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Traffic and residue management systems: effects on fate of fertilizer N in corn

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Abstract

Soil compaction has been recognized as a problem limiting crop production, especially in the Southern Coastal Plain of the USA. Development of tillage and residue management systems is needed to alleviate soil compaction problems in these soils. Fertilizer nitrogen (N) management is also an important factor in these management systems. In 1988, a study was initiated with a wide-frame (6.3 m) vehicle to determine the interactive effects of traffic, deep tillage, and surface residue management on the fate of fertilizer N applied to corn (*Zea mays* L.) grown on a Norfolk loamy sand (fine-loamy, siliceous, Thermic, Typic Kandiudults). Corn was planted into a winter cover crop of 'Tibbee' crimson clover (*Trifolium incarnatum* L). Treatments included: traffic (conventional equipment or no traffic): deep tillage (no deep tillage, annual in-row subsoiling, or one-time only complete disruption); residue management (no surface tillage or disk and field cultivation). The one-time only complete disruption was accomplished by subsoiling at a depth of 43 cm on 25 cm centers in spring 1988. In 1990-1991, fertilizer applications were made as ^{15}N-depleted NH_4NO_3 to microplots inside each treatment plot. The 1990 and 1991 data are reported here. In 1990 an extreme drought resulted in an average grain yield of 1.8 Mg grain ha^{-1}. whereas abundant rainfall in 1991 resulted in 9.4 Mg grain ha^{-1}. Deep tillage Increased corn dry matter production in both years. In 1991, grain yields indicated that corn was susceptible to recompaction of soil owning to traffic when residues were incorporated with surface tillage. In the dry year, plant N uptake was increased 27% with deep tillage and decreased 10% with traffic. In the wet year, a surface tillage x deep tillage x traffic interaction was observed for total N uptake, fertilizer N uptake, and total fertilizer N recovery in the plant-soil system. When combined with traffic, plant N uptake was reduced with the highest intensity tillage treatment (135 kg N ha^{-1}) because of root-rrestricting soil compaction. and with the lowest intensity tillage treatment (129 kg N ha^{-1})

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because of increased N losses. In these soils, leaving residues on the soil surface can reduce the detrimental effect of traffic on corn production, but if no surface tillage is performed, deep tillage is needed.

Keywords: ^{15}N; Soil compaction; Surface tillage; Deep tillage; Traffic

1. Introduction

Few decisions in crop production will have a greater impact on the plant-soil environment than the choice of tillage systems. Not only does tillage have a great impact on the physical and chemical characteristics of soil, but soil compaction caused by equipment from various tillage operations has been recognized as a major crop production problem (Bakken et al., 1987; McConnell and Frizzell, 1989; Oussible et al., 1992). For example, the sandy soils of the southeastern USA Coastal Plain are susceptible to the formation of traffic pans which can limit plant rooting to the plow layer and restrict plant utilization of soil water and nutrients (Kashirad et al., 1967). Research has shown that several tillage and cultural practices have varying degrees of success at relieving the effects of soil compaction; these practices include deep plowing, subsoiling, chiseling, and crop rotation (Elkins et al., 1977; Bowen, 1981; Reeves and Touchton, 1986). Deep tillage, such as subsoiling (Kamprath et al., 1979; Chancy and Kamprath, 1982; Box and Langdale, 1984; Reeves and Touchton, 1986), as well as controlled traffic (Dumas et al., 1973; Nelson et al., 1975; Williford, 1982) have been shown to have beneficial effects for crop yields on these sandy soils. Conservation tillage systems may also help alleviate problems with soil compaction because these systems typically require fewer trips across the field with lighter-weight equipment and tractors. In addition, research on physical characteristics of soil indicated that leaving residues on the surface increased the bearing capacity of soil (Sommer and Zach, 1992; Reeves et al., I992). However, very little research on the interaction of these residue management, deep tillage, and traffic systems has been conducted.

The effects of both tillage systems and soil compaction on crop productivity is in part due to their influence on N dynamics in the plant-soil system. Conservation tillage has been reported to increase N leaching (Thomas et al., 1973; Tyler and Thomas, 1977), denitrification (Olson et al., 1979; Rice and Smith, 1982; Linn and Doran, 1984), and N immobilization (Gilliam and Hoyt, 1987). Soil compaction decreases plant N uptake by physical impedance and stress on plant roots (Castillo et al., 1982; Garcia et al., 1988), increases N losses through denitrification (Bakken et al., 1987; Torbert and Wood, 1992), and affects N application efficiency (Jenkinson et al., 1985). For example, Torbert and Wood (1992) reported that soil compaction alteration of pore spaces promoted soil microsite anaerobiosis, resulting in increased denitrification.

Studies on corn production have not examined the integrated effects of residue management with deep tillage and traffic. The objective of this study was to evaluate the interaction of residue management (surface tillage), deep tillage, and traffic on corn yield and N dynamics.

2. Materials and methods

A field study was initiated in 1988 on a Norfork loamy sand at the E.V. Smith Research Center of the Alabama Experiment Station in east-central Alabama, USA (32°24'N, 85°54'W). The soil is highly compactible and has a well-developed hardpan at the 18-20 cm depth. Initial levels of phosphorus and potassium were in the ‘high’ range (175 kg ha^{-1} and 120 kg ha^{-1}, respectively). Cation exchange capacity averaged 2.02 $cmol_c$ kg^{-1}, and organic matter averaged 10.0 g kg^{-1}. Soil pH averaged 6.4.

A winter cover crop of ‘Cahaba White’ vetch (*Vicia sativa* L.) was planted in the autumns of 1987 and 1988, and ‘Tibbee’ crimson clover was planted in autumns of 1989 and 1990. The cover crop was killed with an application of paraquat (1,1'-dimethyl-4,4' bipyridinium ion) 4-7 days before planting corn each spring. Pioneer 3165 hybrid corn was planted on 4 May 1988 and 15 April 1989, and Dekalb 689 was planted on 4 April 1990 and 1 April 1991 in 75 cm rows at seeding rate of 59000 seeds ha^{-1}. Three weeks after planting, stands were thinned to a uniform 49400 plants ha^{-1}. The eight row plots were 21.3 m long. Application of 34 kg N ha^{-1} and 49 kg P ha^{-1} was made at planting over the row in a 10 cm surface band with ammonium polyphosphate liquid fertilizer. Four weeks after planting, 134 kg N ha^{-1} was applied in a narrow surface band 25 cm from the row as 32% UAN fertilizer N solution.

Weeds were effectively controlled with an early post-emergence broadcast application of atrazine (6-chloro-N-ethyl-N'-[1-methylethyl]-1,3,5-triazine-2.4-diamine) (0.9 kg active ingredient (ai) ha^{-1}) plus alachlor (2-chloro-N-[2,6-diethylphenyll-N-[methoxymethyl]acetamide) (1.7 kg ai ha^{-1}) and a shielded sprayer application of glyphosate (N-[phosphonomethyl]glycine) (0.34 kg ai ha^{-1}) 8 weeks after planting.

The experimental design was a strip-split plot design of four replications (Gomez and Gomez, 1984). Vertical factors were deep tillage: (1) no deep tillage; (2) annual in-row subsoiling; (3) one-time only complete disruption. Subsoiling depth was 40-44 cm. The one-time only complete disruption was accomplished by subsoiling on 25 cm centers before planting in 1988. Horizontal factors were traffic: (I) no traffic; (2) trafficked. Intersection or subplot treatments were residue management (surface tillage): (I) no surface tillage; (2) disked-field cultivation to incorporate previous crop and cover crop residue.

All operations were done with an experimental wide-frame tractive vehicle (WFTV) designed to allow untrafficked research plots of 6.1 m width. A detailed description of the vehicle and its capabilities has been published by Monroe and Burt (1989) and Reeves et al. (1992). In the trafficked plots, a 4.6 Mg tractor with 470 mm x 970 mm tires inflated to an average pressure of 125 kPa was driven through the plots to simulate traffic that would have been applied by an operation. Random traffic patterns were applied in the autumn, to simulate land preparations-planting operations for planting the cover crop; uniform traffic patterns were established during the cropping season to simulate operations done by a farmer with four-row equipment, With the four-row traffic pattern, every corn row in the trafficked plots had a trafficked and a non-trafficked interrow.

The experimental area for the study was split into two duplicate experimental areas, with one planted to corn and the other planted to soybean (*Glycine max* (L.) Merr.). Each of these crops received identical deep tillage, surface tillage, and traffic treatments, and were rotated each year so that corn followed soybean production.

During 1990-1991, additional research was initiated to evaluate N dynamics. An area of 4.6 m length inside each plot of 21 m length was isolated to receive fertilizer applications separate from the rest of the plot. Inside this area, micro and macro fertilizer application of Triple super phosphate, zinc sulfate, borate, and sul-po-mag was made at a rate sufficient to supply 28 kg S ha^{-1}, 23 kg P ha^{-1}, 20 kg K ha^{-1}, 12 kg Mg ha^{-1}, 6 kg Zn ha^{-1}, and 2 kg B ha^{-1}. Fertilizer N application was made by broadcasting 168 kg N ha^{-1} as NH_4NO_3 to all except a 2.3 m by 1.8 m microplot situated to include four rows of corn. Inside each microplot, application of “N-depleted NH_4NO_3 was applied at a rate of 168 kg N ha^{-1}. Microplots were rotated to new locations within plots each year.

Grain yield and stover dry matter determinations were made from a hand-harvested section totaling 3 m of row from the middle two rows within the micro plots at maturity. Grain yields were adjusted to 155 g kg^{-1} moisture content. Plant samples were dried at 65°C (until weight loss was complete) and ground in a Wiley mill to pass a 0.44 mm screen. Two soil cores (3.2 cm diameter) were collected from the trafficked interrow (of those plots receiving traffic) inside the microplots to a depth of 90 cm. Each core was sectioned into 0-15, 15-30, 30-60, and 60-90 cm depth increments. Selected plots were also sampled in the row and in the non-trafficked interrow inside the microplots to determine if soil sample position in relation to traffic affected soil N content. Immediately after collection, the soil samples were frozen for transport to the laboratory. The total N content of both plant and soil samples was determined using a permanganate-reduced iron modification of a semimicro-Kjeldahl method (Bremner and Mulvaney, 1982). Distillates were concentrated for isotope-ratio analyses, which were performed as described by Mulvaney et al. (1990), using an automated mass spectrometer (Nuclide Model 3-60-RMS; Measurement and Analysis Systems, Bellefonte, PA), (Trade names and products are mentioned solely for information, No endorsement by the US Department of Agriculture is implied.) Soil bulk density, used in calculation of fertilizer N recovery, was determined for each sample depth increment of each plot from intact soil cores collected to a depth of 90 cm.

The term fertilizer N in this paper is used to denote N added to the plant-soil system through fertilizer application. The term native soil N is used to denote plant N from sources other than fertilizer application (plant total N-plant fertilizer N). The term total fertilizer N recovery is used to reflect fertilizer N recovered in both the plant and the soil. Statistical analysis of data was performed using analysis of variance (ANOVA) and means were separated using least significant difference (LSD) at 10% probability level (Statistical Analysis Systems Institute, Inc., 1982). The term trend is used to designate appreciable non-significant treatment effects with probability levels above 10%.

3. Results and discussion

3.1. Corn yield

Data for the 1990 and 1991 growing season only are reported. Weather conditions were exceptional during both seasons, with low rainfall totals (274 mm) and poor distribution in the 1990 growing season, and high rainfall totals (439 mm) and excellent distribution in the 1991 growing season (Fig. 1). The contrasting weather patterns produced drastically different growing conditions in which to evaluate corn production as affected by traffic, surface tillage, and deep tillage.

In the dry year of 1990, deep tillage, both complete disruption and in-row subsoiling, increased stover production compared with no deep tillage (Table 1). Traffic significantly decreased stover production in 1990, reducing stover dry matter from 6.6 to 5.6 Mg ha^{-1} ($LSD_{0.10}$=O.S). There was a deep tillage x surface tillage x traffic interaction effect on total dry matter production in 1990 (Table 2). In 1990, the greatest total dry matter production was observed in the no-traffic treatment combined with complete disruption and surface tillage treatments (10.7 Mg ha^{-1}), whereas the lowest total dry matter production was observed with traffic in combination with no deep tillage and surface tillage (6.2 Mg ha-1).

Whereas the stover production levels were not greatly different between years, with an average stover dry weight of 6.1 Mg ha^{-1} in 1990 compared with 6.3 Mg ha^{-1} in 1991, corn grain yields in 1990 were exceptionally low, with an average grain yield production of 1.8 Mg ha^{-1} in 1990 compared with 9.4 Mg ha^{-1} in 1991. Drought stress early in the 1990 growing season was not as great as later in the season (Fig. 1), resulting in stover production comparable with that in the 1991 growing season. However, after that period, drought conditions drastically reduced grain production. In 1990, the largest plants, as indicated by total dry weight, produced the lowest corn grain yield. Larger plants were more severely stressed by the drought conditions, i.e. they had a greater demand for water than smaller plants, resulting in a reduced ability to partition plant resources into grain production. For example, deep tillage treatments had harvest indices (grain weight/total plant weight) of 0.21 and 0.19 for complete disruption and in-row subsoiling, respectively, whereas the treatment with no deep tillage had a harvest index of 0.31.

In 1990, a significant traffic x surface tillage interaction was observed (Table 3), with grain yield increasing when surface residues remained and traffic was

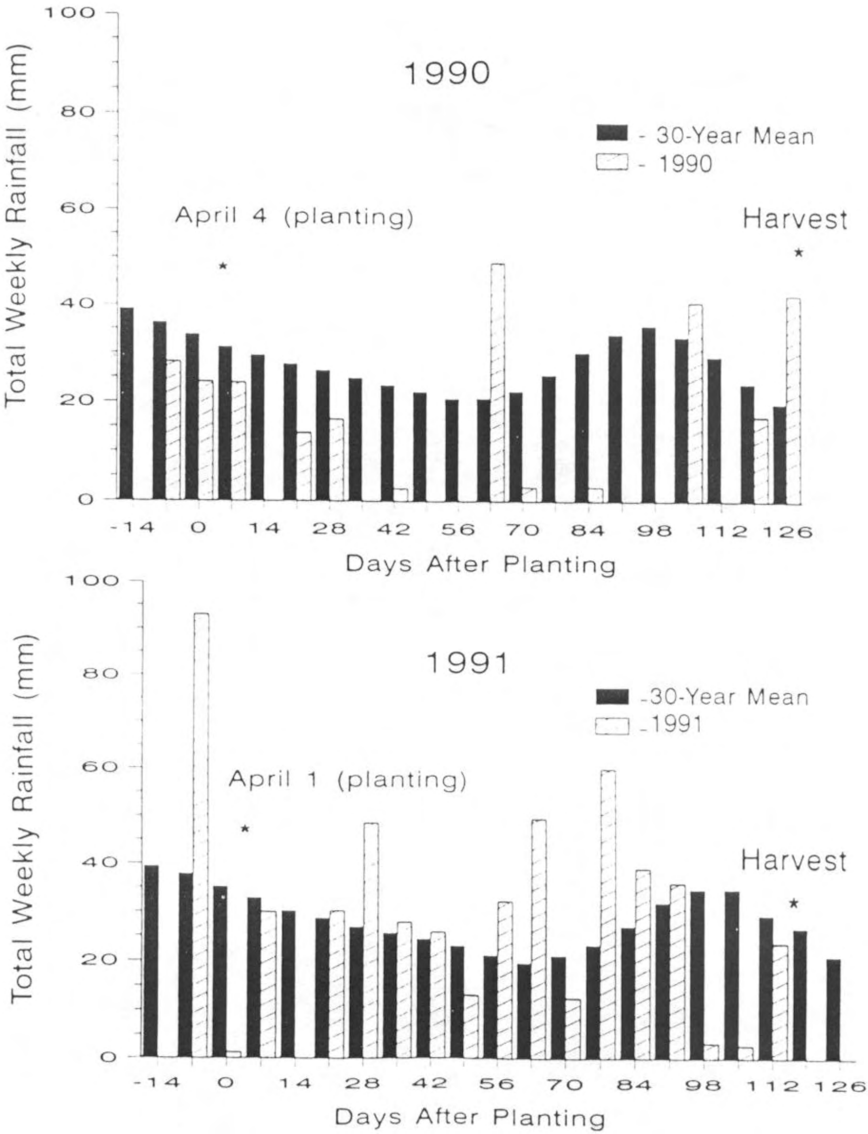


Fig. 1. Total weekly rainfall during 1990 and 1991 growing seasons in relation to 30 year mean rainfall.

applied. In this year, a traffic x deep tillage x surface tillage interaction was also observed for grain yields (Table 2), but no distinguishable patterns could be ascertained. With the unusual growth response observed in this dry year, with larger plants producing smaller grain yields, this three-way interaction was probably a result of the differing ability of the plants to partition resources under these extreme stress conditions. However, the extreme conditions leading to this plant resource partitioning confound interpretation of results, and we believe that, for

Table 1
Influence of deep tillage on corn stover, grain, and total plant dry matter (Mg ha^{-1}) in 1990 and 1991

Deep tillage	1990			1991		
	Stover	Grain	Total plant	Stover	Grain	Total plant
Complete disruption[1]	7.18	1.90	9.08	6.04	9.23	15.32
In-row subsoil	6.35	1.51	7.86	7.13	10.00	17.13
None	4.77	2.10	6.87	5.71	8.93	14.64
$LSD_{0.10}$	1.13	ns	1.43	ns	ns	ns

[1]Subsoiled at 40–44 cm depth on 25 cm centers once only in 1988.
ns, Not significant.

Table 2
Influence of deep tillage, surface tillage, and traffic on corn yield and total plant dry matter (Mg ha^{-1}) in 1990

Deep tillage	Surface tillage			No surface tillage		
	No traffic	Traffic	Mean	No traffic	Traffic	Mean
Grain Yield						
Complete disruption[1]	1.9	1.6	1.7	1.2	2.9	2.0
In-row subsoil	1.1	1.5	1.3	1.8	1.7	1.8
None	2.4	1.9	2.2	1.9	2.2	2.0
Mean	1.8	1.6		1.6	2.3	
$LSD_{0.10}$ any two means				2.35		
Dry matter						
Complete disruption[1]	10.7	7.7	9.2	8.6	9.3	9.0
In-row subsoil	7.4	7.9	7.7	8.8	7.4	8.1
None	7.9	6.2	7.0	6.5	6.9	6.7
Mean	8.7	7.3		8.0	7.9	
$LSD_{0.10}$ any two means				5.1		

[1]Subsoiled at 40–44 cm depth on 25 cm centers once only in 1988.

the 1990 season, treatment effects are better judged by total dry matter production. Likewise, although deep tillage resulted in lower grain yields in this year, the yield levels were so low (1.8 Mg ha^{-1}) that yield responses to treatments were of no economic consequence.

In 1991, a significant reduction in grain, stover, and total dry matter production was observed as a result of traffic. Traffic reduced stover production 13% and total dry matter was reduced by 10% compared with no traffic, with 6.7 vs. 5.9 Mg ha^{-1} stover dry matter and 16.5 vs. 14.9 Mg ha^{-1} total dry matter, for no traffic and traffic, respectively. In addition, a significant traffic x surface tillage interaction was observed for corn grain yield (Table 3). Whereas traffic had no effect on grain yield when no surface tillage was performed, traffic applied to plots receiving surface tillage reduced grain yield 16%. A similar trend was ob-

Table 3
Influence of surface tillage and traffic on grain yield and total plant dry matter production ($Mg\ ha^{-1}$) in 1990 and 1991

Surface tillage	1990			1991		
	No traffic		Traffic	No traffic		Traffic
Grain						
Surface tillage	1.81		1.65	10.33		8.73
No surface tillage	1.63		2.27	9.28		9.27
$LSD_{0.10\ \text{surface tillage within traffic}}$		0.54			0.36	
$LSD_{0.10\ \text{traffic} \times \text{surface tillage}}$		ns			1.19	
Total dry matter						
Surface tillage	8.65		7.26	17.21		14.53
No surface tillage	7.97		7.86	15.83		15.22
$LSD_{0.10}$		ns			ns	

ns, Not significant.

served in both 1990 ($P \leq 0.19$) and 1991 ($P \leq 0.11$) for dry matter production. This is probably due to greater recompaction of soil following surface tillage. The reduced negative impact of traffic with no surface tillage is probably a result of both reduced traffic trips across the field with this tillage system and increased bearing capacity of the soil when the soil surface was not tilled to incorporate residues. Soil physical measurements reported by Reeves et al. (1992) on this same study indicated that the bearing capacity of soil was increased when residues of cover crops were not incorporated, with a reduction in cone resistance in the upper 20 cm of the soil profile following traffic of up to one-half that compared with disking and field cultivation following traffic. Similar results have been reported by Sommer and Zach (l992), who found that soil pore space was not decreased by traffic if conservation tillage practices had been in place for more than 18 months.

Similar to the dry year of 1990, in 1991 a trend for deep tillage to increase dry matter production was observed. In 1991, annual subsoiling increased both stover production ($P \leq 0.12$) and total dry matter production ($P \leq 0.12$).

3.2. *Plant N response*

In 1990, total plant N uptake was significantly affected by both traffic and deep tillage treatments. In that year, traffic decreased total plant N uptake by 10% compared with no traffic, with 98 kg N ha^{-1} vs. 109 kg N ha^{-1} for traffic and no traffic, respectively. Likewise, N in stover was also decreased by traffic, with 75 kg stover N ha^{-1} and 88 kg stover N ha^{-1} for trafficked and no traffic, respectively ($LSD_{0.10}$=5.3). No deep tillage reduced total plant N uptake by 20-27% compared with deep tillage (Table 4). In addition, in 1990, stover N was in-

Table 4
Influence of deep tillage on fertilizer N uptake and total N uptake in corn stover and in corn total plant (kg N ha^{-1}) in 1990

Deep tillage	Fertilizer N		Total N	
	Stover	Total plant	Stover	Total plant
Complete disruption[1]	45.0	55.5	94.5	117.4
In-row subsoil	36.2	44.0	88.7	107.1
None	29.1	41.0	61.3	86.0
$LSD_{0.10}$	8.9	9.8	13.2	15.8

[1]Subsoiled at 40–44 cm depth on 25 cm centers once only in 1988.

Table 5
Effect of deep tillage and traffic on stover fertilizer N uptake (kg N ha^{-1}) in 1990

Deep tillage	No traffic	Traffic
Complete disruption[1]	51.2	38.8
In-row subsoil	37.2	35.1
None	30.3	28.0
$LSD_{0.10\ \mathrm{traffic \times deep\ tillage}}$	10.6	
$LSD_{0.10\ \mathrm{deep\ tillage\ within\ traffic}}$	10.4	

[1]Subsoiled at 40–44 cm depth on 25 cm centers once only in 1988.

creased by surface tillage, with 86 kg stover N ha^{-1} and 77 kg stover N ha^{-1} for surface tillage and no surface tillage, respectively ($LSD_{0.10}$=7.7).

Total plant uptake of fertilizer N was also affected by deep tillage, with the complete disruption tillage treatment significantly increasing fertilizer N recovery in the plant compared with no deep tillage (Table 4). Whereas traffic did not significantly change the total fertilizer N uptake in plants, a traffic x deep tillage interaction was observed for fertilizer N in stover (Table 5). In the dry year of 1990, stover dry matter was affected more than grain yield by tillage and traffic treatments; therefore, treatment effects on N uptake are reflected more by stover N uptake than by total plant N uptake which included grain N uptake. In that year, traffic significantly decreased stover fertilizer N uptake within the complete disruption tillage treatment. This indicated that although treatment effects on fertilizer N were minimized in the dry growing season, traffic did affect fertilizer N uptake by corn. No significant differences were observed for fertilizer N uptake in grain.

In 1991, with favorable rainfall, a deep tillage x surface tillage x traffic interaction was observed for total N uptake (Table 6). In-row subsoiling increased total plant N uptake within each of the surface tillage and traffic combinations compared with the other deep tillage treatments. Within the in-row subsoiling tillage treatment, traffic decreased plant N uptake 12% when averaged across surface tillage treatments, but no differences were observed for surface tillage within the in-row subsoiled treatment. These results demonstrate the beneficial effects

Table 6
Influence of deep tillage, surface tillage, and traffic on total plant N uptake ($kg\ N\ ha^{-1}$) in 1991

Deep tillage	Surface tillage			No surface tillage		
	No traffic	Traffic	Mean	No traffic	Traffic	Mean
Complete disruption[1]	188.4	134.8	161.6	161.3	163.0	162.2
In-row subsoil	195.6	176.3	186.0	198.2	169.1	183.7
None	177.7	150.9	164.3	157.0	128.7	142.9
Mean	187.2	154.0		172.2	153.6	
$LSD_{0.10\ \text{traffic within deep tillage}}$			33.9			
$LSD_{0.10\ \text{surface tillage within deep tillage}}$			20.6			
$LSD_{0.10\ \text{surface tillage \& traffic combinations within deep tillage}}$			29.1			

[1]Subsoiled at 40–44 cm depth on 25 cm centers once only in 1988.

of subsoiling, and agree with previous research conducted on sandy soils which reported increased yields owing to increased available soil water and N utilization from below the tillage pan with subsoiling (Chancy and Kamprath, 1982).

Within the complete disruption tillage treatment. when surface residues were incorporated, the highest plant N uptake was observed without traffic and the lowest plant N uptake was observed with traffic (Table 6). The intensity of tillage associated with the complete disruption treatment makes this treatment the most susceptible to recompaction by traffic (Reeves et al., 1992; Raper et al., 1994). In addition, unlike the in-row subsoiling tillage treatment which received deep tillage annually, this tillage treatment received deep tillage at the initiation of the study only (in 1988), making the complete disruption susceptible to residual effects caused by traffic from previous years. However, traffic had no effect on total plant N uptake when surface tillage was not performed within complete disruption treatments, probably as a result of decreased compaction with no tillage. Reeves et al. (1992) reported decreased soil penetrometer cone resistance measurements in this same study when minimal disturbance of surface residues were allowed, and an increase in cone resistance when traffic was combined with the intensive tillage of surface tillage and complete disruption.

In the treatment with no deep tillage, traffic decreased total plant N uptake (Table 6). Without traffic, the no deep tillage was not substantially different from the complete disruption. However, unlike complete disruption. surface tillage increased plant N uptake with the no deep tillage treatment. This result demonstrates the need in these soils for some form of tillage for corn production.

A deep tillage x surface tillage x traffic interaction was also observed for fertilizer N uptake in the plant (Table 7). Similar to total plant N uptake, a reduction in fertilizer N uptake was observed for complete disruption combined with surface tillage and traffic and with no deep tillage combined with no surface tillage and traffic. Complete disruption combined with surface tillage and no traffic resulted in the greatest fertilizer N uptake in 1991. Fertilizer N uptake in the other deep tillage, surface tillage, and traffic treatment combinations did not vary greatly.

Table 7
Effect of deep tillage, surface tillage, and traffic on total plant fertilizer N uptake (kg N ha^{-1}) in 1991

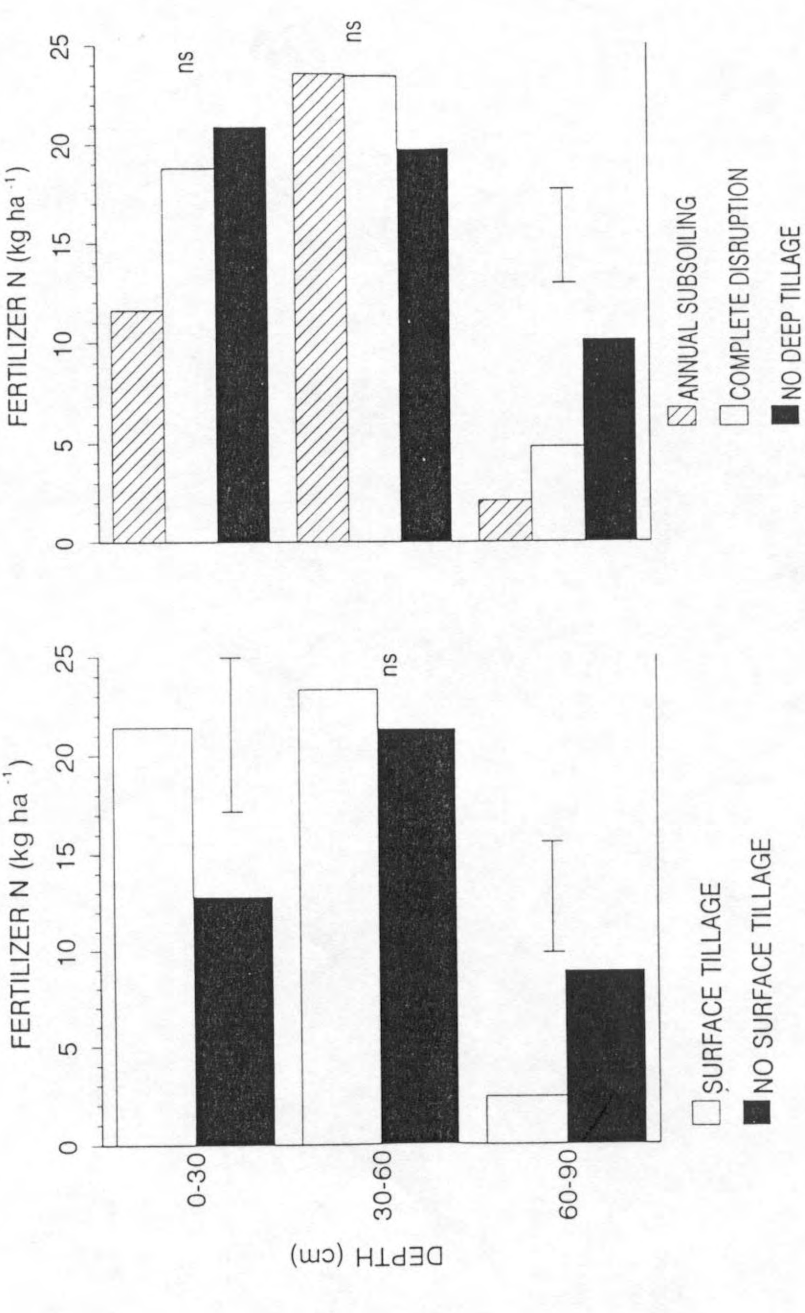
Deep tillage	Surface tillage		No surface tillage	
	No traffic	Traffic	No traffic	Traffic
Complete disruption[1]	99.6	61.8	85.3	87.6
In-row subsoil	86.8	86.8	95.0	86.8
None	91.8	76.9	83.9	61.1
$LSD_{0.10\ \text{traffic within deep tillage}}$		18.1		
$LSD_{0.10\ \text{surface tillage within deep tillage}}$		13.1		
$LSD_{0.10\ \text{surface tillage \& traffic combinations within deep tillage}}$		18.5		
$LSD_{0.10\ \text{deep tillage within deep tillage \& traffic combination}}$		24.7		

[1]Subsoiled at 40–44 cm depth on 25 cm centers once only in 1988.

The N in plants attributed to native soil N uptake (total N-fertilizer N) was not greatly different from that observed from total N uptake. Traffic significantlv decreased native soil N uptake, with 77 kg N ha^{-1} and 89 kg N ha^{-1} for traffic and no traffic, respectively ($LSD_{0.10}$=9.1). In-row subsoiling significantly increased native soil N uptake compared with no deep tillage, with 96 kg N ha^{-1} and 75 kg N ha^{-1} for in-row subsoil and no deep tillage, respectively ($LSD_{0.10}$= 17.2). In addition, the contribution of native soil N to total plant N uptake was also significantly increased by surface tillage compared with no surface tillage. Native soil N contributed 90 kg N ha^{-1} to the total plant N uptake with surface tillage compared with 80 kg N ha^{-1} ($LSD_{0.10}$= 5.5) with no surface tillage. As a dry matter response to surface tillage (averaged over traffic and deep tillage treatments) was not observed, these results indicate that an increase in the available N for plant uptake was responsible. This was probably due to an increase in mineralization of N from residues when surface incorporation was performed. Varco et al. (1989) reported an increase in total N uptake when a legume cover crop (*Vicia villosa* Roth.) was incorporated compared with leaving residues on the surface. The increased uptake of native soil N by corn plants when surface residues were incorporated undoubtedly contributed to the surface tillage x deep tillage x traffic interaction observed for total N uptake in the corn plant.

3.3. Soil fertilizer N recovery

The total fertilizer N recovered in the soil was not significantly affected by tillage or traffic treatments in either year. Likewise, no significant differences were observed for fertilizer N content of soil samples taken in trafficked and non-trafficked interrows in either year, although a trend for fertilizer N to be increased in the trafficked interrow compared with the non-trafficked interrow was observed (data not shown). In the dry year of 1990, more fertilizer N was recotiered in the soil than in the wet year of 1991, with 62 kg fertilizer N ha^{-1} and 44 kg fertilizer N ha^{-1} recovered in soil in 1990 and 1991, respectively, when averaged over all



g. 2. Fertilizer N content of soil at three depth increments in 1991 as affected by surface and deep tillage. Horizontal lines, $LSD_{0.10}$; ns, not significant.

tillage and traffic treatments. Higher fertilizer N levels in the dry year were probably a result of reduced soil N losses under these dry soil moisture conditions, Measurable amounts of fertilizer N were found in the 60-90 cm depth in both years (4.0 kg fertilizer N ha^{-1} and 5.5 kg fertilizer N ha^{-1} for 1990 and 1991, respectively, averaged over all tillage and traffic treatments) indicating that appreciable N movement had occurred below the traffic pan in both years.

Although no significant treatment differences were found in the total fertilizer N remaining in soil in 1991, significant treatment differences were observed in fertilizer N distribution by depth, with both surface tillage and deep tillage treatment effects observed. No significant differences were found between the three deep tillage treatments at soil depths of 0-30 cm or 30-60 cm; however, treatment involving no deep tillage significantly increased the amount of fertilizer N at the 60-90 cm depth compared with in-row subsoiling (Fig, 2). This was probably caused by a restriction on deep rooting in the no deep tillage treatment resulting in a reduction of plant fertilizer N uptake from the 60-90 cm depth compared with the other deep tillage treatments.

Significant differences in the fertilizer N content at both the 0-30 cm and the 60-90 cm depths were observed for surface tillage treatments. At the 0-30 cm depth, surface tillage increased fertilizer N content remaining in soil, whereas at the 60-90 cm depth, surface tillage decreased the fertilizer N content remaining in soil (Fig. 2). Increases in fertilizer N content at the 0-30 cm depth were probably a result of increased mineralization of native soil N reducing the demand for fertilizer N by corn. This result is consistent with the observed higher levels of native soil N in corn plants as a result of surface tillage. In addition, an increase in continuous pores in the no surface tillage plots could have increased NO_3-N movement below the traffic pan compared with the surface tillage plots. The elimination of plowing of the soil surface has been shown to increase continuous pores and to increase the movement ofsurface-applied fertilizers (McMahon and Thomas, 1976; Tyler and Thomas, 1977; Gilliam and Hoyt, 1987). This supposition would be consistent with the higher fertilizer N content observed at the 60-90 cm depth for the no surface tillage plots compared with surface tillage plots (Fig. 2).

3.4. Total fertilizer N recovery

Total fertilizer N recovered in the plant-soil system was not significantly affected by any of the tillage or traffic treatments in the dry year of 1990. However, unlike fertilizer N recovered in soil, total fertilizer N recovered in the plant-soil system was less than that recovered in 1991, with 108 kg fertilizer N ha^{-1} and 128 kg fertilizer N ha^{-1} recovered in 1990 and 1991, respectively, averaged over all tillage and traffic treatments. This indicates that although soil N loss mechanisms, such as nitrate leaching and denitrification, may be reduced under dry soil conditions, without adequate plant N uptake, substantial N losses continued to reduce the total amount of N in the plant-soil system.

In the wet year of 1991, a significant deep tillage x surface tillage x traffic inter-

Table 8
Effect of deep tillage, surface tillage, and traffic on total recovered fertilizer N in the plant–soil system ($kg\ N\ ha^{-1}$) in 1991

Deep tillage	Surface tillage		No surface tillage	
	No traffic	Traffic	No traffic	Traffic
Complete disruption[1]	142.6	124.0	124.8	131.6
In-row subsoil	124.1	120.7	142.3	117.8
None	135.1	128.0	139.1	100.8
$LSD_{0.10}$ surface tillage & traffic combinations within deep tillage		26.3		

[1]Subsoiled at 40–44 cm depth on 25 cm centers once only in 1988.

action was observed for total fertilizer N recovered in the plant-soil system. The observed treatment effects were similar to those observed with plant fertilizer N uptake, with the greatest total fertilizer N recovery observed in the least soil compacting treatment of complete disruption combined with surface tillage and no traffic (Table 8). The lowest total fertilizer N recovery occurred with the most soil compacting treatment of traffic in combination with no deep tillage and no surface tillage. However, unlike the treatment effects observed for plant fertilizer N uptake, the complete disruption combined with surface tillage and traffic did not vary greatly from the fertilizer N recovery observed for the other tillage and traffic treatments. This indicated that the reduction in plant N uptake in this treatment was not due to N losses but rather to a restriction on retrieval by the plant of the N in soil.

The reduction in total recovered fertilizer N with the no deep tillage treatment combined with no surface tillage and traffic treatment was an indication that with this tillage-traffic combination, N losses also contributed to the observed effects. As discussed above, with the fertilizer N distribution in soil, both surface tillage and no deep tillage increased the fertilizer N movement in the soil profile. Consistent with this, although the three-way interaction was not significant, soil fertilizer N content within the no deep tillage treatment combined with no surface tillage and traffic was observed to be lowest in the 0-30 cm depth and highest in the 30-60 cm and 60-90 cm depths compared with the other tillage and traffic treatments (data not shown). These effects of fertilizer N movement in the soil profile combined with reduced plant N uptake owing to traffic resulted in fertilizer N losses being greatest in the no deep tillage and no surface tillage with traffic treatment.

4. *Conclusions*

The results reported here were for two extreme years for rainfall conditions. Whereas grain yields between years indicated drastically different responses to tillage and traffic treatments, total dry matter and plant N uptake data indicated that similar responses to tillage and traffic treatments occurred during these two years. Treatment effects were reduced in the dry year so that only main effects were observed, whereas in the wet year, tillage and traffic treatment interactions were prevalent.

In general, data from this study indicated that in these sandy soils some form of tillage is needed. These soils respond to deep tillage, but when deep tillage is not performed, then surface tillage is needed. In addition, traffic is detrimental to these soils, especially when associated with high-intensity tillage. The effect of soil compaction caused by wheel traffic may be very persistent, especially in the subsoil (Boone, 1988; Hakansson et al., 1988). Voorhees et al. (1986) found that increased bulk density and reduced hydraulic conductivity caused by traffic still persisted after 4 years, and Blake et al. (1976) found that subsoil compaction persisted 9 years after treatment application. It is noteworthy that although soil physical condition was negatively affected by traffic, no grain yield response to traffic was detected in the first 2 years of this study (Reeves et al. 1992). After 3 years, however, traffic resulted in detrimental effects on plant N uptake; after 4 years (and favorable growing season) both grain yield and plant N uptake were detrimentally affected by traffic, dependent on tillage system.

Fertilizer N in soil indicated that N movement in the soil profile occurred in both the dry year and the wet year of the study. Although no significant differences occurred in the total amount of fertilizer N remaining in soil, differences in distribution by depth did occur. The fertilizer N content at the 60-90 cm depth was increased when residues were not incorporated by disking, probably owing to increased movement of fertilizer N in the soil profile. Additionally, no deep tillage increased the fertilizer N content at the 60-90 cm depth, probably as a result of reduced root extraction of N from below the traffic pan.

Detrimental plant responses occurred in both the most intensely tilled and the least intensely tilled treatments when combined with traffic. With traffic, the no deep tillage combined with no surface tillage (low-intensity tillage) and the complete disruption combined with surface tillage (high-intensity tillage) resulted in reduced plant N uptake compared with the other traffic and tillage treatments. The detrimental effect of traffic on the plant was mostly responsible for reduced N uptake with the high-intensity tillage system, whereas in the low-intensity tillage treatment, N losses were also a factor in reduced plant N uptake. These results indicate that in these sandy soils, which are susceptible to the formation of traffic pans, not incorporating plant residues can reduce the detrimental effect of traffic on plant yields and plant N uptake; however, some form of deep tillage such as in-row subsoiling is needed when no surface tillage is performed.

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