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SEDIMENT AND NUTRIENT LOSSES IN REDUCED TILLAGE SYSTEMS ON DAIRY FARMS

A Thesis in

Agronomy

by

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ABSTRACT

No-tillage (NT) cropping systems have been promoted as a way to reduce sediment and nutrient losses in runoff from agricultural fields. However, on dairy farms where manure is surface applied, NT may have lower nitrogen (N) use efficiency along with higher nutrient losses in runoff than when manure is incorporated. The N efficiency of applied manure and the amount of sediment and nutrient loss in runoff may be influenced by soil drainage properties. This study was conducted in 2007 and 2008 to compare the effects of NT and chisel/disking (CD) on the N-fertilizer equivalence of manure and sediment and nutrient loss on a well-drained (WD) and somewhat poorly drained (SPD) soil.

The first experiment compared the N-fertilizer equivalence of incorporated dairy manure in a CD corn silage (*Zea mays*, L.) system without cover crop with that of surface-applied manure in a NT system with a cereal rye (*Secale cereale*, L.) cover crop. The study was done on a well-drained (WD) site (Hagerstown silt loam; fine, mixed, semiactive, mesic Typic Hapludalf) and a somewhat poorly-drained (SPD) site (Buchanan gravelly loam; fine-loamy, mixed, semiactive, mesic Aquic Fragiudult), both of which had been in NT for more than 10 years. The trial was laid out in a randomized complete block split-plot design with four replications, with the tillage systems as main-plots and four nitrogen fertilizer rates as sub-plot treatments. The same amount of manure, calculated to supply approximately 50% of N-needs of corn with incorporation within 24 hours, was applied in both NT and CD. In the first year, manure was incorporated in CD in 24 hours, but in the second year manure could not be incorporated in CD until after 7 days due to rainfall shortly after manure application. The N-fertilizer equivalence of surface applied manure and the optimum nitrogen application rates in NT were not significantly

different than in CD on both soil types. In the second year of the study, NT yields were significantly greater than CD yields at higher N-rates on the WD soil, most likely due to greater moisture stress in the CD system as well as reduced soil quality. Pre-sidedress soil nitrate test levels on both soil types and crude protein content of silage on the WD soil was lower in NT in both years, which suggest nitrogen uptake was reduced in NT, although this did not negatively affect crop yield. The study suggests that the nitrogen fertilizer equivalence of surface applied manure in a long-term NT system with cover crop is not significantly different from that of incorporated manure in a CD system without a cover crop.

A rainfall simulation experiment was done in the same study on plots that received 56 kg N ha^{-1}. Rainfall simulations (6 cm hr^{-1}) were performed shortly after planting, at mid-season, and after harvest on runoff plots (2x2 m). In both years and on both soils, NT had significantly lower runoff volumes and lower total sediment loads than CD. Runoff and sediment loss generally did not differ between tillage systems immediately after planting on both soil types. In NT, runoff volume declined throughout the season resulting in NT having significantly lower runoff volumes than CD by mid-season on the WD soil but not until after harvest on the SPD soil. On average, NT had lower total phosphorus loads than CD on the WD soil, but had higher loads on the SPD soil. Total dissolved phosphorus constituted 73% of total phosphorus in NT, whereas it constituted only 15% in CD with little difference between soils. Highest dissolved phosphorus losses occurred in NT immediately after manure application, whereas particulate phosphorus losses (in CD) occurred throughout the season. Total dissolved nitrogen losses appeared to be primarily affected by runoff volume, and were therefore reduced in NT on the WD site. NT may reduce runoff and erosion on WD and SPD soils, may reduce total phosphorus loss on WD soils, but may increase it on SPD soils. Most phosphorus loss in NT occurred shortly after manure application and was in dissolved form. Runoff and sediment control are significant benefits of NT on WD and SPD soils, however, dissolved phosphorus losses shortly after surface application of manure can be a concern.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

Abbrev.	Stands For
ADF	acid detergent fiber
BMP	best management practice
CD	chisel/disked
CP	crude protein
DON	dissolved organic nitrogen
EDI	effective depth of interaction
FCC	full canopy closure
FW	flow-weighted
$H_2PO_4^-$	orthophosphate
HCC	half canopy closure
K	potassium
K_2O	potash
N	nitrogen
NDF	neutral detergent fiber
NH_3	ammonia
NH_4^+	ammonium
NO_2^-	nitrite
NO_3^-	nitrate
NT	no-tillage
NUE	nitrogen use efficiency
P	phosphorus
PA	State of Pennsylvania
PHA	post-harvest
PP	particulate phosphorus
PPL	post-plant
PSNT	pre-sidedress soil nitrogen test
PVC	polyvinyl chloride
SPD	Somewhat poorly-drained [soil]

Abbrev.	Stands For
TDP	total dissolved phosphorus
TDN	total dissolved nitrogen
TP	total phosphorus
TS	total solids/sediment
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
WD	well-drained [soil]

Introduction

Erosion and nutrient loss caused by runoff from agricultural land is an important environmental concern. The export of sediment and nutrients into streams and rivers causes eutrophication of bodies of water which may negatively affect aquatic life (USEPA, 2002; USEPA and USDA, 2006). No-till (NT) farming has been promoted as a best management practice (BMP) in order to reduce sediment and nutrient losses (Pennsylvania Conservation Partnership, 1999). No-till farming practices reduce soil disturbance while maintaining residue cover. These two factors work together to reduce soil erosion and increase infiltration. Many nutrients adhere to or form bonds with soil particles; therefore, reducing soil erosion may lead to reduced nutrient losses.

The types of tillage systems in use today vary according to the percentage of soil surface covered by crop residue and the amount of soil disturbance caused by tillage operations (Table 1). A NT system is a type of conservation tillage system that maintains crop residue cover and disturbs no more than 25% of the soil surface (Wiebe and Gollehon, 2006). A cover crop may be grown during the off-season.

Table 1. Key characteristics of tillage systems†.

Type of Tillage	Soil Surface Cover	Soil Disturbance
No-till	~75% (varies)	<25%
Conservation tillage	≥30%	varies
Reduced tillage	15-30%	varies
Conventional tillage	<15%	100%

† Source: Wiebe and Gollehon, 2006

Conventional tillage, by contrast, causes complete disturbance of the soil and often leaves little or no residue on the soil surface. It is commonly performed using a moldboard plow which inverts the soil thus incorporating any previous crop residue. A common tillage system in PA is reduced tillage which leaves 15-30% of the soil surface covered with residue (Wiebe and Gollehon, 2006). A chisel plow is commonly used for primary tillage and a disk harrow for secondary tillage.

Over the past two decades, the acreage farmed using NT systems in the U.S. has increased steadily whereas other tillage systems have remained steady or declined (Fig. 1; Conservation Technology Information Center, 2004). NT systems offer many potential benefits over other tillage systems which has spurred its high rate of adoption.

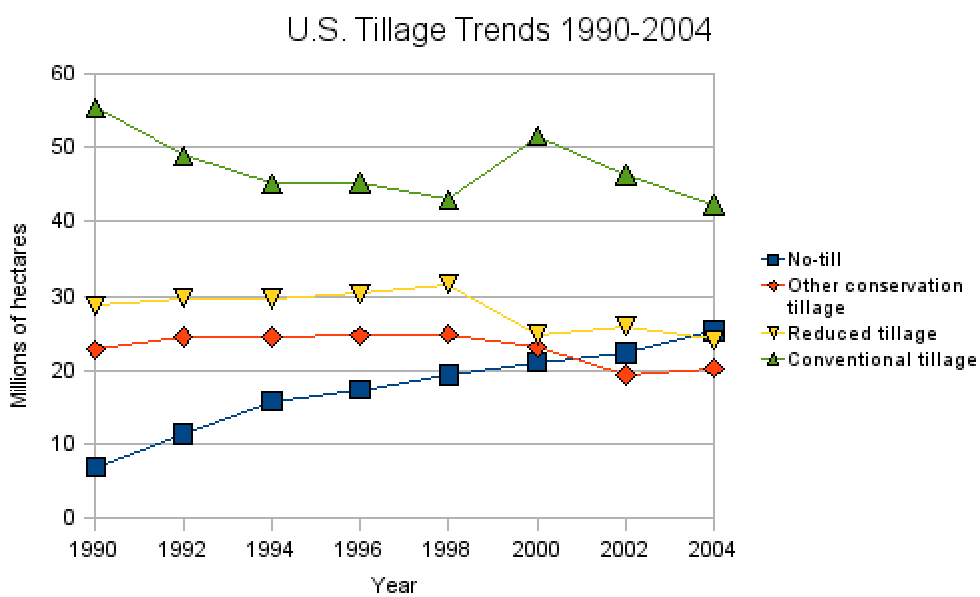

Fig. 1. Tillage trends from 1990-2004 (Conservation Technology Information Center, 2004).

NT reduces the number of equipment passes over the field by a factor of three as compared to conventional tillage systems (Tebrügge and Wagner, 1995) which reduces labor needs, fuel costs and soil compaction. Crop residue cover left on the soil surface reduces the impact of raindrops, thereby minimizing crusting and sealing and resulting in improved infiltration, reduced runoff and erosion, and higher soil moisture content (Wagger and Denton, 1992; Rice and Smith, 1982). In addition, the accumulation of organic matter and nutrients near the surface in a NT system enhances biological activity, increases the presence of earthworms and the formation of deep vertical burrows that improve infiltration, thereby reducing runoff and erosion (Tebrügge and Düring, 1999; Kladivko et al., 1997).

Despite the potential benefits of NT systems, there are two potential concerns in relation to dairy farms that use manure to meet most of the crop N needs. In NT, the nitrogen availability factor of unincorporated manure is recommended to be much lower (20%) than manure incorporated in tilled systems within one day (40%) (The Pennsylvania State University, 2007). NT may also have higher losses of nutrients in runoff from unincorporated manure than in tilled systems (Eghball and Gilley, 1999; Mueller et al., 1984). Other studies have shown NT to have lower N-fertilizer efficiency (Sims et al., 1998; Stecker et al., 1995). Few studies have directly compared the effects of tillage on N efficiency and sediment and nutrient loss on soils with different drainage properties. Sims et al. (1998) compared two soils with different drainage properties under similar cropping systems but with different climatic conditions. Therefore, they could not differentiate the effect of soil type from that of climate in their results.

In this study, sediment and nutrient runoff losses were compared between NT and chisel/disked (CD) systems by analyzing the various species and quantities of nitrogen and phosphorus lost to runoff through the simulation of rainfall events on soils with different drainage properties. Furthermore, since nitrogen may be lost through several different pathways, the N-fertilizer equivalence of applied manure and the N-efficiency of inorganic fertilizer were compared between these two systems through a yields analysis at varying mineral N fertilizer application rates. The N-fertilizer equivalence is measured as the yield response to applied N fertilizers.

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Chapter 1: Tillage effect on nitrogen fertilizer equivalence of dairy manure

Abstract

In no-tillage (NT) systems surface applied manure may have lower nitrogen availability due to greater ammonia volatilization and denitrification than if incorporated, especially on poorly-drained soils. This experiment compared the N-fertilizer equivalence of incorporated dairy manure in a chisel/disk (CD) system without cover crop with that of surface-applied manure in a NT system with a rye (*Secale cereale*, L.) cover crop. The study was done on a well-drained (WD) site (Hagerstown silt loam; fine, mixed, semiactive, mesic Typic Hapludalf) and a somewhat poorly-drained (SPD) site (Buchanan gravelly loam; fine-loamy, mixed, semiactive, mesic Aquic Fragiudult), both of which had been in NT for more than 10 years. The trial was laid out in a randomized complete block split-plot design, with the tillage systems as main-plots and nitrogen fertilizer rates as sub-plot treatments. The same amount of manure, calculated to supply approximately 50% of N-needs of corn (*Zea mays,* L.) with incorporation within 24 hours, was applied in both NT and CD. In the first year, manure was incorporated in CD in 24 hours, but in the second year manure could not be incorporated in CD until after 7 days due to rainfall shortly after manure application. The N-fertilizer equivalence of surface applied manure and the optimum nitrogen application rates were not significantly different between tillage systems on both soil types. In the second year of the study, NT yields were significantly greater than CD yields at higher N-rates on the WD soil, most likely due to greater moisture stress in the CD system as well as reduced soil quality. In both years, pre-sidedress nitrate test levels were

lower in NT on both soil types and the crude protein content of silage was lower in NT on the WD soil, which suggests nitrogen uptake was reduced in NT, although this did not negatively affect crop yield. This study suggests that the N-fertilizer equivalence of surface applied manure in a long-term NT system with cover crop is similar to that of incorporated manure in a CD system without a cover crop.

Introduction

Tillage systems affect soil nitrogen cycling in both positive and negative ways. The net movement of nitrogen out of the soil profile or the immobilization of nitrogen may result in reduced yields. The crop nitrogen fertilization regiment must complement the tillage system in order to maximize yields and profit while minimizing environmental consequences. In dairy systems, where manure is applied to meet most of the crop's nitrogen needs, the tillage system may be of critical importance. Of particular concern, gaseous N losses from unincorporated dairy manure in NT systems may result in lower yields than in CD systems where manure is incorporated. The extent of these losses may be affected by soil drainage properties.

Nitrogen can be lost from the soil or otherwise be made unavailable to a crop through several different pathways including leaching, volatilization, denitrification, immobilization, and runoff (Havlin et al, 2005). Anions such as nitrate (NO_3^-), which is the dominate species of plant available N in soil, can be leached out of the root zone during rain events. The potential for leaching is potentially influenced by the rate of infiltration which tends to be increased in NT systems (Wagger and Denton, 1992). Nonetheless, there is contradictory research on whether NT results in higher levels of NO_3^- leachate as compared to tilled plots which may be explained by differences in soil drainage properties or the presence of an off-season cover crop. For instance, Zhu et al. (2003) found no significant difference in NO_3^- leachate between NT and tilled plots and Stoddard et al. (2005) while Tyler and Thomas (1977) found NT to have higher levels of NO3- leachate on well-drained soils. Elsewhere, Angle et al. (1993) found NT to have lower levels of NO_3^- leachate on moderately well-drained soil or soil with impeded drainage. The study of Angle et al. (1993) included a barley cover-crop while the other studies did not. Cover crops are promoted as an integral part of NT systems and may greatly reduce off-season nutrient losses from leaching (Duiker and Myers, 2006). Cover crops scavenge for and assimilate into their biomass N that remains in the soil after the principal crop is harvested. After cover crops are killed off with herbicide prior to planting, they release N as they decompose that may be available to the subsequent crop.

In NT systems, mineral N fertilizers and manures are often not incorporated (e.g. by subsurface banding or injection). This may increase ammonia (NH_3) volatilization losses in manures and fertilizers that contain urea (Keller and Mengel, 1985). Conversely, incorporation of these amendments increases their contact with soil particles and reduces exposure to the atmosphere. This promotes the microbial immobilization of NH_4^+ or the adsorption of NH_4^+ to negatively charged colloids and organic matter and reduces volatilization losses. The incorporation of urea to a depth of 2.5 cm has shown to nearly eliminate ammonia volatilization (Fenn and Miyamoto, 1981; Keller and Mengel, 1985). The incorporation of mineral N fertilizers and manures also decreased the susceptibility to runoff losses. Little et al. (2005) has shown that incorporation of N fertilizers and manures can reduce total N in runoff by 26-95% depending on the type of tillage performed.

Nitrate may also be lost through denitrification caused by anaerobic bacteria in soils with high moisture content. Rice and Smith (1982) found significantly higher levels of denitrification in NT than in CD on well-drained soils concluding that untilled soils maintain higher soil moisture contents and therefore anoxic conditions leading to denitrification. Rochette et al. (2008) demonstrated that NT had higher levels of denitrification than tilled on heavy clay soil, but not on loam soil. Crop residue may also affect dentrification. Aukakh et al. (1991) found that unincorporated wheat residue, which had a high C:N ratio, resulted in significantly lower levels of denitrification during short periods (8-10 days) of near-saturated conditions than incorporated wheat residue. NT systems which often use small grain cover crops may experience a similar reduction in denitrification as compared to tilled systems. From these previous studies, it appears that soil properties strongly influence the effect of tillage on denitrification losses.

Another fate of applied manure or N fertilizer is immobilization. Plant available N may be immobilized in soils where crop residue with a high C:N ratio is incorporated or left on the surface. Rice and Smith (1984) have shown up to 10% higher short-term immobilization of N fertilizer in NT than in CD. Tillage may speed up organic matter decomposition, therefore, crop residue with a low C:N ratio may mineralize N faster with tillage than under NT management.

As indicated, N losses through denitrification and leaching may be strongly influenced by soil drainage properties which therefore may affect crop yields. Stecker et al. (1995) showed that the maximum yield in well-drained soils may be significantly higher in NT as compared to CD systems. Other studies have found no significant differences in yields at any N rate (Al-Kaisi and Kwaw-Mensah, 2007) and no significant difference in maximum yield and economic optimums (Kwaw-Mensah and Al-Kaisi, 2006; Bandel et al., 1975) between NT and CD systems on moderately well-drained and somewhat poorly-drained soils.

Studies have also found that differences in precipitation and early-season temperature may confound the effect of tillage on yields on soils with different drainage properties. Torbert et al. (2001) and Al-Darby and Lowery (1986) found that NT had significantly higher yields in low rainfall years. Sims et al. (1998) found CD had significantly higher yields in years when the spring soil temperature was relatively low; but, in years with warm spring soil temperatures, they found NT had significantly higher yields. In the spring, NT soils warm up slower than tilled soils due to the insulation of residue covering the soil surface and its ability to conserve soil moisture. This can result in a delay in planting and possibly a shorter growing season.

The objective of this study was to determine the N fertilizer equivalence of unincorporated manure in NT and manure incorporated within 24 hours in CD systems and to compare the optimum N rate, and maximum yield response of NT and CD systems on soils with different drainage properties and similar weather conditions. The N fertilizer equivalence is measured as the yield response to applied N fertilizer.

Materials and Methods

Two fields were selected in Centre County, Pennsylvania approximately 3 km from each other at The Pennsylvania State University Russell E. Larson Agricultural Research Center in Rock Springs, Centre County, Pennsylvania (40°44’N, 77°57’W). One soil consisted of well-drained (WD) to excessively well-drained Hagerstown silt loam (Fine, mixed, semiactive, mesic Typic Hapludalfs) with an average slope of 8%. The other soil was a somewhat poorly drained (SPD) Buchanan gravely loam (Fine-loamy, mixed, semiactive, mesic Aquic Fragiudults) which had an average slope of 7%. The two soils were selected to investigate whether the effect of tillage on N fertilizer equivalence of manure N depended on soil drainage properties. Both fields had been managed with no-till practices for more than 10 years prior to this trial. Tillage and planting operations were performed along the contour.

Each field was laid out in a split-plot design with 4 replicates (Fig. 2). Tillage (NT or CD) constituted the main plot treatments, whereas nitrogen fertilizer rates (0, 56, 112, and 168 kg ha-

[1]) were the sub-plot treatments. Plots were 4.6 m wide by 9.1 m long. Tillage plots were maintained in the same location throughout this study.

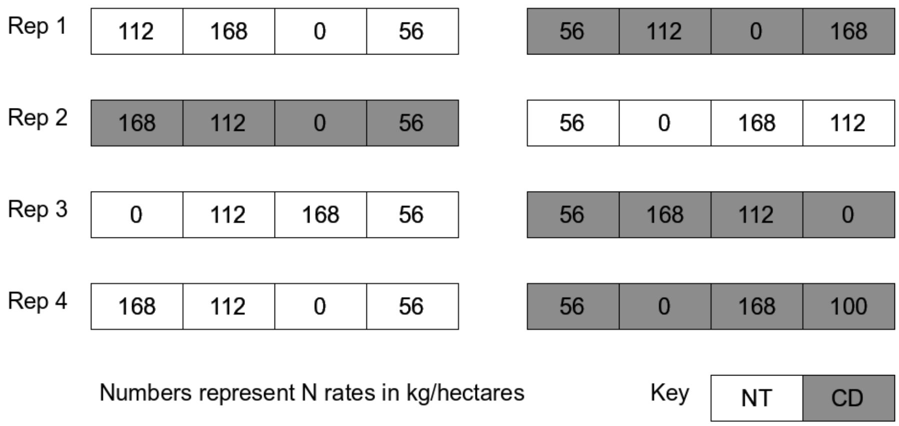

Fig. 2. Experimental design for yield study comparing the effects of no-till (NT) and chisel/disking (CD) on the yield response to four rates of inorganic fertilizer in manured systems.

In the fall of the first year, the fields were planted to a cereal rye (Secale c*ereale*, L., variety not stated) cover crop at a seeding rate of 126 kg ha^{-1}. The rye in the CD plots was dessicated with 0.84 kg ha^{-1} ae glyphosate (2.4 L ha^{-1} Roundup® Original) in the seedling stage so no cover crop was present in these plots in the spring. In the fall of the second year, cereal rye was only planted in the NT strips on both soils at the same seeding rate. Thus, this study compares a no-till system which includes a cover crop to supply residue cover with a chisel-disk system without a cover crop. Good weed control was achieved in both tillage systems using a combination of pre- and post-emergence herbicides.

Soil fertility samples were taken to a depth of 15 cm in fall or early spring of each year (Table 2). The pH was 6.1 on the WD and 5.7 in the SPD soil prior to planting the first corn crop. On the SPD soil, the cover crop showed signs of nutrient deficiencies likely caused by low pH in the first year of the study. The recommended lime was applied early in 2007 at rates of 3,400 kg ha^{-1} and 5,600 kg ha^{-1} on the WD and SPD soils, respectively and additional lime was applied the following fall which corrected the pH to 6.4 and 6.3 on the WD and SPD soils, respectively.

The cereal rye cover crop was dessicated with 0.84 kg ha^{-1} ae glyphosate (2.4 L ha^{-1} Roundup® Original) in early May when it reached boot stage (just prior to seed head emergence). Cover crop biomass samples were taken from NT plots in 0.5 m^2 rectangular frames, dried at 60°C for 48 hours and weighed.

After cover crop dessication in NT plots, liquid dairy manure was applied to all plots to meet approximately half of the N requirement of corn (total N-requirement was estimated at 168 kg N ha^{-1} assuming a maximum yield of 47 Mg ha^{-1} at 65% moisture). Reduced manure rates were necessary to ensure a crop response to N fertilizer applied. The N contribution from manure assumed 40% N availability based on incorporation within 24 hours after application (The Pennsylvania State University, 2007). A manure sample was taken at the time of application and sent to the Penn State Analytical Laboratory for nutrient analysis (Table 3). Additional fertilizer applications were adjusted according to manure phosphorus (P) and potassium (K) contributions.

Table 2. Fertility test levels for the well-drained (WD) Hagerstown silt loam soil and the somewhat poorly drained (SPD) Buchanan gravely loam soil in 2007 and 2008.

	Hagerstown (WD Soil)		Buchanan (SPD Soil)	
Soil Properties	2007	2008	2007	2008
pH	6.1	6.4	5.7	6.3
Mehlich 3 P, ppm	46	33	43	34
K, ppm	139	73	90	90
Ca, meq/100 g	1103	874	1443	1084
organic matter, %	2.6	NA	3.2	NA

Table 3. Properties of manure applied to the well-drained (WD) and somewhat poorly drained (SPD) soils in 2007 and 2008.

	WD Soil		SPD Soil	
Manure Properties	2007	2008	2007	2008
solids, %	6.4	14.1	5.1	14.1
total nitrogen, g L^{-1}	3.5	3.6	2.5	3.6
total P_2O_5, g L^{-1}	1.1	1.4	0.5	1.4
total K_2O, g L^{-1}	3.1	2.6	1.7	2.6
Manure Applications				
rate applied, m^3 ha^{-1}	50.1	67.0	33.9	57.4
total nitrogen applied†, kg ha^{-1}	175.0	240.0	82.5	205.0

† total nitrogen applied does not take into account potential differences in availability between tillage systems

The experimental protocol called for manure to be incorporated on the CD plots by chisel plowing followed by disking one day after application. In 2007, manure was incorporated within 24 hours of application, but in 2008, manure was not incorporated until 7 days and 23 days after application on the WD and SPD soil, respectively, due to five days of rainfall amounting to 4.0 cm shortly after manure application. In 2008, 1.4 cm of rainfall fell on both fields in the span of 48 hours following manure application. According to the Penn State Agronomy Guide (2007), 1.3 cm of rainfall is equivalent to mechanical incorporation and therefore, rainfall was expected to have incorporated manure in both NT and CD and thus reduce ammonia volatilization losses.

Corn (Dekalb variety DKC52-59) was planted in each field using a John Deere 1780 Max-Emerge® planter at a seeding rate of 74,000 seeds ha^{-1}. At approximately the V-6 stage, soil samples were taken to a depth of 31 cm in each plot. Soil samples of the four replications of each treatment were composited and no statistical analysis was therefore possible. The soil samples were sent to the Penn State Analytical Lab for pre-sidedress soil nitrogen tests (PSNT). The test results were used to assess the contribution of N from organic sources including manure and cover crop residue. Fertilizers were chosen that are known to have a low potential for ammonia volatilization. In the first year of this study, N fertilizer was surface-applied as ammonium nitrate after soil samples for the PSNT test had been taken. In the second year ammonium sulfate was used because no ammonium nitrate could be obtained.

Corn was harvested for silage leaving approximately 23 cm of stalk in the field. Silage wet weight for each plot was recorded. A representative silage sample for each plot was taken, placed in a sealed bag, and immediately put on ice to prevent fermentation. Periodically throughout the day, the chilled samples were moved to a freezer. The frozen silage samples were placed in tared fabric bags, weighed, and dried at 60°C for 3 days. Samples were then weighed again to determine the percent moisture content of the harvested silage, which was then used to calculate yield at 65% moisture content. The dried silage samples were ground to pass through a 1 mm mesh sieve. Samples of the four replications of each treatment were composited and sent to DairyOne labs in Ithaca, New York for forage analysis using near infrared reflectance spectroscopy. The crude protein (CP), ADF, and NDF values were used to compare forage quality.

To consistently assess differences in soil moisture retention, the results of soil moisture measurements collected as part of the study described in Chapter 2 of this thesis were used. In that study, conducted using the same plots, moisture readings were taken 24 hours after applying 3 cm of simulated rainfall to determine the ability of each tillage system to retain soil moisture.

Data for each soil were analyzed independently. The optimum N rates and maximum yields were obtained for each tillage treatment and replication using SAS Proc GLM and SAS

Proc NLIN to optimize a quadratic-plateau response curve. These values were compared for each tillage and replication that produced a well-defined plateau within the range of N fertilizer rates using SAS Proc Mixed with blocking. Not all replications reached a plateau within the given range of N fertilizer rates. Therefore, a quadratic response model was used instead to compare yields by tillage so as to include all four replications. The quadratic and quadratic-plateau models were both significant fits ($p<0.05$) for both soils, years, and tillage combinations.

Results and Discussion

Cover Crop Biomass

In 2007 and 2008, cover crop biomass on the NT plots on the WD soil was almost twice that of the biomass on the SPD soil. Dry matter production on the WD soil averaged 1131 and 2203 kg ha^{-1} while the dry matter production on the SPD was 477 and 1323 kg ha^{-1} in 2007 and 2008, respectively. This was likely due to the presence of a fragipan on the SPD soil that helped to restrict drainage and increase soil moisture, something that is commonly observed in such soils (Needelman et al. 2004).

Stand Counts/Emergence

In 2007 on the SPD soil and in 2008 on the WD soil, the NT plots had significantly lower stand counts than the CD plots (Table 4). In 2007, it is possible that the poor drainage properties on the SPD soil combined with the higher moisture holding capacity and cooler soils associated with NT may have caused an increase in seed rot, therefore reducing stand counts. However, no direct measurements of seed rot were made in this study. In 2008, one tilled replication experienced rutting and compaction by the manure spreader resulting in areas of severe ponding on this soil. This may have offset the lower stand counts on NT plots which resulted in no significant difference between tillage treatments. Lower stand counts on the NT plots on the WD soil may have been caused by planting challenges through the heavy rye cover crop residue.

Table 4. Corn stand counts for no-till (NT) and chisel/disked (CD) treatments in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	Stand Counts	
Tillage	2007	2008
	——— plants ha^{-1} ———	
	WD Soil	
CD	67,022	69,891*
NT	67,156	67,246
	SPD Soil	
CD	66,842*	65,453
NT	63,211	66,887

* Indicates tillage is significantly different ($P \leq 0.05$) within each year and soil

Yield Analysis

In both years, there was no significant difference in yields between NT and CD treatments on either soil for the plots that received only manure (no inorganic N fertilizer). This suggests that the N-equivalence of incorporated manure in a CD system is similar to that of surface applied manure in a NT system. However, only in the first year (2007) was manure incorporated within 24 hours in the CD system, whereas in the second year (2008) manure was incorporated after 7 days on the WD soil, and after 23 days on the SPD soil. Because ammonia volatilization is so sensitive to the timing of incorporation, the second year did not allow us to evaluate the N-equivalence of surface applied vs incorporated manure. In fact, it can be reasoned, that in the second year of the study nitrogen volatilization was reduced in both systems due to the effect of precipitation shortly after manure application. In addition, the rates of manure applied were low, and experimental variability may have overwhelmed treatment effects. According to the Penn State Agronomy Guide (2007), only 20% of the N content of unincorporated manure applied during the spring as in NT is estimated to be available to the growing crop whereas approximately 40% is estimated to be available when manure is incorporated within 24 hours as in CD. If these estimates are accurate, then the highest manure rate applied in this study (67 m^3 ha^{-1}; Table 3) resulted in a gross contribution of 240 kg total N ha^{-1}, equivalent to 96 kg available N ha^{-1} in CD and 48 kg available N ha^{-1} in NT. Therefore, there was only a difference of 17 to 48 kg available N ha^{-1} between the two tillage treatments for the range of manure application rates tested. These differences may have been overwhelmed by spatial variability in soil N and other properties impacting crop yields. Indeed, at the rate of 0 kg applied N ha^{-1} (Fig. 3), standard errors were estimated to be from 6-86 kg applied N ha^{-1}, similar in magnitude to range in available manure N. Large spatial variability in soil N, particularly crop available forms, is well documented (e.g., Cambardella et al., 1994).

In both years, there was no significant difference in crop yield between NT and CD on either soil in the yields when all N rates were assessed together. Similar results have been reported elsewhere (Al-Kaisi and Kwaw-Mensah, 2007). However, when treatment differences were assessed for single rates of N application only, then some significant differences did exist in the second year of the study on the WD soil. Specifically, NT yields were significantly elevated above CD at 112 and 156 kg applied N ha^{-1}. These differences suggest the emergence of a temporal trend in yield potential resulting from the introduction of CD to soils that had formerly been under NT management. A likely hypothesis is that CD impacted the moisture retention of the soils (Rice and Smith, 1982). In fact, observations from a related study that took place at the same time and on the same fields revealed significantly greater volumetric moisture in the surface of the NT soils than the CD soils after controlled wetting and drying intervals (Table A-3), consistent with the elevated yield potential observed in the 2008 trials.

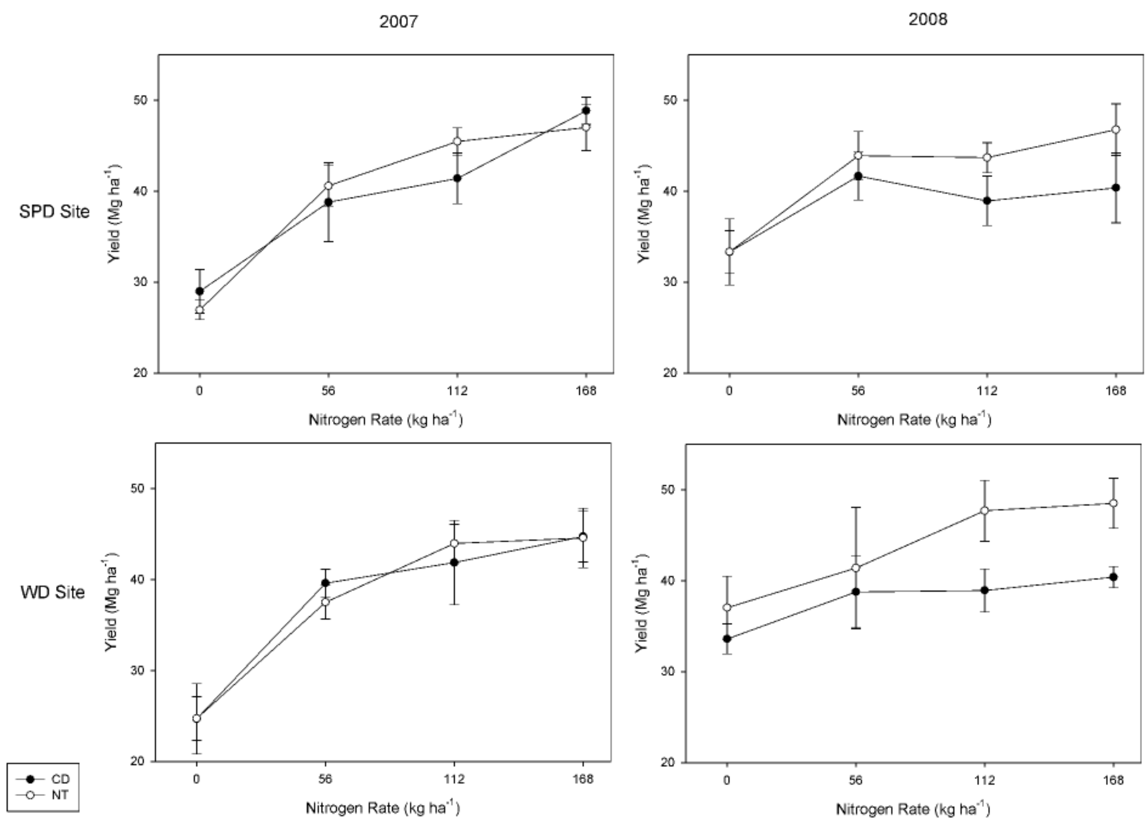

Fig. 3. Average yield response in no-till (NT) and chisel/disked (CD) treatments to four mineral fertilizer N rates in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

There were no significant differences in yield plateaus or optimum N rates between NT and CD in each year and on each soil. Kwaw-Mensah and Al-Kaisi (2006) and Bandel et al. (1975) studies produced similar results. In this study, not all replications produced well-established plateaus. A quadratic-plateau model requires the three lowest N rates to establish the quadratic portion of the curve and the two highest N rates to establish the plateau. With only four N rates used in this study, this was not always possible due to some plots which had too high or too low yield response to applied N. Replications that did not produce a well-established plateau were omitted from the comparison of maximum yield and optimum N rates by tillage.

Pre-sidedress Nitrate Corn Test

In both years, the PSNT indicated that the CD plots retained higher levels of NO_3-N than the NT plots on both soils as was expected. However, these findings are not consistent with yield observations. As described above, there was no significant difference in yield response between tillage systems across all N rates on both soils, and, when only the highest N rates were considered on the WD soil in 2008, NT actually had a significantly greater yield response than did CD. This suggest that the PSNT is not always well linked to yield response (Meisinger, 1992), and it is possible that other factors, such as soil moisture overwhelmed the differences suggested by the PSNT.

Table 5. Pre-sidedress soil nitrogen test results for no-till (NT) and chisel/disked (CD) treatments in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	2007		2008	
Tillage	Soil NO_3^--N	Recommendation	Soil NO_3^--N	Recommendation
	ppm	kg ha^{-1}	ppm	kg ha^{-1}
		WD Soil		
CD	18.8	66.4	33.9	0.0
NT	12.4	91.5	8.0	106.5
		SPD Soil		
CD	14.3	84.0	20.0	30.5
NT	11.9	93.4	18.6	42.0

Silage Quality

Some trends between tillage treatments were suggested from silage quality measurements, although results were inconsistent across indicators, and, due to lack of replication, could not be statistically assessed. In both years, the NT silage showed evidence of lower crude protein contents (Fig. 4) at each N rate on the WD soil. This corresponded well with the PSNT results, but it is unclear why it did not result in a significant difference in yield response. It is also unclear why the difference in crude protein was only evident on the WD soil. There was little difference in ADF or NDF between NT and CD in both years and on both soils (Table 6).

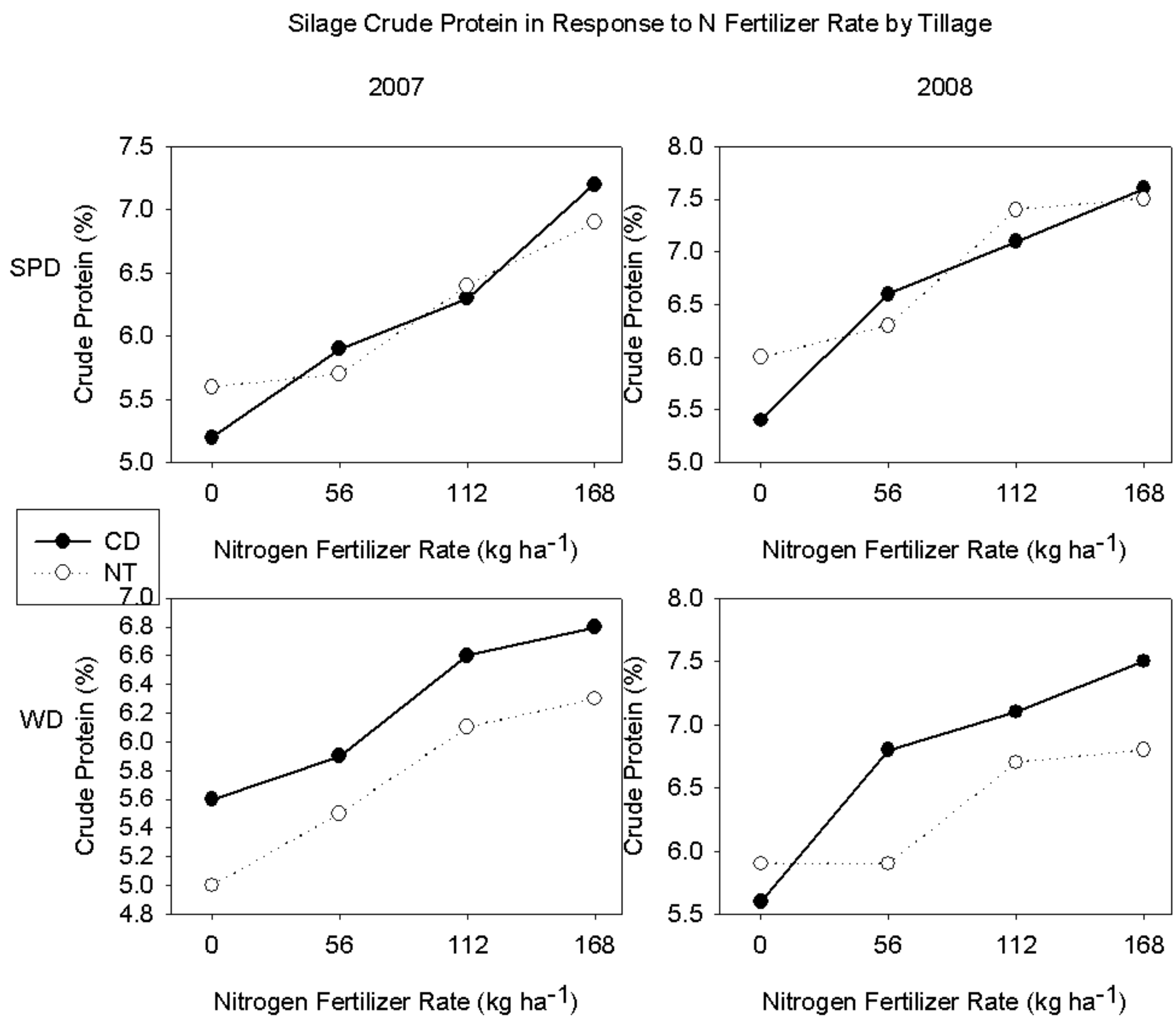

Fig. 4. Average crude protein content of silage for no-till (NT) and chisel/disked (CD) treatments in response to four N rates for in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

rainfall prevented incorporation of the manure within 24 hours in the CD treatment, therefore, no differences in N-fertilizer equivalence due to tillage were expected in that year. Additionally, low manure application rates may have meant that experimental variability overwhelmed treatment effects in the first year. Nonetheless, the results of this study warrant further investigation. The benefits of long-term no-tillage may explain why nitrogen fertilizer equivalence of surface applied manure was similar in NT compared with CD in this study. Higher infiltration in long-term no-tillage may facilitate faster absorption of liquid manure which could reduce ammonia volatilization. Further, the use of a cover crop in NT may have resulted in uptake of nitrogen during the off-season, some of which may have been released during the corn growing season. Additionally, long-term no-tillage may have built up, a higher level of soil organic matter content than in the CD system. Greater nitrogen release from this larger pool of organic matter may have compensated for nitrogen volatilization losses. The effects of greater biological activity (e.g. earthworms, microbes) in long-term no-tillage on ammonia volatilization of manure N needs to be investigated.

In this study, lower PSNT values in NT as compared to CD on both soil types and lower crude protein content in NT on the WD soil suggest that nitrogen availability and uptake were reduced in NT, although yields were not negatively affected. Therefore, at least an additional field season is necessary to confirm these results and further studies are required with higher manure application rates.

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Chapter 2: Sediment and Nutrient Losses in Runoff

Abstract

Widespread adoption o f no-tillage (NT) crop production has been credited with improved soil and moisture conservation, but concerns exist as to the fate of nutrients in surface applied manure in NT systems. This study compared runoff losses of sediment and nutrients from incorporated dairy manure in a chisel/disk (CD) system without cover crop with that of surface-applied manure in a NT corn (*Zea mays*, L.) system with a rye (*Secale cereale,* L.) cover crop. The study was done in 2007 and 2008 on a well-drained (WD) site (Hagerstown silt loam; fine, mixed, semiactive, mesic Typic Hapludalf) and a somewhat poorly-drained (SPD) site (Buchanan gravelly loam; fine-loamy, mixed, semiactive, mesic Aquic Fragiudult), both of which had been in NT for more than 10 years. The trial was laid out in a randomized complete block design with 4 replications. Rainfall simulations (6 cm hr^{-1}) were performed shortly after planting, at mid-season, and after harvest on runoff plots (2x2 m). In both years and on both soils, NT had significantly lower runoff volumes and lower total sediment loads than CD. Runoff and sediment loss generally did not differ between tillage systems immediately after planting on both soil types. In NT, runoff volume declined throughout the season resulting in NT having significantly lower runoff volumes than CD by full canopy closure on the WD soil but not until after harvest on the SPD soil. On average, total phosphorus loads were lower in NT on the WD soil, but were higher on the SPD soil. Total dissolved phosphorus constituted 73% of total phosphorus in NT, whereas it constituted only 15% in CD with little difference between soils. Highest dissolved phosphorus losses occurred in NT immediately after manure application,

whereas particulate phosphorus losses (in CD) occurred throughout the season. Total dissolved nitrogen losses appeared to be primarily affected by runoff volume, and were therefore reduced in NT on the WD site but increased on the SPD site. This study suggests NT may reduce runoff and erosion on WD and SPD soils, may reduce total phosphorus loss on WD soils, but may increase it on SPD soils. Runoff and sediment control are important benefits of NT on WD and SPD soils; however, dissolved phosphorus losses immediately after surface application of manure can be a concern on all soils.

Introduction

In the EPA's "National Water Quality Inventory: Report to Congress" of 2002 (USEPA, 2002), agricultural activities were cited as a top contributor of pollutants that impair fresh water bodies throughout the United States. Of the bodies of water surveyed, approximately 45% of rivers and streams, 47% of lakes, ponds, and reservoirs, and 32% of bays and estuaries were classified as impaired and unable to fully support their designated use(s). Agricultural runoff was cited as the most likely cause of impairment on approximately 37% of rivers and streams and 30% of lakes, ponds, and reservoirs. The EPA and USDA 2006 Joint Evaluation Report of the Chesapeake Bay (USEPA and USDA, 2006) estimated that 40% of N, 45% of P, and 62% of sediment entering the bay in 2004 came from agricultural sources.

The pathway that pollutants take from agricultural lands to bodies of water is determined by the mechanism of transport and the form of the pollutant. The dominant transport mechanism for sediment is surface runoff; however, transport mechanisms for nutrients vary and also include atmospheric emission and ground water flow, making control of nutrient losses more complex to mitigate (Mosier et al., 1998). Sediment-bound phosphorus can be lost in runoff through erosion whereas dissolved phosphorus can be lost with no detachment or movement of soil particles. Soluble forms of P present in manure in high concentrations are a concern especially in livestock-based agricultural systems such as the dairy farms in the Northeastern U.S. (Rotz et al., 2002). Year after year of spreading large amounts of manure can lead to a buildup in soil phosphorus levels (Sharpley et al., 2001). Manure recommendations are often made to meet the N need of a crop. Phosphorus is then applied in levels that exceed the crop need causing a net build-up of phosphorus. Over time this may reduce the P sorption capacity of a soil and excess P is more likely to be released to the environment (The Pennsylvania State University, 2007).

Nitrogen species behave differently. Nitrate (NO_3^-) may leached out of the soil profile especially in course textured soils in humid environments (Brady and Weil, 2002). Nitrate may also be lost through denitrification in soils with poor drainage properties, high moisture content, or during and after rain events (Rice and Smith, 1982; Mosier et al., 2002). Ammonia (NH_3) may be lost to volatilization from manure or other urea-based fertilizers (Keller and Mengel, 1986; Bussink and Oenema, 1998).

The effect that a tillage system has on runoff volume can vary depending on a number of other factors: slope, tillage history, and landscape position/drainage properties (Seta et al., 1993; Daverede et al., 2003; Kleinman et al., 2006). Slope can have a much greater effect on tilled soils than on untilled soils because a greater slope permits runoff to breach the ridges left after the tillage operation. Seta et al. (1993) concluded that NT had significantly lower runoff volumes than chisel plowed plots on soils with a 9% slope. Conversely, Daverede et al. (2003) concluded that NT had significantly higher runoff volume compared than chisel plowed plots with a 5.5% slope on soils with similar drainage properties. Differences in slope may explain these contradictory results; however, Daverede et al. suggested that the long NT history of the plots of Seta et al. may have improved infiltration and may also explain differences in runoff.

Daverede et al. (2003) and Seta et al. (1993) both found that NT had lower TS concentrations in runoff than the chisel plowed plots. Seta et al. (1993) also showed the TS loads were lower in NT than in chisel plowed plots. However, lower TS concentrations in NT does not necessitate lower TS loads. Runoff volume may account for much of the TS loss even if the TS concentrations are low. Kleinman et al. (2006) measured higher TS concentrations but lower TS loads in runoff on a Berks soil compared with an adjacent Albright soil under the same management. The Berks soil had a steeper slope and was located on the sideslope whereas the Albrights soil had a gentler slope and was located on the footslope. The latter had poorer drainage which may have increased ponding and thus protected the soil from the impact of raindrops. It had lower TS concentrations but higher runoff volumes despite its gentler slope. Runoff on this soil was caused by rain that fell on an already saturated soil (saturation excess) whereas runoff on the Berks soil was caused by rainfall which exceeded the rate of infiltration (infiltration excess). The cause of runoff, whether by saturation excess or by infiltration excess, affects the volume of soil subject to the forces of detachment and transportation by altering the effective depth of interaction (EDI). This is the depth above which the rainfall or runoff water interacts with the soil to the same degree (Ahuja et al., 1981). The EDI is primarily determined by rainfall energy, soil slope, slope length, runoff rate (Ahuja et al., 1982), and also soil aggregation (Sharpley, 1985).

While a poorly drained soil may have higher runoff volumes, this may not necessarily cause higher TS loads. Wilson et al. (2003) found sediment loss actually decreased as runoff increased in a NT system. They suspected that high levels of residue cover produced a boundary layer effect which minimized water to soil contact, thus reducing sediment detachment at higher runoff rates. They also found that even the carryover effects of a history of residue contributed significantly to reducing the TS concentration in runoff. In other studies, residue cover in NT systems has been shown to reduce both runoff and sediment loss (Unger, 1994).

The effect of runoff on nutrient loss is complex. Nutrient loss depends on both physical forces as well as the specific chemical properties of the nutrient species and soil. Nutrient ions can adhere to clay colloids or organic matter (Brady and Weil, 2006) and may also form bonds with other elements in the soil. In both circumstances, the soluble form of a nutrient is precipitated out of solution which reduces the mobility of the nutrient except by erosion. For surface applied nutrients, this can prevent its movement into the soil profile which would protect it from runoff loss.

Up to 98% of TP found in runoff may be found in particulate form (PP) and can be significantly correlated to the TS concentration in runoff (Udeigwe et al., 2007). Other research has confirmed a strong positive linear relationship between TS and PP concentrations in runoff (R-squared of 0.68; Fraser et al., 1999) and has shown sediment to be a major carrier of P (Andraski et al., 1985). Therefore, PP losses are affected by many of the same factors and processes affecting TS loss such as rainfall intensity (Fraser et al., 1999) and the length of flow path (Sharpley and Kleinman, 2003).

The effect of tillage on total dissolved phosphorus (TDP) may be different than that of PP. Eghball and Gilley (1999) found TP loads were significantly lower in NT than on disked plots. They found disked plots to have increased PP loads but lower total dissolved phosphorus (TDP) loads than NT plots. PP loss is more susceptible to loss by erosion on tilled soils in the absence of residue cover whereas tillage can reduce the losses of other soluble species of P through the incorporation of surface applied amendments (Eghball and Gilley, 1999). Therefore, a system that reduces the loss of one form of P may lead to an increase in another form of P. This can produce seemingly contradictory results in regards to the effectiveness of tillage to reduce total P loads if not both dissolved and particulate constituents are reported.

In one study, Sharpley et al. (1992) found that as residue cover increases, TDP made up a greater portion of total P. Manure may be a dominant source of dissolved forms of P if not incorporated. In a study with no manure applied, Andraski et al. (1985) found no significant difference in dissolved P loads between NT and chisel tilled plots. However, in another study with applied manure, Mueller et al. (1984) found significantly greater TDP losses in NT than CD.

The species of N in runoff are dynamic. They are highly mobile and can change from one species to another very rapidly through both biotic and chemical reactions. In a tilled system, inorganic N fertilizer and N-contributing manures are incorporated whereas in a NT system, they are left on the surface and are therefore susceptible to runoff losses. Application of urea-based fertilizers and manures may be followed by a significant amount of ammonia (NH_3) volatilization which may affect N losses in runoff. Furthermore, any effect that NT has on increasing N concentrations in runoff may be negated by the effect that NT has on reducing runoff volume resulting in no significant difference in N loads. In a manured sorghum and wheat study, Eghball and Gilley (1999) found that NT had substantially higher NH_4^+-N concentrations and slightly higher NO_3^--N concentrations in runoff than disked treatments. However, only the NH_4^+-N loads were significantly higher in NT than in disked. This may not be of practical concern since the NH_4^+ is a smaller percentage of total dissolved N (TDN) whereas NO_3^- makes up a majority of TDN in runoff (Kleinman, 2006). Conversely, a non-manured study found NT to have significantly higher NO_3^- concentrations in runoff but significantly lower NO_3^- loads in

NT as compared to chisel plowed and no significant difference in NH_4^+ concentrations or loads (Seta et al., 1993).

The objective of this study was to determine the effect of NT and CD systems on water, sediment, and nutrient runoff at different times of the year on soils with different drainage properties.

Materials and Methods

Field Management

Two fields were selected in Centre County, Pennsylvania approximately 3 km from each other at the Russell E. Larson Agricultural Research and Education Center in Rock Springs, Central Pennsylvania (40.72° N 77.93° W). One field consisted of well-drained (WD) to excessively well-drained Hagerstown silt loam soil (Fine, mixed, semiactive, mesic Typic Hapludalfs) and had an average slope of 8%. The other field was a somewhat poorly drained (SPD) Buchanan gravely loam soil (Fine-loamy, mixed, semiactive, mesic Aquic Fragiudults) and had an average slope of 7%.

Each experiment was laid out in a randomized complete block design with 4 replicates (Fig. 5). Blocks (replications) were oriented parallel to the contour. Plots were 4.6 m wide by 9.1 m long. Tillage plots were maintained in the same location throughout this study.

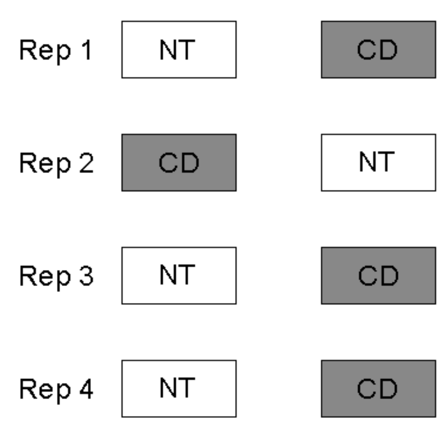

Fig. 5. Experimental design for the runoff study comparing the effects of no-till (NT) and chisel/disking (CD) on runoff.

In the fall of the first year, the fields were planted to a cereal rye (Secale c*ereale*, L., variety not stated) cover crop at a seeding rate of 126 kg ha^{-1}. The rye in the CD plots was dessicated with 0.84 kg ha^{-1} ae glyphosate (2.4 L ha^{-1} Roundup® Original) in the seedling stage so no cover crop was present in these plots in the spring. In the fall of the second year, cereal rye was only planted in the NT strips on both soils at the same seeding rate. Good weed control was achieved in both tillage systems using a combination of pre- and post-emergence herbicides.

Soil fertility samples were taken to a depth of 15 cm in fall or early spring of each year. The pH was 6.1 on the WD and 5.7 in the SPD soil prior to planting the first corn crop. On the SPD soil, the cover crop showed signs of nutrient deficiencies likely caused by low pH in the first year of the study. The recommended lime was applied early in 2007 at rates of 3,400 kg ha^{-1} and 5,600 kg ha^{-1} on the WD and SPD soils, respectively and additional lime was applied the following fall which corrected the pH to 6.4 and 6.3 on the WD and SPD soils, respectively.

Rye cover crop was dessicated with 0.84 kg ha^{-1} ae glyphosate (2.4 L ha^{-1} Roundup® Original) in early May when it reached boot stage (just prior to seed head emergence). Cover crop biomass samples were taken from NT plots in 0.5 m^2 rectangular frames, dried at 60°C for 48 hours and weighed.

After cover crop dessication in NT plots, manure was applied to all plots to meet approximately half of the N requirement of corn (total N-requirement was estimated at 168 kg N ha^{-1} assuming a maximum yield of 47 Mg ha^{-1} at 65% moisture). The N contribution from manure assumed 40% N availability based on incorporation within 24 hours after application (The Pennsylvania State University, 2007). A manure sample was taken at the time of application and sent to the Penn State Analytical Laboratory for nutrient analysis. Additional mineral fertilizer applications were adjusted according to manure phosphorus (P) and potassium (K) contributions.

Experimental protocol called for manure to be incorporated on the CD plots by chisel plowing followed by disking one day after application. In 2007 manure was incorporated according to plan, but in 2008, manure was not incorporated until 1 and 3 weeks after application on the WD and SPD soil, respectively, due to five days of rainfall amounting to 4.0 cm shortly after manure application. Significant rainfall (1.4 cm) over the span of 48 hours following manure application in 2008 is expected to have incorporated the manure thus reducing ammonia volatilization losses in both NT and CD treatments that year.

Corn (Dekalb variety DKC52-59) was planted in each field using a John Deere 1780 Max-Emerge® planter at a seeding rate of 74,000 seeds ha^{-1}. Nitrogen fertilizer was sidedressed at a rate of 56 kg ha^{-1} at approximately the V-6 stage to meet the remaining crop N need. Fertilizers were chosen that are known to have a low potential for ammonia volatilization. In the first year of this study, N fertilizer was surface-applied as ammonium nitrate. In the second year ammonium sulfate was used because no ammonium nitrate could be obtained. Corn was harvested for silage leaving approximately 23 cm of stalk in the field.

Rain Simulations

Immediately after planting prior to seedling emergence, a 2x2 m steel frame with a collection gutter was pounded into the ground to a depth of 5 cm approximately one corn row in from the downslope side of each plot. Silicon caulk was used to seal edges. Runoff was collected at the downslope end in 12-L PVC collapsible jug placed in collection pits.

Rainfall simulations were performed shortly after planting (PPL), at half canopy closure (HCC; 2007 only), at full canopy closure (FCC), and shortly after harvest (PHA) similar to the protocol developed by the National Phosphorus Research Project (2001). Plots were presoaked for 30 minutes at a rate of 6 cm hr^{-1} one day prior to each set of rainfall simulations. If runoff was generated, the rainfall was halted and continued after all ponding water had infiltrated to ensure that approximately 3 cm of rainfall had infiltrated to saturate the top soil in both the NT and CD plots.

Before each rain simulation, six soil moisture readings within each plot were also taken with a Thetaprobe (Delta-T Devices Ltd., Burwell, Cambridge, UK). The same number of readings was taken in the furrows as on the ridges in the tilled plots. Each rain simulation ran for exactly one hour at a rate of 6 cm hr^{-1} regardless of the amount of runoff. This rate and duration approximates a ten-year storm for this area. The time to runoff onset was recorded and the runoff volume was recorded in 5-minute intervals. At the end of each simulation, a 1-L composite sample of runoff was taken after thorough mixing and was immediately placed on ice in a cooler. At the end of each day of simulations, the samples were placed in a cool room at 4°C. A portion of each sample was filtered (0.45 µm) less than 24 hours after collection. Runoff was analyzed for TS, TP, TDP (unfiltered samples) and NO_3^-/NO_2^-(nitrite), NH_4^+, and TDN (filtered samples). Both nutrient concentrations (g L^{-1} or mg L^{-1}) and total loads (g m^{-3} or mg m^{-3}) were calculated.

Runoff Analysis

The composite runoff samples taken from each rain simulation event that produced runoff was filtered within 24 hours through a 0.45 micron membrane filter into two 50-mL centrifuge tubes, following the recommended best practices of Pierzynski (2000). Filtering the samples quickly prevented soluble forms of nutrients from re-adhering to suspended sediment or otherwise precipitating out of solution. One 50-mL filtered tube and the remaining unfiltered sample were immediately placed in a cool room at 4°C to await P determination. The second 50-mL filtered tube was immediately placed in a freezer at -12°C to await N determination.

To determine the TS concentration, a 200-mL subsample was collected from the remaining unfiltered sample, which was dried at 40°C, allowed to cool for 24 hours, and weighed. TS load was calculated by multiplying TS concentration by runoff volume.

The P concentration in runoff was fractionated PP and TDP components. The total dissolved phosphorus method required filtering the sample through a 0.45 micron membrane filter prior to digestion. For TP and TDP determination, organic and non-labile P was oxidized to inorganic P using an alkaline persulfate digestion (Patton and Kryskalla, 2003) on unfiltered and filtered samples, respectively. The final P concentrations were determined colorimetrically from a molybdenum-blue reaction using the method developed by Murphy and Riley (1962). PP concentrations were approximated by subtracting TDP from TP concentrations.

The N concentration in runoff was fractionated into four categories. All nitrogen analysis was performed on filtered samples thus omitting particulate N. Nitrogen concentrations were determined on a two-channel Lachat QuickChem 8000 Flow Injection Analyzer (Lachat Instruments, Loveland, Colorado). TDN was mineralized by in-line persulfate digestion using QuikChem method 10-107-04-3-B (Liao, 2003) and NH_4^+ and NO_3^-/NO_2^- was analyzed in accordance with QuikChem Method 10-107-06-2-A (Prokopy, 2003) and 10-107-04-1-A (Wendt, 2003), respectively. DON was approximated by subtracting NH_4^+ and NO_3^-/NO_2^- (which approximates inorganic N) from TDN.

Statistical Analysis

All statistical analysis was performed using SAS® 9.1 for Windows (SAS Institute Inc. Charlotte, NC). Runoff and TS loads were analyzed using all four dates of simulations in 2007. In June 2007, the rain water was contaminated with high levels of P and N. Therefore, the data from the June simulations from both years were excluded from the analysis of P and N species to maintain a balanced design. The SPD and WD fields were analyzed separately since there were no replications of soil drainage type. Proc Mixed with repeated measures was used to increase precision in determining the effect that tillage had on the response variables throughout the season. Concentrations averaged across multiple events were flow-weighted (FW) within each treatment group while omitting plots with zero runoff volume. Proc Mixed (without repeated measures) was used to determine the effect that tillage had on the response variables at each date of simulations. Average concentrations for each treatment group within a single event also omitted plots with zero runoff volume but were not weighted. All average loads (unweighted) included plots with zero runoff volume.

Results and Discussion

Runoff

In both years and on both soils, NT had significantly lower runoff volumes across all simulation events (Table A-4). Seta et al. (1993) reported similar results on a soil with a similar slope and long-term NT history. On average on the WD soil, 11% of the simulated rain ran off in NT, whereas in CD, 41% ran off. On the SPD soil, 20% of simulated rain ran off in NT, whereas in CD 25% ran off. Therefore, CD generated 3.9 times more runoff than NT on the WD soil and

1.3 times more runoff than NT on the SPD soil, averaged over all seven rainfall simulation events. Results suggest that NT may have less of an effect on reducing runoff from poorly-drained soils than from well-drained soils, however, a direct comparison is not possible due to lack of replicated soils with similar drainage properties.

The SPD Buchanan soil had a fragipan 60-75 cm deep (as indicated by the presence of mottles; Soil Survey Staff, 2005) which has been shown to inhibit water percolation (Needelman et al., 2004). Early in the season, such soils have a shallow water table and during the season saturated conditions often occur above the fragipan. This can result in runoff caused primarily by saturation excess in both tillage systems alike. However, no apparent link between antecedent soil moisture content (to a depth of < 4 cm) and runoff volume (Fig. 6) was observed, either by tillage treatment or across events. For most events, it is likely that runoff generation resulted from infiltration excess (6 cm hr^{-1} storm on soils with estimated conductivities of < 6 cm hr^{-1}) or, in the case of the events on the SPD soil immediately following planting, a result of soil moisture saturation below the 4-cm depth measured with the capacitance sensor. Nonetheless, the soil moisture content was significantly higher in NT than in CD prior to each simulation event which suggests that NT has higher moisture retention than CD.

The response of runoff to tillage differed much over the growing season (Fig. 6). Early in the season, runoff generation was often prevented or delayed on tilled plots due to high ridges created by the corn planter and steel borders on either side of the plot which caused water to pond. This resulted in higher runoff volumes in NT than in CD on the SPD soil (although only significant in 2008) where saturation excess likely caused the benefits of improved infiltration in NT to be unnoticeable.

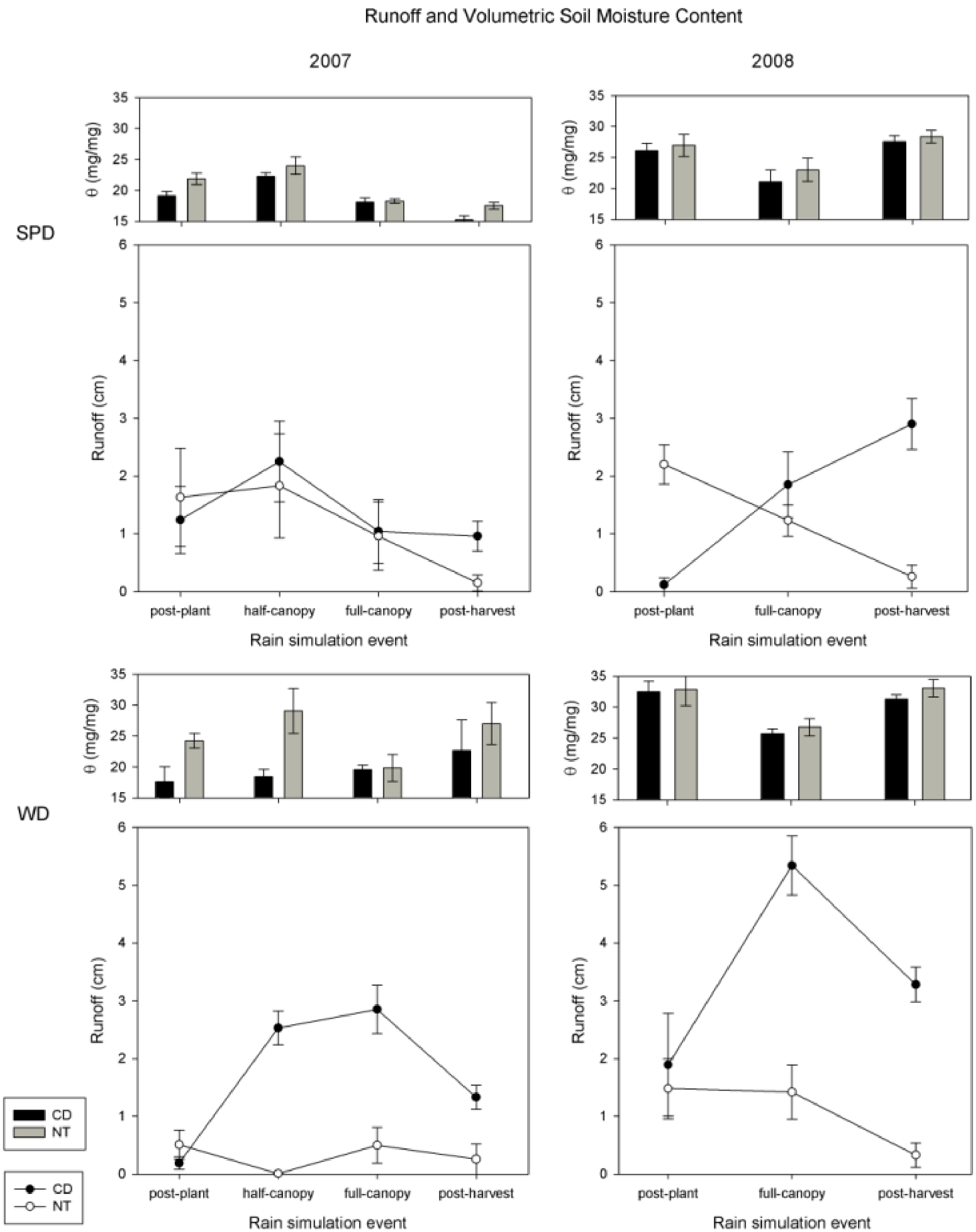

Fig. 6. Runoff volume and soil volumetric moisture content of no-till (NT) and chisel/disked (CD) treatments for rainfall simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly drained (SPD) soil.

Therefore, on a poorly-drained soil where saturation excess runoff predominates, CD is most beneficial in reducing runoff early in the season due to the presence of large ridges. However, later in the season, when tilled plots experience sealing and crusting and the ridges have leveled out, NT is more advantageous in reducing runoff. On a well-drained soil, where infiltration excess predominates, NT is generally more beneficial in reducing runoff throughout the season.

In each year and on each soil, NT had significantly longer time or higher accumulated rainfall until runoff onset (Table 7) except onset was not significant in 2007 on the WD soil. However, a significant difference was only observed at one individual event (2008, WD soil, FCC). The onset of runoff was highly correlated with total volume of runoff for all treatments. Therefore, NT may be even more advantageous in preventing runoff for similar events of shorter duration.

Table 7. Average accumulated rainfall to runoff onset of no-till (NT) and chisel/disked (CD) treatments for rainfall simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	Accumulated rainfall to runoff onset				
	Rain simulation event				
Tillage	PPL†	HCC	FCC	PHA	Average
	cm				
		2007 WD Soil			
CD	1.4	0.7	0.7	0.8	0.9
NT	1.5	1.0	1.2	0.4	1.0
		2007 SPD Soil			
CD	2.7	0.4	1.5	0.7	1.3*
NT	1.5	1.3	2.0	2.3	1.8
		2008 WD Soil			
CD	2.4	NA	0.4*	0.5	1.1*
NT	1.3	NA	1.4	2.0	1.5
		2008 SPD Soil			
CD	4.2	NA	1.9	0.5	1.8*
NT	1.3	NA	1.9	3.8	2.2

* Indicates tillage is significantly different (P≤0.05) within each year and soil
† PPL=post-plant; HCC=half canopy closure; FCC=full canopy closure; PHA=post-harvest

TS Loss

Only one NT plot per 4 replications on the WD soil produced runoff at both HCC and PHA. Due to the lack of replications TS and nutrient concentrations of NT and CD on the WD soil cannot be statistically compared for those events and only total loads were statistically analyzed. No-till had significantly lower TS loads than CD in both years and on both soils (Table 8) corresponding with previous studies (e.g. Seta et al., 1993; Angle et al., 1984; Choudhary et al., 1997). NT also had significantly lower TS concentrations than CD in both years and on both soils also corresponding to Seta et al. (1993) as well as Daverede et al. (2003). On average over all seven rainfall simulation events, CD generated 11.7 times more TS in runoff than NT on the WD soil, and 5.0 times more TS loss than NT on the SPD soil. In both years, differences in TS loads were not significant between NT and CD for the simulation event immediately after planting on either soil but differences developed in later events on the WD soil. TS loads were not significantly different between tillage treatments on the SPD soil except after harvest in 2008, when NT had lower TS loads than CD. Total solids concentrations were consistently lower in NT at all individual simulation events, although not always significantly due to high variability. They were similarly affected by tillage systems on both soil types.

Table 8. Average total solids (TS) concentrations and loads of no-till (NT) and chisel/disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	TS concentrations					TS loads				
	Rain simulation event					Rain simulation event				
Tillage	PPL†	HCC	FCC	PHA	FW Avg.	PPL	HCC	FCC	PHA	Average
	$g\ L^{-1}$					$g\ m^{-2}\ hr^{-1}$				
2007 WD Soil										
CD	0.95	0.92‡	0.36	0.63‡	0.70*	2.1	23.2*	9.9*	8.1*	10.8*
NT	0.51	0.22‡	0.14	0.08‡	0.35	3.5	0.0	0.7	0.2	1.1
2007 SPD Soil										
CD	1.14*	0.78*	0.47	0.60	0.74*	13.9	17.3	4.9	6.4	10.6*
NT	0.16	0.20	0.11	0.17	0.18	3.3	3.6	1.0	0.2	2.0
2008 WD Soil										
CD	1.23	NA	0.57*	0.90	0.90*	24.6	NA	28.2*	30.1*	27.7*
NT	0.36	NA	0.12	0.27	0.20	3.8	NA	1.6	1.0	2.1
2008 SPD Soil										
CD	0.71‡	NA	0.14*	0.76*	0.48*	0.8	NA	2.7	22.3*	8.6*
NT	0.21‡	NA	0.02	0.32	0.15	4.6	NA	0.3	0.6	1.9

* Indicates tillage is significantly different ($P \leq 0.05$) within each year and soil

† PPL=post-plant, HCC=half canopy closure, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted

‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.

Phosphorus Loss

In both years, NT had higher TP loads on the SPD soil but lower TP loads on the WD soil (Table A-5). On average, TP loss was 1.8 times greater in CD than in NT on the WD soil, but on the SPD soil TP loss was 1.4 times greater in NT than in CD. NT had significantly lower TP concentrations than CD in both years on both soils which indicates that runoff volume rather than TS concentrations controls TP losses on the SPD soil.

In NT, TDP made up approximately 73% of the TP in runoff whereas in CD, PP made up approximately 85% of TP in runoff with little difference between soils. Eghball and Gilley (1999) found similar results. This suggests that although NT may result in lower PP losses as compared to CD, in systems where manure is surface-applied, NT may result in higher TDP losses.

In both years and on both soils, NT consistently had higher TP loads than CD after planting (Fig. 7; only significantly in 2008 on the SPD soil) after recent manure application. In NT, the first rain simulation event after manure application produced 78% of the TP load summed across all events. By the end of the season, NT consistently had lower TP loads than CD (only significant in 2008 for both soils). On both soils, the runoff volumes in NT were highest at PPL when the TDP concentrations were also the highest whereas in CD the runoff volumes were highest at mid-season when the TDP concentrations were low. Therefore, the temporal interaction between periods of high runoff and periods of high source nutrient concentrations are critical factors that determine TP loss.

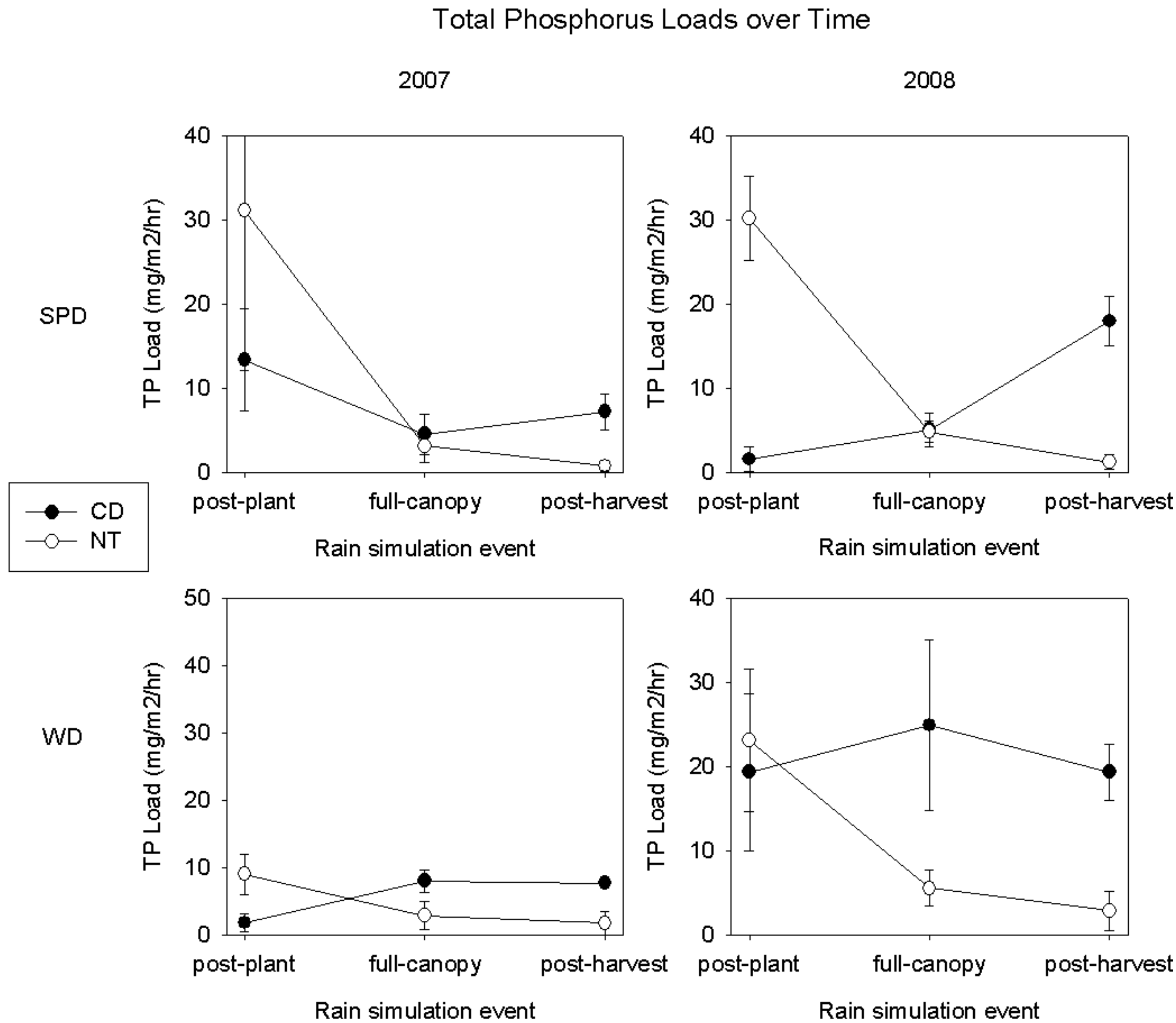

Fig. 7. Total phosphorus (TP) loads over time for no-till (NT) and chisel/disked (CD) in 2007 and 2008 on a somewhat poorly-drained (SPD) and a well-drained (WD) soil.

NT had lower PP loads and concentrations than CD in both years and on both soils (Table 9). The average PP load over all rainfall simulations was 4.8 times greater in CD than in NT on the WD soil, and 2.7 times greater in CD than in NT on the SPD soil. NT had lower PP loads at most events (although not always significant) except immediately after planting where NT had mixed results. The PP loads followed similar trends over time as TS loads and runoff volume. In

NT, the PP loads declined throughout the season. This resulted in greater differences between tillage treatments especially late in the season. The PP concentrations, however, appeared to be more influenced by the presence of the corn canopy. These were lowest at full canopy closure and rebounded after harvest. PP and TS concentrations were highly correlated for each tillage system on each soil. This corresponded with previous research (Udeigwe et al., 2007; Fraser et al., 1999). The Pearson's coefficient was especially high in CD on the SPD soil (Table 10).

Table 9. Average particulate phosphorus (PP) concentrations and loads of no-till (NT) and chisel/ disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	PP concentrations				PP loads			
	Rain simulation event				Rain simulation event			
Tillage	PPL†	FCC	PHA	FW Avg.	PPL	FCC	PHA	Average
	mg L^{-1}				mg m^{-2} hr^{-1}			
				2007 WD Soil				
CD	0.65	0.24	0.51‡	0.45*	1.56	6.76*	6.53*	4.95*
NT	0.71	0.05	0.15‡	0.35	3.77	0.20	0.40	1.45
				2007 SPD Soil				
CD	0.93	0.38*	0.61	0.64*	10.38	3.68	6.14	6.73*
NT	0.36	0.07	0.20	0.27	6.42	0.72	0.25	2.46
				2008 WD Soil				
CD	0.88*	0.42	0.50	0.60*	17.26	20.50	16.59*	18.12*
NT	0.50	0.08	0.35	0.31	7.36	1.06	1.68	3.37
				2008 SPD Soil				
CD	1.06	0.19	0.56*	0.51*	1.40*	3.78	16.24*	7.15*
NT	0.30	0.14	0.28	0.22	5.88	1.73	0.64	2.75

* Indicates tillage is significantly different ($P \leq 0.05$) within each year and soil

† PPL=post-plant, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted

‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.

Table 10. Correlations between total solids (TS) and particulate phosphorus (PP) concentrations for no-till (NT) and chisel/disked (CD) treatments in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	Correlations between TS and PP concentrations	
Tillage	WD Soil	SPD Soil
	—— Pearson correlation coefficient† ——	
CD	0.747	0.848
NT	0.731	0.621

† All P-values are ≤ 0.005

NT had 3.1 times greater TDP losses than CD, and on the SPD soil, NT had 6.9 times higher TDP load than CD. NT consistently had higher TDP loads (both years on both soils) but the differences were only significant in 2008 (both soils). Prior to this study, both soils had a manure-free history. By the second year of this study, a possible accumulated effect of two manure applications may have resulted in a decrease in the soils' P sorption capacity. Previously, Mueller et al. (1984) found that NT with manure had significantly higher dissolved P loads than NT without manure and CD with and without manure. Therefore, the history of surface-applied manure in NT may determine the effectiveness of NT to control P losses.

Significant differences in TDP loads were only observed during the rainfall simulations immediately after planting in 2008 on the SPD soil. NT had substantially higher loads (although not significantly) early in the season caused by the recent surface application of manure. TDP loss quantities and differences between NT and CD steadily declined throughout the season on both soils. In both years, NT had higher TDP concentrations on both soils (Table 11). Concentrations were higher in NT than in CD throughout the season (though not always significantly).

Table 11. Average total dissolved phosphorus (TDP) concentrations and loads of no-till (NT) and chisel/disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	TDP concentrations				TDP loads			
	Rain simulation event				Rain simulation event			
Tillage	PPL†	FCC	PHA	FW Avg.	PPL	FCC	PHA	Average
	mg L^{-1}				mg m^{-2} hr^{-1}			
				2007 WD Soil				
CD	0.11	0.05*	0.10‡	0.08*	0.24	1.26	1.13	0.87
NT	1.75	0.43	0.53‡	0.73	5.24	2.66	1.37	3.09
				2007 SPD Soil				
CD	0.25*	0.11	0.11	0.16*	2.96	0.83	1.08	1.62
NT	1.37	0.21	0.27	1.00	24.67	2.40	0.50	9.19
				2008 WD Soil				
CD	0.11*	0.09*	0.09	0.10*	2.09	4.43	2.77	3.10*
NT	0.93	0.29	0.29	0.67	15.76	4.49	1.20	7.15
				2008 SPD Soil				
CD	0.11	0.07*	0.06*	0.07*	0.14*	1.27	1.75	1.05*
NT	1.07	0.25	0.23	0.76	24.26	3.09	0.54	9.30

* Indicates tillage is significantly different (P≤0.05) within each year and soil
† PPL=post-plant, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted
‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.

Nitrogen Loss

In both years, NT had higher TDN concentrations regardless of soil drainage (highest early in the season; Table A-6). On the SPD soil, however, average TDN load was either not significantly different (2007) or higher (2008) in NT as compared to CD. In NT, the first rain simulation event after manure application produced 50% and 91% of TDN loads summed across all rain simulation events on the WD and SPD soils, respectively. After the first simulation event (shortly after manure application), the TDN loads and concentrations dropped substantially for NT (Fig. 8) and the loads generally continued to decline for the rest of the season despite side-dressing fertilizer after the HCC event.

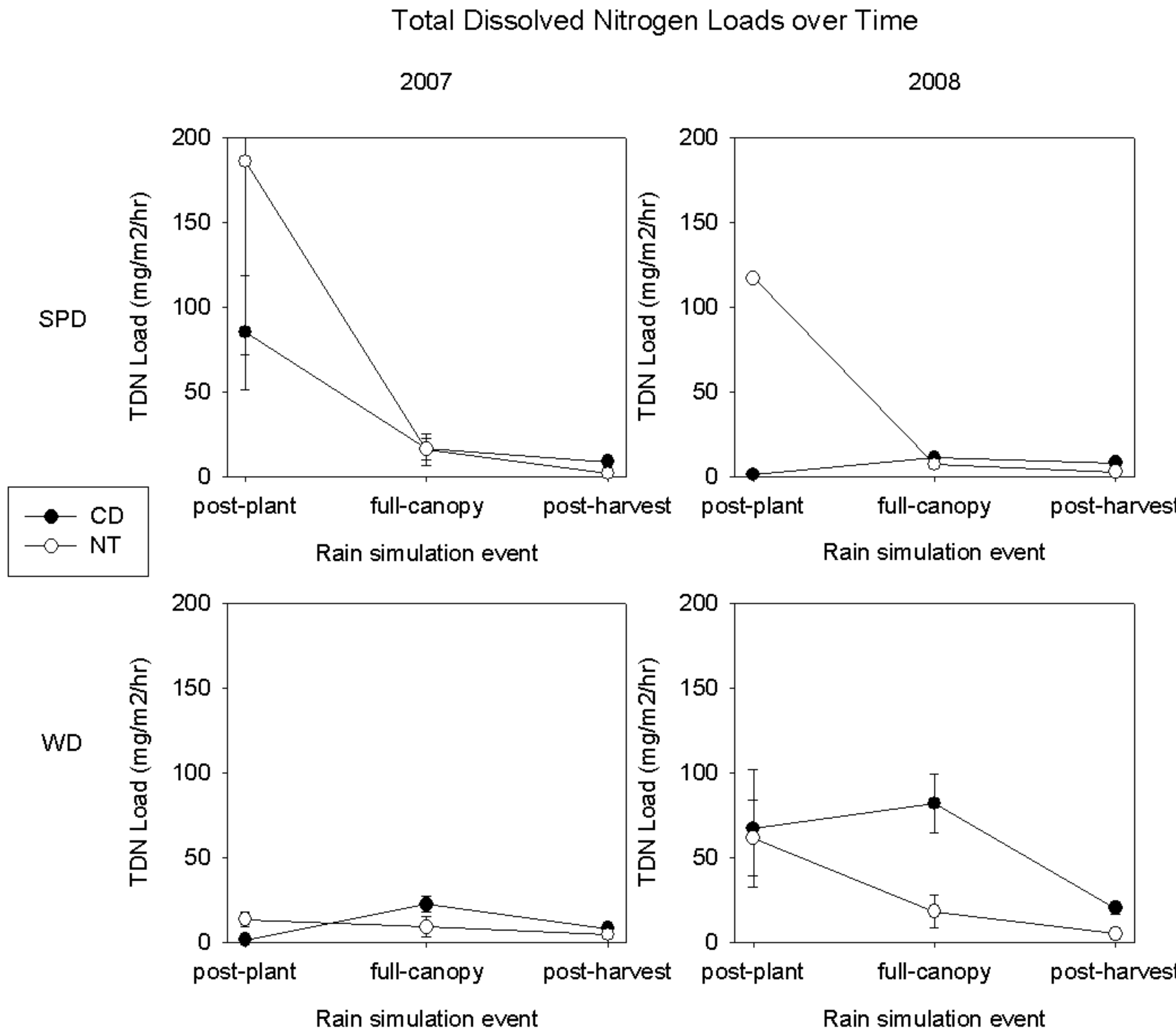

Fig. 8. Total dissolved nitrogen (TDN) loads over time for no-till (NT) and chisel/disked (CD) in 2007 and 2008 on a somewhat poorly-drained (SPD) and a well-drained (WD) soil.

In both years, NT had lower NH_4^+ loads on both soils (Table 12). On the WD soil, NT had higher NH_4^+ concentrations in 2007 but not in 2008. The latter was likely caused by unanticipated rainfall which fell within 24 hours of manure application thus incorporating the manure in the NT plots. This was evident from the rain simulation event at PPL in 2008 on the

WD soil which was the only PPL event in both years in which NT had significantly lower NH_4^+ loss.

On the SPD soil, NT had significantly lower NH_4^+ concentrations in both years. This contradicts the studies of Seta et al. (1993) who found no significant difference in NH_4^+ concentrations or loads between NT and chisel plowed in a non-manured study and Eghball and Gilley (1999) who found NT to have higher NH_4^+ concentrations and loads conducted on a soil with similar drainage properties but with substantially larger rain simulation plots. However, lower NH_4^+ loads in this present study, appear to be primarily a result of NT having lower runoff volumes as compared to CD.

Table 12. Average ammonium (NH_4^+) concentrations and loads of no-till (NT) and chisel/disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	NH_4^+ concentrations				NH_4^+ loads			
	Rain simulation event				Rain simulation event			
Tillage	PPL†	FCC	PHA	FW Avg.	PPL	FCC	PHA	Average
	mg L^{-1}				mg m^{-2} hr^{-1}			
			2007 WD Soil					
CD	0.18	0.14	0.08‡	0.13*	0.31	3.67	1.00	1.66*
NT	0.33	0.18	0.11‡	0.20	1.31	0.94	0.30	0.85
			2007 SPD Soil					
CD	0.49	1.02	0.12	0.54*	6.12	5.63	0.87	4.21*
NT	0.42	0.22	0.10	0.34	7.28	2.06	0.11	3.15
			2008 WD Soil					
CD	0.29*	0.31	0.11	0.23*	5.54	15.80*	3.48*	8.27*
NT	0.16	0.19	0.13	0.18	2.37	3.06	0.34	1.92
			2008 SPD Soil					
CD	0.21	0.20	0.09	0.16*	0.20*	2.82*	2.54*	1.85*
NT	0.18	0.07	0.11	0.14	3.97	0.88	0.25	1.70

* Indicates tillage is significantly different (P≤0.05) within each year and soil
† PPL=post-plant, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted
‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.

In both years, NT had higher NO_3^-/NO_2^- concentrations than CD on both soils, however, the loads varied by year and soil (Table 13). In NT, 62% and 94% of NO_3^-/NO_2^- loads (summed across all rain simulation events) were produced during the first simulation event (PPL) after manure application on the WD and SPD soils, respectively. Therefore, the average NO_3^-/NO_2^- loads for the season were strongly influenced by the high loads at PPL especially on the poorly-drained soil. The loads and the concentrations both declined for each successive rain simulation event.

Table 13. Average nitrate (NO_3^-) concentrations and loads of no-till (NT) and chisel/disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	NO_3^- concentrations				NO_3^- loads			
	Rain simulation event				Rain simulation event			
Tillage	PPL†	FCC	PHA	FW Avg.	PPL	FCC	PHA	Average
	mg L^{-1}				mg m^{-2} hr^{-1}			
2007 WD Soil								
CD	0.12	0.24	0.19‡	0.19*	0.25	7.09	2.52	3.29*
NT	1.59	0.96	0.68‡	0.95	5.70	4.57	1.77	4.01
2007 SPD Soil								
CD	4.36*	1.78	0.37	2.17*	65.71	7.29	3.07	25.35
NT	8.94	0.92	0.57	5.71	146.61	9.52	0.88	52.34
2008 WD Soil								
CD	1.73	0.38	0.25	0.79*	46.41	19.92*	8.22	24.85
NT	2.45	0.60	0.95	1.58	38.75	8.8	3.55	17.03
2008 SPD Soil								
CD	1.05	0.22	0.22*	0.38*	0.37*	3.20	6.05*	3.20*
NT	3.63	0.21	0.76	2.27	79.44	2.57	1.82	27.94

* Indicates tillage is significantly different ($P \leq 0.05$) within each year and soil
† PPL=post-plant, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted
‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.

In both years, NT had higher DON concentrations on both soils and higher loads only consistently on the SPD soil (Table 14). The higher DON concentrations are a result of organic matter contributions from unincorporated manure in NT plots although the DON loads appear to be more influenced by runoff volume and soil drainage properties than by tillage.

On the WD soil, DON accounted for 43% and 36% of TDN in CD and NT, respectively. On the SPD soil, DON accounted for 21% and 23% of TDN in CD and NT, respectively. Therefore, DON represents a substantial amount of N exported from agricultural lands and requires further research.

Table 14. Average dissolved organic nitrogen (DON) concentrations and loads of no-till (NT) and chisel/disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	DON concentrations				DON loads			
	Rain simulation event				Rain simulation event			
Tillage	PPL†	FCC	PHA	FW Avg.	PPL	FCC	PHA	Average
	mg L^{-1}				mg m^{-2} hr^{-1}			
				2007 WD Soil				
CD	0.45	0.40*	0.36‡	0.39*	0.85	11.60	4.53	5.66*
NT	1.76	0.65	0.94‡	0.98	6.46	3.53	2.43	4.14
				2007 SPD Soil				
CD	1.16	0.31	0.42	0.63*	13.19	3.26	4.61	7.02*
NT	2.28	0.46	0.60	1.35	31.97	4.31	0.71	12.33
				2008 WD Soil				
CD	0.81*	0.81	0.26	0.62*	15.28*	46.09	8.39	23.26
NT	1.40	0.33	0.33	0.87	20.32	6.64	1.07	9.34
				2008 SPD Soil				
CD	0.59	0.30	0.01*	0.24*	0.52*	4.81	0.27	1.87*
NT	1.52	0.28	0.30	1.02	33.41	3.65	0.65	12.57

* Indicates tillage is significantly different ($P \leq 0.05$) within each year and soil
† PPL=post-plant, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted
‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.

Conclusions

Chisel/disked had 3.9 times more runoff than NT on the well-drained soil and 1.3 times more runoff on the poorly-drained soil averaged across all rain simulation events. This lower runoff volume in NT as compared to CD may be expected to reduce the loss of sediment and nutrients. However, most of the dissolved nutrient loss in NT occurred immediately following the surface application of manure in the spring. At that time, NT often had higher runoff volumes. Therefore, lower overall runoff volume in NT as compared to CD may have little affect on overall nutrient loss when considering a high temporal variability in the source nutrient concentrations.

CD had 11.7 times greater TS loss than NT on the well-drained soil and 5.0 times greater TS loss on the poorly-drained soil averaged across all simulation events. NT consistently had lower average TS concentrations than CD on both soils. Therefore, NT may greatly reduce soil loss from agricultural lands as compared to CD.

No-till had lower TP loss than CD on the well-drained soil but higher TP loss on the poorly-drained soil. In NT, 73% of TP lost in runoff was in dissolved form (TDP) and 81% of TDP originated from the first simulation event of each season. In CD, 85% of TP lost was in particulate or sediment-bound form (PP) and PP losses were more evenly distributed throughout the season. NT consistently had lower PP losses than CD which was highly correlated with TS losses. NT had substantially higher TDP losses than CD early in the season (although not always significantly) due to the recent surface-applied manure application. However, TDP losses declined rapidly after the first major rain event and were close to the levels of the CD treatment for the remainder of the season. In addition, future research needs to include particulate organic nitrogen which may be an important source of N-loss to surface water in agricultural systems.

NT had lower TDN losses than CD on the well-drained soil but higher or no difference in TDN losses on the poorly-drained soil. NT consistently had higher average TDN concentrations which suggests that lower TDN losses in NT were primarily caused by lower runoff volumes. NT had lower NH_4^+ losses than CD on both well-drained and poorly-drained soils which may have been a result of increased volatilization. NT had higher DON losses on the poorly-drained soil likely due to low infiltration prior to runoff onset. Tillage had an inconsistent effect on NO_3^-/ NO_2^- loads in both years and on both soils. Additional research is recommended to compare sediment-bound N loss in runoff from NT and CD systems on soils with different drainage properties after considering the different results obtained for particulate versus dissolved species of phosphorus.

This study suggests that in manured systems, NT with residue may provide a significant reduction in erosion as compared to CD regardless of soil drainage properties. No-till may also significantly reduce dissolved N and total P runoff losses on WD sites. However, NT may have higher dissolved N and total P losses than CD on poorly-drained sites.

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APPENDIX A: SUPPLEMENTAL DATA

Table A-1. Fertility test levels for the well-drained (WD) Hagerstown silt loam soil and the somewhat poorly drained (SPD) Buchanan gravely loam soil in 2007 and 2008.

	Hagerstown (WD Soil)		Buchanan (SPD Soil)	
Soil Properties	2007	2008	2007	2008
pH	6.1	6.4	5.7	6.3
Mehlich 3 P, ppm	46	33	43	34
K, ppm	139	73	90	90
Ca, meq/100 g	1103	874	1443	1084
organic matter, %	2.6	NA	3.2	NA

Table A-2. Properties of manure applied to the well-drained (WD) and somewhat poorly drained (SPD) soils in 2007 and 2008.

	WD Soil		SPD Soil	
Manure Properties	2007	2008	2007	2008
solids, %	6.4	14.1	5.1	14.1
total nitrogen, g L^{-1}	3.5	3.6	2.5	3.6
total P_2O_5, g L^{-1}	1.1	1.4	0.5	1.4
total K_2O, g L^{-1}	3.1	2.6	1.7	2.6
rate applied, m^3 ha^{-1}	50.1	67.0	33.9	57.4

Table A-3. Average volumetric soil moisture content of no-till (NT) and chisel/disked (CD) treatments one day after presoaking with 3 cm of rainfall performed in 2007 and 2008 on a well-drained (WD) and somewhat poorly-drained (SPD) soil.

	Volumetric Moisture Content				
	Rain simulation event				
Tillage	PPL†	HCC	FCC	PHA	Average
	m3/m3				
		2007 WD Soil			
CD	17.6	18.4	19.6	22.7	19.7*
NT	24.3	29.1	19.8	27.0	23.9
		2007 SPD Soil			
CD	19.1	22.3	18.1	15.3*	17.5*
NT	21.9	24.0	18.3	17.6	19.2
		2008 WD Soil			
CD	32.5	NA	25.7	31.3	29.8*
NT	32.9	NA	26.8	33.1	30.9
		2008 SPD Soil			
CD	26.1	NA	21.1	27.6	24.9*
NT	27.0	NA	23.0	28.4	26.1

* Indicates tillage is significantly different (P≤0.05) within each year and soil

† PPL=post-plant, FCC=full canopy closure, HCC=half canopy closure PHA=post-harvest

Table A-4. Average runoff volume of no-till (NT) and chisel/disked (CD) treatments for rainfall simulations performed in 2007 and 2008 on a well-drained (WD) and somewhat poorly-drained (SPD) soil.

	Runoff volume				
	Rain simulation event				
Tillage	PPL†	HCC	FCC	PHA	Average
	cm				
			2007 WD Soil		
CD	0.2 (3/4)‡	2.5* (4/4)	2.9* (4/4)	1.3* (4/4)	1.7* (15/16)
NT	0.5 (3/4)	0.0 (1/4)	0.5 (3/4)	0.3 (1/4)	0.3 (8/16)
			2007 SPD Soil		
CD	1.2 (4/4)	2.3 (4/4)	1.0 (4/4)	1.0 (4/4)	1.4* (16/16)
NT	1.6 (3/4)	1.8 (3/4)	1.0 (3/4)	0.2 (2/4)	1.1 (11/16)
			2008 WD Soil		
CD	1.9 (4/4)	NA	5.3* (4/4)	3.3* (4/4)	3.5* (12/12)
NT	1.5 (4/4)	NA	1.4 (4/4)	0.3 (3/4)	1.1 (11/12)
			2008 SPD Soil		
CD	0.1* (2/4)	NA	1.9 (4/4)	2.9* (4/4)	1.6* (10/12)
NT	2.2 (4/4)	NA	1.2 (4/4)	0.3 (3/4)	1.2 (11/12)

* Indicates tillage is significantly different (P≤0.05) within each year and soil

† PPL=post-plant; HCC=half canopy closure; FCC=full canopy closure; PHA=post-harvest

‡ Fraction in parentheses is the proportion of plots that produced runoff

Table A-5. Average total phosphorus (TP) concentrations and loads of no-till (NT) and chisel/disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	TP concentrations				TP loads			
	Rain simulation event				Rain simulation event			
Tillage	PPL†	FCC	PHA	FW Avg.	PPL	FCC	PHA	Average
	mg L^{-1}				mg m^{-2} hr^{-1}			
				2007 WD Soil				
CD	0.76	0.29	0.61‡	0.53*	1.80	8.01	7.66	5.82*
NT	2.46	0.49	0.68‡	1.07	9.01	2.86	1.77	4.54
				2007 SPD Soil				
CD	1.18	0.50	0.71	0.80*	13.34	4.51	7.21	8.35*
NT	1.73	0.28	0.47	1.27	31.08	3.12	0.75	11.65
				2008 WD Soil				
CD	0.99	0.50	0.58	0.69*	19.36	24.93	19.36*	21.22*
NT	1.43	0.37	0.64	0.98	23.11	5.55	2.88	10.51
				2008 SPD Soil				
CD	1.17	0.25	0.62	0.58*	1.53*	5.06	17.98*	8.19*
NT	1.37	0.38	0.51	0.98	30.15	4.82	1.18	12.05

* Indicates tillage is significantly different ($P \leq 0.05$) within each year and soil

† PPL=post-plant, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted

‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.

Table A-6. Average total dissolved nitrogen (TDN) concentrations and loads of no-till (NT) and chisel/disked (CD) treatments from rain simulations performed in 2007 and 2008 on a well-drained (WD) and a somewhat poorly-drained (SPD) soil.

	TDN concentrations				TDN loads			
	Rain simulation event				Rain simulation event			
Tillage	PPL†	FCC	PHA	FW Avg.	PPL	FCC	PHA	Average
	mg L^{-1}				mg m^{-2} hr^{-1}			
			2007 WD Soil					
CD	0.74	0.77	0.62‡	0.71*	1.41	22.36	8.06	10.61*
NT	3.69	1.78	1.74‡	2.13	13.47	9.04	4.49	9.00
			2007 SPD Soil					
CD	6.01*	3.08	0.91	3.33*	85.02	16.18	8.55	36.58
NT	11.63	1.60	1.27	7.40	185.85	15.89	1.71	67.82
			2008 WD Soil					
CD	2.83	1.50	0.62	1.65*	67.24	81.81*	20.09	56.38*
NT	4.01	1.09	1.40	2.62	61.44	18.08	4.96	28.16
			2008 SPD Soil					
CD	1.84	0.72	0.28*	0.77*	1.09*	10.83	7.84*	6.59*
NT	5.33	0.56	1.18	3.43	116.82	7.10	2.72	42.21

* Indicates tillage is significantly different ($P \leq 0.05$) within each year and soil

† PPL=post-plant, FCC=full canopy closure, PHA=post-harvest; FW=flow-weighted

‡ Indicates statistics could not be performed due to insufficient number of plots that produced runoff.