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Erosion and Nutrient Losses From Zero Tillage on a Clay Soil

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Conventional tillage (CT) and zero tillage (ZT) farming systems were compared in terms of losses of sediment, nitrogen (N) and phosphorus (P) in surface runoff from watersheds with heavy clay soils in central Texas, U.S.A. CT included several sequential tillage operations that resulted in burial of most of the plant residue from the previous crop. ZT involved no primary or secondary tillage, and crops were planted through the residue from the previous crop. ZT had no effect on runoff amounts but reduced the loss of sediment, N, and P relative to CT. Similar results were obtained for each of the three crops used in the study. The EPIC (Erosion-Productivity Impact Calculator) model successfully simulated the effect of tillage on runoff, sediment, and nutrient loss with the exception of soluble N and P.

1. Introduction

The effects of agricultural practices on water quality is a major concern in many parts of the world. The primary pollutants of concern are sediment, fertilizers, pesticides, and animal waste. Several reports written in the early 1970s addressed the need for research to define mechanisms of non-point source pollutant loss, and to devise soil and crop management practices to minimize such loss (Stanford *et al.*,[1] Water Resources Committee[2]). A number of studies soon followed with the object of quantifying sediment and chemical movement from various agricultural systems into surface and/or subsurface waters draining from associated land areas (e.g. Schuman *et al.*,[3,4] Jackson *et al.*,[5] Burwell *et al.*,[6] Kissel *et al.*,[7,8] Chichester,[9] Chichester *et al.*[10]). Intensity of soil tillage was recognized as a factor controlling the amount of runoff and soil erosion which occurred on cropland. The amount of runoff and soil loss, in turn, directly affected soluble and adsorbed chemical transport, particularly plant nutrients from fertilizer application.

A number of recent studies have evaluated tillage practices as components of farming systems. These practices are being developed to conserve the soil resources and reduce non-point source pollution of water supplies. Studies involved both natural and simulated rainfall (Römkens *et al.*,[11] Angle *et al.*,[12] Wendt and Burwell,[13] Pesant *et al.*,[14] Berg *et al.*[15]).

Most of the research has involved loam-textured soils because of their extensive occurrence in agricultural areas. However, clay-textured soils are agriculturally important in many parts of the world and present unique management problems related to soil and water conservation. Relatively little research has been conducted to measure the impact of conservation practices used on these slowly permeable and highly erosive clay soils on water quality. The object of this study, therefore, was to compare the losses of sediment and fertilizers in surface runoff from clay soils farmed with conventional tillage practices with that from clay soils farmed with zero tillage practices. The studies were conducted on heavy clay soils in central Texas, USA.

2. Materials and Methods

The study was conducted in the Blackland Prairie of Texas, USA. The Blackland Prairie is a 4·7 Mha highly productive, rain-fed agricultural region in central Texas. The climate of the area is sub-humid with mild winters and hot summers. Mean monthly temperatures range from 9°C in January to 29°C in August. Mean annual rainfall is about 880 mm. On average, the wettest month is May (116 mm), and the driest month is July (47 mm).

Six small watersheds on the watershed facility of the Grassland, Soil and Water Research Laboratory near Riesel, Texas, were used for the study. The watershed

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sizes ranged from 4·0 to 8·4 ha, and the slopes ranged from 1 to 3%. The soil is Houston Black clay, a fine montmorillonitic clay in the thermic family of Udic Pellusterts that is about 60% clay. The soil can absorb water rapidly when dry, but swells when wet and becomes slowly permeable. The soil is moderate to low in N and P and high in K (Godfrey[16]) and requires N and P fertilizer for crop production.

Wheat (*Triticum aestivum* L.), grain sorghum (*Sorghum bicolor* L.) and corn (*Zea mays* L.) were grown in rotation on the watersheds during a 5-yr study (1985–1989). A conventional (CT) system was used on three watersheds, and a zero tillage (ZT) system was used on the other three watersheds. The crops were assigned to watersheds such that each crop was grown on both a CT and a ZT watershed in a given year. The cropping sequence permitted a "pairing" of CT and ZT watersheds with the same crop in a given year. Replication was not practical since only six watersheds were available for the study. The CT and ZT systems could not be assigned randomly to watersheds each year because of the need to maintain the residual effect of ZT from year to year. No two watersheds are hydrologically identical. The "paired" watershed approach is subject to inherent differences in runoff characteristics, crop production, and other factors, but offers the best method of making direct experimental comparisons of the effects of treatments. Direct comparison of surface runoff, sediment loss (erosion) and nutrient loss (N and P) from CT and ZT systems were possible each year.

The CT system was the traditional tillage system used in the area that included several sequential tillage operations resulting in an almost complete burial of plant residues from the previous crop. It usually included chopping the standing crop residue after harvest followed by chisel tillage, heavy discing, light discing, harrowing, and field cultivation. The CT system caused considerable soil disturbance and involved numerous passes.

The ZT system, in contrast, involved no soil tillage, either primary or secondary. Crop residues were left standing or lying on the soil surface to provide erosion protection during the year. Crops were planted through the residue layer, and weed control was accomplished by the use of herbicides. Machine wheel travel was restricted, as much as possible, to fixed traffic lanes on 2 m centres in order to minimize soil compaction in the cropped areas between the wheel traffic lanes.

Planting dates and fertilizer application methods and rates were the same for both CT and ZT. Corn and sorghum were planted in rows spaced 0·68 m apart in March and April, respectively, and both crops were harvested in August. Wheat was planted in rows spaced 0·15 m apart in October or November and harvested the following June. Fertilizer was applied to each crop in solution on the surface with 11 kg ha^{-1} of N and 17 kg ha^{-1} of P applied at planting and approximately 130 kg ha^{-1} of N and 14 kg ha^{-1} of P applied about 30 d after planting corn and sorghum and 90 d after planting wheat.

Each watershed was equipped with a calibrated weir and a water-stage recorder. Runoff volume for each event was determined by numerically integrating the water-stage record over time for the event. Samples of the runoff water and suspended sediment were taken during each event using a Chickasha-type automatic pumping sampler (Miller *et al.*[17]). Samples were pumped from the stream and stored in 400 ml bottles at specified time intervals. The samples were refrigerated at the collection point and then transported to a refrigerated storage area and kept at 4°C until processed.

Samples were analysed in the laboratory for sediment concentration and soluble and sediment-adsorbed N and P. Sediment concentration data were runoff-weighted to determine total sediment loss for each event. Chemical analysis data were used to compute runoff-weighted mean concentrations for each runoff event. The mean concentration data were then combined with the runoff and sediment data to calculate total loss of N and P (both soluble and sediment-adsorbed) for each event.

Paired *t*-tests were used to assess tillage effects on annual runoff, sediment, and nutrient loss from each pair of watersheds and the effect of each crop within each tillage system on an individual storm basis.

The study data were used to evaluate the potential of the Erosion-Productivity Impact Calculator (EPIC) model (Williams *et al.*[18]) for simulating the effects of ZT on the losses of runoff, sediment, N, and P. EPIC performs all calculations on a daily basis using readily available inputs and simulates processes including hydrology, weather, plant nutrient movement, crop growth, soil temperature, and other factors. Soil, crop, tillage, weather, and other data were input to EPIC and daily simulated values of runoff, sediment, and N and P lost in runoff were obtained. Simulations were made for each of the six watersheds for each of the 5-yrs of the study.

3. Results

3.1 *Crop yields*

In most cases, crop yields were substantially reduced with ZT relative to CT (Table 1). Most of the

Table 1
Tillage system and crop yield (kg ha^{-1}) for each watershed

	1985		*1986*		*1987*		*1988*		*1989*	
Watershed	*Crop*	*Yield*	*Crop*	*Yield*	*Crop*	*Yield*	*Crop*	*Yield*	*Crop*	*Yield*
W-13 (CT)	Sorghum	6334	Corn	6121	Sorghum	5826	Wheat	3322	Corn	6308
Y-6 (ZT)	Sorghum	5103	Corn	2893	Sorghum	2483	Wheat	2022	Corn	3713
W-12 (CT)	Corn	4794	Sorghum	4717	Wheat	1735	Corn	7288	Sorghum	5643
Y-8 (ZT)	Corn	4758	Sorghum	2748	Wheat	1363	Corn	5187	Sorghum	1532
Y-13 (CT)	Sorghum	6455	Wheat	2670	Corn	4397	Sorghum	6418	Wheat	190†
Y-10 (ZT)	Sorghum	4427	Wheat	2250	Corn	4014	Sorghum	2632	Wheat	0†

† Wheat yield severely limited due to low temperature damage.

reduction was due to weeds on the ZT watersheds that were not adequately controlled with herbicides, although the swelling nature of the soil may have played a part. The primary purpose of this paper, however, is to address the runoff, sediment, and nutrient movement characteristics of the ZT system rather than the crop production results.

3.2 *Runoff*

Runoff amounts for individual events varied greatly between CT and ZT systems depending on size of event, time of year, rainfall spatial variability, crop growth stage, and many other factors. In general, annual runoff from ZT watersheds slightly exceeded that from CT watersheds, although the differences were not significant for any watershed pair. This result is consistent with the findings of Lal *et al.*,[19] and Jones *et al.*[20] The mean annual runoff for each tillage system averaged across all years and all crops is given in Table 2. Runoff on the Houston Black clay soil tends to be almost zero when the soil is dry prior to a rainfall event but large when the soil is wet, regardless of the crop or tillage system. These data obtained over the 5-yr study tend to suggest that the ZT system, in which large amounts of crop residue are maintained on the soil surface and the soil surface layer is not disturbed by tillage, may cause a small increase in runoff relative to the traditional CT system.

Table 2
Mean annual losses of runoff, sediment, N, and P from CT and ZT watersheds

	CT	*ZT*
Runoff, mm	143	152
Sediment, kg ha^{-1}	1864	70†
Soluble N, kg ha^{-1}	6·6	3·1†
Absorbed N, kg ha^{-1}	2·5	0·3†
Soluble P, kg ha^{-1}	0·8	0·6
Absorbed P, kg ha^{-1}	0·9	0·1†

† Means of ZT and CT are significantly different at 5% level based on paired *t*-test of annual totals.

3.3 *Sediment*

Sediment loss from the ZT watersheds was consistently much less than from the CT watersheds for all watershed pairs. Mean annual sediment loss from all ZT and CT watersheds was 70 kg ha^{-1} and 1864 kg ha^{-1}, respectively (Table 2). The crop residue on the surface of the ZT watersheds was apparently highly effective in controlling the loss of sediment from runoff events.

3.4 *Nitrogen*

The loss of soluble N varied greatly depending on the timing of runoff events relative to N application, size of runoff events, and other factors. The annual loss of soluble N varied from 36·6 kg ha^{-1} for CT watershed Y-13 during 1986 to zero for three of the six watersheds (both CT and ZT) during 1988, a year with very little runoff. The loss of soluble N was dependent on runoff amount, but was also affected by tillage system. The mean annual loss of soluble N was reduced about 50% with ZT relative to CT (Table 2).

The loss of N transported with the sediment (absorbed N) was strongly dependent on tillage system. The mean annual loss of absorbed N for CT was 2·5 kg ha^{-1} compared with 0·3 kg ha^{-1} for ZT. Since absorbed N was calculated from N concentration and sediment loss, the loss of absorbed N was directly related to the loss of sediment for each tillage system.

Table 3
Mean annual runoff, sediment, N, and P lost from CT and ZT watersheds by crop

	Corn		*Wheat*		*Sorghum*	
	CT	*ZT*	*CT*	*ZT*	*CT*	*ZT*
Runoff, mm	133	143	156	158	142	156
Sediment, kg ha^{-1}	2868	269†	779	50†	1752	224†
Soluble N, kg ha^{-1}	5·5	2·6	13·3	4·4†	3·1	2·8
Absorbed N, kg ha^{-1}	3·0	0·4†	1·4	t†§	2·7	0·5
Soluble P, kg ha^{-1}	0·3	0·5	1·5	0·5	0·6	0·8
Absorbed P, kg ha^{-1}	1·4	0·1†	0·5	t§	0·8	0·1

† Means of ZT and CT are significantly different at 5% level based on paired t-test of storm event totals.
§ t denotes trace amount.

3.5 *Phosphorus*

The loss of soluble P, like that of soluble N, was closely related to the amounts of runoff and timing of events relative to P application. Only small quantities of soluble P were lost, and there was no detectable effect of tillage system. Loss of absorbed P was small but closely associated with sediment loss and significantly less from ZT than from CT (Table 2).

3.6 *Crop effects*

Mean annual losses of runoff, sediment, and nutrients for each of the three crops are given by tillage system in Table 3. The results are similar to the above results obtained by averaging across all crops within a tillage system. Runoff amounts were not significantly different between CT and ZT for any of the three crops, but sediment loss was significantly reduced with ZT relative to CT for each crop. Absorbed N and P were both reduced with ZT for each crop (significantly for corn and wheat), apparently due to the reduction of sediment with ZT. Soluble N and P were both essentially equal for CT and ZT for both corn and sorghum, but were both less with the ZT system under wheat. Most of the runoff occurred in the spring when there were large amounts of standing biomass on the wheat watersheds (both ZT and CT).

3.7 *EPIC simulations*

The results of the EPIC simulations are given in Table 4. The mean annual simulated values, in general, compare well with the actual data. Simulated data indicate slightly greater runoff from ZT than for CT and much less sediment, absorbed N and absorbed P from ZT, all consistent with the results from the actual data. However, the simulated soluble N and P for ZT relative to CT are inconsistent with the actual data. Overall, the simulation results show that EPIC can be used successfully to simulate the effects of converting from CT to ZT in terms of runoff volumes, sediment and absorbed N and P.

Table 4
Mean annual losses of runoff, sediment, N, and P simulated with EPIC compared with measured data

	CT		*ZT*	
	Simulated	*Measured*	*Simulated*	*Measured*
Runoff, mm	135	143	151	152
Sediment, kg ha^{-1}	1607	1864	123	70
Soluble N, kg ha^{-1}	5·8	6·6	5·7	3·1
Absorbed N, ka ha^{-1}	3·0	2·5	0·3	0·3
Soluble P, kg ha^{-1}	1·9	0·8	2·5	0·6
Absorbed P, kg ha^{-1}	0·5	0·9	t†	0·1

† t denotes trace amount

4. Conclusions

The 5 yr of this study is too short a time to give an accurate estimate of mean annual runoff, sediment, and nutrient loss as affected by tillage system because of annual variations in weather. The paired watershed approach, however, enables conclusions to be made regarding the relative differences between CT and ZT systems for clay soils.

Converting from CT to ZT resulted in no significant change in mean annual runoff from the Houston Black clay soil. Sediment loss, on the other hand, was greatly reduced with ZT relative to CT.

The loss of N in solution was reduced with ZT but P losses in solution remained unchanged. Nitrogen and P that moved absorbed on sediment, did so in proportion to the amount of sediment lost and, therefore, were significantly less with ZT than with CT.

Runoff, sediment, and nutrient losses for the three-crop rotation were consistent for each crop except for the loss of soluble N and P from wheat. Soluble N and P losses from wheat were less from ZT than from CT.

Nitrogen lost in runoff (both soluble and absorbed) from the CT system was about 6% of that applied as fertilizer. With ZT, the loss was reduced to 2%. Phosphorus loss was 5 and 2% for CT and ZT, respectively. With either system, the economic loss in terms of fertilizer costs was not large. From an environmental standpoint, both tillage systems appeared to perform well with only minor annual losses of N, P, and sediment but the cumulative losses could have significant downstream implications over long time periods. Use of ZT should help reduce the loss of sediment and nutrients and alleviate possible long-term negative effects on downstream water resources.

EPIC was successfully used to simulate the effects of CT and ZT on runoff and the loss of sediment and nutrients with the exception of soluble N and P. A physically based simulation model such as EPIC can be a valuable tool for evaluating the environmental consequences of tillage systems. The modeling approach, when combined with sound experimental data, enable long-term effects of tillage systems to be quantified by simulation of the processes using long-term weather records.

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