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Short communication

# Vertical tillage impacts on water quality derived from rainfall simulations

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ABSTRACT

Increasing soluble phosphorus (SP) loads to Lake Erie occurring around the same time as the implementation of no-tillage in the watershed has led to speculation that this important conservation practice is a primary cause of the SP loading. Thus, conservationists are interested in finding management practices that will minimize stratification of P, which may be common in no-tillage systems, while also minimizing erosion losses that result from conventional tillage practices. As no-tillage was marketed as a practice to decrease sediment and total P (TP) loads, it is important to examine adoption of future conservation practices for their impact on multiple resource concerns. This study was conducted to determine if a shallow vertical tillage practice was sufficient to minimize P, N and atrazine loading from long-term no-tillage fields in a corn-soybean rotation, while maintaining minimal erosion. Rainfall simulations (average intensity of 53 mm $h^{-1}$) were performed on no-tillage and vertical tillage plots ($5 \times 1$ m) sufficient to produce 30 min of runoff. Runoff was collected every 2.5 min, and analyzed for sediment and nutrients ($NH_4$–N, $NO_3$–N, total Kjehldahl N (TKN), SP and TP). Runoff was delayed by 17 min using vertical tillage; however, the steady-state rate of runoff was significantly greater from vertical tillage compared to no-tillage. There were no significant differences for N from runoff ($NH_4$–N, $NO_3$–N, or TKN). There was a trend of slightly higher SP loads from vertical tillage than no-tillage. Total P losses were correlated with sediment, and were observed to be higher from vertical tillage than no-tillage. The primary advantage that vertical tillage has with respect to nutrient losses is in delaying runoff initiation, however this effect could be nullified in subsequent runoff events. If P loading to surface waters is the primary concern, it would appear from the data presented in this study that vertical tillage may not be an appropriate practice, and in fact may impose greater risks due to greater erosion and associated TP losses.

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## 1. Introduction

Soluble P (SP) loads from the agricultural landscapes of the Western Lake Erie Basin began increasing in the mid-1990s (Richards et al., 2010), which occurred around the same time that adoption of no-tillage practices in the watershed reached a plateau. Increasing SP loads have been shown to be highly correlated to the increasing size of harmful algal blooms (HABs) in Lake Erie (Stumpf et al., 2012). No-tillage practices were being heavily promoted at a time when it was thought that sediment and total P (TP) reductions would improve water quality. Recent work has shown that practices like no-tillage often do a good job of reducing TP losses; however, they can increase SP losses (Smith et al., 2015a). Therefore, it is essential that further study of conservation practices that are intended to address one resource concern also take into consideration other constituents.

Interestingly, TP loads have been declining for the same period that SP loads have been increasing (SERA-17, 2009). While there have been no definitive answers as to why increasing SP loads and the concomitant increase in algal blooms have occurred, some have speculated increasing SP loads are due to P stratification in no-tillage soils (Pelley, 2010; Richards et al., 2010). Stratification of P in no-till soils has been documented (Sharpley and Smith, 1994; Sharpley, 2003).

Agriculture has been identified as one of the main culprits associated with P loading to freshwater systems, but this is not the

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only problem being blamed on agriculture. Nitrogen loading from agriculture has been linked with hypoxia in the Gulf of Mexico (Rabalais et al., 2001). Deposition of sediments from row crops is known to induce sedimentation in streams, rivers and reservoirs, diminishing the capacity of these systems to convey or store water. Pesticides used in agriculture have been found to be excessively high in drinking water sources (Environmental Working Group, 1995), which requires expensive treatment before the water can be consumed.

Critics of no-till have ignored other potential causes of P-related Lake Erie eutrophication (Kozacek, 2014; Schaefer, 2013; Smith et al., 2015c), and have latched on to P stratification associated with no-till. Thus, there have been many conservation-minded practitioners who have sought ways to find methods of farming that will limit P stratification that is known to result from no-tillage, but without using invasive tillage tools. This line of reasoning has led to an interest in a technology being marketed as "vertical tillage." This technology tills the upper 5–15 cm of soil (Peter, 2009; Davidson, 2010; Fischer, 2011). Vertical tillage is generally done to reduce the size of residue from the previous crop to ensure that planting will not be inhibited by excessive residue. There has been little research with regard to how this technology will influence contaminant (sediment, nutrient and pesticide) transport from fields. The objective of this study was to compare vertical tillage and long-term no-till as they relate to nutrient, sediment and atrazine losses in runoff water using rainfall simulations.

## 2. Materials and methods

The site selected for this study was on a private farm near West Lafayette, Indiana. The soils in the field were Parr loam (fine-loamy, mixed, active, mesic Oxyaquic Argiudolls). The field had been no-tilled for 10 years, with a corn (*Zea mays* L.)/soybean (*Glycine max* (L.) Merr.) rotation. At the time of this study, the field was cropped to corn and soybean residue was present from the previous crop. Plots were $5 \times 1$ m, and were constructed with approximately a 3% slope.

The two treatments for this study were long-term no-tillage and vertical tillage prior to planting. Plots were constructed such that there were four replications of each treatment. The bulk of the field was cultivated for the first time using one pass with a Salford RTS (Salford Farm Machinery Ltd., Osceola, IA) to conduct the vertical tillage operation approximately one week prior to this study. No natural precipitation occurred between the vertical tillage operation and this study. The long-term no-tillage treatment plots were placed in a portion of the field where the vertical tillage operation was not performed.

Artificial rainfall was applied to plots at a rate of 75 mm $h^{-1}$ until 30 min of runoff had been collected (SERA-17, 2015). The primary modification from the National Research Project for Simulated Rinfall – Surface Runoff Studies Protocol was that we used 5 m plots instead of 2 m plots, based on experience in 5 m plots tending to be more representative of relative field runoff losses from treatments as per Smith and Pappas (2010). Due to time constraints, no pre-rain wetting of the plots was performed. The mean time for simulations was 60 min, which represented a storm with a 50-year return period. Mean volumetric water content ($\theta_v$) values in plots prior to the start of rainfall simulations was 0.28 $cm^3\,cm^{-3}$. Runoff samples were collected every 2.5 min, beginning as soon as runoff was first observed. A 60 mL sample was collected for analysis of TP, and a 20 mL sample was collected for analysis of SP. Specifics for analysis of SP and TP samples are presented below. For the rainfall simulations reported here, there was no application of manure or fertilizer prior simulated rainfall other than what was applied to the entire field. Rainfall simulations on plots occurred on May 12, 2009. The nutrient runoff component of this study was a portion of a larger study, with the primary objective of comparing the impacts of vertical tillage to no-tillage on agrichemical fate and transport. As such, the study was conducted one day after the field was sprayed with isoxaflutole and atrazine to optimize for the pesticide runoff loss component. The field had just been planted, so corn plants had not yet emerged from the soil.

As the study was designed primarily to assess pesticide transport from a worst case scenario (i.e., 24 h following application), the rainfall simulations were conducted 1 day after pesticides were applied. Windy conditions were persistent during the date of rainfall simulations, and while attempts were made to minimize the effect of the wind (i.e., use of wind barriers), there was an impact on the actual amount of rainfall that was applied to each plot. We measured the amount of precipitation each plot received by placing seven rain gauges around the edges of each plot. The total rainfall in each gauge was recorded at the end of each event. Mean artificial precipation applied was 49 mm $h^{-1}$ for the no-till plots and 57 mm $h^{-1}$ for the vertical tillage plots.

The 20 mL runoff sample collected from each plot was filtered (0.45 um) and acidified to pH < 2 with $H_2SO_4$. This aliquot was used for SP analysis. After initial processing and transport to the laboratory, all samples were frozen until SP and TP analysis was performed. All nutrient analyses were conducted colorimetrically with a Konelab Aqua 20 (EST Analytical, Medina, OH). Soluble P was analyzed on the filtered acidified samples using EPA method 365.2 (U.S. EPA, 1983). Total P was analyzed using EPA method 365.4 for TP (U.S. EPA, 1983), after sulfuric acid digestion of the unfiltered samples. Total Kjehldahl N was analyzed colorimetrically after digestion using EPA method 351.2 (U.S. EPA, 1983).

Data from the rainfall simulations are represented as the flow weighted concentration and cumulative load. To calculate the flow weighted concentration, the total mass of the contaminant was divided by the total discharge. In addition to these two metrics, a third metric was calculated to assess P transport. This was accomplished by normalizing the contaminant loads for the

**Table 1**
Influence of no-tillage and vertical tillage on stratification of nutrients in soil.

| Treatment | Depth (cm) | WSP[a] (mg $kg^{-1}$) | Mehlich 3 P (mg $kg^{-1}$) | PSR[b] (unitless) | $NO_3$–N (mg $kg^{-1}$) | $NH_4$–N (mg $kg^{-1}$) |
|---|---|---|---|---|---|---|
| No-till | 0–5 | 26.6 | 227 | 0.182 | 70.5 | 49.2 |
| | 5–15 | 11.8 | 102 | 0.076 | 34.1 | 16.0 |
| | P[c] | <0.05 | <0.01 | <0.01 | <0.01 | <0.01 |
| Vertical tillage | 0–5 | 14.6 | 154 | 0.122 | 31.3 | 63.9 |
| | 5–15 | 6.2 | 114 | 0.077 | 13.4 | 15.4 |
| | P | <0.01 | <0.05 | <0.01 | <0.01 | <0.01 |

[a] Water soluble P.
[b] P sorption ratio.
[c] Levels of significance are for a variable are comparisons of depth within the treatment. There were no significant differences in comparing treatments within a profile depth between treatments.

amount of precipitation (Smith and Pappas, 2010), and was decided to be an important variable, given the uneven distribution of rainfall resulting from the windy conditions. We decided to normalize for the amount of precipitation because this is a potential metric that could normalize contaminant losses based on the inputs into the system (amount of land contributing to the runoff, and amount of precipitation driving the hydrology of the system). The precipitation for the rainfall simulations was calculated as the amount of precipitation applied using the simulators.

Load and concentration data were log normally distributed and were, therefore, log-transformed prior to statistical analysis. Statistical analysis was conducted to compare treatment effects for cumulative runoff parameters, as well as discrete runoff samples. This was accomplished by using the log-transformed data, and making comparisons using analysis of variance (ANOVA) in JMP v. 6.0.0 (SAS Institute, 2005).

## 3. Results and discussion

### 3.1. Vertical tillage impacts on soil

No-till plots contained 70% soybean residue cover at the time of rainfall simulations, while vertical till plots contained 50% residue cover ($P = 0.06$). Not only was there less residue cover, but the vertical tillage treatment also reduced the size of the residue and detached residue that had previously been firmly attached to the soil (i.e. standing soybean stalks).

As expected, nutrient stratification was apparent in the no-till plots (Table 1). Water soluble P and Mehlich 3 P concentrations in the 0–5 cm profile were significantly greater than what was observed in the 5–15 cm soil profile of the no-till plots. These data are consistent with that of soils from no-till corn/soybean fields in Pennsylvania as well as pasture systems (Sharpley, 2003). Some practitioners have hypothesized that vertical tillage may provide sufficient soil mixing to either minimize stratification or at least increase the contact between the soil and fertilizer and/or labile P pools to decrease P solubility. However, there were no significant differences between soil nutrient concentrations when comparing the no-till and vertical tillage treatments within a given depth. Since P levels were significantly stratified, the P saturation ratio also showed significant stratification in both no-till and vertical tilled plots. To effectively decrease P stratification, deep tillage (i.e. deeper than 15–20 cm) would likely thoroughly mix P throughout the profile and result in the P in the soil being less susceptible to runoff losses (Sharpley, 2003). However, this measure is not seriously recommended unless Mehlich 3 values in the surface layer are excessive (i.e. >500 mg $kg^{-1}$), as this form of tillage may lead to increased erosion.

Stratification of PSR was observed in both treatments (Table 1). However, there was no statistical difference in PSR between treatments at either the 0–5 or the 5–15 cm depth.

### 3.2. Vertical Tillage Impacts on Hydrology

Initiation of runoff was significantly delayed by vertical tillage. Mean time for runoff to occur for the no-tillage plots was 20 min 30 s, while runoff initiation from the vertical tillage plots occurred at 37 min 40 s (Fig. 1). While the total runoff volume for the two treatments was similar (2.2 cm from vertical tillage and 1.9 cm from no-tillage), there was a significant difference in the steady state rate of flow from the plots (0.09 cm $min^{-1}$ from vertical tillage and 0.05 cm $min^{-1}$ from no-tillage). Higher peak runoff following conventional tillage systems than no-till systems has been observed in other studies (Deizman et al., 1989; Truman et al., 2007). Tillage is known to decrease aggregate stability in

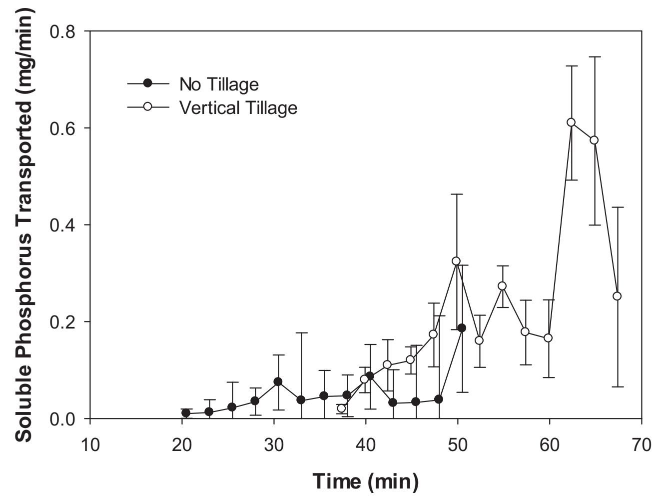


**Fig. 1.** Soluble phosphorus transported via runoff from no-tillage and vertical tillage plots. Error bars represent standard error.

comparison to no-till soils (Park and Smucker, 2005; Blanco-Canqui et al., 2009). Reduced aggregate stability is probably why vertical tillage resulted in greater steady state runoff rates than no-till. Furthermore, in subsequent rainfall events, runoff initiation could occur quicker with vertical tillage due to surface sealing.

### 3.3. Vertical Tillage Impacts on Water Quality

There were no significant differences for any of the metrics measured between vertical tillage and no-tillage for N ($NH_4$–N, $NO_3$–N, or TKN) losses (Table 2). This result would indicate that implementation of vertical tillage within the Mississippi River Basin would have no benefit for reducing N losses to surface water, and thus the Gulf of Mexico. In reality, in the tile-drained landscape of the Midwestern US, it is likely that more N gets to surface waters through subsurface tile flow rather than surface runoff (Drury et al., 1993; Kladivko et al., 2004), thus without studying these practices at the field or watershed scale, it is difficult to predict the true impact on water quality at larger scales.

Sediment loads were more than three times greater from the vertical tillage treatment (Table 2). Greater sediment concentrations and loads with tillage compared to no-till have been found in many studies (Kimmell et al., 2001; Warnemuende et al., 2007; Verbree et al., 2010). In a study of various tillage intensities, it was found that following the pass of a coulter, there was more sediment loss than using a chisel plow (Romkens et al., 1973). In the current study, the vertical tillage pass would most resemble the coulter pass in comparison to other more intensive tillage types.

Total P loads were significantly greater (55.4 g $ha^{-1}$) from the vertical tillage than the no-tillage plots (20.2 g $ha^{-1}$) (Table 2). Total P concentrations were twice as high from the vertical tillage plots as the no-tillage plots. This is not a surprising finding, since sediment loads were greater from the vertical tillage treatment. Kimmell et al. (2001) reported similar findings in a grain sorghum–soybean rotation in Kansas.

Soluble P loads showed a trend of being slightly greater from the vertical tillage plots compared to the no-tillage plots; however, this trend was only significant at $P < 0.15$ (Table 2). While this level of confidence is not sufficient to say these differences are significant, it is sufficient to indicate that vertical tillage does not reduce SP losses from these lands as suggested by some practitioners, and could potentially be detrimental to water quality. Further, this finding leads us to implore future researchers to also examine the impact of vertical tillage on SP loss compared

**Table 2**
Values for nutrient and sediment losses from no-tillage and vertical tillage plots.

| | Loads | | | Flow weighted concentration | | | Precipitation normalized loads | | |
|---|---|---|---|---|---|---|---|---|---|
| | No-till ($g\,ha^{-1}$) | Vertical till ($g\,ha^{-1}$) | *P* | No-till ($mg\,L^{-1}$) | Vertical till ($mg\,L^{-1}$) | *P* | No-till ($g\,ha^{-1}\,mm^{-1}$) | Vertical till ($g\,ha^{-1}\,mm^{-1}$) | *P* |
| $NH_4$–N | 96.2 | 107 | 0.74 | 0.80 | 0.58 | 0.69 | 1.76 | 1.48 | 0.23 |
| $NO_3$–N | 99.8 | 133 | 0.52 | 0.91 | 0.70 | 0.88 | 1.88 | 1.80 | 0.75 |
| TKN | 256 | 338 | 0.38 | 2.08 | 1.84 | 0.67 | 4.66 | 4.70 | 0.58 |
| Soluble P | 8.2 | 25.8 | 0.14 | 0.07 | 0.14 | 0.37 | 0.16 | 0.36 | 0.32 |
| Total P | 20.2 | 55.4 | 0.04 | 0.15 | 0.30 | 0.02 | 0.36 | 0.78 | 0.03 |
| Sediment | 418,000 | 1,306,000 | 0.01 | 3,320 | 7,100 | 0.01 | 7,580 | 18,400 | 0.03 |
| Atrazine | 72 | 94 | 0.44 | 0.572 | 0.508 | 0.51 | 0.65 | 0.65 | 0.98 |

to other tillage practices. Tillage has been shown to have variable results on SP, but generally greater SP losses are observed from no-tillage than tilled fields. In a grain sorghum–soybean rotation, SP loads varied between slightly less to slightly greater from no-till compared to tilled plots (Kimmell et al., 2001). Significantly greater SP concentrations were observed when comparing no-tillage to a rotational tillage system in a corn–soybean rotation (Smith et al., 2007). Field scale studies in the Western Lake Erie Basin (Smith et al., 2015a) demonstrated that no-tillage resulted in less TP loss, but greater SP loss compared to conventional tillage and rotational tillage (i.e., tilling before corn but not before soybean). Studies of tillage and P transport in Ontario, Canada have found conservation tillage can increase SP loss compared to tillage with a moldboard plow (Gaynor and Findlay, 1995). Similar results were observed in Mississippi, with moldboard plowing causing greater TP and sediment losses but less SP than conservation tillage treatments (McDowell and McGregor, 1984).

Field scale studies have shown that roughly 50% of SP and TP losses from fields occurred through tile drains (Smith et al., 2015b). In the soils of this region, there appears to be rapid macropore flow of surface runoff that reaches tile drains. While tile drainage was outside of the scope of the current study, vertical tillage should be compared to no-tillage and conventional tillage practices in monitored fields where both surface runoff and tile discharge are monitored. While one may hypothesize that any operation that can break macropore flow (such as vertical tillage) would necessarily decrease the loss of P to tile drains, this may not necessarily be true. Smith et al. (2015b) found the lowest relative loads of SP and TP in tile from a no-till field compared to rotational till and conventionally tilled soils. This hypothesis should not only be tested at the field or small watershed scale for P but for the components of N as well.

There were no significant differences in atrazine loads or concentrations between vertical tillage and no-till plots. Warnemuende et al. (2007) found rotational tillage lowered atrazine concentrations compared to no-till. Other studies have shown greater atrazine losses following tillage compared to no-till (Pantone et al., 1996) or no significant difference in atrazine loss when comparing conservation tillage to tillage with a moldboard plow (Gaynor et al., 1995).

Due to the windy conditions, and uneven distribution of simulated rainfall, the precipitation normalized loads were applied to compare treatments in this study (Table 2). As with load and concentration data, there were no significant differences between treatments for $NH_4$–N, $NO_3$–N or TKN precipitation normalized loads. Precipitation normalized loads were more than twice as high for TP and sediment from the vertical tillage treatment compared to the no-tillage treatment.

Soluble P lost from no-tillage plots was initially 0.01 $mg\,min^{-1}$ and increased to a range of 0.04–0.08 $mg\,min^{-1}$ (Fig. 1). The initial SP lost from the vertical tillage plots was 0.019 $mg\,min^{-1}$ and increased to the range of 0.16–0.6 $mg\,min^{-1}$. There was considerably more variability in the SP data from vertical till than no-tillage, perhaps due to the elevated levels of sediment in those samples, which can react quickly to bind SP from solution. Total P lost from the no-tillage plots was initially 0.13 $mg\,min^{-1}$ for each discrete sample, and increased to a peak of 0.40 $mg\,min^{-1}$ (Fig. 2). Vertical tillage plots initially lost 0.28 $mg\,min^{-1}$, and this increased from 1.1 to 1.4 mg $min^{-1}$ observed in discrete samples after 10 min of runoff initiation.

Sediment transported from the no-till plots increased slightly from 4.2 $g\,min^{-1}$ sediment to a peak of 8.8 $g\,min^{-1}$ of sediment following the onset of runoff (Fig. 3). In contrast, sediment loss from the vertical tillage plots increased from 6.4 $g\,min^{-1}$ to 27 $g\,min^{-1}$ sediment within the first 10 min of runoff. For each discrete sample collected during this study, the TP transported was regressed as a function of the sediment transported (Fig. 4). There was a significant relationship between the two ($P < 0.001$) and the sediment lost in each discrete sample accounted for 46% of the variation in the TP mass observed in each discrete sample. In Fig. 4, it is also easy for the reader to visualize how greater sediment and TP concentrations were associated with the vertical tillage plots than the no-tillage plots.

From these data, it would appear that the primary benefit to using vertical tillage over no-tillage with respect to nutrient transport is the delay in initiation of runoff. It should be noted that this study was only concerned with the first runoff event. Thus, if crusting were a problem, such as can be the case with other tillage

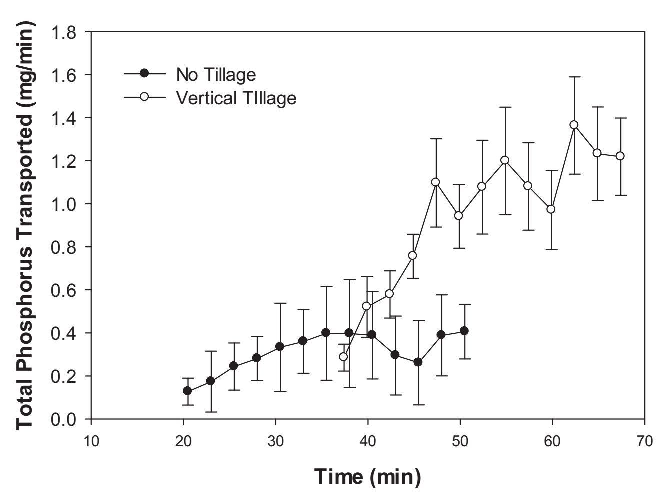


**Fig. 2.** Total phosphorus transported via runoff from no-tillage and vertical tillage plots. Error bars represent standard error.

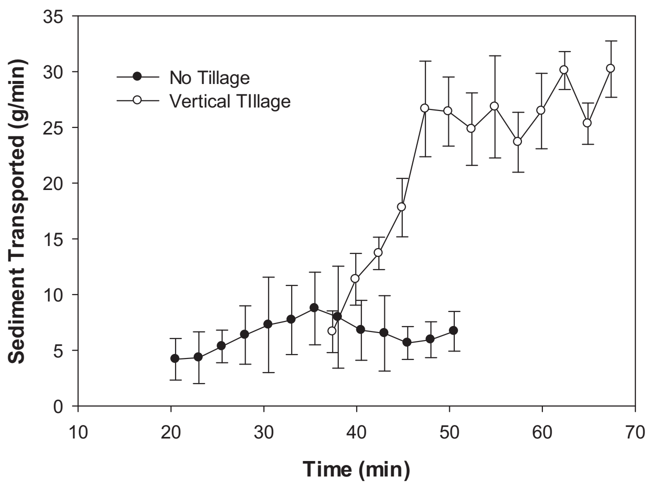


**Fig. 3.** Sediment transported via runoff from no-tillage and vertical tillage plots. Error bars represent standard error.

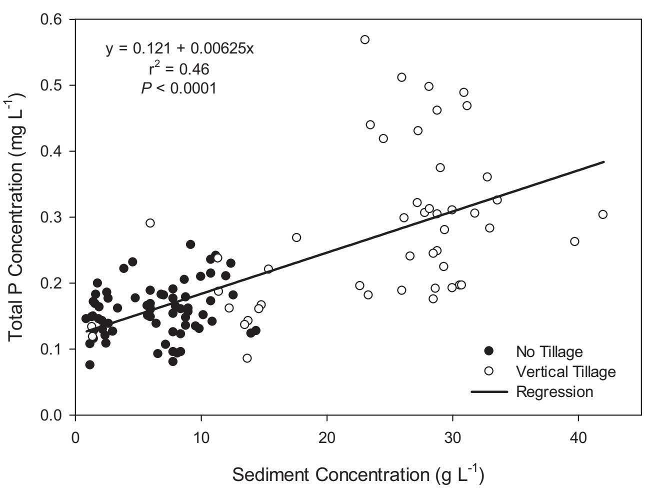


**Fig. 4.** Relationship between total phosphorus and sediment mass transported during 30 min of runoff from no-tillage and vertical tillage plots.

operations, this effect could well be negated in subsequent runoff events.

## 4. Summary and Conclusions

Some advocates have promoted vertical tillage as one method farmers can use to decrease nutrient losses that may result from no-tillage induced nutrient stratification. While the vertical tillage in this study did delay runoff, the sealing that occurred in the vertical tillage soil resulted in greater total amount of runoff, and thus greater sediment and TP losses. Some practitioners are recommending vertical tillage to reduce SP losses, a claim that is unfounded based on this study. Therefore, based on the results of this study, the authors recommend to not use vertical tillage in areas where sediment and P loadings from surface runoff are an important issue. Instead, other techniques should be used to minimize the risk of sediment and P loadings.

## Disclaimer

Mention of a trade name, proprietary product or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products that may be suitable.


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