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Surface Residue and Soil Moisture Affect Fertilizer Loss in Simulated Runoff on a Heavy Clay Soil

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ABSTRACT

The potential for non-point-source pollution of surface waters from agricultural lands continues to be a concern. Our objective was to determine the effect of surface residue management and fertilizer application timing in regards to soil moisture conditions on nutrient losses in runoff. Studies were conducted using a rainfall simulator that applied 125 mm h⁻¹ for 3 h to an Austin (Udorthentic Haplustoll) clay soil. Soil surface residue treatments were chisel tillage with no added corn (*Zea mays* L.) residue (CT-NAR), chisel tillage with added corn residue (CT-AR), and bermudagrass [*Cynodon dactylon* (L.) Pers.] sod (sod). Rainfall simulation was made following fertilizer (16–9–0 N–P–K) application to relatively dry (350 g kg⁻¹ moisture) and relatively wet (500 g kg⁻¹) soil on each of the residue treatments. Runoff samples collected from a 1-m² area were analyzed for NO₃⁻-N, NH₄⁺-N, and PO₄⁻-P concentration and amount (kg ha⁻¹). When fertilizer was applied to relatively dry soil, nutrient losses from both wet and dry runs combined were less than the losses with fertilizer applied to relatively wet soil. For wet runs, the CT-AR treatment reduced total PO₄⁻-P loss nearly sevenfold and NH₄⁺-N loss fivefold compared with CT-NAR (1.2 vs. 8.0 kg PO₄⁻-P ha⁻¹; 3.9 vs. 18.9 kg ha⁻¹ NH₄⁺-N), due to increases in time before initiation of runoff and lower nutrient concentrations in runoff. For our conditions, therefore, reduction in nutrient losses in runoff can be achieved by maintaining surface crop residue and applying N and P fertilizers to relatively dry soils. The largest loss of fertilizer nutrients occurred with sod treatments: losses of PO₄⁻-P for the relatively wet soil were ≈41% of PO₄⁻-P fertilizer applied (51.9 kg PO₄⁻-P ha⁻¹). This indicates that granular fertilizer application to pastures on heavy clay soils with vertic properties may make a significant contribution to non-point-source pollution; careful management of granular fertilizer applications is thus called for, especially soil water content, when fertilizing sod.

APPLICATION OF FERTILIZERS to agricultural lands continues to be a major concern because of the potential non-point-source pollution contribution to the eutrophication of surface waters and the possible human health risks associated with nutrient losses. Application of fertilizer in the most efficient manner possible is important so that farmers can both optimize their profits and minimize the potential non-point-source pollution hazard.

One effective means of reducing non-point-source pollution from crop land is the use of conservation till-

age systems. These systems are known to be very effective in reducing erosion and limiting the amount of nutrients that leave the field in sediment (McDowell and McGregor, 1984; Angle et al., 1984; Römkens et al., 1973). Potter et al. (1995) found that maintaining a residue cover on a heavy clay soil with no-tillage systems preserved infiltration rates and controlled erosion. The sediment component of runoff generally has been shown to carry most of the plant nutrients off the field (Andraski et al., 1985; Barisas et al., 1978; Owens and Edwards, 1993).

While the nutrient concentration in the sediment portion of runoff is greatly reduced with surface residue cover, several studies have shown that the concentration in the solution phase is often increased with conservation tillage (Torbert et al., 1996; Alberts and Spomer, 1985; Römkens et al., 1973; McDowell and McGregor, 1984). This has been attributed to lack of incorporation of fertilizers into the surface layer (Baker and Lafren, 1982; Timmons et al., 1973, Whitaker et al., 1978); and to the decomposition of plant materials on the surface (Johnson et al., 1979; Mostaghimi et al., 1988). The most important of these is probably the lack of incorporation of fertilizers. Timmons et al. (1973) reported that nutrient losses declined as the level of fertilizer incorporation increased.

Losses of nutrients in runoff have been reduced with subsurface application of fertilizers (Beyrouy et al., 1986; Römkens et al., 1973; Timmons et al., 1973; Whitaker et al., 1978). For example, Beyrouy et al. (1986) reported a 20 to 40% increase in fertilizer recovery at the end of the year when urea–ammonium nitrate (UAN) solution was applied subsurface compared with surface application. The use of fertilizer bands on dry soil may also reduce nutrient loss in runoff. In a rainfall simulation study, Torbert et al. (1996) found that very little N in runoff could be attributed to liquid fertilizer applied in a surface band to dry soil. Using ¹⁵N techniques to trace the fertilizer, they found that only an average of 1.6 kg N ha⁻¹ lost in runoff during a 30 min rainfall event could be attributed to the application of 135 kg fertilizer N ha⁻¹.

Broadcast applications of granular fertilizer may increase nutrient losses, as the fertilizer will not be transported into the soil as quickly as banded fertilizers.

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Abbreviations: CT-AR, chisel tillage with added residue; CT-NAR, chisel tillage–no added residue; RDF, fertilizer applied under relatively dry soil moisture conditions; RWF, fertilizer applied under relatively wet soil moisture conditions; sod, bermudagrass sod.

Application of dry fertilizers to the soil surface is likely to continue, however, because of other agronomic and economic considerations, such as product and equipment availability. For example, subsurface applications in conservation tillage systems can be especially difficult because of the need to limit disturbance of surface residues that provide erosion control. Subsurface application of fertilizer in pasture is rare due to the resulting damage to the grass.

While the application of fertilizer to the soil surface will continue because of agronomic and economic reasons, the environmental impact of surface application of fertilizer may be reduced with wise application timing. However, the potential impact of soil moisture conditions as it is affected by the surface residue has not been studied in heavy clay soils. It is important to understand the potential impact of management decision, so that producers can make judicious choices in their management decisions. This study was conducted to examine the effects of soil surface residue management and soil moisture conditions on fertilizer losses in simulated rainfall conditions.

MATERIALS AND METHODS

A rainfall simulator was used to generate runoff on an Austin (fine-silty, carbonatic, thermic Udorthentic Haplustolls) clay soil at Temple, TX, during 24 Oct. to 2 Dec. 1994. The simulator, similar to that described by Miller (1987), used a Spraying Systems Wide Square Spray 30 WSQ nozzle¹ at a nominal rate of 125 mm h⁻¹. Drop size was 2.5 mm and kinetic energy was 23 J m⁻² mm⁻¹ (Miller, 1987). A 1-m² area plot on 2 to 3% slope was surrounded by a metal frame driven 0.1 m into the soil to define the study area. Rainfall application was also made to a 10-m² area around the study area. The rainfall simulator was calibrated by measuring water flow before each simulation run and a water sample was collected for background level correction of phosphorus (PO₄⁻-P) and nitrogen (NH₄⁺-N and NO₃⁻-N). The 1-m² study area would be substantially a measure of the interrill erosion, as little concentration into channels occurred.

Rainfall simulation was made to three different surface residue conditions: chisel tillage with no added corn residue (CT-NAR), chisel tillage with an added corn surface residue (CT-AR), and bermudagrass sod (sod). The chisel tillage system, used for corn production, consisted of flail-shredding residue, tandem disking, chisel tilling, tandem disking, and field cultivating. True no-tillage is not typically practiced in these soils; instead, conservation tillage is practiced and consists of limiting the amount of tillage performed and leaving the residue on the surface. The limited tillage system practiced in this area is based on reducing the number of passes with tillage implements to leave residue on the surface, but to provide an adequate plowed surface for planting. Therefore, the CT-AR treatment consisted of adding a surface residue back to the 1-m² area to simulate limited tillage as practiced on these soils (Potter et al., 1995). The surface residue from 1 m² in an adjacent untilled area was used to replace the surface residue. The bermudagrass sod treatments were conducted in established sod plots that had been planted to bermudagrass

3 years prior to the initiation of the study, on land previously used for row crop production [corn; grain sorghum, *Sorghum bicolor* (L.) Moench; and wheat, *Triticum aestivum* L.]. The bermudagrass sod was managed as a hay pasture, with an average grass height of 9 cm at the time of rainfall simulation. The percent surface residue cover for each of the three residue management treatments (measured by a pin drop method described by Morrison et al., 1996) is given on Table 1.

Rainfall was simulated under relatively dry soil water (dry run) and relatively wet soil water conditions (wet run). The average gravimetric water content measured before and after the rainfall simulations on the plowed and sod plots are given on Table 1. These soil water contents approach those commonly occurring during periods when local farmers apply fertilizer. Rain was initiated under antecedent dry conditions and continued for 3 h, resulting in the relatively wet condition. After 48 h, simulated rainfall was applied to the relatively wet condition and continued for another 3 h. No natural rainfall occurred on the study area during the 48 h that separated dry and wet runs during the course of the study. The rainfall rates were chosen to provide an adequate rainfall rate that would provide runoff for all of the surface conditions under study. While rain intensities were at rates commonly occurring in Bell county Texas (2-year storm; Maidment, 1992), the 3-h duration approached that of a 50-year storm (Hershfield, 1961).

Rainfall simulation was made following granular fertilizer application under both the relatively dry soil moisture condition (RDF) and the relatively wet soil moisture condition (RWF) in each of the three surface residue treatments. A second rainfall simulation, (relatively wet run) was conducted for the plot receiving fertilizer application on dry soil. Rainfall simulation was also performed with no fertilizer application (control) under both wet and dry soil moisture conditions. The fertilizer applications to the runoff plots were made as granular 16-9-0 N-P-K, which is a mixture of 42% monoammonium phosphate (NH₄H₂PO₄) and 58% ammonium sulfate [(NH₄)₂SO₄] at a rate which provided 134 kg N ha⁻¹ and 168 kg P₂O₅ ha⁻¹ (74 kg P ha⁻¹).

Runoff samples were sequentially collected from the down slope edge of the study area every 20 minutes for both the dry and the wet runs for the duration of the 3-h simulation. Runoff rates were determined by transferring runoff water to tanks by peristaltic pumps, monitoring water height and calculating runoff volume every 5 s.

Runoff solutions were colorimetrically analyzed for NO₃⁻-N, NH₄⁺-N, and PO₄⁻-P concentration using a Technicon Autoanalyzer II C (Technicon Instruments Corp., Tarrytown, NY) and methods published by Technicon Industrial Systems (1973). The solution amount of NO₃⁻-N, NH₄⁺-N, and PO₄⁻-P was calculated by multiplying the solution concentration by the water volume during each sample increment.

Table 1. Mean gravimetric soil moisture content and mean percent surface residue cover (means of measurements from all rainfall simulations) on a heavy clay soil (Temple, TX).

Management	Initial soil condition (dry run)	Relatively wet soil condition (wet run)
	Moisture content, g kg ⁻¹	
Chisel tillage-no added residue	349 (0.3)†	501 (0.7)
Chisel tillage-added residue	349 (0.3)	501 (0.7)
Bermudagrass sod	348 (0.7)	407 (0.5)
	Residue cover, %	
Chisel tillage-no added residue	14 (7.9)	14 (7.9)
Chisel tillage-added residue	68 (7.6)	68 (7.6)
Bermudagrass sod	96 (2.3)	96 (2.3)

† Values in parentheses indicate 1 standard deviation, n = 3.

¹ Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the production, the use of the name by USDA implies no approval of the product to the exclusion of others that may be suitable.

Table 2. Influence of surface residue conditions on losses of sediment and total N in sediment during rain simulation runs on a heavy clay soil (Temple, TX) for relatively wet and dry soil moisture conditions (means of three replicates).

Management	Dry run		Wet run	
	Sediment	Total N	Sediment	Total N
	Mg ha ⁻¹	kg ha ⁻¹	Mg ha ⁻¹	kg ha ⁻¹
Chisel tillage-added residue	0.01a†	0.02a	0.03a	0.07a
Chisel tillage-no added residue	0.25b	0.62b	0.67b	1.29b
Bermudagrass sod	0.01a	0.05a	0.01a	0.07a

† Means followed by the same letter are not significantly different (α 0.10).

Solution samples were corrected for background PO₄⁻-P, NO₃⁻-N and NH₄⁺-N concentration. At the end of the simulation run, a sample of the cumulative runoff water was collected and sediment was separated from solution to determine total suspended sediment load. Total N concentration of sediment samples were determined by dry combustion using a FISON NA1500 N and C determinator (CE Elantech, Inc., Lakewood, NJ).

The experimental design was a randomized complete block with three replications. Data were analyzed using GLM procedures and means were separated using a protected least significant difference (LSD) at 10% probability level (SAS Institute, 1982).

RESULTS

Sediment Loss

Total mean sediment lost during the 3-h run was significantly reduced in the CT-AR treatment compared with CT-NAR (Table 2). Sediment losses were very similar for the CT-AR and the sod plots. Sediment losses from the CT-NAR treatment, averaging 0.25 and 0.67 Mg ha⁻¹ were 20-fold greater, resulting in a 12-fold increase in N lost in sediment, compared with the average of the CT-AR and sod treatments. These results clearly demonstrate the benefits of residue cover in controlling soil erosion and reducing erosional losses of nutrients in sediment as previously reported in the literature (Meyer et al., 1970; Römkens et al., 1973; Lindstrom et al., 1979; Angle et al., 1984; Gilley et al., 1987).

Solution Nutrient Loss

The nutrient losses in solution with storm runoff are affected by two factors, the concentration of nutrients in runoff solution, and the volume of runoff. Changes in either of these factors could change the total amount of nutrients lost in the solution phase of runoff. The concentrations of NH₄⁺-N, and PO₄⁻-P in runoff solution from the clay soil during the simulated rainfall (125 mm h⁻¹) are illustrated in Fig. 1 and 2, respectively, while the amounts (kg ha⁻¹) of NH₄⁺-N, and PO₄⁻-P are illustrated in Fig. 3 and 4, respectively. The probability of a greater *F*-value for each treatment factor at each sampling increment are given in Table 3.

In the CT-NAR system with the RDF fertilizer application treatment on the dry rainfall simulation run, the amounts of PO₄⁻-P and NH₄⁺-N were relatively low, with 0.2 kg ha⁻¹ PO₄⁻-P and 0.6 kg ha⁻¹ NH₄⁺-N at 60 min, and remained relatively uniform during the runoff

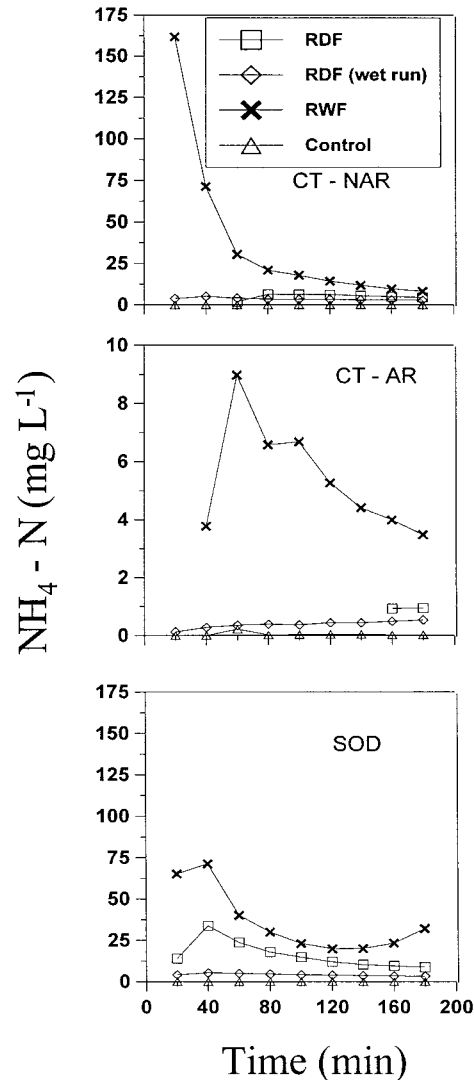


Fig. 1. The concentration of NH₄⁺-N in the runoff solution during simulated rainfall (125 mm h⁻¹) on a heavy clay soil as affected by surface residue condition and granular fertilizer application timing. Sod, bermudagrass sod; CT-NAR and CT-AR, chisel tillage with no added residue and with added residue, respectively; RDF and RWF, fertilizer applied under relatively dry and relatively wet soil moisture conditions, respectively. Note difference of scale for CT-AR.

collection period (Fig. 3 and 4). The runoff nutrient amounts measured in the wet run for the RDF treatment were also relatively low and remained nearly uniform for the duration of this simulated runoff event (Fig. 3 and 4). In contrast, fertilizer application in the CT-NAR under RWF fertilizer application treatment resulted in the greatest NH₄⁺-N and PO₄⁻-P amounts compared with the other surface residue treatments (Fig. 3 and 4), with nutrient amounts of 0.9 kg ha⁻¹ PO₄⁻-P and 2.5 kg ha⁻¹ NH₄⁺-N at the 60 min sampling point. While the NH₄⁺-N and PO₄⁻-P amounts quickly decreased in the RWF treatment, the amounts remained greater compared with the other fertilizer application treatments for the duration of the runoff collection period (Fig. 3 and 4).

In the CT-AR treatment with the RDF fertilizer ap-

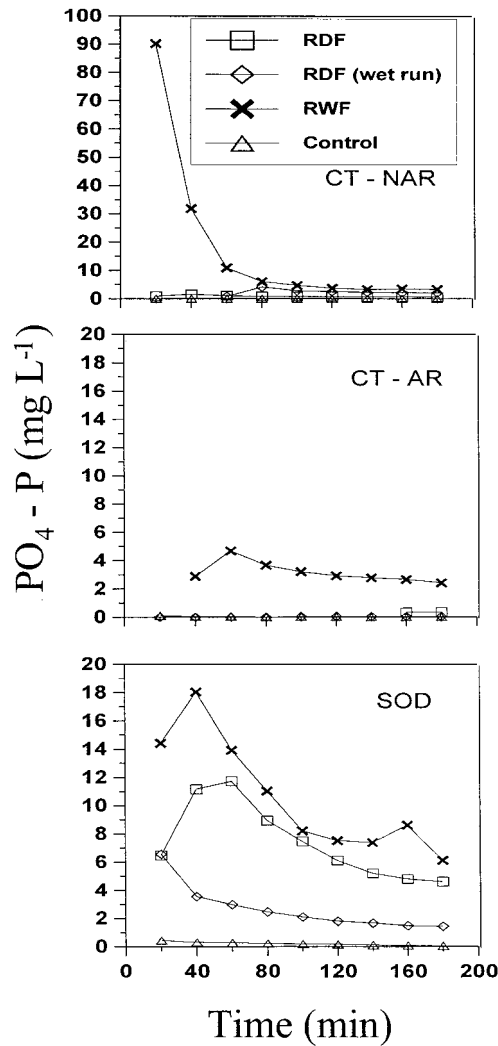


Fig. 2. The concentration of PO_4-P in the runoff solution during simulated rainfall (125 mm h^{-1}) on a heavy clay soil as affected by surface residue condition and granular fertilizer application timing. Sod, bermudagrass sod; CT-NAR and CT-AR, chisel tillage with no added residue and with added residue, respectively; RDF and RWF, fertilizer applied under relatively dry and relatively wet soil moisture conditions, respectively. Note difference of scale for CT-NAR.

plication treatment, the nutrient amounts were less than those measured with the CT-NAR (Fig. 3 and 4). With the CT-AR treatment, the initiation of runoff was delayed on the dry run compared with the CT-NAR treatment, and once runoff was initiated, the nutrient amounts were very low and persisted at the same level through the wet run (Fig. 3 and 4).

With the RWF application treatment in the CT-AR, the nutrient amounts in runoff were less than those measured under the CT-NAR treatment (Fig. 3 and 4). Maximum nutrient amounts measured were $18.2 \text{ kg ha}^{-1} \text{ NH}_4^+-\text{N}$ and $10.2 \text{ kg ha}^{-1} \text{ PO}_4^--\text{P}$ compared with $0.8 \text{ kg ha}^{-1} \text{ NH}_4^+-\text{N}$ and $0.3 \text{ kg ha}^{-1} \text{ PO}_4^--\text{P}$, for CT-NAR and CT-AR treatments, respectively.

The dissolved nutrient amounts in runoff from the bermudagrass sod were significantly different from those measured with the CT-NAR and CT-AR treat-

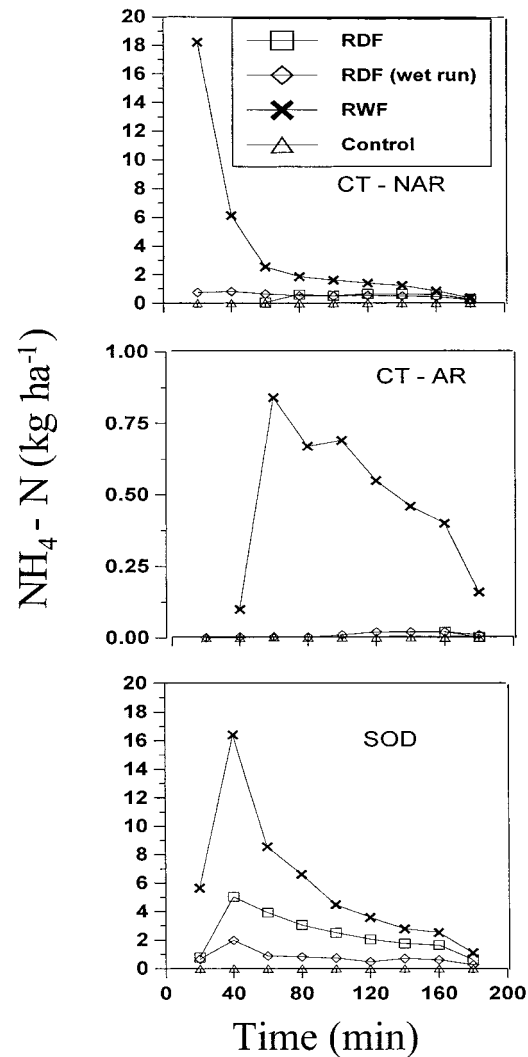


Fig. 3. The NH_4-N loss in the runoff solution during simulated rainfall (125 mm h^{-1}) on a heavy clay soil as affected by surface residue condition and granular fertilizer application timing. Sod, bermudagrass sod; CT-NAR and CT-AR, chisel tillage with no added residue and with added residue, respectively; RDF and RWF, fertilizer applied under relatively dry and relatively wet soil moisture conditions, respectively. Note difference of scale for CT-AR.

ments, in both the pattern with time and the relative difference between fertilizer application treatments (RWF and RDF) (Fig. 3 and 4). With sod, the nutrient losses with RDF fertilizer application treatment on the dry rainfall simulation run approached or exceeded those measured with RWF fertilizer application treatment for the other surface residue treatments (CT-NAR and CT-AR) (Table 4). On the wet run of the RDF treatment, the amount of $PO_4^--\text{P}$ remained relatively high compared with the CT-NAR and CT-AR treatments, but decreased with the time of the simulation (Fig. 4), while the amount of $NH_4^+-\text{N}$ remained relatively uniform and slightly above that measured with the no-fertilizer added control (Fig. 3).

As observed with the other surface residue treatments, the RWF application treatment in sod resulted in greater nutrient amounts in runoff compared with the

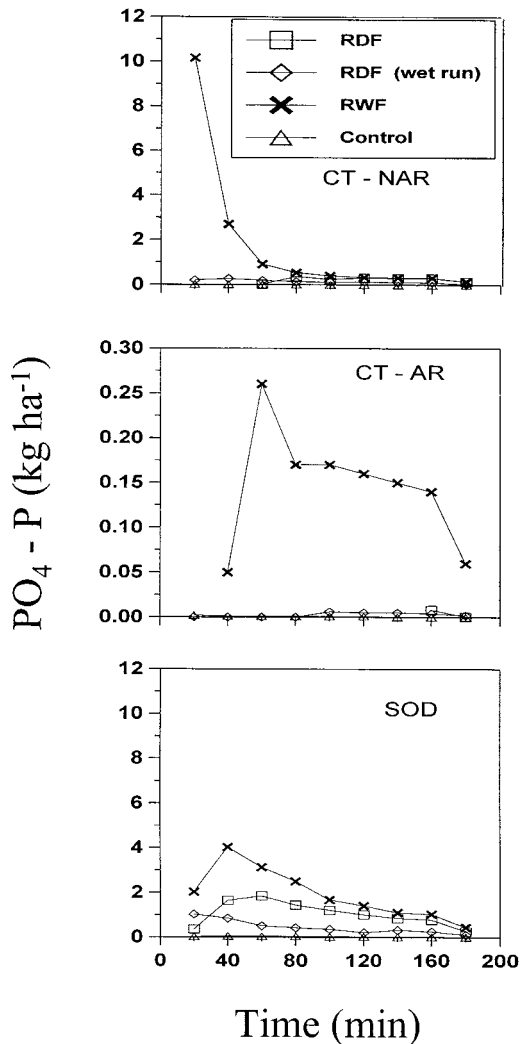


Fig. 4. The PO_4-P loss in the runoff solution during simulated rainfall ($125\ mm\ h^{-1}$) on a heavy clay soil as affected by surface residue condition and granular fertilizer application timing. Sod, bermudagrass sod; CT-NAR and CT-AR, chisel tillage with no added residue and with added residue, respectively; RDF and RWF, fertilizer applied under relatively dry and relatively wet soil moisture conditions, respectively. Note difference of scale for CT-AR.

RDF fertilizer application treatments. However, unlike the other surface residue treatments, with sod the NH_4^+-N and PO_4^-P amounts in runoff remained relatively high throughout the rainfall simulation, increasing near the end of the simulation period (Fig. 3 and 4). Compared with the CT-NAR treatment, nutrient amounts in runoff from sod were initially lower, with $5.6\ kg\ ha^{-1}\ NH_4^+-N$ and $2.0\ kg\ ha^{-1}\ PO_4^-P$ for sod compared with $18.2\ kg\ ha^{-1}\ NH_4^+-N$ and $10.2\ kg\ ha^{-1}\ PO_4^-P$ for CT-NAR at 20 min. But amounts increased quickly above levels measured with the CT-NAR, with $3.6\ kg\ ha^{-1}\ NH_4^+-N$ and $1.4\ kg\ ha^{-1}\ PO_4^-P$ for sod and $1.4\ kg\ ha^{-1}\ NH_4^+-N$ and $0.3\ kg\ ha^{-1}\ PO_4^-P$ for CT-NAR at 120 min.

No significant statistical differences between surface residue treatment and granular fertilizer application treatments were observed for the NO_3^-N amount (or total NO_3^-N losses) in the rainfall simulation (data not shown). This included no significant difference between

Table 3. Probability of greater F -value for granular fertilizer application treatment and soil surface treatment for NH_4^+-N and PO_4^-P concentration and NH_4^+-N and PO_4^-P content in runoff at each sampling increment (20–180 min) on a heavy clay soil (Temple, TX).

Treatment	$P > F$									
	20	40	60	80	100	120	140	160	180	
	NH_4^+-N concentration									
Fertilizer	0.001	0.004	0.001	0.001	0.001	0.001	0.001	0.001	0.007	0.179
Surface	0.050	0.078	0.016	0.003	0.001	0.001	0.001	0.001	0.021	0.157
	PO_4^-P concentration									
Fertilizer	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Surface	0.001	0.031	0.006	0.003	0.001	0.001	0.001	0.001	0.008	0.001
	NH_4^+-N content									
Fertilizer	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.008
Surface	0.001	0.004	0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	PO_4^-P content									
Fertilizer	0.001	0.001	0.017	0.004	0.002	0.001	0.001	0.001	0.001	0.041
Surface	0.013	0.059	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.004

the control and the other granular fertilizer application treatments. This was likely the result of utilizing a N fertilizer with all of the N in the ammonium form. Since significant statistical differences were measured for both the NH_4^+-N and PO_4^-P amounts in runoff, the nonsignificant effect for NO_3^-N in runoff solution indicated that the differences observed in this study were predominately due to the short-term effect of granular fertilizer applications before a storm of $125\ mm\ h^{-1}$ intensity.

Cumulative Runoff Nutrient Losses in Solution

The cumulative amounts of NH_4^+-N and PO_4^-P lost in solution for the rainfall simulation are presented in Table 4. With fertilizer applied to wet soil, the CT-AR treatment reduced the cumulative loss of PO_4^-P nearly sevenfold and the NH_4^+-N loss by fivefold compared with the CT-NAR system. This reduction resulted from both increases in time before the initiation of runoff and lower nutrient concentrations once runoff was initiated (Fig. 1 and 2).

The largest cumulative loss of nutrients in solution occurred with the sod surface residue treatment. This resulted from both a quicker initiation of runoff compared with the tilled treatments and an increase in nutrient concentrations during the duration of the runoff events. For example, the nutrient concentrations during the wet run of the RDF fertilizer application treatment remained relatively high for sod, unlike the CT-NAR and CT-AR treatments that had nutrient concentrations only slightly above that measured with the control (Fig. 1 and 2). There appears to be a mechanism (other than infiltration) that slowed the movement of nutrients into the soil profile in the sod treatment compared with the tilled treatments. This mechanism could be an interaction between the fertilizer and the thatch layer of the sod, as has been reported for insecticide movement through sod (Sears and Chapman, 1982).

The losses of PO_4^-P measured under the wet soil condition was approximately 41% of the PO_4^-P fertilizer applied. The total nutrient loss from the sod was 46% less for NH_4^+-N and 25% less for PO_4^-P with both the simulation runs of the RDF application timing treatments combined compared with the one RWF applica-

Table 4. Influence of surface residue conditions and granular fertilizer application timing on cumulative $\text{NH}_4^+\text{-N}$ and PO_4^-P losses in runoff solution from a heavy clay soil (Temple, TX) (means of three replicates).

Management	Dry application	Dry application (wet run)	Wet application	Control
		$\text{NH}_4^+\text{-N, kg ha}^{-1}$		
Chisel tillage-added residue	0.02Ax†‡	0.10Ax	3.88Bx	0.01Ax
Chisel tillage-no added residue	3.00Ax	4.82Ax	18.91Bx	0.00Ax
Bermudagrass sod	21.02Ay	6.84Bx	51.92Cy	0.08Dx
$\text{PO}_4^-\text{P, kg ha}^{-1}$				
Chisel tillage-added residue	0.01Ax	0.02Ax	1.16Bx	0.01Ax
Chisel tillage-no added residue	1.52Ax	1.27Ax	7.96By	0.02Ax
Bermudagrass sod	9.27Ay	3.68Bx	17.35Cz	0.25Dx

† Within columns, means followed by the same lowercase letter (x, y, z) do not differ significantly ($\alpha = 0.10$).

‡ Within rows, means followed by the same uppercase letter (A, B, C, D) do not differ significantly ($\alpha = 0.10$).

tion run, over the duration of the rainfall (375 mm). This indicated that in a heavy clay soil under wet soil moisture conditions (500 g kg^{-1}), granular fertilizer application to pastures may result in a significant contribution to runoff loading of surface waterways.

DISCUSSION

These data demonstrate the influence of surface residue management and granular fertilizer application timing on runoff losses of nutrients in solution for heavy clay soils. Nutrient losses in solution were much larger when fertilizer applications were made to wet soil conditions compared with when fertilizer was applied to dry soil. In fact, when fertilizer was applied to dry soil, nutrient losses from both the wet and dry rainfall simulations combined were less than the losses that occurred when fertilizer was applied to the wet soil condition. This agrees with results indicating that less than 2% of applied fertilizer N was lost following a 30-min runoff event when fertilizer was applied under dry soil conditions in a heavy clay soil (Torbert et al., 1996). In that study, higher fertilizer loss applied in liquid form were observed in the no-tillage system compared to the conventional tillage system in the solution phase of runoff. However, in that study, liquid fertilizer was applied to a dry soil surface and all of the significant difference between tillage treatments was attributed to the NO_3 form, with no significant difference observed for NH_4 losses in solution (Torbert et al., 1996). In this study, under tilled soil conditions, nutrient losses in soil solution were reduced when surface residues were present. Therefore, when granular fertilizer applications are not incorporated, a reduction in nutrient losses in runoff from a heavy clay soil could likely be achieved by maintaining surface crop residues and applying fertilizers to dry soil.

It is also important to note that most of the nutrient loss during the 3-h simulation with the RWF application treatment in all surface residue treatments occurred within the first 40 min of the runoff initiation (Fig. 3 and 4). Since most rainfall events are short in duration,

the environmental impact of fertilizer application timing with soil moisture condition in all three surface residue conditions may be more important under actual rainfall conditions.

Overall, the loss patterns of total $\text{NH}_4^+\text{-N}$ and PO_4^-P amounts (Fig. 3 and 4) during the runoff simulation were not greatly different from the patterns observed for nutrient concentrations (Fig. 1 and 2). This indicated that the runoff nutrient losses were dominated by $\text{NH}_4^+\text{-N}$ and PO_4^-P concentration and not by the total volume of runoff water. This implies that factors that affect nutrient concentration will be the most important factor determining losses of fertilizer from a heavy clay soil. The exceptions to this were treatments that delayed runoff initiation. For example, the initiation of runoff in the dry run generally took much longer compared with runoff initiation in the wet run. This delay in runoff was also affected by the surface residue treatment, with the runoff initiation with CT-AR taking much longer compared with the CT-NAR treatment. Runoff from sod occurred very quickly, even during the dry run. This was likely caused by the consolidation of the near surface soil resulting from shrinking and swelling of these clay soils (Potter et al., 1995).

In addition, the time to runoff initiation may be a major mechanism that determines the concentration of fertilizer in the runoff solution. Granular fertilizer applied to the soil surface must dissolve before being carried into the soil during infiltration of water. Any mechanism that either increases the rate of water infiltration or delays the initiation of runoff, increases the amount of fertilizer that moves into the soil and thus minimizes immediate loss in runoff water. For example, in all of the surface residue treatments, the highest nutrient concentration in solution were with the RWF fertilizer application treatments, which were also the application treatments where the times from rain initiation to runoff initiation were the shortest. With the sod, runoff was initiated quickly, even in the dry run, which resulted in relatively high nutrient concentrations in solution throughout the simulation compared with the other surface residue treatments. This resulted in a dramatic increase in the cumulative loss of $\text{NH}_4^+\text{-N}$ and PO_4^-P in solution for sod compared with the other surface residue treatments. This indicated that granular fertilizer application to pastures may make a contribution to non-point-source pollution and that careful management of fertilizer applications, especially soil moisture condition, should be considered when fertilizing sod.

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