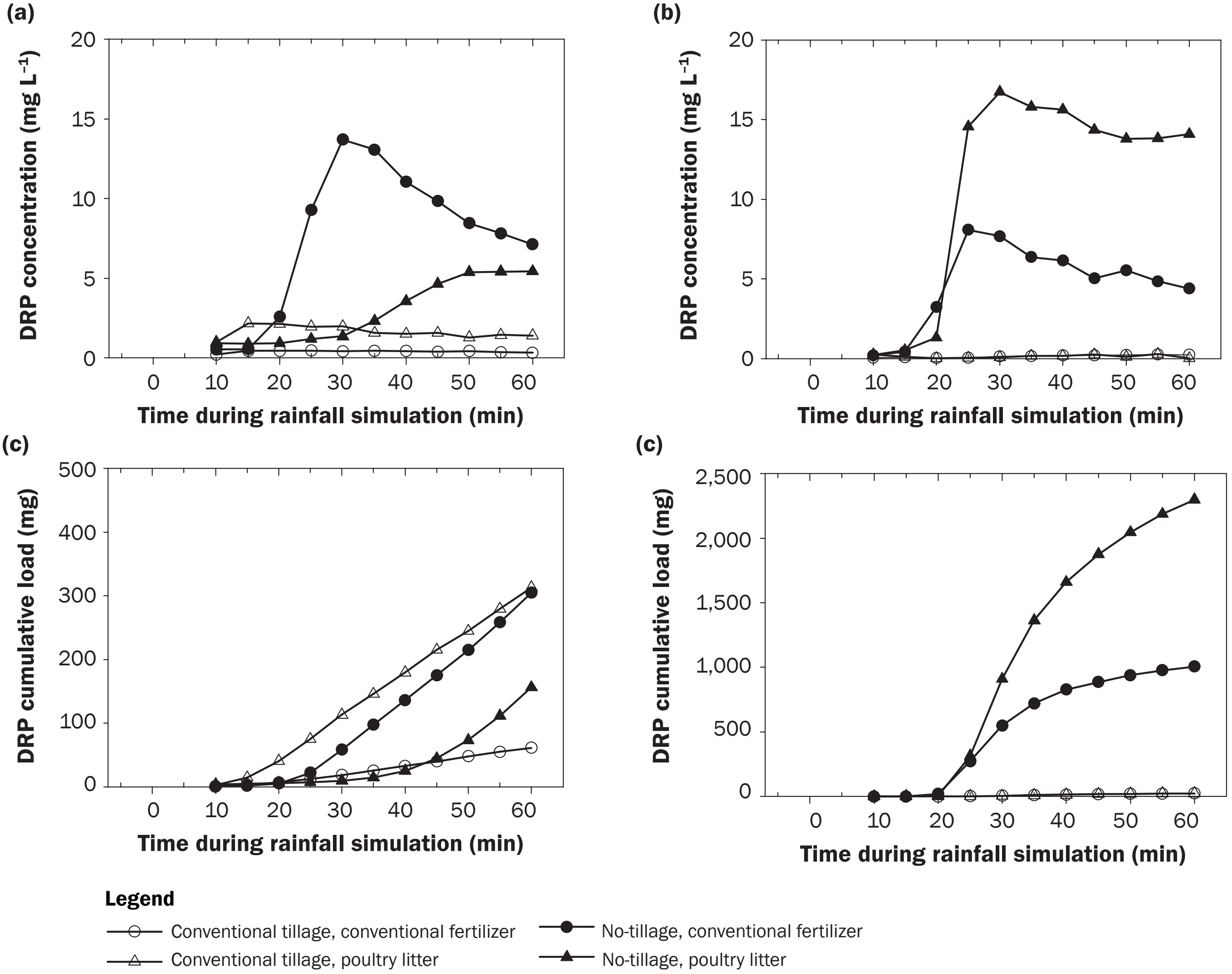
infiltration rate (Year 1 FR) and the presence of residues in the NT system, which would reduce rainfall impact energy and reduce the rate of water flow across the soil surface.

Ammonium-Nitrogen Concentration and Load. The 5-minute concentration and load for NH_4-N during the FR simulation in figure 4 (table 3) shows that NH_4-N concentration remained below 2 mg L^{-1} for CT treatments and NTPL over the simulation period. In contrast, NH_4-N concentration of NTCF rose significantly above the other treatments during the interval from 25 minutes to 45 minutes. The greater concentrations of NH_4-N for NTCF demonstrates high potential for runoff losses of NH_4NO_3 fertilizer applied to the soil surface. Even though runoff from this plot was minimal, the greater concentration contributed to greater load as seen in the cumulative loss (figure 4c). The FWMCs of NH_4-N (in milligrams per liter) for the whole simulation (total) were 0.4 for CTCF and 1.2 for CTPL and greater at 5.4 for NTPL and 15.4 for NTCF (tables 6 and 7). A significant difference was present between CTCF and NTCF and between NTCF and NTPL (table 7). The contrasts between CTCF and CTPL and between NTPL and CTPL were not significant. Total FWMC was 13-fold greater for NT compared with CT. Cumulative 5-minute loads for NH_4-N (figure 4c) illustrate the combined influences of concentration and runoff volume where at 30-minute NH_4-N load of NTCF was significantly greater for other treatments. Total NH_4-N load was 8.9-fold greater for NTCF (567 mg) compared with CTCF (64 mg) while the difference between CTPL and NTPL (230 mg and 213 mg, respectively) was negligible (tables 3, 6, and 7).

The 5-minute NH_4-N concentration during the VR simulation was low for CTCF and CTPL over the rainfall simulation, while that for NTPL rose between the 15- and 25-minute intervals and remained near 40 to 60 mg L^{-1} from 25 minutes to the end of the simulation (figure 4b). During this period, NH_4-N concentration for the two CT treat-

Figure 6

The 5-minute (a and b) treatment average concentration, and (c and d) cumulative load for dissolved reactive phosphorus (DRP) through the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for cumulative load.



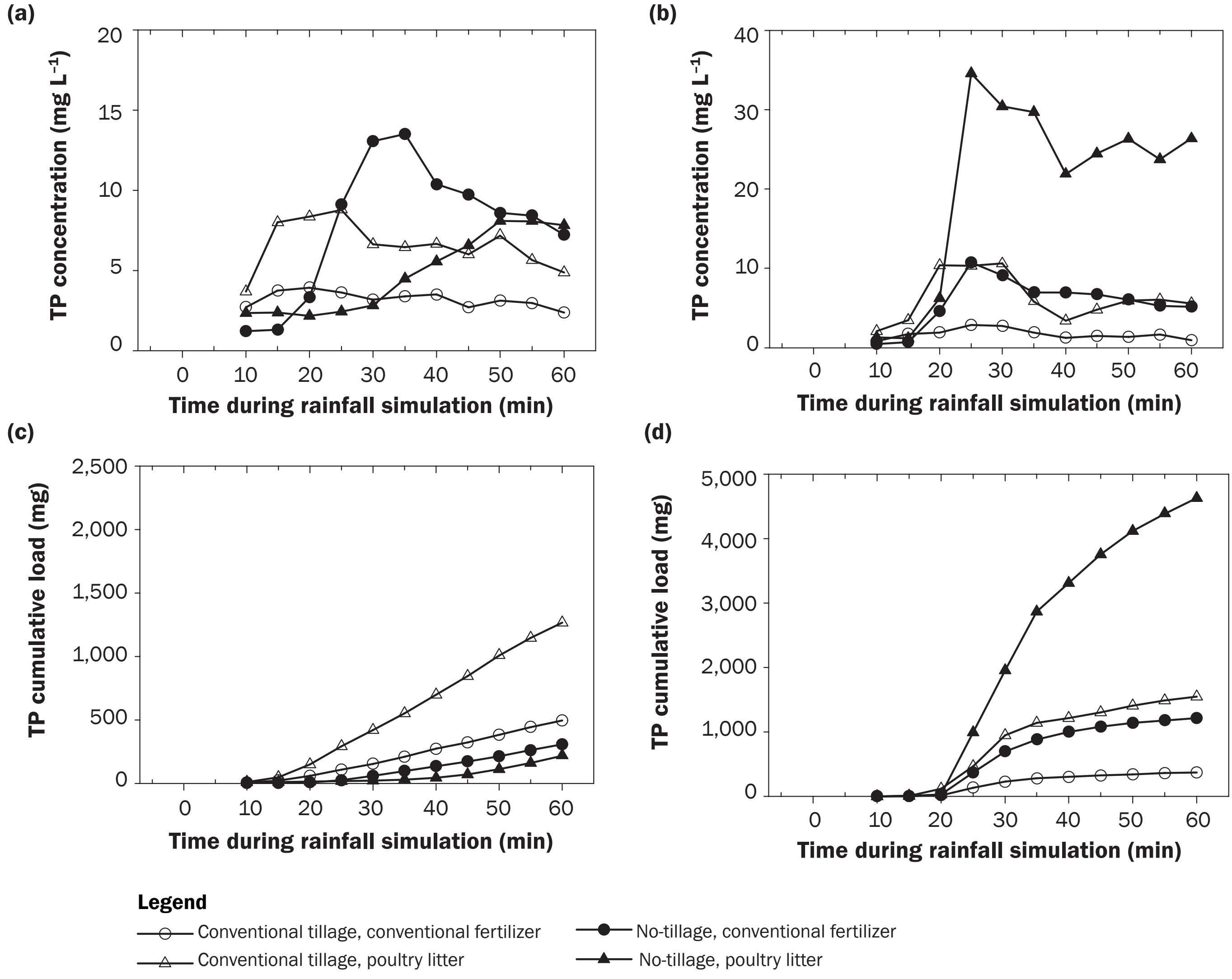
ments was different from the NTPL, while in contrast they were not different from NTCF. Over the whole simulation period FWMCs for CTCF and CTPL were 0.3 mg L^{-1} and 0.7 mg L^{-1}, respectively, whereas FWMC was greater for NTCF and NTPL (11.2 mg L^{-1} and 50.3 mg L^{-1}, respectively; tables 6 and 7). On average, there was an approximately 60-fold difference in FWMC between NT and CT, with much of this due to NTPL. The FWMC difference between fertilizer source showed PL to be 4.5-fold greater than CF. The larger contributing source of NH_4-N in runoff from NT changed from CF in the FR simulation to PL in the VR simulation. The conversion of uric acid in PL to urea then to NH_4-N and NO_3-N is microbially mediated, and the high losses of NH_4-N in the VR simulation indicates this process must have started before PL application to plots just prior to the rainfall simulation. Because the runoff losses among treatments were not different, NH_4-N load demonstrated a similar response to that for concentration.

Nitrate-Nitrogen Concentration and Load. The NO_3-N concentrations and cumulative loads for the FR and VR simulations are shown in figure 5. For the FR and VR simulations, the tillage × fertilizer × time effect for NO_3-N concentration was significant with greater concentrations over time (after 15 minutes for FR and after 20 minutes for VR) for NTCF compared with CTCF, CTPL, and NTPL (table 3).

The NO_3-N FWMC in FR and VR was low for NTPL (<0.25 mg L^{-1}) and CTPL and CTCF (0.1 to 1.8 mg L^{-1}). In contrast, it was higher and greatest for NTCF at 14.5 mg L^{-1} and 15.3 mg L^{-1}, for FR and VR, respectively. Differences between CTCF and CTPL and between CTPL and NTPL were not significant in either year (table 7). The greater FWMC in NTCF was the overriding factor contributing to the difference between fertilizer treatments (7.3 mg L^{-1} versus 0.1 mg L^{-1} in the FR simulation and 8.6 mg L^{-1} versus 0.8 mg L^{-1} in the VR simulation for CF versus PL, respectively) as well

Figure 7

The 5-minute (a and b) treatment average concentration, and (c and d) cumulative load for total phosphorus (TP) through the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for concentration and cumulative load.



as tillage treatments (7.3 mg L^{-1} versus 0.1 mg L^{-1} in FR and 7.8 mg L^{-1} versus 1.6 mg L^{-1} in VR for NT versus CT, respectively). The NTCF treatment had by far the largest NO_3-N load of the four treatments in both years (531 g versus 6 to 25 g in FR and 2,328 g versus 37 to 327 g in VR). Numerically, simulation period NO_3-N loads in VR were 4- to 15-fold larger than in FR, which probably was related to the greater runoff in VR.

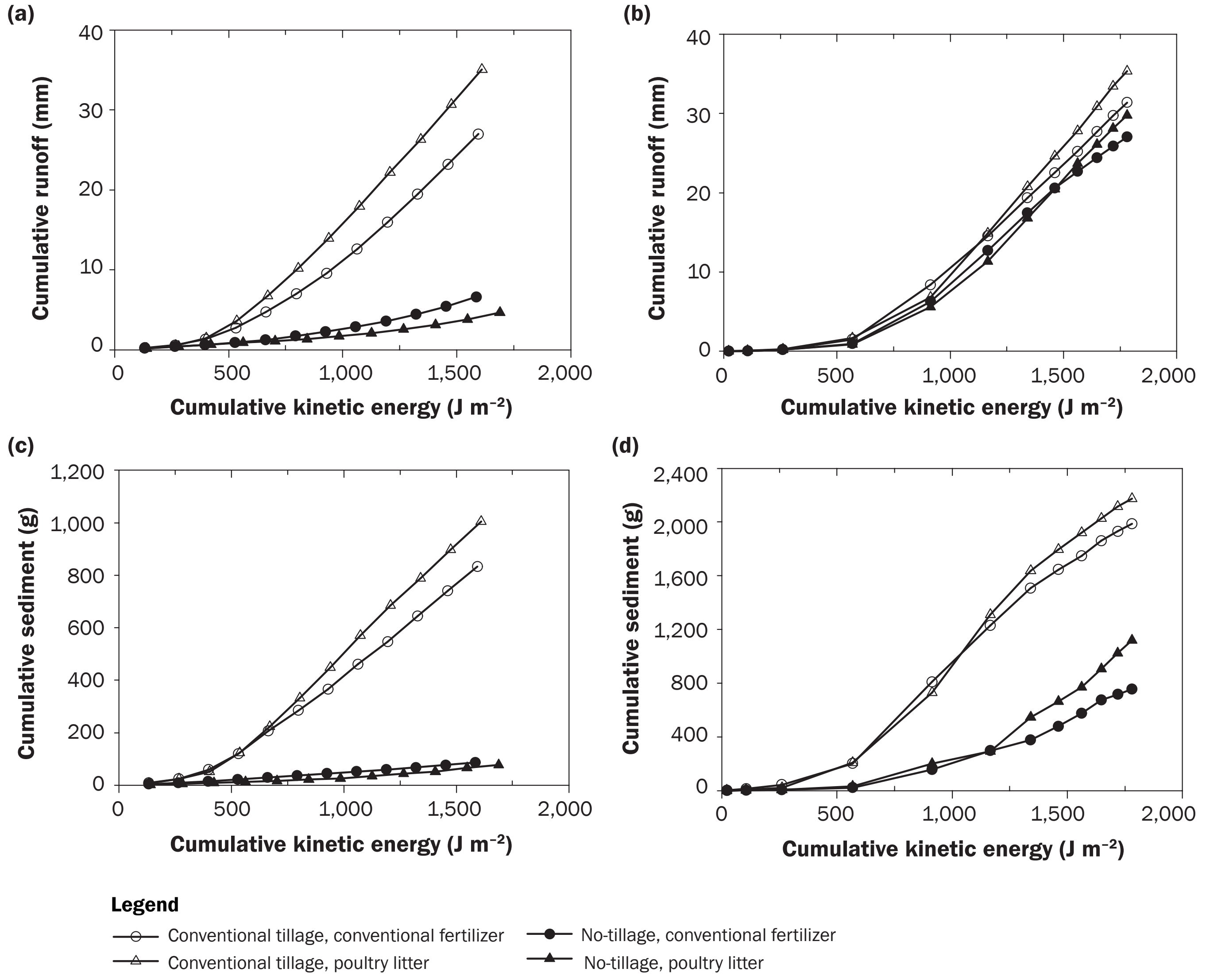
Dissolved Reactive Phosphorus Concentration and Load. Concentrations and loads of DRP for the FR and VR simulations are shown in figure 6. There was a significant tillage × fertilizer × time interaction for DRP concentration and load for the FR simulation (table 3). From the 25-minute through the 45-minute interval, NTCF had greater 5-minute DRP concentrations compared with the CTCF, CTPL, and NTPL. Beginning at the 50-minute interval, DRP concentrations for NTCF and NTPL were not different, but these two were different from CTCF and CTPL.

The DRP concentration and load over the VR simulation were influenced by significant tillage × time interactions (table 3), where concentrations were greater from NT plots compared with CT plots from 25-minute interval through the end of the simulation and loads were greater during the 25- to 50-minute interval. The DRP concentration for CT treatments remained <0.3 mg L^{-1} with no apparent discernable trend. In contrast, peak 5-minute DRP concentration for NT treatments were 8.1 mg L^{-1} at 25 minutes for NTCF and 15.8 mg L^{-1} at 35 minutes for NTPL. Peak 5-minute DRP loads were 4.1 mg at 30 minutes for CTCF, 5.3 mg at 35 minutes for CTPL, and 277.0 mg for NTCF and 595.4 mg for NTPL, both at 30 minutes.

For the FR and VR simulations, DRP FWMCs were relatively low in CTCF (0.4 mg ha^{-1} and 0.1 mg ha^{-1}, respectively) and CTPL (1.6 mg L^{-1} and 0.1 mg L^{-1}, respectively) (tables 6 and 7). In the NT treatments, DRP FWMCs for NTCF were similar for

Figure 8

Cumulative kinetic energy of simulated rainfall versus (a and b) cumulative runoff depth, and (c and d) cumulative sediment mass loss during the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for cumulative sediment.



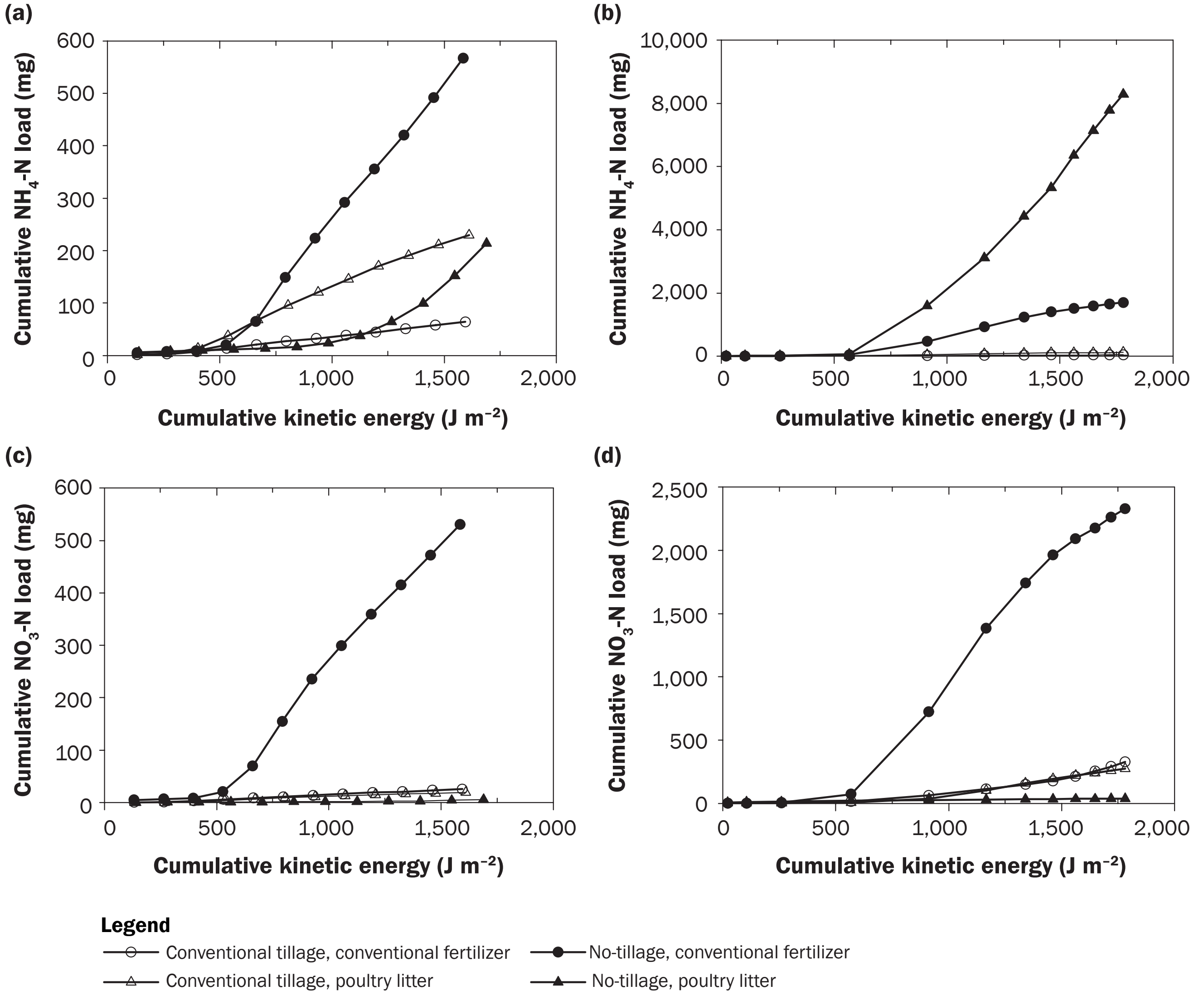
both years (6 to 8 mg L^{-1}), while values for NTPL were numerically lower for FR (4.0 mg L^{-1}) compared with VR (15 mg L^{-1}). The greater DRP FWMCs in NT compared with CT during both years reflects nutrient source placement on the soil surface and lack of incorporation in the NT treatment.

Total Phosphorus Concentration and Load. The response for TP concentration in the FR simulation was somewhat different from the other nutrients (figure 7 and table 3). At the 15-minute interval, TP concentration of CTPL was about two times that of NTCF and NTPL. At the 30- and 35-minute intervals, TP concentration of NTCF was greater than CTCF, CTPL, and NTPL. For the remaining 40- to 60-minute interval, TP concentration of NTCF was greater than that of CTCF. In contrast to the significant three-way interaction for TP concentration, load was influenced by a tillage × time interaction, where, on average, TP load was 70 g greater for CT compared with NT from the 20- to the 55-minute interval. During the last 5-minute interval, TP total loads were 49.9, 118.1, 47.7 and 57.1 mg, for CTCF, CTPL, NTCF, and NTPL, respectively. The cumulative TP load for CTPL was greater than the other treatments in the FR simulation (1,265 g versus 220 to 495 g; tables 6 and 7).

In the VR simulation, TP concentration and load both had significant three-way interactions (table 3). The TP runoff concentration for NTPL was greater than that of other treatments from 25 minutes until the end of the simulation. For the 25- and 30-minute intervals the TP concentrations for CTPL and NTCF were greater than that from CTCF. As shown in tables 6 and 7, the TP FWMC for NTPL (27.6 mg L^{-1}) was larger than CTPL (7.5 mg L^{-1}) and NTCF (8.0 mg L^{-1}). The difference between NTCF and CTCF was also significant (8.0 mg L^{-1} versus 2.1 mg L^{-1}). Similar to TP concentration, TP load for NTPL was greater than

Figure 9

Cumulative kinetic energy of simulated rainfall versus (a and b) cumulative load of ammonia-nitrogen (NH_4-N), and (c and d) cumulative load of nitrate-nitrogen (NO_3-N) during the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for cumulative load.



that for the other treatments from 25 minutes through 50 minutes. Total P load for the 60-minute simulation averaged 3,089 g for the PL treatment, which was nearly 4 times the loss from the CF treatments. Load for TP was greatest for NTPL (4,630 g) and least for CTCF (368 g).

Potter et al. (2006), Truman et al. (2007), Franklin et al. (2007), and Franklin et al. (2012) reported rainfall simulation runoff, sediment, and nutrient losses from a Coastal Plain Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) managed under CT and strip tillage (ST). The rainfall simulator and rainfall intensities were the same as in our study. They used a duration of 70 minutes compared with our 60 minutes. Broiler litter was used only in the Franklin et al. (2012) study; the rest used only inorganic fertilization. Strip tillage creates a cultivated 15 cm wide, 20 cm deep loosened soil area for seed placement. Their plots had residue from an earlier rye cover crop incorporated in CT but not ST.

Potter et al. (2006) observed rainfall-to-runoff partitioning of 45% to 51% from CT and 20% to 23% from ST, and 3.9-fold greater sediment loss from CT than ST. Truman et al. (2007) reported that total runoff was 2.35 times greater from CT than from ST for both FR and VR. Sediment loss was 4.2-fold greater from CT than ST. Franklin et al. (2007) found no difference in FWMC of NH_4-N in runoff between CT and ST under either FR or VR soon after planting cotton following a rye cover crop. Under VR, load of NH_4-N in runoff was greater from CT than ST during the 25- to 35-minute period. For NO_3-N, both FWMC and load were significantly greater from ST than CT, with differences much greater under FR than VR. There was significantly greater FWMC for DRP from ST than CT under both FR and VR. The effect of tillage was greater for the FR than for VR.

There was significantly greater FWMC and load for TP from CT than from ST under both FR and VR.

Franklin et al. (2012) reported differences in P and N runoff from broiler litter fertilized plots managed as CT and ST systems using VR intensity after prewetting plots with irrigation to activate preapplied herbicide. Broiler litter was incorporated in the soil after application in CT but not ST plots. Total runoff was greater from CT than ST. Strip tillage plots had significantly greater FWMC for DRP and NH_4-N. There was no difference in FWMC for NO_3-N, TP, and total N between tillage treatments. Loads of DRP and NH_4-N were significantly greater from ST than CT even though runoff was greater from CT than ST. These results suggest that water soluble DRP and NH_4-N in the broiler litter were more available for transport in ST than CT. Loads of NO_3-N, TP, and total N were greater from CT than ST.

The potential erosivity of rainfall is often tied to kinetic energy, which is used in soil erosion models such as RUSLE 2 (USDA ARS 2013). Kinetic energy of rainfall is nonlinearly related to intensity. Storms with the same kinetic energy might arise from a sequence of different storm intensities. Storm kinetic energy influences detachment of soil particles, soil sealing, and runoff, and therefore soil loss (Parsons and Stone 2006). Figures 8 to 10 present the observed cumulative runoff, sediment, and nutrient load during the 60 minutes of FR and VR rainfall simulations in relation to cumulative kinetic energy. The responses are similar to those reported in Parsons and Stone (2006).

Figures 8a and 8c illustrate, for the FR simulation, there is increasing divergence of cumulative runoff and sediment among treatments with increasing cumulative kinetic energy. At the same cumulative kinetic energy, cumulative runoff and sediment differ among treatments with greater difference between tillage than fertilizer treatments. During the VR simulation, runoff response was similar among treatments (figure 8b). For sediment, the responses appear similar to those of FR except that the magnitudes were greater (figure 8d). The impact of cumulative kinetic energy on cumulative load of NH_4-N is more pronounced in NTCF under FR and NTPL under VR simulations (figures 9a and 9b). The impact of cumulative kinetic energy on cumulative load of NO_3-N was similar in both simulations where NTCF plots showed a greater response than the other treatments (figure 9c and 9d). The DRP response under the FR simulation appears similar between CTPL and NTCF and greater than that between CTCF and NTPL, which show similar responses. Under the VR simulation, only NT treatments showed response to cumulative kinetic energy with divergence in response between NTPL and NTCF after a cumulative kinetic energy value of 1,000 J m^{-2}. For TP load the response to cumulative kinetic energy was more pronounced for CTPL with FR and for NTPL with VR compared with the other treatments. Generally, at the same cumulative kinetic energy level the impact on sediment and nutrient load was greater with VR than with FR; however, this is confounded with the differences in antecedent SWC between the two years.

Our FR simulation targeted 57 mm h^{-1}, which has a return period of 10 years (Perica et al. 2013). In contrast, if each VR 5-minute interval average was maintained for 60 minutes, return periods would be <1 to 7 years for the first 10 minutes and the 40- to 60-minute periods. However, for the periods ending at 15, 20, 25, 30, and 35 minutes, equivalent return periods would be 25, 500, 1,000, 500, and 50 years, respectively (Perica et al. 2013). Hence, for 25 minutes of the 60-minute simulation (42%), VR intensities represent more extreme events. Recent and expected changes in climate of the US Southeast reported by Ingram et al. (2013) indicate increased incidences of larger and more intense storms. If these projections are accurate, then more runoff and sediment loss will be expected from agricultural fields, with a greater percentage coming from CT systems.

The observed runoff, infiltration, sediment loss, nutrient concentration, and load patterns reflect the interaction between cropping systems management and characteristics of the simulated rainfall. A synthesis of 14 years of research from this site (Endale et al. 2010) characterized cropping system management effects on soil physical, chemical, and biological properties and provided some insight into the rainfall simulation response among the systems. Soil C at 0 to 15 cm has increased from 8.4 g kg^{-1} in 1991 to 13.3 g kg^{-1} in the CT and 16.6 g kg^{-1} in NT in 2005. Soil N similarly increased from 0.80 to 1.24 g kg^{-1} and 1.45 g kg^{-1}, respectively. Change in soil C and N in both CT and NT are attributed to large amounts of crop biomass from both the winter cover crop and summer cash crop as well as additions of PL.

Römkens et al. (2002) stressed the complexity of processes leading to soil erosion and how a series of other factors impact the magnitude and importance of each of these processes. They particularly stressed how our understanding is limited on the roles of surface roughness, different storm intensities and sequences, and subsurface soil water pressure on the erosion process. They suggest processes being influenced by a strong interaction between changing surface condition of roughness, surface sealing, erosive power of runoff, and antecedent soil water. All these and other factors would have been in play in the research reported here and would have been different for the two simulation regimes. We noted much variability in our data among treatment replications, perhaps attesting to the observations of Römkens et al. (2002).

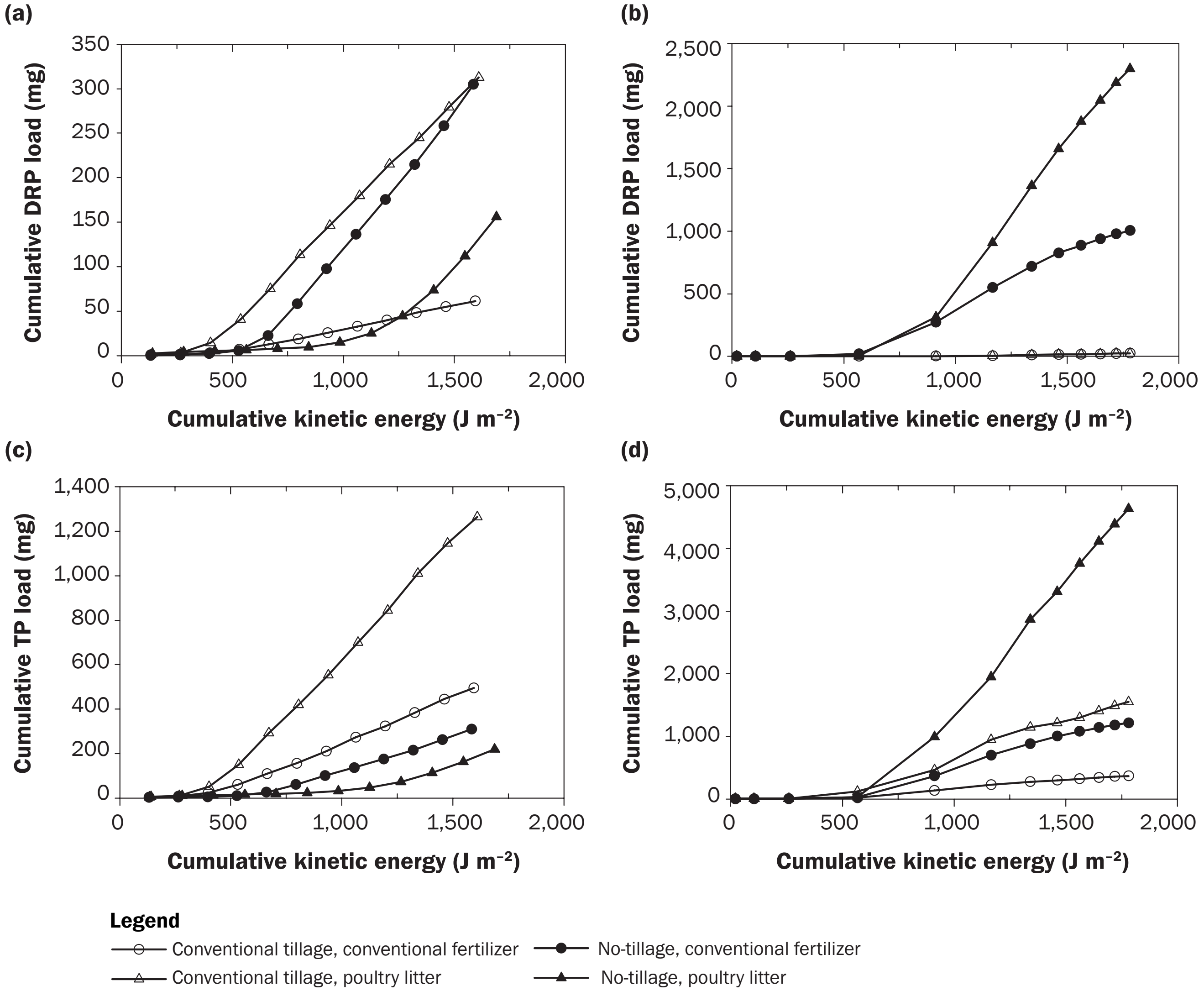
Summary and Conclusions

Conservation tillage systems and animal manures can be important tools for sustainable food production and maintaining ecosystem services in the 21st century, provided they are used judiciously and in a manner that does not harm the environment. Regional diferences in climate, soils, and cropping systems will create challenges to using these effectively and sustainably. Our rainfall simulations reveal the following:

1. Even at the intensity of the FR treatment (57 mm h^{-1}; 10-year return period), long-term NT management (including cover crops) can significantly reduce runoff and sediment loss compared with CT on Piedmont soils like the Cecil used in this study.
2. Poultry litter applied to the surface of NT soil near in time to a rainfall event results in the greatest concentrations and loads of NH_4-N, DRP, and TP under VR, pointing to the need for more research into alternative application methods under NT such as subsurface banding, P- versus N-based delivery, or composting or pelletizing. On the other hand, these plots had the lowest NO_3-N concentration and load under VR.
3. If climate projections of larger and more intense storms for this region are accurate, then more runoff and sediment loss will be expected with CT but more nutrient losses will be expected with NT.

Figure 10

Cumulative kinetic energy of simulated rainfall on (a and b) cumulative load of dissolved reactive phosphorus (DRP), and (c and d) cumulative load of total phosphorus (TP) during the 60-minute rainfall simulations under (a and c) constant fixed rate (FR) in 2004 and (b and d) variable rate (VR) in 2005 by treatment. Note scale difference between FR and VR for cumulative load.



4. Agricultural management practices that limit potential losses of sediment and nutrients from agricultural fields should be implemented to protect the environment, particularly for fields where poultry and other types of animal manure are surface applied.

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