Tillage and Fertilizer Effects on Crop Yield and Soil Properties over 45 Years in Southern Illinois

Rachel L. Cook* and Andrew Trlica

ABSTRACT

Reducing soil disturbance may limit erosion, but many still consider tillage essential for seedbed preparation, particularly on poorly drained soils. Our objective was to quantify tillage and fertilizer management effects after 45 yr [21 in continuous corn [Zea mays L.] (CC) and 24 in corn–soybean [Glycine max (L.) Merr.] (CS) rotation] on a somewhat poorly drained silt loam near Belleville, IL. Four tillage (moldboard plow [MP], chisel tillage [ChT], alternate tillage [AT], and no-till [NT]) and five fertilizer (no fertilization, N-only, N+NPK starter, NPK+NPK starter, and NPK broadcast) treatments were evaluated. With N, P, and K fertilizer, yields were similar for tilled and NT treatments, averaging 8.73 Mg ha⁻¹ for CC and 11.93 Mg ha⁻¹ for rotated corn and soybean. Below recommended soil-test values resulted in NT yielding less than tilled treatments even though soil test P, K, and pH were similar. No-till with N, P, and K fertilizer, yields were similar for tilled and NT treatments, averaging 8.73 Mg ha⁻¹ for CC and 11.93 Mg ha⁻¹ and 3.70 Mg ha⁻¹ for rotated corn and soybean. Below recommended soil-test values resulted in NT yielding less than tilled treatments even though soil test P, K, and pH were similar. No-till with N, P, and K increased soil organic matter (OM) to 27.6 g kg⁻¹ (20.5 g kg⁻¹ in all other treatments), with the great increase from 0- to 5-cm. No-till treatments showed stratification of P and K, but it had no effect on yield. No excessive pH stratification was observed. Overall, fertilizer management predominately influenced crop yield and with complete NPK management non-tilled yields were similar to tilled, even on flat, somewhat-poorly drained soils. No-till with NPK management therefore may allow farmers to maintain high yields while reducing soil and nutrient losses.

In North America’s midwestern Corn Belt, agriculture contributes to soil erosion and nutrient losses with far-reaching environmental consequences such as hypoxia in the Gulf of Mexico (Diaz and Rosenberg, 2008) and long-term loss of farm soil productivity (Pimentel et al., 1995; Lal, 2004). Conservation tillage practices, such as ChT and NT, aim to minimize soil disturbance and increase soil residue cover (Hobbs et al., 2008). These practices can help mitigate the environmental impact of corn and soybean production by reducing soil loss and nutrient runoff (Angle et al., 1984; Wendt and Burwell, 1985; Shipitalo et al., 2013), surface and groundwater pollution (Glenn and Angle, 1987; Kanwar et al., 1997), fuel consumption (Doster et al., 1983; Brown et al., 1989; Chase and Duffy, 1991) and greenhouse gas emissions (Kern and Johnson, 1993; Pacala and Socolow, 2004; Bernacchi et al., 2005; Omonode et al., 2011).

Studies have shown that conservation tillage and NT can improve soil physical properties such as infiltration, bulk density, water retention, structure, and water-stable aggregates (Karlen et al., 1994; Cassel et al., 1995; Kumar et al., 2012a, 2012b). Long-term no-till can also lead to vertical and horizontal stratification of P, K, pH, and OM, but there is little evidence that stratification affects yield (Dick et al., 1991; Ismail et al., 1994; Holanda et al., 1998; Duiker and Beegle, 2006).

Unfortunately, a general perception remains that the benefits of reduced tillage such as soil conservation may be outweighed by decreased yield and lower economic returns, except on well-drained, highly sloped, and erodible land (Triplett and Dick, 2008; Pittelkow et al., 2015). Corn-yield reductions during the first several years after conversion to NT from conventional tillage have been noted particularly on poorly drained soils, in CC rotations, on certain soil types (e.g., high OM, fine texture), and in colder, wetter, and more northerly climates (Griffith et al., 1988; Dick et al., 1991; Iragavarapu and Randall, 1995; West et al., 1996; Hussain et al., 1999; Govaerts et al., 2005; DeFelice et al., 2006; Tliver et al., 2012). However, other NT studies have shown no distinct effect of tillage on yield (Kapusta et al., 1996) and even a yield advantage in certain years (Dick et al., 1991; Griffith et al., 1988; Grandy et al., 2006a; Herbeck et al., 1986), indicating that relative crop performance under NT may depend on environmental and management interactions.
Long-term experiments are crucial to understanding how management will affect soil properties and crop yield over time (Richter et al., 2007). Only a limited number of midwestern studies have tracked yield and soil changes for more than 20 yr (Dick et al., 1991; Ismail et al., 1994; West et al., 1996; Vyn et al., 2000; Tarkalson et al., 2006; Karlen et al., 2013). Given the impact of site factors such as climate, soil, and cropping practices on relative yield and soil properties due to tillage and fertilizer, the scattered geographic breadth in these long-term studies may have contributed to the formation of a “common knowledge” that does not adequately account for regional differences.

This study examines the effect of 45 yr of fertilizer and tillage treatments in CC (1970–1990) and CS rotation (1991–2014) on corn and soybean yield, soil chemical properties, and plant nutrient status in a somewhat poorly drained soil in southern Illinois, where NT is typically applied more often on sloping, highly erodible sites. As one of the longest running continuous reduced- and NT experiments in the midwestern Corn Belt, this study addresses the following questions: How do corn and soybean yield respond over time to different tillage, fertilizer, and crop rotation systems in southern Illinois? How do soil properties (extractable P and K, OM, pH, and stratification) change in response to tillage and fertilizer management? Do soil properties or plant tissue analyses suggest associations with yield response?

**MATERIALS AND METHODS**

In 1970 a full-factorial tillage by fertility study was established on a somewhat-poorly drained Bethalto silt loam (fine-silty, mixed, superactive, mesic Udollic Endoaqualf) at the Southern Illinois University Belleville Research Center (BRC) near Belleville, IL (exact field-plot coordinates: 38.519179° N, 89.843248° W). Treatments were distributed in a randomized split-plot design with Tillage as the main plot and Fertilizer as the split-plot. Each treatment plot was 6 by 8 m consisting of eight planted rows at 76 cm (30 inch) spacing. Each fertilizer and the split-plot. Each treatment plot was 6 by 8 m consisting of eight planted rows at 76 cm (30 inch) spacing. Each fertilizer and

Four tillage treatments were applied: (i) MP to 15 to 20 cm; (ii) spring disking followed by chisel-point cultivator or ChT to 15 to 20 cm; (iii) AT, with no-till for 2 yr followed by MP for 1 yr; and (iv) NT with no soil disturbance other than the planter (Table 1).

Five fertilizer treatments were applied consisting of: (i) unfertilized check (Control); (ii) broadcast nitrogen only (N-only); (iii) broadcast nitrogen plus NPK starter (N+NPKstarter); (iv) broadcast NPK plus NPK starter (NPK+NPKstarter); and (v) broadcast NPK only (NPK) randomized within each tillage strip. Fertilizer treatments were only applied in years during which corn was planted. Starter fertilizer was applied with the planter and placed 5 cm to the side and 5 cm below the corn seed at planting. Specific fertilizer application rates during the course of the study were adjusted to reflect increased knowledge of crop requirements (Table 1). After some adjustments during the first 4 yr, fertilizer application rates were maintained unchanged until 2000, when rates were adjusted and starter fertilizer treatments (N+NPKstarter and NPK+NPKstarter) were switched to NPK broadcast. Calcitic limestone was applied periodically to maintain soil pH at approximately 6.5. The sites were kept essentially weed free using pre- and post-emergent herbicides (See supplemental information for additional site and treatment history).

All corn and soybean yields were corrected to 155 and 130 g kg⁻¹ moisture content, respectively. Results from 1970 to 1990 (Kapusta et al., 1996) are included in this study to permit analysis of long-term yield trends and shifts in soil properties. Soil sampling in 5-cm increments was conducted in the fall of 1978, 1983, 1990, 1999, and 2013 in NPK broadcast, N-only, and Control fertilizer treatment plots. This study focused on soils sampled in 1990 and 2013 because they represent approximately 20 yr for each cropping system, were the most complete, well documented, and corresponded to available plant tissue analysis data. Soil samples were taken from 0- to 5-, 5- to 10-, 10- to 15-, 15- to 20-, and 20- to 25-cm depth increments. Plant-available K was extracted by ammonium acetate or the Mehlich-III method, available P was extracted by Bray P1, and OM was determined by loss on ignition. Available secondary and micronutrients were extracted with Mehlich-III. Soil pH was determined using a 1:1 soil/water method. Corn

### Table 1. Fertilizer and tillage treatments, 1970 to 2014. Note: No fertilizer was applied before soybean seasons (odd-numbered years after 1990).

<table>
<thead>
<tr>
<th>Fertilizer treatment</th>
<th>N-P-K kg ha⁻¹ 1970–1973†</th>
<th>N-P-K kg ha⁻¹ 1974–1999</th>
<th>N-P-K kg ha⁻¹ 2000–2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0–0–0</td>
<td>0–0–0</td>
<td>0–0–0</td>
</tr>
<tr>
<td>N-only</td>
<td>140–0–0</td>
<td>196–0–0</td>
<td>196–0–0</td>
</tr>
<tr>
<td>N+NPKstarter</td>
<td>129–0–0 +</td>
<td>179–0–0 +</td>
<td>196–24–140</td>
</tr>
<tr>
<td>Tillage treatment</td>
<td>Seedbed preparation steps</td>
<td>Seedbed preparation steps</td>
<td>Seedbed preparation steps</td>
</tr>
<tr>
<td>Moldboard (MP)</td>
<td>Moldboard plow, tandem disk, cultivator, culti-mulcher</td>
<td>Moldboard plow, tandem disk, cultivator, culti-mulcher</td>
<td>Moldboard plow, tandem disk, cultivator, culti-mulcher</td>
</tr>
<tr>
<td>Chisel (ChT)</td>
<td>Tandem disk, chisel plow, tandem disk, cultivator, culti-mulcher</td>
<td>Tandem disk, chisel plow, tandem disk, cultivator, culti-mulcher</td>
<td>Tandem disk, chisel plow, tandem disk, cultivator, culti-mulcher</td>
</tr>
<tr>
<td>Alternate (AT)</td>
<td>Two years No-till, 1 yr MP treatment</td>
<td>Two years No-till, 1 yr MP treatment</td>
<td>Two years No-till, 1 yr MP treatment</td>
</tr>
<tr>
<td>No-till (NT)</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

† In 1973 total K application rates were 112 kg ha⁻¹ in the N+NPKstarter and 224 kg ha⁻¹ in the NPK and NPK+NPKstarter fertilizer treatments.
ear-leaf samples were taken in 1990 and 2014 and analyzed for tissue nutrient concentration using inductively-coupled plasma spectrophotometry following microwave digestion. All soil and tissue laboratory analysis was performed by Brookside Labs, New Bremen, OH.

Yields across each rotation were analyzed with a mixed linear model. The model included fixed effects of Tillage, Fertilizer, and Tillage × Fertilizer, and random effects for the class variables Year (to account for year-to-year variability), Replicate (Rep), Rep × Tillage, and Year × Rep × Tillage (to account for whole-plot error). The Kenward–Roger method was used to estimate the denominator degrees of freedom of the $F$ statistics (Kenward and Roger, 1997). A repeated measures statement was included with a first order auto-regressive [AR(1)] covariance structure with Rep × Tillage × Fertilizer as the subject. Tukey’s HSD was applied for separation of means with $\alpha = 0.05$. To analyze yield trends over time, year was also included as a fixed linear- and quadratic covariate in the model to account for changes in yield over time (sample SAS code available in Supplemental Information). For analytical consistency the NPK-applied fertilizer treatments (N+NPKstarter, NPK+NPKstarter, NPK) were kept separate across the 1970 to 2014 time horizon. Proc glimmix (SAS Institute Inc., Cary, NC) in SAS version 9.3 was used to estimate the linear mixed models. Trends in yield were analyzed by groupings suggested by Tukey’s mean separation for yield in each rotation.

Soil properties after approximately 20 yr of each crop rotation (CC in 1970–1990 and CS in 1991–2014) were evaluated for long-term management and rotation effects on available soil P and K, OM, and pH. Plow layer (0–15 cm) soil properties were estimated as the average of the increment data from 0 to 5, 5 to 10, and 10 to 15 cm. Plow-layer available P, K, OM, and pH were analyzed as a split-plot model with fixed effects for Tillage, Fertilizer, and Tillage × Fertilizer, and random effects for Rep and Rep × Tillage in 1990 and 2013. Least-square means of the soil parameters were compared for each treatment to Illinois recommended soil test values (Fernández and Hoeft, 2009). The per-plot change from 1990–2013 ($\Delta$) was calculated and the least-square means were compared to zero. A stratification index for each soil parameter was calculated as the ratio of the top 5 cm to the total amount (for P, K and OM in kg ha$^{-1}$, assuming soil bulk density of 1000 kg m$^{-3}$) or average (for pH) across the 0- to 20-cm depth (Franzluebbers, 2002). Corn ear-leaf nutrient contents were analyzed for 1990 and 2014 by the same model design as soil properties. Nutrient deficiencies were determined by comparing the least-square means to recommendations published for Illinois (Fernández and Hoeft, 2009).

**RESULTS AND DISCUSSION**

**Yield across Rotations**

Continuous corn, rotated corn, and soybean yields with separation of means for the each phase are shown in Fig. 1. Corn and soybean yields in this study were within the range reported for other midwestern sites under both CC and CS practices (Ismail et al., 1994; Karlen et al., 1991; Linden et al., 2000; Olson et al., 2013; Vyn et al., 2000; West et al., 1996; Wilhelm and Wortmann, 2004). As measured elsewhere (Kanwar et al., 1997; West et al., 1996; Wilhelm and Wortmann, 2004), rotated corn yields were generally higher than CC yields (by about 3.0 Mg ha$^{-1}$). Yield differences among tillage treatments were lower in the CS phase, in parallel with findings in other tillage and rotation studies (Dick and Van Doren, 1985; Griffith et al., 1988; Kanwar et al., 1997).

Yield in CC was affected by Tillage ($P < 0.001$) and Fertilizer ($P < 0.001$) treatments, and there was an indication of an interaction ($P = 0.087$; Table 2). Yields were similar across all the complete NPK treatments (NPK, N+NPKstarter, and NPK+NPKstarter), that is, there were no yield differences due to incorporation of P and K compared to surface application in no-till, similar to results elsewhere (Fink and Wesley, 1974). Furthermore, as previously reported for this site and others (Howard et al., 2002; Kapusta et al., 1996), there was
no significant increase in corn yield associated with banding starter fertilizers for any of the tillage treatments. The complete NPK treatments consistently had higher corn yields than N-only plots. In N-only plots, NT yielded less than ChT or MP treatments. Yields in Control plots were overall lowest, with NT lower than ChT within Control plots.

For the CS phase of this study, corn yield was affected by Fertilizer \((P < 0.001)\), Tillage \((P < 0.001)\), and their interaction \((P < 0.001)\). Similar to corn yields in the CC phase, all complete NPK treatments in the CS phase were similar across tillage treatments and higher than N-only or Control treatments, as has been seen in other studies (Halvorson et al., 2006; Ismail et al., 1994). Other studies have also shown that corn yield differences among tillage treatments tended to be smaller than differences between NPK and non-fertilized treatments (Karlen et al., 1991; West et al., 1996). Also similar to the CC phase, rotated corn yield in the N-only/NT treatment was lower than other N-only/Tilled treatments. The Control treatments continued to have the lowest yields during the CS phase and as in the CC phase, NT yields were lower than ChT yields.

Soybean yield was also affected by Fertilizer \((P < 0.001)\), Tillage \((P < 0.084)\), and their interaction \((P < 0.001)\). Yields in all complete NPK treatments were similar for all tillage treatments. A minimal impact of tillage on soybean yield has been noted in other studies (West et al., 1996; Hussain et al., 1999). Control and N-only treatments in tilled plots (MP, ChT, and AT) had similar but lower yields than complete NPK fertilizer treatments. No-till yields were similar in Control and N-only treatments, but lower than AT in the N-only treatment and lower than all other tillage treatments in the Control plots.

The mean soybean yield response to P and K in this study was a 19% increase in complete NPK plots compared to Control and N-only plots. This response was relatively smaller than the mean corn response to N fertilizer (205% for CC and 263% for rotated corn in the complete NPK and N-only plots when compared to Control treatments). Other studies have shown similar soybean yield responses to P and K under low soil test values similar to this experiment (Dodd and Mallarino, 2005; Mallarino et al., 1991).

To evaluate the potential for yield penalty during the first 5 yr of NT (1970–1974), yields under ChT and MP tillage were compared to NT yields under both the NPK and NPK+NPK starter fertilizer treatments, since both treatments had similar total fertilizer application rates. The mixed linear model showed no differences between the two Fertilizer treatments \((P > 0.374)\), a significant effect for Tillage \((P < 0.009)\),

Table 2. Summary of linear mixed model results for the Type III test of fixed effects for Tillage (T), Fertilizer (F), and Year (linear, Y, and quadratic, \(Y^2\)) effects on crop yield (continuous corn, rotated corn, and soybean). Degrees of freedom of Fisher \(F\) statistic (numerator and denominator) are shown with probability of null result \((P > F)\).

<table>
<thead>
<tr>
<th>Effect</th>
<th>Continuous corn</th>
<th></th>
<th>Roated corn</th>
<th></th>
<th>Soybean</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Num. df/Den. df</td>
<td>(F)</td>
<td>P &gt; F</td>
<td>Num. df/Den. df</td>
<td>(F)</td>
<td>P &gt; F</td>
</tr>
<tr>
<td>Tillage</td>
<td>3/245</td>
<td>5.27</td>
<td>0.002</td>
<td>3/150.9</td>
<td>1.35</td>
<td>0.261</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>4/588.8</td>
<td>32.45</td>
<td>&lt;0.001</td>
<td>4/211.4</td>
<td>205.32</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>T x F</td>
<td>12/588.8</td>
<td>1.55</td>
<td>0.101</td>
<td>12/211.4</td>
<td>1.81</td>
<td>0.048</td>
</tr>
<tr>
<td>Year</td>
<td>1/17.05</td>
<td>4.72</td>
<td>0.044</td>
<td>1/9.026</td>
<td>0.13</td>
<td>0.725</td>
</tr>
<tr>
<td>Y x T</td>
<td>3/249.3</td>
<td>2.10</td>
<td>0.101</td>
<td>3/154.1</td>
<td>0.82</td>
<td>0.487</td>
</tr>
<tr>
<td>Y x F</td>
<td>4/619.7</td>
<td>36.78</td>
<td>&lt;0.001</td>
<td>4/252.9</td>
<td>11.70</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Y x T x F</td>
<td>12/619.7</td>
<td>2.34</td>
<td>0.006</td>
<td>12/252.9</td>
<td>0.89</td>
<td>0.063</td>
</tr>
<tr>
<td>Year^2</td>
<td>1/17.05</td>
<td>1.43</td>
<td>0.248</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Y^2 x T</td>
<td>3/249.5</td>
<td>1.68</td>
<td>0.172</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>Y^2 x F</td>
<td>4/623</td>
<td>25.08</td>
<td>&lt;0.001</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Y^2 x T x F</td>
<td>12/623</td>
<td>2.41</td>
<td>0.005</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 3. Estimated model coefficients for each treatment grouping (± standard error) for continuous corn, rotated corn, and soybean yield, with \(R^2\) values for each model. Trend lines are based on predicted values from the mixed linear model.

<table>
<thead>
<tr>
<th>Continuous corn</th>
<th>Control</th>
<th>NPK (all)</th>
<th>N-only/NT</th>
<th>N-only/Tilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_0)</td>
<td>2.521</td>
<td>±0.189</td>
<td>5.234</td>
<td>±0.103</td>
</tr>
<tr>
<td>(B_1)</td>
<td>0.088</td>
<td>±0.040</td>
<td>0.541</td>
<td>±0.022</td>
</tr>
<tr>
<td>(B_2)</td>
<td>0.008</td>
<td>±0.002</td>
<td>0.015</td>
<td>±0.001</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.213</td>
<td>0.645</td>
<td>0.407</td>
<td>0.533</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rotated corn</th>
<th>Control</th>
<th>NPK (all)</th>
<th>N-only/NT</th>
<th>N-only/Tilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_0)</td>
<td>6.009</td>
<td>±0.253</td>
<td>12.07</td>
<td>±0.182</td>
</tr>
<tr>
<td>(B_1)</td>
<td>0.004</td>
<td>±0.019</td>
<td>0.012</td>
<td>±0.013</td>
</tr>
<tr>
<td>(R^2)</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.126</td>
<td>0.109</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soybean</th>
<th>NPK (all)</th>
<th>No-PK/NT</th>
<th>No-PK/Tilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_0)</td>
<td>3.156</td>
<td>±0.103</td>
<td>2.559</td>
</tr>
<tr>
<td>(B_1)</td>
<td>0.080</td>
<td>±0.020</td>
<td>0.067</td>
</tr>
<tr>
<td>(B_2)</td>
<td>0.002</td>
<td>±0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.067</td>
<td>0.030</td>
<td>0.076</td>
</tr>
</tbody>
</table>
and no interaction ($P > 0.724$). Linear contrasts using aggregated NPK and NPK+NPKstarter data showed NT yield was 0.60 Mg ha$^{-1}$ lower than the combined mean yield for MP and ChT treatments ($P < 0.008$). Several studies have found corn yield reductions during the first several years after switching to NT, particularly in continuous corn systems (e.g., Karlen et al., 2013; Phillips et al., 1997; So et al., 2009). This early reduction in NT corn yield was similar to that reported during the first several years of NT in studies on poorly drained, fine-textured soils (Al-Kaisi and Yin, 2004; Dick et al., 1991; Griffith et al., 1988). Historical records do not provide any insight into lower yields in the first several years of NT, as there were no recorded observed conditions pertaining to weed control, pests, planting problems, or otherwise to allow speculation as to the cause of this result. In contrast, across the entire 20-yr CC period differences in yield among tillage treatments were small and not statistically or agronomically significant. Short-term studies, therefore, may overestimate transient tillage effects, highlighting the importance of continuing to invest in long-term studies.

The effect of tillage every third year in an otherwise NT cropping system (AT) resulted in yields similar to MP or ChT in Control and N-only treatments, and similar to all other tillage treatments in complete NPK plots. This result is in contrast to more northerly poorly drained sites, where periodic tillage has shown improved yield when compared to continuous NT (Iragavarapu and Randall, 1995).

Yield Trends

There were significant interactions between year as a continuous variable and treatment effects. Linear or quadratic yield trend equations, based on the predicted values from the mixed model for each phase of the study are presented in Table 3. Quadratic year effects were excluded from the model for CS because they were nonsignificant ($P = 0.341$). Treatments for each rotation were grouped to visualize yield trends based on Tukey’s HSD results across all years (Fig. 2). Corn yields in CC and CS treatment groups were split into four groups: (i) all-NPK (all complete NPK treatments with all tillage treatments) (ii) N-only/Tilled (MP, ChT, AT), (iii) N-only/NT, and (iv) Control (all tillage treatments).

During the CC phase of this study, yields in the all-NPK group were the highest, increasing to a plateau in the mid-1980s. Yields in N-only/Tilled treatments also increased over time but were lower than for the all-NPK group. In contrast, N-only/NT yield increased until approximately 1980 and then started to decline. Control treatment yields remained lower, but may have increased slightly over time.

Rotated corn yield was overall higher than for CC, but no longer increased over time. Yields remained constant over time for all-NPK and Control groups. Yields declined somewhat in N-only/Tilled and N-only/NT treatments, with N-only/NT yields becoming similar to Control treatment levels.

For soybean yield, Tukey’s HSD results grouped treatments as (i) all-NPK (all complete NPK treatments with all tillage treatments), (ii) No-PK/Tilled, and (iii) No-PK/NT (i.e., No-PK grouped the Control and N-only treatments together, and Tilled grouped the MP, ChT, and AT tillage treatments together). The all-NPK group maintained a higher yield throughout the entire study than either the No-PK/Tilled group or the No-PK/NT group, which consistently had the lowest yield. The all-NPK group showed a general increase in yield over time and possibly plateaued by the end of the period, but in the two No-PK groups soybean yields declined over time.

The lack of long-term upward trends in corn yield was a surprise considering the introduction of improved hybrids each year. Gradual yield declines have been noted in other
long-term tillage studies where inadvertent macronutrient limitations may have been induced (Karlen et al., 2013). Additionally, CC, rotated corn, and soybean mean yields and yield trends indicate that no-till treatments seemed to be more negatively affected than tilled treatments with lack of P and K application.

**Soil Properties**

In complete NPK treatments, plow-layer P and K soil test values were well above the minimum recommendations in 1990 for corn and soybean production in southern Illinois (15 mg kg⁻¹ for Bray P1 and 150 mg kg⁻¹ for ammonium acetate or Mehlich III K), but by 2013 had declined significantly to near the recommended levels (Fig. 3). Removal rates of P and K estimated based on mean yields in corn and soybeans in complete NPK plots (Fernández and Hoeft, 2009) showed that fertilizer additions in 1990 exceeded corn grain removal by 10 kg ha⁻¹ for P and 63 (N+NPKstarter) to 119 kg ha⁻¹ (NPK and NPK+NPKstarter) for K. After switching to a CS rotation in 1991, the balance of P shifted to –24 kg ha⁻¹ (net removal) while the K balance was –4 (N+NPKstarter) to 53 kg ha⁻¹ (NPK and NPK+NPKstarter) per 2-yr rotation up to 1999. After fertilizer rates were modified in 2000, the net nutrient balance per 2-yr rotation was –39 kg ha⁻¹ for P and –24 kg ha⁻¹ for K. The decline in available P and K from 1990 to 2013 in these treatments is likely due to the persistent shortfall in fertilizer nutrient

![Graphs showing soil properties](image-url)

**Fig. 3.** Mean Bray P1, extractable K, and pH (0–15 cm) for (left) 1990 and (right) 2013 in Control, N-only, and NPK-broadcast treatments. Error bars show standard error of mean (n = 4). Illinois soil test recommendations shown as dashed line; shaded band shows range of baseline measurements taken before 1970. * Indicates below Illinois soil test recommendations (P < 0.05). △ Indicates change ≠ 0 from 1990 to 2013 (P < 0.05).
replacement after 1990. The consistent- to slightly declining yield of corn and soybeans during the CS period may indicate a slow onset of P or K deficiency, since as noted above improved hybrid seed were continually introduced over the course of the experiment. However, if P or K limitation played a role in limiting yield on these plots, there were no clear soil test indicators of deficiency according to Illinois crop recommendations.

In 1990, all Control treatment soil available P was above recommended levels but was below recommended levels for N-only in all tillage treatments except ChT ($P < 0.011$ for all tests; Fig. 3). By 2013 available P was below recommended in every N-only treatment ($P < 0.031$), Control/AT ($P = 0.006$), and Control/NT ($P < 0.001$). The decrease from 1990 to 2013 in available P was significant in every Control treatment

Fig. 4. Changes to soil profile in NPK-broadcast plots in 1990 (open symbols) after 21 yr of continuous corn (CC), and in 2013 (closed symbols) following 23 yr of a corn–soybean (CS) rotation. Error bars show standard error of mean, arrows indicate direction of significant change in stratification index.
(P < 0.018) but did not change significantly in N-only/NT treatments (P = 0.100). Available K was below recommended levels in the Control and N-only treatments in 1990 and 2013 (P < 0.001 for each treatment in each year) and did not change from 1990 to 2013 in either the Control or N-only treatment (P > 0.418 for all treatments in all years).

Across both CC and CS rotations, corn and soybean yield in N-only/NT plots tended to be lower than for N-only/Tilled treatments (MP, ChT, AT), but there were no corresponding significant differences in available soil P and K concentrations among N-only tillage treatments in either 1990 or 2013 (data not shown). If greater soil P or K deficiency was the cause of lower yield in N-only/NT compared to N-only/Tilled treatments, this additional deficiency was not detected in bulk soil test values. Though Control treatments indicated inadequate K since 1990 and inadequate P since at least 2013, it is likely that N deficiency caused yield limitations in these plots, given the lack of N inputs. Decline in the native supply of available P and K due to crop export resulted in soil test levels falling below adequate levels in both Control and N-only treatments, and the decline to below adequate levels was more rapid in the N-only treatments in P (and also possibly in K) where yield and subsequent export rates were consistently higher due to N fertilization. Soil micronutrient test values (Supplemental Information) did not indicate limitations in any treatment according to Illinois recommendations.

In 1990, soil P stratification was highest in NPK/NT and tended to be lower in MP plots (Supplemental Information) and in 2013 remained higher in NT, increasing in N-only/NT (P < 0.001) and declining in Control/AT (P = 0.009) and Control/ChT (P = 0.021; Fig. 4). In NPK plots, P stratification did not change even though available P in the plow layer declined between 1990 and 2013. Potassium was less stratified overall than P and highest under ChT. Soil K stratification declined in every treatment from 1990 to 2013 except NPK/MP (P = 0.246) and possibly in N-only/NT (P = 0.070), in parallel with the declines in plow layer available K. Within NPK treatments the stratification of P and K was higher under NT than other tillage treatments, as previously observed with conservation tillage (Cruse et al., 1983; Robbins and Voss, 1991), but there was no clear relationship between yield and nutrient stratification similar to previous research (Fink and Wesley, 1974; Dick et al., 1991; Karlen et al., 1991, Yin and Vyn, 2002). If P and K stratification had influenced yield, a greater yield difference between MP (low stratification) and NT (higher stratification) in NPK treatments might have been observed.

In general, soil pH was maintained within a range suitable for corn production in all treatments, but may have been slightly acidic for optimal soybean production (Fernández and Hoefi, 2009). Soil pH in 1990 was above the Illinois recommended minimum for corn except for N-only/AT (P < 0.001) and NPK/NT (P = 0.004) treatments. In 2013, pH in Control treatments was still adequate but had declined (P < 0.003 for all tillage treatments), and was below recommended levels in all other treatments (P < 0.017) except N-only/NT and NPK/ChT. Previous studies have shown lime recommendations may differ based on N fertilizer application and crop productivity (Ismail et al., 1994) but may not vary significantly between NT and other tillage treatments (Duiker and Beegle, 2006). In 1978 and 1983 lime was applied at a uniform rate of 6.7 Mg ha⁻¹, and starting in 1991 agricultural lime was applied according to plot-by-plot lime requirement (with a target pH of 6.5). The blanket lime application rate used before 1991 may explain the variability of soil pH among treatments in 1990, as there was the potential for mismatch between the lime applied vs. the specific lime requirements driven by plot-specific differences in N-fertilizer application and crop residue breakdown.

Surface applications of lime to NT has been shown to result in elevated pH in the top 0 to 5 cm, but by an amount that is not significant agronomically (Duiker and Beegle, 2006). In 1990, soil in the Control/NT treatment was the most relatively basic (higher pH stratification) in the surface 0 to 5 cm, while the NPK/AT and N-only/AT treatments had the lowest relative surface pH. Within NPK treatments, lack of lime incorporation in NPK/NT plots appeared to cause slightly higher pH stratification index (pH in surface soil was relatively higher) in 1990, but by 2013 NPK/NT pH stratification was similar to

![Fig. 5. Soil organic matter (g kg⁻¹) in (left) 1990 and (right) 2013. Error bars show standard error of the mean (n = 4). Letters indicate groupings by Tukey’s HSD (P < 0.05) for Tillage × Fertilizer interaction. A, Δ indicates change ≠ 0 from 1990 to 2013 (P < 0.061). Shaded horizontal band shows range of baseline measurements taken before 1970.](image-url)
other NPK tillage treatments since pH stratification increased in both NPK/AT and NPK/ChT (surface layers became relatively more basic). By 2013 pH stratification indices were overall closer to 1.0 (i.e., surface layer similar to whole profile) and less variable among treatments, with slightly more basic surface soil in NT and AT. Overall plow layer pH and stratification of pH were not associated with differences in yield among treatments.

Soil OM analysis in 1990 showed a significant effect for tillage ($P < 0.001$) and fertilizer ($P < 0.001$) and suggested an interaction ($P = 0.107$) (Fig. 5). Fertilizer use in 1990 tended to result in higher OM, likely the result of greater productivity and crop residue inputs. In 1990, OM concentrations were highest in NPK/NT and similar to the N-only/NT treatment ($P < 0.05$). In 2013, OM showed a significant tillage by fertilizer interaction ($P = 0.036$), with higher OM in the NPK/NT treatment (27.6 g kg$^{-1}$) than all other treatments, which had a mean concentration of 20.5 g kg$^{-1}$. The combination of high crop residue production in NPK plots with the low soil disturbance associated with NT presumably allowed for enhanced accumulation of OM in this treatment. Organic matter increased significantly between 1990 and 2013 in both Control/NT ($P = 0.061$) and NPK/NT ($P = 0.046$). No-till management has been shown in numerous other studies to result in higher OM accumulation in the surface soil layers compared with more intensive tillage regimes (Karlen et al., 1994; Deen and Katakai, 2003; Gål et al., 2007; Olson et al., 2005; Kumar et al., 2012a).

Soil OM was the most stratified in the NPK/NT treatment in both 1990 and 2013 due to the lack of vertical mixing of crop residue (Dick et al., 1991; Ismail et al., 1994; Duiker and Beegle, 2006), while all MP treatments were lowest in OM stratification in both years (Supplemental Information). The significantly higher OM content in the NPK/NT plow layer was primarily due to elevated OM in the surface 0 to 5 cm. Even though AT treatments were only tilled every third year, stratification declined in NPK/AT and Control/AT from 1990 such that the soil OM profile in 2013 resembled the MP treatments. Other studies have noted it may take 4 to 5 yr after plowing for soil conditions to begin to resemble long-term no-till (Pierce et al., 1994), and continuous no-till may be required to maintain other beneficial changes in soil properties (Grandy et al., 2006b). Measurements of soil C deeper in the profile are required to better estimate the long-term net soil carbon balance associated with different production systems at this site (Baker et al., 2007).

### Plant Tissue

Corn nutritional status as revealed by ear-leaf nutrient concentrations in 1990 showed adequate N in all treatments except Control treatments (recommended N concentration of 29 g kg$^{-1}$, $P < 0.001$), but no N deficiency was indicated in the 2013 sampling in any treatment (Fig. 6). The introduction of N-fixing soybean with more easily decomposable residue into the rotation in 1991 may have least partially eliminated the N tissue deficiency seen in Control treatments.

A P deficiency was indicated in the 1990 Control/AT ($P = 0.034$) and 2013 Control/ChT treatments ($P = 0.033$; recommended P concentration of 2.5 g kg$^{-1}$). Tissue P concentrations in 1990 also showed a significant Tillage × Fertilizer interaction ($P < 0.001$), with Control/NT values higher than in all other treatments and the N-only treatments at the lowest end of the range. By 2013, there were significant main effects for Tillage and Fertilizer ($P < 0.001$), with tissue P concentrations showing that NPK+NPK$\text{starter} = \text{N+NPK} = \text{NPK} > \text{Control} = \text{N-only treatments},$ and tissue P concentrations in MP plots higher than in NT or ChT treatments, potentially due to greater release of organic P with more intensive tillage (Buchanan and King, 1993). Soil P in N-only was below recommended levels and lower than NPK plots in both 1990 and 2013, but corn tissue P in both years was only slightly lower in N-only than NPK plots and did not clearly indicate P deficiency in either fertilizer treatment. This result was unexpected considering the under-application of P fertilizer based on maintenance recommendations since 1991.

In contrast to the tissue P results, in 1990 K deficiency (recommended K concentration of 19 g kg$^{-1}$) was indicated in all Control and N-only plots ($P < 0.001$) and all the N+NPK$\text{starter}$ plots ($P < 0.002$). Corn tissue K in 1990 showed a significant Tillage×Fertilizer interaction ($P < 0.001$) with higher K concentrations in NPK/NT plots and the lowest values in N-only and Control/NT treatments. The N-only/NT treatment had lower tissue K concentration than the other N-only tillage treatments in 1990. The overall inadequate levels of soil available K in N-only plots were associated with lower tissue K, but did not seem to explain the lower corn tissue K specifically seen in N-only/NT. A K deficiency was also indicated...
in NPK/ChT ($P = 0.016$) and NPK/MP ($P = 0.106$) and in NPK+NPKstarter/ChT ($P = 0.010$) and NPK+NPKstarter/AT ($P = 0.059$). The N+NPKstarter treatment received K application rates that were 56 kg ha$^{-1}$ lower than NPK and NPK+NPKstarter treatments until the year 2000 (Table 1), which likely led to consistent indication of K deficiency in these treatments in 1990. Alterations in clay mineral chemistry may have exacerbated K deficiencies in NT in the absence of P and K fertilizer, since weathering processes in NT may be slower than in MP plots (Karathanasis and Wells, 1989).

In 2013, corn tissue K was significantly affected by Tillage ($P = 0.039$) and Fertilizer ($P < 0.001$), but not their interaction ($P = 0.526$). Tillage treatments were not separated by Tukey’s HSD, implying no specific tillage-related release of K for crop uptake. All NPK+NPKstarter and NPK treatments were similar and higher than in the N-only and Control treatments. N+NPKstarter and Control treatments were similar and in the middle of the range. Tissue K values in the N+NPKstarter plots increased from 2010 to 2013, presumably in response to higher K application rates introduced in 2000. All Control treatments showed signs of K deficiency ($P < 0.060$), except MP ($P = 0.563$). All the N-only ($P < 0.001$), N+NPKstarter/ChT ($P = 0.060$), and N+NPKstarter/NT ($P = 0.026$) treatments also showed potential K deficiencies.

Corn yield was consistently lower in CC and CS in N-only/NT, and soybean yields were lower in N-only/NT and Control/NT treatments, paralleling the low corn ear leaf tissue K in NT treatments without P and K addition. However, while plant tissue K results are suggestive of K as a limiting factor for yield in N-only and particularly in N-only/NT treatments, plant tissue results can be difficult to interpret and may not clearly indicate nutrient limitations on crop yield (Mallarino and Higashi, 2009). Future field treatments at this site may investigate the effect on yield of increasing K application rates.

All micronutrient tissue concentrations indicated sufficient supply in both 1990 and 2013, except for B ($P < 0.001$ in all treatments, 1900 and 2013), which was indicated to be about 4 mg kg$^{-1}$ deficient in 1990 and about 2 to 3 mg kg$^{-1}$ deficient in 2013 based on a recommended tissue concentration of 10 mg kg$^{-1}$. However, it is unlikely that a response in corn yield would be seen to B application in southern Illinois (Fernández and Hoeft, 2009; Mallarino, personal communication, 2015).

CONCLUSIONS

With complete NPK management and sufficient soil test P and K levels, NT was equal to any of the other tillage management treatments, even in a fine textured, somewhat poorly drained, <2% sloping field site. The only treatment that was capable of increasing or maintaining elevated OM was NPK/NT, though the increase was primarily confined to the surface soil layer (0–5 cm). Stratification of P and K was somewhat higher in NT but was not associated with differences in yield and pH stratification was not excessive in NT. When soil P and K test values were below recommended levels, NT suffered a relatively greater yield penalty than similar tilled treatments, even though plow-layer extractable soil P, K, and pH levels were not dramatically different. Plant tissue results indicated that corn yield may have been limited by K deficiencies in plots showing low soil test K. Recommended maintenance applications of K based on crop yield were evidently not sufficient to prevent a decline in soil test K values. The results of this study argue for periodic soil test evaluation to prevent inadvertent nutrient limitations. Assuming proper weed control and fertility management, high corn and soybean yields can be maintained under continuous NT while also enhancing OM and reducing soil and nutrient loss in southern Illinois.

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REFERENCES


