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Nitrogen and Phosphorus Runoff Losses from Variable and Constant Intensity Rainfall Simulations on Loamy Sand under Conventional and Strip Tillage Systems

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ABSTRACT

Further studies on the quality of runoff from tillage and cropping systems in the southeastern USA are needed to refine current risk assessment tools for nutrient contamination. Our objective was to quantify and compare effects of constant (Ic) and variable (Iv) rainfall intensity patterns on inorganic nitrogen (N) and phosphorus (P) losses from a Tifton loamy sand (Plinthic Kandiudult) cropped to cotton (*Gossypium hirsutum* L.) and managed under conventional (CT) or strip-till (ST) systems. We simulated rainfall at a constant intensity and a variable intensity pattern (57 mm h^{-1}) and collected runoff continuously at 5-min intervals for 70 min. For cumulative runoff at 50 min, the Iv pattern lost significantly greater amounts ($p < 0.05$) of total Kjeldahl N (TKN) and P (TKP) (849 g N ha^{-1} and 266 g P ha^{-1} for Iv; 623 g N ha^{-1} and 192 g P ha^{-1} for Ic) than did the Ic pattern. However, at 70 min, no significant differences in total losses were evident for TKN or TKP from either rainfall intensity pattern. In contrast, total cumulative losses of dissolved reactive P (DRP) and NO_3–N were greatest for ST-Ic, followed by ST-Iv, CT-Ic, and CT-Iv in diminishing order (69 g DRP ha^{-1} and 361 g NO_3–N ha^{-1}; 37 g DRP ha^{-1} and 133 g NO_3–N ha^{-1}; 3 g DRP ha^{-1} and 58 g NO_3–N ha^{-1}; 1 g DRP ha^{-1} and 49 g NO_3–N ha^{-1}). Results indicate that constant-rate rainfall simulations may overestimate the amount of dissolved nutrients lost to the environment in overland flow from cropping systems in loamy sand soils. We also found that CT treatments lost significantly greater amounts of TKN and TKP than ST treatments and in contrast, ST treatments lost significantly greater amounts of DRP and NO_3–N than CT treatments. These results indicate that ST systems may be losing more soluble fractions than CT systems, but only a fraction the total N (33%) and total P (11%) lost through overland flow from CT systems.

FURTHER studies on the quality of runoff from tillage and cropping systems in the southeastern USA are needed to refine current risk assessment tools for nutrient contamination (Rawls et al., 1980; Tarkalson and Mikkelsen, 2004). These tools are used to establish nutrient management plans, which are required on many farms to ensure sustainability of the management system as well as good water quality. Across the globe, many risk assessment tools are being developed using data collected from rainfall simulations (Kleinman et al., 2004). While there is some concern as to the reliability of these efforts to simulate natural conditions, there is also support across disciplines for the use of rainfall simulation experiments to obtain some estimate of the magnitude of potential losses from a great variety of management systems, soils, and landscapes (Sauer et al., 1999; Emmerich, 1999; Gilley et al., 2001; Penn et al., 2004; Schroeder et al., 2004; Tarkalson and Mikkelsen, 2004).

Many studies have used rainfall simulation to evaluate nutrient losses in runoff from cropping and tillage systems (Andraski et al., 1985; McIsaac et al., 1987; Zhao et al., 2001; Eghball et al., 2002; Daverede et al., 2003; Little et al., 2005). Studies have also been conducted to determine nutrient losses, primarily P, from systems which either incorporate or do not incorporate nutrient sources such as animal manures and inorganic fertilizers (Mostaghimi et al., 1988; Yoon et al., 1994; Gascho et al., 1998; Eghball and Gilley, 1999; Tarkalson and Mikkelsen, 2004). Some of these studies determined that, compared with unfertilized systems, incorporation of nutrients results in no significant changes in nutrient loss, or that nutrient losses are decreased when nutrients are incorporated (Yoon et al., 1994; Zhao et al., 2001; Tarkalson and Mikkelsen, 2004; Daverede et al., 2003). Tarkalson and Mikkelsen (2004) compared P losses in runoff from bare Piedmont soils with broiler litter or inorganic fertilizer applied on the surface or incorporated into the soil (simulated disking). They found that incorporation of both broiler litter or inorganic fertilizer resulted in P losses that were not significantly different from soils with no P applied.

In other studies, incorporation of manure into soils significantly reduced both N and P losses in surface runoff. For example, Pote et al. (2003) found that when broiler litter was incorporated into grasslands total P and total N runoff losses were significantly lower than total P and total N losses from surface-applied litter. Little et al. (2005) using different tillage implements in croplands found that regardless of tillage implement, total N and total P losses in runoff were reduced when dairy slurry was incorporated rather than surface-applied.

Runoff losses of dissolved, particulate phosphorus and other P fractions (P) vary with nutrient source (Elliott et al., 2005) and with application method (Gascho et al., 1998; Daverede et al., 2004). Some studies have found that systems that incorporate nutrient sources into the

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Abbreviations: CT, conventional tillage; DRP, dissolved reactive phosphorus; Ic, constant rainfall intensity; Iv, variable rainfall intensity; ST, strip tillage; TKN, total Kjeldahl nitrogen; TKP, total Kjeldahl phosphorus; WSP, water-soluble phosphorus.

soil have greater total N and P losses than systems that leave nutrients on the surface (Gascho et al., 1998; Eghball and Gilley, 1999; Bundy et al., 2001; Daverede et al., 2004); on the other hand, systems that leave nutrients on the surface, such as no till or strip till, have greater dissolved nutrient (algal-available P; water-soluble P [WSP]; dissolved reactive P [DRP]; total dissolved P) losses than systems with incorporated nutrients. Little et al. (2005) found that incorporation of crop residues and manures reduced losses of DRP, total P, NH_4–N, NO_3–N, and total N compared with unincorporated treatments. In another study, Andraski et al. (1985) subsurface-banded fertilizer applications to remove the surface-applied variable and compared three conservation tillage systems to conventional tillage. They found that conventional tillage systems lost a significantly greater amount of total P than conservation tillage systems and that there were no consistent differences in the dissolved P fraction losses in runoff between tillage systems.

Many of the current rainfall simulation techniques use a constant rate of rainfall, but natural rainfall seldom falls at a constant rate (Bosch et al., 1999; Frauenfeld and Truman, 2004). The degree of runoff, soil loss, and phosphorus transported may vary between natural rainfall and constant rate rainfall simulations (Shahlaee et al., 1991; McIsaac and Mitchell, 1992; Cox and Hendricks, 2000; Kleinman et al., 2004). If natural rainfall records are available for areas of interest, simulating rainfall at natural intensity patterns for what is thought to be the most vulnerable time periods could provide more credible data for the development of risk assessment tools.

Our objective was to quantify and compare effects of constant (Ic) and variable (Iv) rainfall intensity patterns on inorganic N and P loss in runoff from a Tifton loamy sand (Plinthic Kandiudult) cropped to cotton (*Gossypium hirsutum* L.) and managed under conventional-till (CT) and strip-till (ST) systems.

MATERIALS AND METHODS

The study took place on gently sloping (2% slope) broad upland Tifton loamy sands (Fine-loamy, kaolinitic, thermic Plinthic Kandiudults) at the University of Georgia's Gibbs Farm near Tifton, GA (31°26′ N, 83°35′ W) in the spring of 2003. This date was chosen as the time of most vulnerability for surface runoff losses. That is, fields are freshly plowed, vegetative cover has not yet emerged, and rainfall is likely. Tillage treatments, starting in fall 1998, included CT with rye cover (*Secale cereale*), and ST also with rye cover. The CT treatment consisted of fall chisel plowing followed by spring disking and cultivator leveling. The winter rye cover for both treatments was planted in the fall and killed in the spring (1 Apr. 2003) with glyphosate. The winter cover crop was disk harrowed into the top 10 to 15 cm of soil for the CT treatment. The ST treatment consisted of strip tillage in the spring with the winter rye cover planted in the fall. As in the CT treatment, winter rye was killed with glyphosate application, but rather than disking the cover, it was laid down (1 May 2003) and left as surface residue in preparation for strip tillage. Both the CT and the ST treatments were paratilled in the fall of 2002 and were managed in a 3 yr cotton–1 yr peanut rotation. Cotton was planted in 1999, 2000, and 2001 followed by peanuts (*Arachis hypogaea* L.) in 2002. In spring 2003, immediately after planting cotton in 91-cm rows, 12 rainfall simulation plots, each 2 m wide by 3 m long by 15 cm tall, were established and rainfall simulations were run before plant emergence (13–21 May 2003). The stainless steel plot frames (aluminum flumes) were centered over a wheel track and forced into the soil to a depth of 10 cm. This placement resulted in two rows and one wheel track in each plot. Tillage treatments were applied to 0.4-ha fields; within each tillage treatment, six rainfall simulation plots were established. Three Ic and three Iv treatments were also applied to each tillage treatment. Therefore each tillage intensity treatment (CT-Ic, CT-Iv, ST-Ic, ST-Iv) was replicated three times (two tillage systems × two intensity patterns × three replications).

The bulk of the surface residues in the spring of each year were from the winter rye. Residue cover for ST plots (4000 kg ha^{-1}) was not distributed evenly across simulator plots. A 15-cm-wide zone centered over the row remained bare (no surface residue). Conventional tillage residue was incorporated (disk harrowed twice) into the soil during spring disking (29 May and 2 Apr. 2003). Composite (three samples, from uphill and lateral sides) soil samples (0 to 15 cm) were taken from the outside of each plot to measure pH and antecedent moisture content just before rainfall simulations. Antecedent water content was determined gravimetrically (105°C, 24 h) for each plot. In the fall of 2002, bulk density measurements were made in the 0- to 7.5-cm depth by taking soil samples with 7.5-cm i.d. and 7.5-cm-long cylinders, drying (105°C, 24 h), and weighing the samples. The average value was 1330 kg m^{-3} for ST plots and 1320 kg m^{-3} for CT plots.

On 12 May 2003, only starter fertilizer, a liquid solution of urea and ammonium nitrate (28-0-0) was applied (Table 1). The starter fertilizer was trickled on the surface approximately 5 cm from the seed row. In May of the previous years (1999 through 2002) equal application rates of broiler litter (*Gallus gallus domesticus*) were applied (broadcast) to both tillage treatments (Table 1). Other environmental, physical, and chemical characteristics of the experiment site have been described in recent publications (Bosch et al., 2001; Potter et al., 2003; Potter et al., 2004; Bosch et al., 2005).

An oscillating-nozzle rainfall simulator (Foster et al., 1982; Frauenfeld and Truman, 2004) with 80150 veejet nozzles (median drop size = 2.3 mm) was placed 3 m above each plot. Simulated rainfall was applied at a target rate of 57 mm h^{-1} for both Ic and Iv. The coefficient of uniformity ranged from 66 to 73%. The variable rainfall intensity pattern was developed from 5- and 1-min natural rainfall data (30 yr) collected at Tifton, GA. Rainfall patterns during the months March, April, and May were analyzed to determine the pattern that occurred most frequently during the spring row crop planting season. Maximum intensity for Iv was ~130 mm h^{-1} and occurred at 20 min after the start of the simulation. The constant rate pattern was determined from the statistical average of the Iv pattern. Rainfall duration for each simulation was 70 min. Rainfall total, standard deviation, and coefficient of uniformity for each treatment are presented in Table 2 and the rainfall patterns are illustrated in Fig. 1. Extensive detail of the

Table 1. Nutrients (N, P, K) applied for years 2001, 2002, and 2003. In years 2001 and 2002 nutrients were applied as broiler litter. In year 2003 N was applied as starter fertilizer. Application rates were equal for all treatments.

Year	Nitrogen	Phosphorus	Potassium
	kg ha^{-1}		
2001	125	54	104
2002	135	58	112
2003	17 (applied as starter)	none applied	none applied

Table 2. Mean total rainfall depth, standard deviation, and coefficient of uniformity for each tillage intensity treatment, from initiation of rainfall through 70 min of runoff.†

Tillage intensity treatment	Rainfall	Reps	Std. dev.	Coeff. uniformity
	mm	*n*	mm	%
CT-Iv	63.8	3	2.5	73
CT-Ic	60.0	3	3.8	69
ST-Iv	63.8	3	2.5	66
ST-Ic	64.3	3	3.7	68

† CT-Iv, conventional tillage-variable intensity rainfall treatment; CT-Ic, conventional tillage-constant intensity rainfall treatment; ST-Iv, strip tillage-variable intensity rainfall treatment; ST-Ic, strip tillage-constant intensity rainfall treatment.

rainfall intensity pattern is described in Frauenfeld and Truman (2004, Fig. 1). Total rainfall volume applied over the 70-min duration was the same for Ic and Iv patterns, 63 mm. Water for each simulation, obtained from a nearby groundwater well (depth = 166 m) was pumped into a 2-m^3 holding tank and utilized within 2 h of pumping. The well water was from a confined portion of the Upper Floridian aquifer with temperatures that ranged from 15 to 17°C. The National Water Quality Assessment Program described nitrate concentrations in confined areas of the Upper Floridian aquifer as <0.50 mg NO_3–N L^{-1} and total phosphorus concentrations as below 0.05 mg P L^{-1} (Berndt et al., 1998).

Runoff drained into a collection trough at the downslope end of each plot, and samples were collected continuously for each 5-min interval (5, 10…70) throughout the duration of each simulation. A 1-L subsample was taken from an agitated in toto collection tank for each 5-min interval for nutrient analysis. Soil loss was determined gravimetrically from the remaining in toto sample by drying at 105°C until constant weight was achieved and by correcting for subsamples removed for nutrient analysis. Runoff samples were filtered through 0.45-μm cellulose nitrate membranes, placed on ice in dark coolers, and transported to an analytical laboratory for analysis. Samples were analyzed for NH_4^+–N by the salicylate-hypochlorite method (Crooke and Simpson, 1971), for (NO_3^- + NO_2^-)–N by the Griess-Ilosvay method (Keeney and Nelson, 1982), after reduction of NO_3^- to NO_2^- with a Cd column, and for DRP by the molybdate blue method (Murphy and Riley, 1962). Total Kjeldahl N and P (total N and total P, respectively) were determined on unfiltered runoff samples by Kjeldahl digestion according to USEPA method 351.2 (USEPA, 1979) and will be referred to as either total N or total P. Flow-weighted concentrations were calculated by dividing cumulative amounts of nutrients lost over cumulative volume of runoff. Losses were calculated by multiplying concentrations by volumes collected and dividing by plot area.

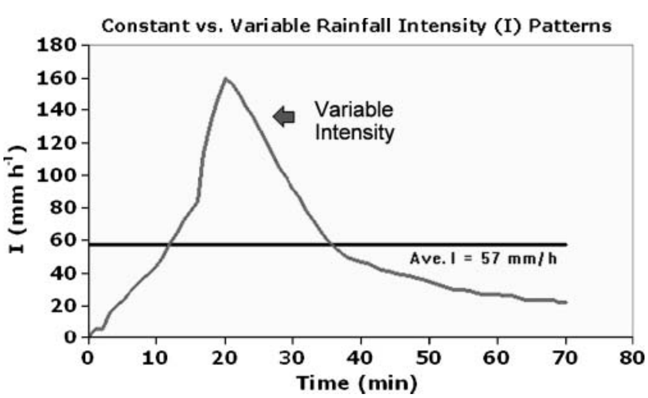

Fig. 1. Rainfall intensity patterns for constant and variable intensity treatments.

For the purpose of nutrient analysis, a secondary set of soil samples (nine subsamples each time) was taken randomly from defined areas before and after each simulated rainfall event from four depth increments (0 to 2 cm, 2 to 8 cm, 8 to 15 cm, and 15 to 30 cm). Sample collections were done with a stainless steel flat scoop for the 0- to 2-cm depth and with a punch auger for the other depths (2.5-cm diam.). Soil samples taken before simulations were taken outside of each plot, within 3 and 15 cm of the plot boundary. Three subsamples were taken from both sides of each plot (six of nine subsamples) and three from the upside end of the plot (three of nine subsamples). Soil samples taken after simulations were taken randomly from within the plots (nine subsamples, same depths) 1 h after stop of rainfall. Composited samples (by plot, depth, and time) were mixed and split for analysis. Two-thirds of the sample was allowed to air-dry (55°C) and the other one third was kept moist at 4°C until analysis was done. Air-dried samples were ground, and sieved through 2 mm. Moist samples were rubbed through a 2-mm sieve. Water content was determined for air-dried and moist samples (105°C) to express soil nutrient content on a dry weight basis.

Soil test phosphorus (STP) was determined with air-dried soil using the Mehlich 1 procedure (Mehlich, 1953) and WSP was determined with moist samples using a 25:1 ratio of deionized water (mL)/soil (g) (Pote et al., 1996). Phosphorus concentrations for STP and WSP extracts were determined colorimetrically (Murphy and Riley, 1962) and expressed on an oven-dry weight basis. Inorganic N was determined by extracting 5 g air-dried soil with 40 mL of 1 *M* KCl for 30 min in a reciprocating shaker, centrifuging (280 × *g*), and measuring NO_3^- and NH_4^+ in the supernatant volume. Extracts were analyzed for NH_4^+–N by the salicylate-hypochlorite method (Crooke and Simpson, 1971), and (NO_3^- + NO_2^-)–N by the Griess-Ilosvay method (Keeney and Nelson, 1982).

An analysis of variance (SAS Institute, 1994) was performed for each 5-min period to evaluate the main effects of rainfall intensity pattern, tillage, as well as interaction between rainfall rate and tillage treatment. Fisher's least significant difference (LSD) was used to separate means and the *p* values for the differences were calculated. Regression analysis (SAS Institute, 1994) was used to determine relationships between soil nutrient data and runoff nutrient results. Means and standard deviations (std) are given for measured data when applicable. We considered differences and relationships to be significant when $p < 0.05$.

RESULTS AND DISCUSSION

Initial soil analyses indicated a median pH of 6.5 and no significant differences in antecedent moisture content between tillage treatments (CT 0.011 kg H_2O kg^{-1} and ST 0.008 kg H_2O kg^{-1}). Analysis of soil particle size distribution indicated that both CT and ST treatments had about 80% sand down to 30-cm depth. Nutrient analysis of soils indicated that STP and WSP were uniformly distributed down to 30 cm in the CT plots. In contrast, STP and WSP were accumulated in the surface layers in the ST plots (Fig. 2). Mean STP for CT treatments from 0 to 2 cm was 24.2 mg kg^{-1} and for ST 175.2 mg kg^{-1}. Mean WSP at 0 to 2 cm was 1.8 mg kg^{-1} for CT treatments and 11.1 mg kg^{-1} for ST treatments. Concentrations of WSP ranging from 12.3 to 23.5 mg kg^{-1} have been considered as elevated soil P concentrations

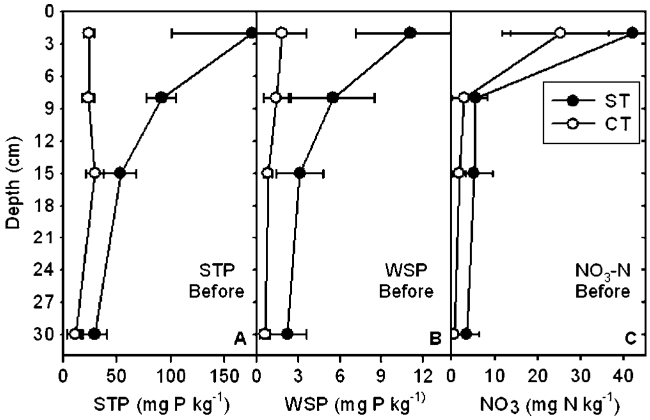

Fig. 2. Soil-extractable Mechlich I P (STP), water-soluble P (WSP), and NO_3–N before rainfall simulations, with depth and between tillage treatments: strip tillage (ST) and conventional tillage (CT). Errors bars are standard deviations.

(Novak and Watts, 2005) for optimum plant growth in southeastern U.S. Coastal Plains soils. The CT treatments, where in previous years broiler litter applications have been incorporated into the soil, are well below these soil P concentrations (WSP). Soil P concentrations for the ST treatments however, are similar to these soil P concentrations (WSP). In both tillage systems, soil NO_3–N and NH_4–N concentrations were greater in the upper 2 cm than in the lower depths.

Analysis of runoff nutrient data indicated that for most variables there was seldom interaction between tillage or rainfall intensity treatments ($p < 0.05$). This was not the case for NH_4–N. Therefore results of main treatment effects (tillage and rainfall intensity) are discussed separately. There was, however, on occasion, an interaction between the tillage and rainfall intensity treatment. When interaction was present it was indicated on the figures for the corresponding collection period.

Effect of Tillage on Nutrient Losses in Runoff

Nitrogen

There was no difference in the flow-weighted concentrations of NH_4–N between tillage treatments (Fig. 3A). Losses of NH_4–N were largest from CT with Iv during the 25- to 35-min period (Fig. 3B). The larger loss of NH_4–N from the CT was apparently due to a larger concentration of KCl-extractable NH_4–N in the upper 2 cm of soil (Fig. 4), which was evident after rainfall simulation. Ammonium in the upper 2 cm of the soil was extremely variable before rainfall simulations and as a result no significant difference in soil NH_4–N was observed. Soil samples taken after the rain had significantly greater NH_4–N in the CT plots than in the ST plots. Incorporated residue has been shown to mineralize organic N at a greater rate than residues left on the surface (Schomberg et al., 1994) and may explain the difference in soil NH_4–N concentrations. The greater concentration of NH_4–N in the soil and the period of intense rainfall on bare surfaces resulted in the largest losses during the 25- to 35-min period from the CT plots with the Iv pattern.

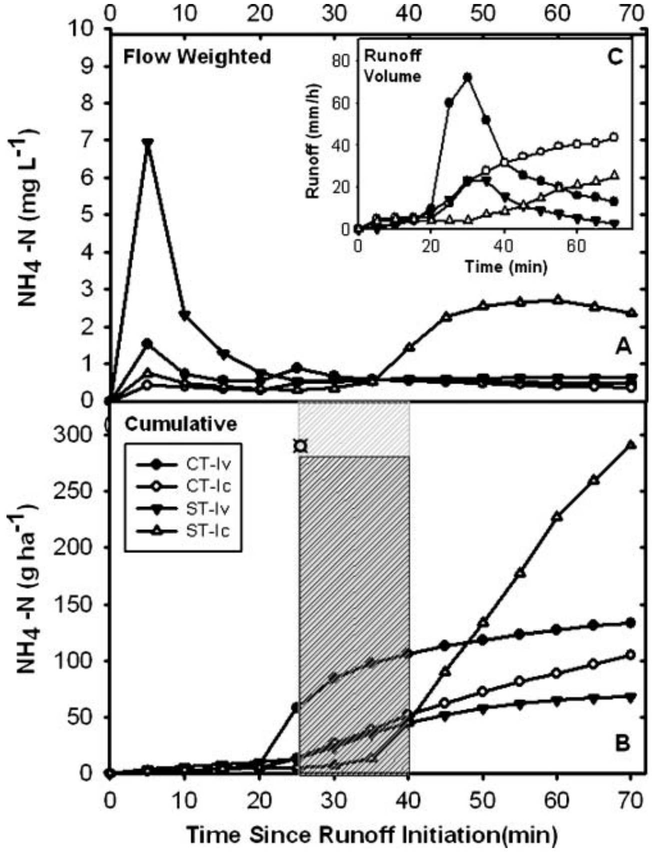

Fig. 3. (A) Cumulative flow-weighted concentrations of NH_4–N for 70 min of runoff, and (B) cumulative NH_4–N losses. The symbol at each 5-min period represents a composite sample for that time period and treatment. Gray shading indicates a significant difference ($p < 0.05$) between tillage treatments strip tillage (ST) and conventional tillage (CT). Black shading indicates a significant difference ($p < 0.05$) between rainfall intensity patterns, constant rate (Ic) and variable rate (Iv). The symbol ¤ indicates interaction was significant ($p < 0.05$) between tillage and intensity pattern for runoff periods (5 min) above which are labeled. In graph A, the inserted graph depicts runoff rates for each treatment studied.

The flow-weighted concentration of NO_3–N was significantly greater for ST than for CT (Fig. 5; 2.01 vs. 0.19 mg N L^{-1}). There was an interaction between tillage and rainfall intensity treatment for loss of NO_3–N at the end of simulation. Differences between tillage systems were much greater for Ic than for Iv. Both flow-weighted concentration and cumulative loss of NO_3–N were significantly larger for ST treatments at the end of the rainfall simulations (Fig. 4). During the 5- to 15-min period, ST had significantly larger concentration of NO_3–N than CT. It should be pointed out that although there were no differences between tillage treatments in soil NO_3–N content at any depth investigated, a significant relationship ($p < 0.05$) was found between soil NO_3–N levels (before rainfall) at 0 to 2 and 2 to 8 cm and NO_3–N in runoff for ST treatments. As soil NO_3–N levels at both depths increased, so did NO_3–N in runoff from ST treatments ($r^2 = 0.69$ for 0 to 2 cm, and $r^2 = 0.86$ for 2 to 8 cm).

Total N losses were found to be the opposite of NO_3–N losses in runoff. Conventional tillage had larger flow-

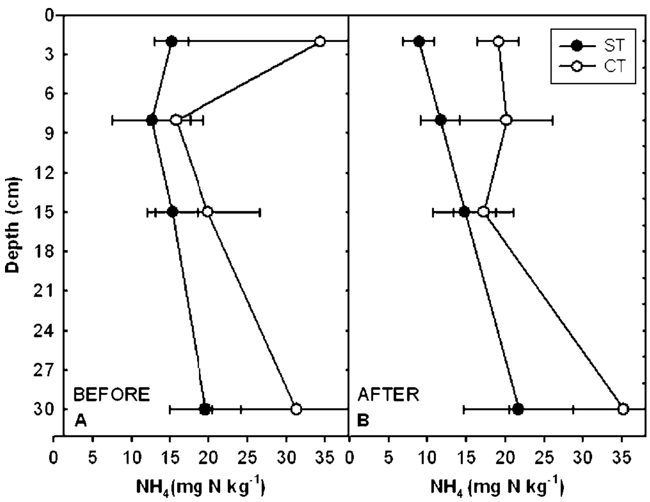

Fig. 4. Soil KCl-extractable NH_4–N with depth. Errors bars are standard deviations. (A) Soil concentrations determined from soil samples taken immediately before rain; (B) soil concentrations determined from soil samples taken 1 h after end of simulation.

weighted total N concentrations than ST during the 25- to 35-min period (Fig. 6A). Losses were even more significant and much more extensive with CT treatments losing more than four times the amount of N for the 70-min duration than the ST treatments (Fig. 6B). Significant differences in losses began at the 25-min period which was similar to NH_4–N losses although significant differences in NH_4–N losses ended by 40 min of runoff.

Both NH_4–N and NO_3–N (dissolved N fractions) were determined from filtered samples and were found to be more readily lost to the environment through overland flow from ST than from CT. Summing the dissolved N fractions measured (NH_4–N plus NO_3–N), losses from the ST (429.1 g N ha^{-1}) plots were more than double those of the CT (173.1 g N ha^{-1}) plots. In contrast, total N which was determined from unfiltered samples was lost to a greater extent from CT (1452.2 g N ha^{-1}) than from ST (601.0 g N ha^{-1}) plots. In fact, total N losses from CT (1452.2 g N ha^{-1}) were more than three times larger than dissolved N (NH_4–N plus NO_3–N) losses from ST (NH_4–N, ST 179.5 g N ha^{-1}; NO_3–N, ST 249.6 g N ha^{-1}). It is unclear whether these results would be repeated if recent applications of broiler litter had been made to the same tillage and soil systems. These results do, however, clearly indicate that when the influence of recent broiler litter applications has been removed, ST systems can lose more soluble N fractions to overland flow than CT systems, but only a third of the total N being lost to the environment through overland flow from CT systems.

Phosphorus

Cumulative flow-weighted concentration (mg PO_4–P L^{-1}) and loss of DRP (g PO_4–P ha^{-1}) in runoff were significantly greater for ST treatments than for CT treatments (Fig. 7) just after 15 min of runoff. Some interaction between tillage and rainfall intensity treatments was identified just following peak rainfall intensities (25 min) for the variable rate treatment and in the last runoff periods (65 to 70 min) when variable rainfall intensities were below constant rainfall intensities. The effect of tillage was greater for the Ic pattern than for the Iv. In grassland systems when fertilizers were freshly applied, Pote et al. (2003) found that N and P losses of both dissolved and total unfiltered forms were greater in runoff when broiler litter was surface-applied than when incorporated into the soil. In an earlier study, Nichols et al. (1994) found no significant differences in nutrient losses (dissolved or particulate) between grass lands where the fertilizer was either surface-applied or incorporated. An important difference between these two studies was the depth of incorporation and degree of fertilizer-soil contact. In the later study, Pote et al. (2003) incorporated fertilizer to at least 8 cm whereas in the earlier study, Nichols et al. (1994) incorporated fertilizers to only approximately 2 cm. In this study, regression analysis between cumulative flow-weighted concentration of DRP and pre-rain, STP, or WSP at depths 0 to 2 (2), 2 to 8 (8), 8 to 15 (15), and 15 to 30 (30) cm indicated that there were no significant relationships for ST. This was not the case for CT treatments (where broiler litter

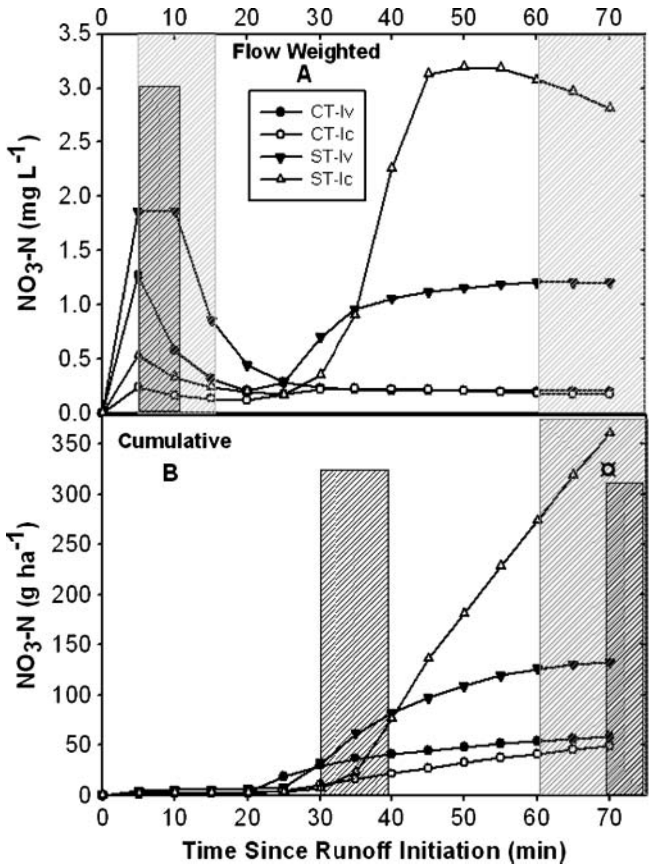

Fig. 5. (A) Cumulative flow-weighted concentrations of NO_3–N for 70 min of runoff, and (B) cumulative NO_3–N losses. Gray shading indicates a significant difference ($p < 0.05$) between tillage treatments, strip tillage (ST) and conventional tillage (CT). Black shading indicates a significant difference ($p < 0.05$) between rainfall intensity patterns, constant rate (Ic) and variable rate (Iv). The symbol ¤ indicates interaction was significant ($p < 0.05$) between tillage and intensity pattern for runoff periods above which are labeled.

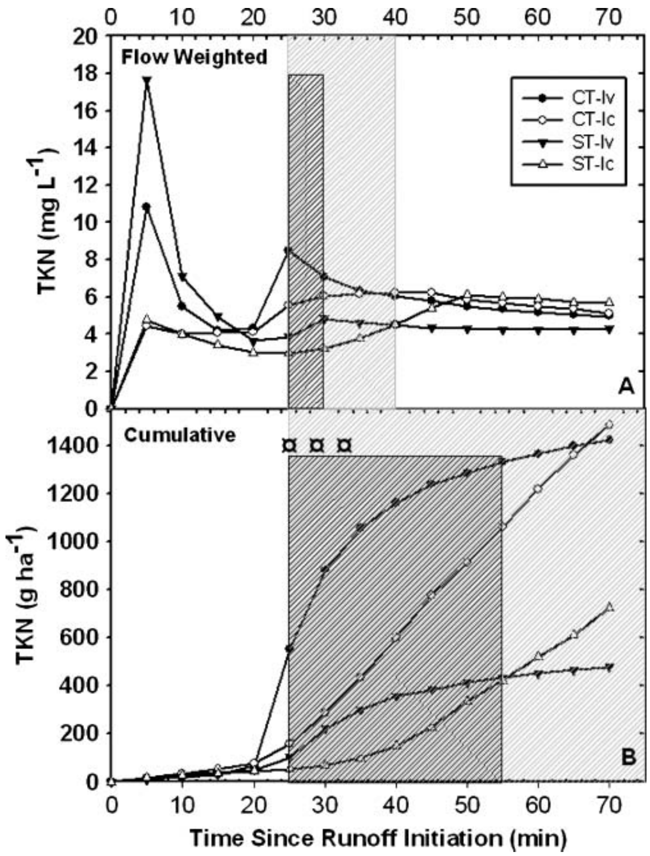

Fig. 6. (A) Cumulative flow-weighted concentrations of total N (TKN) for 70 min of runoff, and (B) cumulative total N (TKN) losses. Gray shading indicates a significant difference ($p < 0.05$) between tillage treatments strip tillage (ST) and conventional tillage (CT). Black shading indicates a significant difference ($p < 0.05$) between rainfall intensity patterns, constant rate (Ic) and variable rate (Iv). The symbol ¤ indicates interaction was significant ($p < 0.05$) between tillage and intensity pattern for runoff periods (5 min) above which are labeled.

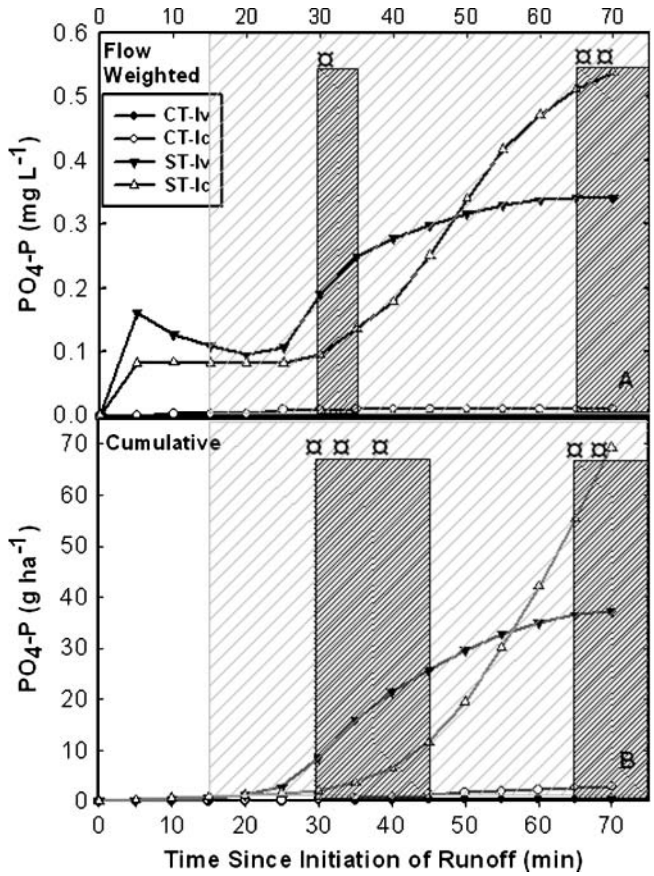

Fig. 7. (A) Cumulative flow-weighted concentrations of PO_4–P for 70 min of runoff, and (B) cumulative PO_4–P losses. Gray shading indicates a significant difference ($p < 0.05$) between tillage treatments, strip tillage (ST) and conventional tillage (CT). Black shading indicates a significant difference ($p < 0.05$) between rainfall intensity patterns, constant rate (Ic) and variable rate (Iv). The symbol ¤ indicates interaction was significant ($p < 0.05$) between tillage and intensity pattern for runoff periods above which are labeled.

had historically been incorporated), where strong relationships ($p < 0.05$) were indicated for STP and total cumulative flow-weighted DRP concentrations at soil depth 2. Both STP and WSP had strong relationships ($p < 0.05$) with total cumulative flow-weighted DRP concentrations at soil depth 8. A relationship between soil phosphorus which extends to 8 cm in a CT system may be explained by the historical incorporation and mixing of the soil in the upper 15 cm. Water-soluble P from the 2-cm depth could be expected to be more easily solubilized during natural rainfall events and translocated down into the 8- to 15-cm depth (Franzluebbers et al., 2002) leaving behind the more tightly bound STP.

Just as was the case with total N, total P losses in runoff were greater in CT than in ST, which was the reverse of the dissolved fraction. Conventional tillage had a greater concentration of flow-weighted total P than ST after 35 min which was 10 min later than total N (Fig. 8A). Even more dramatic, total P losses were more than nine times greater in CT treatments (493 g TKP ha^{-1}) than DRP losses in the ST treatments (53 g PO_4–P ha^{-1}). Similar results have been found by other investigators for systems that leave residue on the surface and when manures have been recently applied to cropping systems (Mostaghimi et al., 1988; Gascho et al., 1998; Eghball and Gilley, 1999; Daverede et al., 2003). In this study, particulate P (total P-DRP) losses in runoff were almost five times larger in CT than in ST, whereas soil loss (Table 3) was almost four times larger from CT than from ST. Given that STP in the top 2 cm of CT soil was one seventh the amount of STP in ST, this indicates that the P concentration in the eroded sediments in CT must have been much greater than the concentrations suggested by either STP or WSP. One possible explanation for this lack of proportionality could be the enrichment ratio described as the ratio of P concentration in eroded sediments to that of the bulk soil (Sharpley, 1985).

As in this study, Andraski et al. (1985), working with cropping systems in fine loamy, Typic Argiudolls found that when fertilizers were incorporated, more particulate nutrient fractions were lost in runoff from tillage systems that did not have surface residues than from those that had surface residues. Unlike this study, they found that dissolved nutrient losses in runoff were also greater for treatments without surface residues than with surface residues. Differences between results from

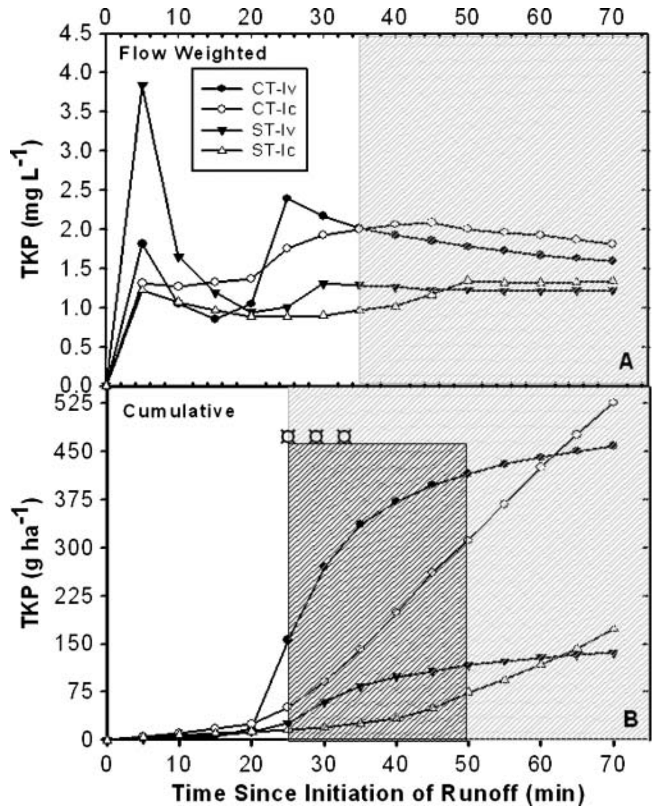

Fig. 8. (A) Cumulative flow-weighted concentrations of total P (TKP) for 70 min of runoff, and (B) total P losses. Gray shading indicates a significant difference ($p < 0.05$) between tillage treatments, strip tillage (ST) and conventional tillage (CT). Black shading indicates a significant difference ($p < 0.05$) between rainfall intensity patterns, constant rate (Ic) and variable rate (Iv). The symbol ¤ indicates interaction was significant ($p < 0.05$) between tillage and intensity pattern for runoff periods above which are labeled.

Andraski et al. (1985) and those included in this paper may be due to soil differences (loam vs. sand) but may also be related to other treatment differences. In the tillage systems investigated by Andraski et al. (1985) surface residues were in the form of chopped corn stalks which were left on the surface the preceding fall, but cover crops were not a part of the system. In this study, rye grain was used as a cover crop and left as surface residue in the ST treatments. First this may suggest that there was a greater amount of residue on the surface in this study (ST treatments) which had a cover crop as part of the tillage system. Residues left to over-winter may have had much of their nutrients leached back into the soil or left near the surface readily available for transport. Bechmann et al. (2005) found that repeated freezing and thawing increased water-extractable P from ryegrass (*Lolium multiflorum* L.) biomass. Residues left to over-winter could therefore lose soluble P to leaching if winter rains followed periods of freezing or if little rain followed, and could be left as highly degraded residues lying on the surface in particulate form vulnerable to transport. Residues which have had much of their growth in early and late spring, such as rye grain in the southeastern United States, would likely not have had the opportunity for the bulk of the biomass to have experienced repeated freezing episodes. Bechmann et al. (2005) suggested that the mechanism for the increase in solubility of P in the biomass was the repeated rupture of cell walls. We speculate that the decomposing rye grain residue in this study could have experienced multiple and repeated cell wall fractures due to tractor traffic thereby increasing the likelihood that residues of the ST treatments may have also had readily soluble nutrients on the soil surface, unlike residues left to over-winter (Andraski and Bundy, 2005) or the residues incorporated into the soil by disking in the CT treatments. In ST treatments the residue left on the surface slightly increased the potential for greater dissolved nutrient losses and greatly decreased particulate N and P losses from the ST treatments, whereas in the CT treatments incorporation of residues removed protection from raindrop impact thereby increased total N and P losses.

Effect of Rainfall Intensity Patterns on Nutrient Losses in Runoff

Nitrogen

No difference was indicated for the flow-weighted concentration of NH_4–N between rainfall intensity treatments (Fig. 3A). During the highest intensity portion of runoff losses (Iv, Fig. 3C), NH_4–N losses (Fig. 3B) were significantly greater for CT-Iv during the 25- to 35-min period than for other treatments.

Flow-weighted concentration of NO_3–N was significantly greater for Iv in the second 5-min period (Fig. 5A; 1.22 vs. 0.25 mg N L^{-1}) than for Ic. Cumulative loss of NO_3–N was significantly larger for Iv during the greatest rate of runoff (30 to 35 min) and at the end of the simulation. There was an interaction between tillage and rainfall intensity treatment for loss of NO_3–N at the end of simulation. The ST-Ic combination lost more total NO_3–N than any of the other treatment combinations. Soil NO_3–N concentrations were not significantly different

Table 3. Mean total losses of ammonium (NH_4–N), nitrate (NO_3–N), total Kjeldahl nitrogen (TKN), dissolved reactive phosphorus (DRP), and total Kjeldahl phosphorus (TKP) for 70 min runoff, and soil loss for tillage and simulated rainfall intensity treatments. Treatments include: conventional tillage-variable intensity rainfall (CT-Iv), strip tillage-variable intensity rainfall (ST-Iv), conventional tillage-constant intensity rainfall (CT-Ic), and strip tillage-constant intensity rainfall (ST-Ic).

Tillage intensity treatment	NH_4–N	NO_3–N	TKN	DRP	TKP	Soil loss
	g N ha^{-1}			g P ha^{-1}		kg ha^{-1}
CT-Iv	133.4a†	58.4c	1422.9a	0.5c	459.3a	2900a
CT-Ic	105.1a	49.4c	1481.5a	2.9c	526.7a	2500a
ST-Iv	68.2a	132.6b	477.8b	37.3b	136.4b	840b
ST-Ic	290.8a	360.6a	724.2b	69.2a	173.7b	640c

† Within a column means followed by the same letter are not significantly different according to Fisher's LSD at $p = 0.05$.

between any of the tillage intensity combinations (data not shown) before or after rainfall simulations. The ST-Iv combination did, however, have the lowest soil concentrations of soil NO_3–N and CT treatments did have greater NH_4–N (as described earlier) and NO_3–N soil concentrations. Nitrogen measurements of the residues were not made, yet one might speculate that the significantly greater loss of NO_3–N in the ST-Iv treatment was due to nitrification of the mineralized NH_4–N in the surface residues. Consequently on the ST-Iv treatments with greater mobilized NO_3–N, greater NO_3–N was lost in runoff.

By the end of the runoff event (70 min) no significant differences were evident for total N losses in runoff between rainfall intensity patterns (Fig. 6A and 6B). Total N losses were much more extensive and interaction was present during peak runoff periods (Fig. 6B) for the Iv pattern. During the 25- to 35-min runoff period, CT-Iv lost significantly larger concentrations of total N than any other treatment combination.

Phosphorus

There was interaction between tillage and rainfall intensity treatment for flow-weighted concentration as well as for loss of PO_4–P at the end of rainfall simulations (70 min) and during peak runoff periods (Fig. 6). For the last 10 min of cumulative runoff, ST-Ic lost significantly more PO_4–P (0.54 mg P L^{-1} and 69.2 g P ha^{-1}), followed by ST-Iv (0.34 mg P L^{-1} and 37.3 g P ha^{-1}), CT-Ic (0.01 mg P L^{-1} and 2.88 g P ha^{-1}), and then CT-Iv (0.001 mg P L^{-1} and 0.46 g P ha^{-1}).

No difference ($p < 0.05$) was found for flow-weighted concentrations of total P between rainfall intensity patterns (Fig. 7A). Significant differences in total P losses were much more extensive and some interaction was present during peak runoff periods as was the case with total N. During the 25- to 35-min period, CT-Iv treatment had significantly larger concentrations and lost more total P than any other treatment/pattern combination. During the 40- to 50-min period, the Iv pattern lost more total P than did the Ic rainfall pattern. By the end of the runoff event no significant differences were evident for total P losses in runoff from either rainfall intensity pattern.

Patterns of loss with time were neither linear nor consistent throughout the rain event regardless of rainfall intensity pattern. These patterns of loss indicate that duration of rainfall event impacts rainfall simulation results and in that, their interpretations should also be reflected in studies for development of risk assessment tools. For instance, if spring planting periods are determined to be the most vulnerable time period for nutrient loss (for a given geographic location), then most likely rainfall event duration should be determined for that geographic area and utilized in simulated rainfall event studies. In addition, peaks in concentration are different depending on nutrient (N or P), nutrient fraction, and tillage. It is interesting to note that concentrations of the soluble fractions for ST-Ic DRP and NO_3 begin increasing at approximately 30 min whereas for NH_4 the increase begins at 35 min. These notable increases in concentrations are not obvious in the CT-Ic treatments for any of the soluble fractions mentioned above. A possible explanation for this difference between ST and CT is that it may take approximately 30 min of exposure to runoff for rye residue to start releasing soluble nutrients in ST systems in the southeastern coastal plain. These increases in concentrations call for further research in the area of soluble nutrient losses in cover crop residues. These notable increases at or just after 30 min suggest that when studying nutrient loss from management systems with surface residues there may be some interest in simulating rain past the usual 30-min time period that many of the published rainfall simulation studies have used.

CONCLUSIONS

The effect of tillage on nutrient losses in runoff had contrasting results depending on nutrient fraction. Strip tillage treatments lost significantly more dissolved nutrients while CT treatments lost significantly more total N and P. Overall, however, ST treatments retained more N and P. In fact, total P losses were more than nine times greater in the CT treatments (493.0 TKP g ha^{-1}) than DRP losses in the ST treatments (53.3 PO_4–P g P ha^{-1}). Similarly, total N losses from CT treatments (1452.2 g N ha^{-1}) were more than three times larger than dissolved N losses from ST treatments (NH_4–N, ST 179.5 g N ha^{-1}; NO_3–N, ST 249.6 g N ha^{-1}). This indicates that ST systems may be losing more soluble fractions than CT systems but only a fraction of the total N and P being lost to the environment through overland flow is from CT systems.

We found no evidence of significant differences in losses of total N or total P in runoff from either rainfall intensity pattern for the 70-min duration. In contrast, losses of DRP and NO_3–N were found to be greatest for ST-Ic, followed by ST-Iv, CT-Ic, and CT-Iv in diminishing order (69.2 g P ha^{-1} and 360.6 g N ha^{-1}; 37.3 g P ha^{-1} and 132.6 g N ha^{-1}; 2.9 g P ha^{-1} and 58.4 g N ha^{-1}; 0.5 g P ha^{-1} and 49.4 g N ha^{-1}). Our results indicate that constant intensity rainfall simulations may overestimate the amount of dissolved nutrients lost to the environment in overland flow from cropping systems in loamy sand soils. Therefore, the use of rainfall simulators that simulate natural rainfall patterns may yield better estimates of the potential for nutrient loss in surface runoff when dissolved fractions are a concern.

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