Profit, yield, and soil quality effects of tillage systems in corn - soybean rotations

R.A. Buman, B.A. Alesii, J.L. Hatfield, and D.L. Karlen

ABSTRACT: Adoption of conservation tillage for corn (*Zea mays* L.) and soybean (*Glycine max* L.) rotations, has stagnated over the past several years despite the evidence of the benefits to erosion control, soil health, and associated natural resources derived from conservation tillage. The Monsanto Centers of Excellence were established to evaluate the potential benefits of conservation tillage across a range of soils and climates. Our objective is to summarize the results from field-scale studies conducted at 13 Monsanto Centers of Excellence sites in nine states from 1998 through 2002. Strip-tillage, no-tillage, and conventional corn production, and narrow- and wide-row, no-tillage and conventional tillage soybean production were evaluated in this study. Nine of the 13 sites included a stale seedbed "fast start" corn treatment by which the seedbed is prepared in the fall by conventional tillage and a spring herbicide burndown if needed. Neither soil bulk density nor crop emergence showed any significant differences among tillage systems for either crop throughout the five-year study. Earthworm populations were higher with no-tillage than conventional tillage. Soil quality indicators were not significantly different among the tillage systems. Soil temperature at the 5 cm depth was similar for strip- and conventional-tillage, with both being higher than no-tillage Yield differences among tillage systems within years were not significant for either crop, but profit for no-tillage and strip-tillage corn was the highest in four of five years. The five-year average profit for soybean was also highest for the no-tillage, narrow-row system. Rotating corn and soybean using no-tillage systems resulted in \$130 to \$145 ha^{-1} (\$53 to \$59 ac^{-1}) more profit than the other practices. Farmers, crop consultants, and others should carefully consider overall profit rather than just crop yield when evaluating alternative tillage practices.

Keywords: Centers of Excellence, conservation tillage, corn, no-tillage, soil quality indicators, soybeans

The adoption of conservation tillage for corn and soybean has stagnated in the U.S. and seen significant decreases in the Midwest since 1994. The 2000 Conservation Technology Information Center (CTIC) National Crop Residue Management Survey reported that since 1990, the number of U.S. cropland acres planted without tillage increased more than 200 percent to 21 million ha (51 million ac). However from 1998 to 2002, the use of conservation tillage (no-till, strip-till, ridge-till, or mulch-till) in the U.S. decreased by approximately 2,430,000 ha (6,000,000 ac). The survey also indicates that conservation tillage for full-season corn has decreased significantly in the Midwest since 1994 (CTIC, 2002b). Even with the evolution of strip-tillage, a system designed to overcome many real or perceived problems associated with no-tillage, adoption of conservation tillage has not increased. For example, the 2002 CTIC survey reported that 17.9 percent (4.6 million ha or 11.5 million ac) of corn in the Midwest was planted using either no-tillage or strip-tillage, while 30.7 percent of soybean area was planted using no-tillage (CTIC, 2002a; b).

Hill (2001) reported that the average time fields were in continuous no-till in Illinois, Indiana, and Minnesota from 1994 through 1999 averaged 2.4, 2.3, and 1.4 years, respectively. Furthermore, during this time period only 13 percent of the Illinois fields and 9 percent of the Indiana fields were in continuous no-till for more than five years. His study also indicated that farmers were more comfortable with no-till soybean than with no-till corn. This higher comfort level has created a rotation utilizing tillage prior to corn followed by no-till soybean.

Farmers throughout the Corn Belt cite many reasons for preferring conventional tillage for corn. The most common include: 1) lower yields, 2) overcoming cold, wet soil conditions, 3) lack of equipment for direct seeding into high residue conditions, and 4) equipment conversion costs (Hill, 1998; Nowak, 2000). In the 1999-2000 Iowa Residue Management Partnership Tillage Survey, 63 percent of the respondents cited lower yield as a factor preventing producers from trying no-till. More than half said machinery cost is one of the three main reasons why more farmers do not adopt no-till. Cold, wet soils was cited as the highest or next to highest problem by more than two-thirds of the respondents and appears to be the largest perceived problem (Nowak 2000).

Researchers have documented the success of various conservation tillage systems with regard to reducing erosion, improving soil health, and preserving natural resources. No-tillage and strip- tillage systems reduce soil erosion and chemical run-off, improve water infiltration, and increase residue cover, organic matter, and earthworm and other soil organism populations (CTIC, 2003). These two tillage systems also reduce labor and decrease the amount of equipment needed for crop production.

The documented benefits of conservation tillage, coupled with evidence of slow adoption, prompted the Monsanto Company to develop geographically-based, field-scale sites to demonstrate and evaluate various tillage practices. The Monsanto Center of Excellence program was initiated in 1997 to collect and disseminate information regarding the impacts of strip-tillage, no-tillage, fast start, and conventional tillage on crop production and various soil properties. The primary audience for this information was local farmers, crop consultants, Natural Resources Conservation Service (NRCS), and other professionals. Our objective for this analysis is to summarize the results from these field-scale studies and to determine

Robert A. Buman is consultant with Agren, Inc. in Carroll, Iowa. **B.A. Alesii** works at the Monsanto Cordilera Ranch in Boerne, Texas. **Jerry L. Hatfield** is the director and **Douglas L. Karlen** is a soil scientist at the National Soil Tilth Laboratory in Ames, Iowa.

Reprinted from the *Journal of Soil and Water Conservation*
Volume 59, Number 6
Copyright © 2004 Soil and Water Conservation Society

how the tillage systems affect profitability for each crop as well as the overall corn/soybean rotation.

Materials and Methods

General design. The Monsanto Center of Excellence project was started in 1997 and is still in operation, although in 2003 many original sites were discontinued and some new ones were added. The 13 sites evaluated for this study (Figure 1) were distributed throughout the Corn and Soybean Belt and generally had a non-replicated, large plot design to accommodate production size equipment (Table 1). With the exception of the Atlantic, Iowa and Mapleton, Minnesota, all Center of Excellence sites were located on privately owned farms, and all of the production operations were performed by the producer.

Each Center of Excellence site was divided, with one-half planted to corn and the other to soybean. The halves were subdivided into three or four plots to compare different tillage practices and rotated from one crop to the other each year. Plot size ranged from 1 to 6 ha with an average size of approximately 1.6 ha. Corn production was evaluated using no-tillage, fall strip-tillage, conventional tillage and fast start systems. Row cleaner planter attachments were used at all sites when planting no-tillage or strip-tillage plots. Conventional tillage was defined as the predominant local fall and/or spring tillage practices. The stale seedbed (fast start) system used standard fall tillage to prepare the seedbed for spring planting. This is followed by a spring herbicide burn down if needed with no additional tillage operations performed before planting. Several Center of Excellence sites did not include the fast start production system as part of their study.

The soybean portion of the field was divided into no-tillage wide row (NTWS), no-tillage narrow row (NTNS), conventional tillage wide row (CTWS), and conventional tillage narrow row (CTNS) plots. The wide row treatment had 76 cm (30 in) row spacing while the narrow row treatments had either 19 cm (7.5 in.), 25 cm (10 in), or 38 cm (15 in) spacing. Several Center of Excellence sites did not include the NTWS or CTWS treatments, because wide row soybean was not meaningful for their location.

This report focuses on the data collected from 1998 through 2002, since the 1997 data set had several missing treatments. Also, since most data collected at an individual location was not replicated, the locations within a year were used as replicates for statistical analysis. Finally, with the exception of soil temperature and water infiltration, which are reported as either differences from conventional tillage or as simple means, data were analyzed using the Tukey method of multiple comparisons (Neter et al., 1985).

Figure 1
Locations of the Center of Excellence sites throughout the United States.

Earthworms. Earthworm populations were estimated for the conventional and no-till treatments by removing a 25 × 25 × 25-cm (15,625 cm^3) cube of soil (10 × 10 × 10-in or 1000 in^3) and placing it on a clear plastic sheet. Samples were collected in the spring during April to mid-May. Each cube of soil was hand sorted to find the total number of earthworms (Blair et al., 1996). At least six random samples were collected from each of the four tillage treatments. The counts for each sample were multiplied by 160,000 and averaged to estimate the number of earthworms per hectare to a depth of 25 cm (10 in). These counts were made to characterize the total earthworm population as an indicator of activity among tillage systems and across sites and not to separate individual species.

Soil bulk density. Soil bulk density samples were collected in the 0 - 20 cm (0-8 in) depth in mid-June, near the crop row (to avoid wheel tracks), approximately ¼, ½, and ¾ of the distance across each tillage plot. Collection, weighing, drying, and calculations followed the procedures outlined by Arshad et al. (1996).

Surface residue. Crop residue remaining on the soil surface within one week after planting was measured at a 45˚ angle to the rows using the line transect method (Shelton et al., 1993). The measurements were made ¼, ½, and ¾ of the distance across each tillage plot.

Percent crop emergence. Stand counts were taken to determine the validity of grower concerns regarding poor emergence with conservation tillage. The number of established plants was determined for all corn and soybean treatments approximately one-week after emergence. Three random counts, 5.3 m (17 ft 5 in) of row length, were taken throughout each plot. The number of plants per row length was used to calculate the number of plants per hectare (2.47 ac). This number was divided by the intended planting rate to estimate the percent emergence

Air and soil temperature. Soil temperatures were recorded every hour using either a HOBO temperature/external logger or a Watchdog Model 125[1] internal/external temperature logger at a 5 cm (2 in) soil depth and 46 cm (18 in) above the soil surface within the no-tillage, strip tillage and conventional tillage treatments. The logger was placed in a radiation shield and supported 18-inches above the soil surface. A six foot cable was threaded through flexible polyethylene tubing with an inside diameter from 0.48 to 0.64 cm (3⁄16 to ¼ in). The tubing extended from the radiation shield to one-inch under the soil surface to prevent rodent damage. The cable was laid on the bottom of a trench 5 cm (2 in) below the soil surface so that the tip of the probe was at least 5 to 10 cm (3 to 5 in) from the radiation shield support. The soil was placed back into the trench and pressed firmly. Any residue removed from

Table 1. Location and information about each Monsanto Centers of Excellence site from which data was collected (1998-2002).

Location	Years	Years experience with no-till or strip till prior to study	Soil type
Streator, IL	1998-2002	0	Harco silt loam - Fine-silty, mixed, superactive, mesic Aquic Argiudolls Patton silty clay loam - Fine-silty, mixed, superactive, mesic Typic Endoaquolls
Sullivan, IL	1997-2002	0	Drummer silty clay loam - Fine-silty, mixed, superactive, mesic Typic Endoaquolls Flanagan silt loam - Fine, smectitic, mesic Aquic Argiudolls
Woodburn, IN	1997-2002	0	Hoytville clay loam - Fine, illitic, mesic Mollic Epiaqualfs
Atlantic, IA	2001-2002	0	Marshal silty clay loam-Fine-silty, mixed, mesic Typic Hapludolls
Rippey, IA	1997-2000	5	Nicollet loam - Fine loamy, mixed, mesic Aquic Hapludolls Clarion loam - Fine -loamy, mixed, mesic Typic Hapludolls Webster clay loam - Fine-loamy, mixed, mesic Typic Hapludolls
Centreville, MD	1999-2000	0	Sassafras - Fine-loamy, siliceous semiactive, mesic Typic Hapludults
Clayton, MI	1997-2002	6	Blount silt laom - Fine, illitic, mesic Aeric Epiaqualfs Morley silty clay loam - Fine, illitic, mesic Oxyaquic Hapludalfs
Easton, MN	1997-2002	6	Okoboji silty clay loam - Fine, smectitic, mesic Cumulic Vertic Endoaquolls Guckeen silty clay loam - Fine, smectitic, mesic Aquertic Hapludolls Canisteo clay loam - Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls Nicollet clay loam - Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
Madison, MN	2000-2002	0	Poinsett silty clay loam - fine-silty, mixed Udic Hapioborolls Waubay silty clay loam - fine-silty, mixed Pachic Udic Haploborolls Colvin silty clay loam - fine-silty, frigid Typic Calciaquolls
Mapleton, MN	2001-2002	0	Marna silty clay - Fine, smectitic, mesic Vertic Epiaquolls Lura silty clay - Fine, smectitic, mesic Cumulic Vertic Epiaquolls Guckeen silty clay loam - Fine, smectitic, mesic Aquertic Hapludolls Beauford clay - Very-fine, smectitic, mesic Typic Epiaquerts
Napton, MO	1999-2002	0	Winterset silty clay loam - Fine, smectitic, mesic Typci Argiaquolls Joy silt loam - Fine-silty, mixed, superactive, mesic Aquic Hapludolls Leslie silt loam - Fine, smectitic, mesic Argiaquic Argialbolls Monona silt loam - Fine-silty, mixed, superactive, mesic Typic Hapludolls
Van Buren, OH	1999-2002	0	Pewamo clay loam - Fine, mixed, active, mesic Typic Argiaquolls Blount silt loam - Fine, illitic, mesic Aeric Epiaqualfs
Menomonie, WI	1999-2002	6	Dakota loam - Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiudolls Pillot silt loam - Fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiudolls

the soil surface prior to installation was replaced. The data from each temperature station was downloaded every two weeks.

In-row soil and air temperatures were collected on an hourly basis from April 1 to June 30 each year for the no-tillage, strip-tillage, and conventional tillage systems. Daily soil temperature for each of the corn tillage systems was determined by averaging the hourly values for the 24-hour period. The temperatures were averaged within each of four time periods (April 1-15, April 16-30, May 1-15, and May 16-31) for each year and tillage system. The data were standardized by subtracting the conventional tillage value from the corresponding no-tillage and strip-tillage values within each time period for every Center of Excellence site/year combination. The temperature differences within a year were first averaged across Center of Excellence sites and then across all five years for each of the three tillage treatments.

Water infiltration. Water infiltration rates were determined for only the no-tillage, NTS, CTC, and CTS using a single-ring infiltrometer (Lowery et al., 1996). The data were simply averaged for each tillage treatment across sites and years. The variation in soil types and number of years in no-tillage created too much variation in the infiltration values for statistical evaluations.

Soil quality indicators. Composite samples from the 0 to 10- and 10 to 20-cm depth were collected in 2001 within each treatment by cooperators at 10 Center of Excellence sites and submitted to the National Soil Tilth

Laboratory (NSTL) where the soil was analyzed using standard methods. Bulk density (BD) was estimated using a modified core method (Blake and Hartge, 1986), in which soil moisture content, determined by drying a sub sample of the cored soil at 105°C, was used to convert the total mass of the field-moist soil core to an oven-dry weight. Soil pH and electrical conductivity (EC) were measured in water using 5 g air dry soil and 5 ml deionized water in a 1:1 soil:water ratio (Watson and Brown, 1998; Rhoades, 1982). Water-stable macro-aggregates (MA) were determined using the methods described by Cambardella and Elliott (1993) and expressed as a percentage of the total soil in aggregates greater than 250 µm in diameter. Soil organic carbon (C), total nitrogen (N), and particulate organic matter C (POM) were determined using the air-dried 2-mm-sieved soil. Total C (after removal of carbonates with 1 M H_2SO_4) and N were measured using dry combustion methods in a Carlo-Erba NA1500 NCS* elemental analyzer (Haake Buchler Instruments, Paterson, NJ). POM was isolated and quantified according to methods described by Cambardella and Elliott (1992) using dry combustion. Phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations were measured by inductively coupled plasma emission spectroscopy (ICP) after extraction with the Mehlich III solution (Mehlich, 1984). Copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were also determined by ICP after extraction with DTPA (diethylenetriaminepentaacetic acid) as discussed by Whitney (1998).

After evaluating tillage effects for each indicator, index values and an overall soil quality index were calculated using the Soil Management Assessment Framework for each site and depth increment. Bulk density, pH, EC, MA, C, and P values were transformed with non-linear scoring curves to create unitless scores that reflect performance of soil functions (Andrews et al., 2002; Cambardella et al., 2004). The shape of each scoring curve is typically some variation of a bell-shape ('mid-point optimum'), sigmoid with an upper asymptote ('more is better'), or sigmoid with a lower asymptote ('less is better') (sensu Karlen and Stott, 1994). Each curve was adjusted for geographic location, thus accounting for inherent organic matter class (taxonomic suborder), texture, climate, sampling time, mineralogy, region, slope, and analytical method for P. Higher index scores and overall soil quality index values are considered to indicate better soil quality. Further information about the theory and development of the Soil Management Assessment Framework can be found in Andrews et al. (2004).

Data for each indicator and the overall soil quality index were analyzed statistically by site and by depth using a general linear model (GLM) procedure (SAS Institute, 1992). However, because of the experimental design and limited number of samples it was not possible to differentiate among all of the treatments (e.g. corn vs. soybean, strip-till vs. no-till, or conventional tillage vs. fast-start). The treatments were therefore classified as either conventional or no-tillage with 'strip-tillage' being grouped with "no-tillage" and 'fast-start' being grouped with "conventional" tillage.

Meteorological conditions. Daily air temperature and rainfall were collected from each Centers of Excellence site from April through October of each year. Weather data for the November through March period was downloaded from the Midwest Regional Climate Center for the NOAA Weather Station nearest each site.

Production practices and costs. Fertilizer rate, amount, and timing were constant across tillage and crop treatments at each Center of Excellence site, but varied among Center of Excellences. Depending upon location, fertilizer was applied either in the fall, split between fall and spring, or at planting in a 2×2 band followed by a side-dress application. A majority of the Center of Excellence sites applied starter fertilizer with the planter to all tillage treatments.

Corn hybrid, soybean variety, and planting rates at each Center of Excellence were representative of the area around each site. The desired plant population for corn was constant for all tillage treatments at a given Center of Excellence, but varied from site to site. Soybean planting rates within a site were constant for a given row spacing in both no-tillage and conventional tillage treatments. However, the narrow row soybean treatment had a higher planting rate than the wide-row treatments. Herbicides were applied as needed following programs that were typical for each Center of Excellence site.

Seed, fertilizer, and pesticide cost information were supplied by the producer. Operational costs were determined using the average custom rate for tillage, fertilizer application, planting, pesticide application, and harvest in the state where the Center of Excellence was located. The operation costs accounted for fuel, labor, depreciation, maintenance, and repairs. The cost of transporting grain from the field to storage was set at \$0.003 kg^{-1} (\$0.07 bu^{-1}) for all sites. A six-month, 10 percent interest fee was calculated for all input expenses incurred from mid-April to harvest the following fall. The production cost for a tillage treatment was calculated by summing of the seed, fertilizer, pesticide, operation, hauling, and interest expenses each year. These costs were averaged across all years and Center of Excellence sites. Land rent was not included in the production cost because of the large variability among Center of Excellences.

Crop yield. Corn and soybean yield were measured with calibrated yield monitors or weigh wagons at each site. Corn yields were adjusted to a water content of 150 g kg^{-1} (15 percent), while the soybeans yields were adjusted to a water content of 130 g kg^{-1} (13 percent). Yields for each tillage treatment were statistically analyzed using sites within a year as replicates.

Crop profit. Income was calculated by multiplying the corn yields (kg ha^{-1}) by \$0.079 kg^{-1} (\$2.00 bu^{-1}) and soybean yields (kg ha^{-1}) by \$0.184 kg^{-1} (\$5.00 bu^{-1}), which did not include commodity payments. These prices were selected as being representative of the study period to match with the production costs used in this study. Profit for each treatment was calculated by subtracting the appropriate production costs from the income. Profits for each tillage system were statistically analyzed using Centers of Excellence sites within a year as replicates.

Crop break even selling price. Break-even selling price were calculated for each tillage system by dividing the five-year average production cost by the five-year average yield. This method was selected because of the variation in price among years and locations. Determining the selling price required to recover the production costs provided a way of normalizing among the locations. The procedures used by Duffy and Smith (2004) were used in these analyses for the different rotations and sites.

Crop rotation profit. Profit for a corn/soybean rotation over the five-year period was calculated by summing the average yearly profit values for both corn and soybean. Annual average profit for the rotation was

determined by dividing by two since both corn and soybean were grown at the Centers of Excellence sites each year. This method provides a way of normalizing across the rotation in an effort to demonstrate changes in profit with tillage practice.

Results and Discussion

Earthworms. Earthworms increase water infiltration and improve soil health (Kladivko, 2001) and are frequently included in farmer assessments of soil health. Earthworm populations increased as soil disturbance decreased and the amount of crop residue increased among the sites. Earthworm populations between no-tillage corn and soybean treatments were not significantly different (Table 2), but both were significantly higher than conventional corn and soybean systems. Populations between conventional corn and soybean treatments were not significantly different. These results concur with other studies that reported earthworm densities increasing with decreasing soil disturbance and increasing organic matter (Blair et al., 1996; Edwards, 1983). The purpose of these measurements were to provide an assessment of the earthworm population as a comparison among tillage systems and no effort was made to separate species or determine the adult vs. juvenile populations within a site.

Soil bulk density. Soil compaction has been cited as a major concern of producers considering the switch to conservation tillage systems (Nowak and Pierce, 2000). The average bulk density values for corn and soybean tillage systems in this study were not significantly different (Table 2). This agrees with a study by Logsdon and Cambardella (2000) who concluded that concerns about compaction of Nicollet, Clarion, and Canisteo soils at two central Iowa sites as a result of no-tillage were unwarranted. Several research studies have shown that well structured soils and soils with macropores and fractures provide a network for root growth and water infiltration, often resulting in no yield reduction, even when the soil is compacted (Voorhees et al., 1989; Logsdon et al., 1992; Kasper et al., 1995; Logsdon and Cambardella, 2000)

Bulk density values can increase with reduced tillage as we found at one Centers of Excellence site where the no-tillage corn, no-tillage soybean, and strip-tillage corn treatments increased with time while values for the conventional tillage corn, conventional tillage soybean, and fast start corn systems remained the same. Through further investigation, however, it was found that the producer was "chasing the combine" with a very large grain cart at harvest time. The producer subsequently fall-ripped the fast start corn, conventional tillage corn, and soybean systems to remove the soil compaction created by the grain cart. The no-tillage and strip-tillage treatments were not tilled, resulting in higher and potentially root-limiting soil bulk densities. Subsequently, the entire site was deep ripped, but the data were still not included because the producer did not attempt to minimize soil compaction by using a controlled wheel pattern. Overall, the bulk density data indicates that soil compaction in strip tillage and no-tillage systems should not be a problem if wheel patterns are controlled and caution is exercised when operating large equipment in the field.

Table 2. Average (1998 - 2002) earthworm population, soil bulk density, surface residue, and crop emergence for no-tillage and conventional tillage corn and soybean at 13 Monsanto Centers of Excellence sites.

Tillage systems	Earthworms / hectare (x 100,000)	Soil bulk density (gm / cm3)	Crop residue (percent)	Crop emergence† (percent)
Strip tillage corn	— ‡	1.19[a]	53.2[b]	94[a]
No-tillage corn	12.86[a§]	1.23[a]	65.2[ab]	92[a]
Fast start corn	— ‡	1.20[a]	22.8[c]	94[a]
Conventional tillage corn	5.36[b]	1.20[a]	16.1[c]	94[a]
Conventional tillage soybeans (wide row)	4.76[b]	1.20[a]	27.8[c]	71[a]
Conventional tillage soybeans (narrow row)	— ‡	— ‡	— ‡	85[a]
No-tillage soybeans (wide row)	10.07[a]	1.24[a]	76.8[a]	73[a]
No-tillage soybeans (narrow row)	— ‡	— ‡	— ‡	84[a]

† The statistical differences are only within a crop and not between crops.

— ‡ Data was not collected for the practice.

§ Means within a row followed by the same letter are not significantly different (P>0.05).

Surface residue. Surface residue is known to reduce erosion by minimizing raindrop splash and creating small dams that slow runoff velocity (Adams, 1966; Kramer and Meyer, 1969; Mannering and Meyer, 1963; Meyer et al., 1970). The mini-dams can also pond water on the soil surface giving it a greater chance to infiltrate into the soil. The reduction of raindrop impact by crop residue reduces surface crusting (Golabi et al., 1988), thereby increasing infiltration. Crop residue also reduces wind erosion by slowing wind speed and preventing direct wind contact with erodible soil particles (Siddoway et al., 1965).

Crop residue cover increased as the amount of tillage decreased, with the no-tillage soybean treatment having significantly higher cover than the other corn and soybean treatments due the previous corn residue (Table 2). The no-tillage and strip-tillage corn treatments also had a significantly higher crop residue cover than the fast start corn, conventional tillage corn, or conventional tillage soybean. The percent residue cover for fast start corn, conventional tillage corn and conventional tillage soybean were not significantly different. These Center of Excellence results concur with those published by Kladivko et al (1986) who reported that the percentage of crop residue on the soil surface increased as tillage intensity decreased.

Crop emergence. No-tillage systems are often thought to have poor plant emergence because of cool, wet soil conditions (Nowak, 2000; CTIC, 2003). Corn and soybean emergence were not significantly affected by any of the tillage practices in these studies (Table 2). Emergence of corn was greater than 90 percent while soybean was around 80 percent for the five years of the study (Table 2). Obtaining a stand was not a problem with any of the different tillage methods across the range of sites

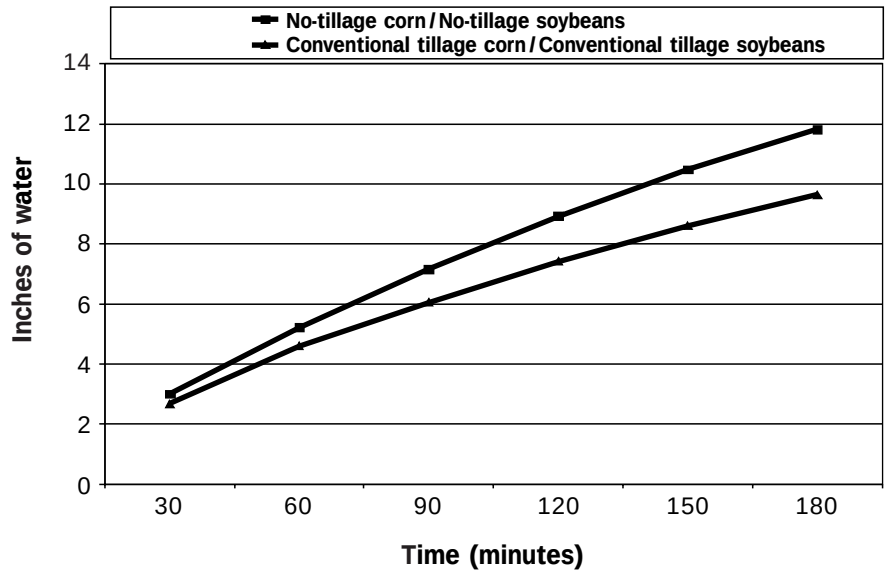
Soil temperature. Cool, wet soil at planting is a major concern expressed by producers for not adopting no-tillage for corn. One reason that no-till soils are often cooler and wetter than tilled soils is that the light colored crop residue has higher sunlight reflectivity than bare soil (Benoit and Lindstrom, 1987). Evaporation from the soil surface is reduced as the surface residue reflects more light. If the residue is removed with row cleaners or similar tools, the soil will start to dry by evaporation. However, as the soil surface dries,

water will move laterally and vertically by capillary action keeping the exposed surface moist for a longer period of time. This results in a slower warm up of the soil seedbed during a wet spring.

To address these concerns, strip-tillage systems were developed to warm and dry a narrow strip of soil similar to conventional tillage. In these Center of Excellence studies, the strip-tillage treatment had soil temperatures similar to the conventional treatment and higher than no-tillage. The 5-year average soil temperature for the strip-tillage was 0.2˚C (0.3˚F), 0.2˚C (0.3˚F), 0.0˚C (0.0˚F), and 0.3˚C (0.6˚F) lower than with conventional tillage for the April 1-15, April 16-30, May 1-15, and May 16-31 time periods, respectively. In comparison, the 5-year average soil temperature for no-tillage was 0.4˚C (0.8˚F), 0.7˚C (1.2˚F), 0.8˚C (1.5˚F), and 0.9˚C (1.6˚F) lower than the conventional tillage treatment, respectively. This study thus verifies that strip-tillage does warm and dry the soil within the strip and is a viable way to overcome producer concerns regarding soil temperature at planting.

Figure 2

Average single ring infiltration rates for soils under a no-tillage or conventional tillage corn / soybean rotation at Monsanto Centers of Excellence sites that have been no-tilled or strip tilled for 1 to 12 years. The infiltration rates were not significantly different and varied from + 1.5 to + 4.9 inches.



Water infiltration. Many long-term no-tillage farmers have noted improvements in water infiltration and decreases in soil erosion (CTIC, 2003). The average water infiltration rate for all of the no-till and conventional corn/soybean rotations was 30 cm (11.8 in) and 24 cm (9.6 in) in a three-hour period, respectively (Figure 2). Provided wheel-traffic is well managed, infiltration rates will generally increase as the number of years that a field is no-tilled increases. For example, at the Easton, MN site where the no-till treatment was well established (Table 1), the no-till plots had an infiltration rate of 13 cm hr^{-1} in 2002 compared to 3.6 cm hr^{-1} for the conventional treatment. In contrast, the Mapleton, MN site which is approximately 27 km north of the Easton site with only a 2-year no-till history had similar infiltration rates for the no-till (8.6 cm hr^{-1}) and conventional (9.3 cm hr^{-1}) systems. These results were similar to Sauer et al. (1990) who found that ponded infiltration for no-tillage soils was equal to or greater than tilled soils. Azooz and Arshad (1996) also found that long-term no-tillage systems generally had higher ponded infiltration rates than conventional tillage systems when the soil was dry, near field capacity, or at field capacity.

Soil quality indicators. Very few significant differences ($P \leq 0.1$) were found among the soil quality indicators measured for the 0 to 10- and 10 to 20-cm depth increments. Soil pH was significantly higher in no-tillage than conventional tillage at the Lenawee, Michigan site (6.4 vs. 6.2, respectively) but only in the top 10 cm. No-tillage resulted in a greater percentage of water stable aggregates (>250μ) in the surface 10 cm at the Woodburn, IN (400 vs. 500 g kg^{-1} for conventional vs. no-till, respectively) and Mennomonie, WI (437 vs. 539 g kg^{-1}, respectively), but none of the sites had significant differences at the 10 to 20-cm depth increment. The Sullivan, IL (24.3 vs. 19.3 and 22.8 vs. 17.6 g kg^{-1}) and Easton, MN (37.7 vs. 32.7 and 33.3 vs. 28.4 g kg^{-1}) sites showed significant differences in the total carbon content for both the 0 to 10- and 10 to 20-cm depth increments, but the higher amounts of total organic C were found with conventional tillage rather than with no-tillage.

The index values calculated using the Soil Management Assessment Framework showed no significant differences between conventional and no-tillage treatments for either depth increment. On a scale of 0 to 100, the overall soil quality index values averaged 68 and 71 or 66 and 71 for the conventional and no-tillage treatments at the 0 to 10- or 10 to 20-cm depth increments, respectively. The individual indicator scores showed that organic C, aggregate stability, and bulk density had the lowest values for the indicators measured, but none of the differences between tillage systems were significant (data not presented). Variability associated with the non-replicated field plot design, length of time that the tillage practices were imposed, and the limited number of soil samples (~70 for each depth from the ten sites) presumably contributed to this result. Finally, although Soil Management Assessment Framework scoring curves have not been developed for all of the measured indicators, our analysis showed that DTPA extractable Zn levels at the Sullivan, IL site were below the 0.9 μg g^{-1} level at which Zn fertilizer would be recommended in Iowa (Sawyer et al., 2003). Soil test K, although probably not yield limiting was also lower than might be desired for future Center of Excellence studies.

Weather. Monthly rainfall and growing degree days were similar to the 30-year average when averaged across sites, although in 3 of 5 years, the monthly average rainfall was greater than the 30-year average. Easton, MN and Woodburn, IN are examples of the differences among sites. The annual patterns at Easton, MN showed typically wet springs through June followed by average amounts for the remainder of the year. In contrast, the precipitation at Woodburn, IN showed wet springs with drier than normal summers. Although, the average conditions across the Centers of Excellence sites were near normal,

Table 3. Five-year average production cost for tillage systems for corn and soybean sites across the Monsanto Centers of Excellence study for 1998-2002.

Crop	Tillage system	Production component cost ($ ha^{-1})						
		Seed	Fertilizer	Pest control	Operation	Haul	Interest	Total
Group A corn	Strip tillage	97.69	136.71	82.20	145.43	26.55	24.43	513.00
	No-tillage	97.91	141.21	83.71	125.03	25.91	23.69	497.00
	Fast start	97.44	139.51	76.08	157.73	26.55	24.87	522.00
	Conventional tillage	97.44	140.54	73.46	164.38	26.90	25.14	528.00
Group B corn	Strip tillage	93.86	139.18	80.50	146.67	26.28	24.33	511.00
	No-tillage	94.01	143.85	83.31	125.01	25.81	23.59	496.00
	Conventional tillage	93.59	144.79	72.45	166.48	26.45	25.19	529.00
Soybean	Conventional tillage (wide-row)	63.98	34.16	49.17	156.46	7.63	15.53	327.00
	Conventional tillage (narrow-row)	73.61	34.16	46.03	155.41	7.75	15.81	333.00
	No-tillage (wide- row)	64.11	34.16	55.07	110.27	7.48	13.52	285.00
	No-tillage (narrow-row)	73.19	34.16	51.18	110.38	7.84	13.80	291.00

Muliply $ ha^{-1} by 0.405 to obtain $ ac^{-1}

the variations within an individual site become dominant when evaluating the effect of different tillage practices.

Differences in average number of growing degree days ranged from 1 to 52 when computed for all sites over the five-year period. Seasonal weather patterns were generally not a major factor in these studies except for the Clayton, Michigan, Woodburn, Indiana, and Van Buren, Ohio sites, which had a wet spring. This delayed planting, and subsequently when rainfall decreased substantially from the 30-year average, decreased crop yield by up to 50 percent compared to the previous three-year average. Across the sites, the general observation about weather was that precipitation was more variable among sites than temperature and differences in growth and yield response can be attributed to soil water more than soil temperature.

Corn production cost. All 13 Center of Excellence sites included in this study evaluated no-tillage, strip- tillage, and conventional tillage corn production systems. The "fast start" system was included at nine of the 13 sites. Results for these two groups were different and are discussed separately. Group A includes the nine sites with no-tillage, strip-tillage, fast start, and conventional tillage systems. Group B includes all 13 sites, but will focus only on the no-tillage, strip-tillage, and conventional tillage treatments.

Within Group A, the five-year average production cost for no-tillage was $16, $25, and $31 ha^{-1} ($6, $10, and $13 ac^{-1}), lower than strip-tillage, fast start, and conventional tillage systems, respectively (Table 3). The five -yr average production cost for no-tillage in Group B was $15 and $33 ha^{-1} ($6 and $13 ac^{-1}), lower than strip-tillage and conventional tillage, respectively (Table 3). Differences in production costs can be attributed mainly to herbicide and tillage. In Group A, strip-tillage, fast start, and conventional tillage required 1.0, 1.7, and 2.0 tillage passes per growing season, respectively, while in Group B, strip-tillage and conventional tillage required 1.0 and 2.0 tillage passes. The Missouri, Illinois, Wisconsin, Michigan, Indiana, Ohio, and Maryland sites also required an additional pre-emergence herbicide application in some years to control

Table 4. Annual and five-year average and standard deviations of yield and profit for four tillage systems for Group A corn sites across the Monsanto Centers of Excellence study for 1998-2002.

Tillage system	1998	1999	2000	2001	2002	Average
	Yield (kg / ha)*					
Strip tillage	10536 (1574)	9971 (972)	9720 (1492)	9218 (1612)	9093 (3970)	9708 (1924)
No-tillage	10159 (1273)	9971 (1154)	9344 (1693)	9156 (1637)	8717 (3913)	9469 (1934)
Fast start	10410 (1329)	10222 (1191)	9595 (1687)	9218 (2026)	9030 (3738)	9695 (1994)
Conventional tillage	10410 (1662)	9971 (1292)	9783 (1718)	9281 (1906)	9595 (3844)	9808 (2084)
	Profit ($ / ha)§					
Strip tillage	315 (164)	268 (118)	267 (130)	204 (132)	205 (333)	252 (175)
No-tillage	300 (135)	282 (122)	241 (119)	219 (120)	196 (324)	248 (164)
Fast start	286 (127)	261 (120)	254 (150)	198 (161)	205 (326)	241 (177)
Conventional tillage	275 (182)	243 (122)	257 (122)	199 (147)	243 (317)	243 (178)

*** Multiply kg ha^{-1} by 0.0159 to obtain bu ac^{-1}**

§ Multiply $ ha^{-1} by 0.405 to obtain $ ac^{-1}

Standard deviation of the Centers of Excellence sites in parenthesis.

Table 5. Annual and five-year average and standard deviations of yield and profit for four tillage systems for Group B corn sites across the Monsanto Centers of Excellence study for 1998-2002.

Tillage system	1998	1999	2000	2001	2002	Average
			Yield (hg/ha)*			
Strip tillage	10535 (1568)	9532 (1568)	9344 (1881)	9532 (1819)	8779 (3574)	9544 (2069)
No-tillage	10222 (1254)	9595 (1505)	8968 (1881)	9407 (1693)	8591 (3449)	9357 (1944)
Conventional tillage	10410 (1630)	9469 (1756)	9407 (2007)	9595 (1944)	9093 (3512)	9595 (2195)
			Profit ($/ha)§			
Strip tillage	314 (164)	218 (181)	245 (121)	231 (148)	193 (302)	240 (183)
No-tillage	303 (135)	236 (174)	226 (107)	242 (131)	202 (290)	241 (167)
Conventional tillage	273 (181)	192 (182)	236 (119)	218 (154)	215 (283)	227 (183)

* Multiply kg ha^{-1} by 0.0159 to obtain bu ac^{-1}

§ Multiply $ ha^{-1} by 0.405 to obtain $ ac^{-1}

Standard deviation of the Centers of Excellence sites in parenthesis.

winter annual and perennial weeds in no-tillage, strip-tillage, and fast start treatments.

Corn yields. Yield is an important variable in determining profitability but should not be used as the only measurement when comparing tillage systems. Grain yield within years was not significantly different among tillage systems for either Group A or B (Table 4 and 5). Numerically, conventional tillage in Group A had a five-year average yield 100, 113, and 339 kg ha^{-1} (1.6, 1.8, and 5.4 bu ac^{-1}) greater than for strip-tillage, fast start, and no-tillage, respectively, with differences among the four tillage treatments ranging from 0 to 878 kg ha^{-1} (0 to 14 bu ac^{-1}). The largest yield differences between conventional tillage and the other treatments were at the Clayton, Michigan; Easton, Minnesota; Madison, Minnesota; Mapleton, Minnesota; Woodburn, Indiana; Van Buren, Ohio; and Menomonie, Wisconsin sites in 2002, presumably because of the cool, wet planting seasons experienced at each site. The weather patterns at each site showed greater precipitation during the spring compared to normal.

For Group B, the five-year average yield for conventional tillage was 51 and 238 kg ha^{-1} (0.8 and 3.8 bu ac^{-1}) higher than for strip-tillage or no-tillage (Table 5). Yield differences among strip tillage, no-tillage, and conventional tillage treatments during the 1998-2002 time period ranged from 63 to 502 kg ha^{-1} (1 to 8 bu ac^{-1}). Once again, the largest differences between tillage systems occurred in 2002 because of the wet cool planting conditions at the Clayton, Michigan; Easton, Minnesota; Madison, Minnesota; Mapleton, Minnesota; Woodburn, Indiana; Van Buren, Ohio; and Menomonie, Wisconsin sites. The large variation in average yield during 2002 was primarily caused by lower yields at the Michigan, Indiana, and Ohio sites (33-70 percent of the previous 3-yr average). This was attributed to having a very wet spring followed by a post-emergence drought at these sites. Overall, the Group B sites showed approximately 50 percent less yield difference than Group A when comparing conventional tillage with the strip- or no-tillage systems. We attribute this to having fewer sites with atypical weather.

Yield differences measured in this study were also similar to those found by others. For example, Al-Kaisi (2002) reported that compared to no-tillage, yield differences for moldboard plowing, ridge tillage, reduced tillage, field cultivation, and strip-tillage were 5 percent or less. Hoeft et al. (2000) found no significant yield difference between no-tillage, strip-tillage, and a two-pass conventional tillage system in a 1999 Illinois study. Similarly, Vetsch and Randall (2002) reported a 3-yr average yield range of only 438 kg ha^{-1} (7 bu ac^{-1}) for strip-tillage, rip-strip, one pass, and no-tillage systems at Waseca, MN. Strip-tillage had the highest yield among the four treatments at Waseca, however profitability of the tillage systems was not determined for any of the studies.

Corn profit. The large variability in environmental conditions and production practices among the 13 Centers of Excellence sites resulted in no statistically significant differences in profit. However, no-tillage and strip-tillage showed the highest profit in 4 of 5 years (Table 4). Within Group A, strip-tillage had a 5-yr average profit that was $4, $9, and $11 ha^{-1} ($2, $3, and $11 ac^{-1}) higher than no-tillage, conventional tillage and fast start systems, respectively. In 1998 and 2000, the strip-tillage system had a $10 to $40 ha^{-1} ($4 to $16 ac^{-1}) higher profit than the other three systems, while in 1999 and 2001 no-tillage had a $13 to $39 ha^{-1} ($5 to $16 ac^{-1}) higher profit. Conventional tillage had the highest profit ($38 to $47 ha^{-1} or $15 to $18 ac^{-1}) only in 2002.

Within Group B, no-tillage and strip-tillage showed the highest profit in 4 of 5 years (Table 5). The five-yr average profit for no-tillage was $1 and $15 ha^{-1} ($0.40 and $6 ac^{-1}) higher than for strip-tillage and conventional tillage, respectively. In 1998 and 2000, strip-tillage had a $9 to $40 ha^{-1} ($4 to $16 ac^{-1}) higher profit than the other two systems, while in 1999 and 2001, no-tillage had $11 to $44 ha^{-1} ($4 to $18 ac^{-1}) higher profit. Once again, conventional tillage had the higher profit ($14 to $22 ha^{-1} or $6 to $9 ac^{-1}) higher profit only in 2002.

Higher profits for no-tillage and strip-tillage confirm that yield should not be the predominant factor when making decisions regarding adoption of tillage practices. Lower production costs ($31 to $33 ha^{-1}) for the no-tillage can offset 408 kg ha^{-1} (6.5 bu ac^{-1}) lower yield when compared to conventional tillage. Similarly, lower production costs for strip-tillage ($15 to $18 ha^{-1}) can offset approximately 219 kg ha^{-1} (3.5 bu ac^{-1}) compared to conventional tillage and still obtain a similar profit.

Corn break even selling price. The break even selling price was lower for no-tillage and strip-tillage than for fast start or conventional tillage, meaning that a producer could receive a lower price for their grain and still make a higher profit with either conservation tillage system. For Group A, the 5-yr average break-even cost was $0.0524, $0.0528, and $0.0539 kg^{-1} ($1.33, $1.34, and $1.37 bu^{-1}) for no-tillage, strip-tillage, and both fast start and conventional tillage, respectively.

Table 6. Annual and five-year average and standard deviations of yield and profit for four tillage systems soybean sites across the Monsanto Centers of Excellence study for 1998-2002.

Tillage system	1998	1999	2000	2001	2002	Average
			Yield (kg/ha)*			
Conventional tillage (wide-row)	3360 (383)	2956 (338)	2419 (797)	2889 (610)	3158 (598)	2956 (545)
Conventional tillage (narrow-row)	3494 (361)	2889 (347)	2553 (640)	2889 (693)	3225 (625)	3010 (533)
No-tillage (wide-row)	3494 (497)	2822 (239)	2352 (788)	2755 (660)	3091 (859)	2903 (609)
No-tillage (narrow-row)	3494 (517)	2956 (376)	2620 (468)	2956 (580)	3225 (757)	3050 (540)
			Profit ($/ha)§			
Conventional tillage (wide-row)	275 (46)	176 (111)	151 (116)	232 (150)	240 (151)	215 (50)
Conventional tillage (narrow-row)	294 (61)	164 (109)	163 (80)	231 (157)	245 (160)	219 (51)
No-tillage (wide-row)	334 (87)	185 (89)	174 (93)	253 (147)	280 (202)	245 (57)
No-tillage (narrow-row)	331 (92)	206 (127)	209 (44)	288 (129)	298 (183)	266 (52)

* Multiply kg ha^{-1} by 0.0159 to obtain bu ac^{-1}

§ Multiply $ ha^{-1} by 0.405 to obtain $ ac^{-1}

Standard deviation of the Centers of Excellence sites in parenthesis.

The 5-yr average break even cost for Group B was $0.0531, $0.0535, and $0.0551 kg^{-1} ($1.35, $1.36, and $1.40 bu^{-1}) for no-tillage, strip-tillage, and conventional tillage, respectively.

Soybean production cost. The five-yr average production cost was lowest for no-tillage (Table 3), primarily because it required zero tillage passes compared to an average of 2.3 passes with conventional tillage. With regard to row spacing, narrow row soybean had a higher production cost than wide rows because of added seed cost and a higher custom rate.

Soybean yield. There were no significant yield differences among the four soybean treatments when evaluated on a yearly basis (Table 6, although the no-tillage narrow row system yielded 0 to 268 kg ha^{-1} (0 to 4 bu ac^{-1}) more than the conventional narrow- or wide-row, and no-tillage wide row treatments. Averaged for the five years, the no-tillage narrow row system produced 147, 40, and 94 kg ha^{-1} (2.2, 0.6, and 1.4 bu ac^{-1}) more than the no-tillage wide row or conventional tillage narrow- and wide-row treatments, respectively.

Soybean profit. As reported for corn, high variability in environmental conditions and production practices among the 13 Centers of Excellence sites resulted in no significant profit differences among the four soybean treatments (i.e. wide and narrow row, conventional and no-tillage). The five-yr average profit, however, was highest for the no-tillage narrow row system (Table 6). Compared to the no-tillage wide row, the conventional tillage narrow row, and conventional tillage wide row treatments, the no-tillage narrow row system had a five-yr average profit that was $21, $47, and $51 ha^{-1} ($9, $19, and $21 ac^{-1}) higher than for the other practices, respectively (Table 6). Data also show that no-tillage wide-row soybean returned $11 to $59 ha^{-1} ($4 to $24 ac^{-1}) more than conventional tillage wide- and narrow-row treatments. Similarly, the no-tillage narrow row system returned $30 to $58 ha^{-1} ($12 to $23 ac^{-1}) more than the conventional tillage wide- and narrow-row treatments. Except for 1998, the no-tillage narrow row treatment had a higher profit than no-tillage wide-row soybean.

Higher profits for no-tillage soybean support the argument that yield should not be the major factor when making decisions about tillage. Lower no-tillage production costs ($36 to $48 ha^{-1}) when compared to conventional tillage can offset approximately 195 to 262 kg ha^{-1} (3 to 4 bu ac^{-1}) in yield loss without reducing profit.

Soybean break-even cost. The break even selling price was lower for no-tillage soybean than for the conventional tillage, demonstrating again that a producer could receive a lower price for no-tillage commodities and still make a higher net profit. The lowest break even selling price was $0.095 kg^{-1} ($2.60 bu^{-1}) for no-tillage narrow row soybean, followed by $0.098 kg^{-1} ($2.67 bu^{-1}) for no-tillage wide row and $0.111 kg^{-1} ($3.01 bu^{-1}) for conventional tillage narrow- and wide-row soybean.

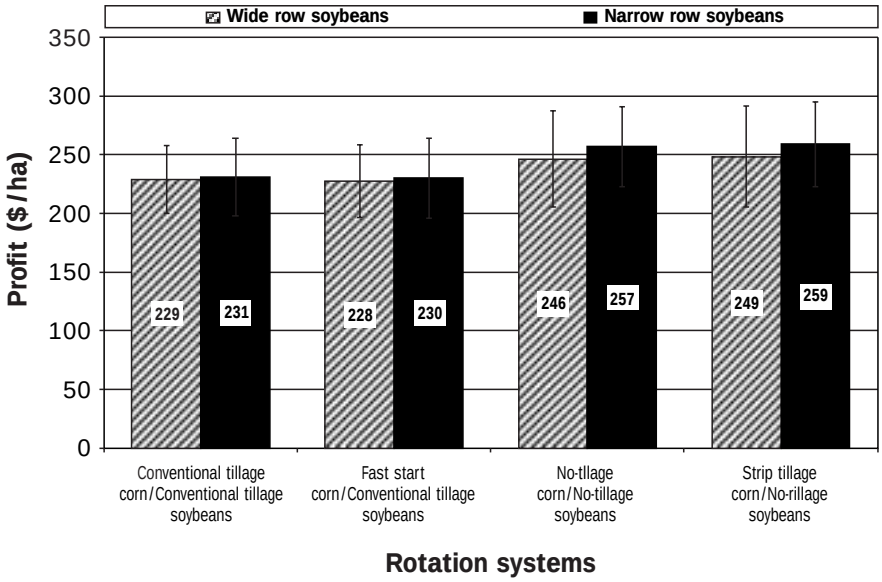
Corn/soybean rotation profit. The no-tillage and strip-tillage corn/soybean rotation systems had higher average yearly profits than the fast start and conventional tillage corn/soybean rotation systems but the profit differences between all eight systems were not were not significantly different (Figure 3). The total five-yr profit for strip-tillage or no-tillage corn followed by no-tillage narrow row soybean was $130 to $145 ha^{-1} ($53 to $59 ac^{-1}) higher than for fast start or conventional tillage corn followed by conventional tillage narrow row soybean (Figure 3). Similarly, the total five-yr for strip-tillage or no-tillage corn followed by no-tillage wide row soybean was calculated to be $85 to $100 ha^{-1} ($34 to $40 ac^{-1}) higher than for fast start or conventional tillage corn followed by conventional tillage wide row soybean.

Summary and Conclusion

Establishment of the Monsanto Centers of Excellence sites has provided important and useful field-scale information regarding tillage systems for corn/soybean rotations. Variability in local environmental conditions, variations in specific management practices at a site, and a generally non-replicated design at individual sites resulted in few statistically significant differences but very consistent trends. An important conclusion drawn from this program is that crop yield should not be the dominant factor used to evaluate tillage systems. No-tillage and strip-tillage corn showed a higher profit in four of five years than conventional or fast start corn production. Production costs for the no-tillage system were $31 to $33 ha^{-1} ($12 to $13 ac^{-1}) lower than for conventional tillage. Therefore, no-tillage could tolerate approximately 408 kg ha^{-1} (6.5 bu ac^{-1}) lower yield

Figure 3

Average overall 5-yr profit of a corn/soybean rotation at Monsanto Centers of Excellence sites (wide row =76 cm (30 in) and narrow row = 18 to 38 cm (7 to 15 in)).



and still return a similar profit for the two systems. Similarly, strip-tillage had ($15 to $18 ha^{-1}) lower production costs than conventional tillage, allowing for approximately 219 kg ha^{-1} (3.5 bu ac^{-1}) lower yield without reducing net profit.

For soybean, the five-yr average profit for no-tillage was higher than for conventional tillage regardless of row width. Once again, lower no-tillage production costs ($36 to $48 ha^{-1}) when compared to conventional tillage allowed for approximately 195 to 262 kg ha^{-1} (3 to 4 bu ac^{-1}) lower yield without creating a difference in profit for the two tillage systems.

Concerns that producers often express in regard to soil quality indicators and other crop production factors (i.e. soil temperature, water infiltration, and plant emergence) in reduced tillage compared to conventional tillage systems were not major issues in this study. Soil bulk density was similar for all tillage treatments provided heavy equipment traffic (e.g. grain carts) was minimized or restricted to a controlled wheel-traffic pattern. Based on the wide variety of conditions encountered at 13 Centers of Excellence sites during the 5-yr study period, producer concerns regarding corn and soybean emergence in no-tillage and strip-tillage systems were not warranted. Earthworm populations were affected by tillage; the no-tillage systems had significantly higher populations than in the conventional tillage systems. Crop residue increased significantly as the amount of tillage decreased. Soil temperatures at the 5 cm (2 in) depth in strip-tillage areas were similar to conventional tillage and warmer than no-tillage corn. Water infiltration rates across the sites were not different and were extremely variable; however, at one site with a long-term (12 yr) no-tillage, the water infiltration rate was 3.6 times faster than conventional tillage. Overall, these production-scale studies confirm the benefits of no-tillage and strip-tillage documented previously in plot-scale studies, but more importantly, they clearly demonstrate that potential profit rather than crop yield should be used when making decisions regarding alternate tillage systems.

Endnote

[1]Mention of a specific trade name or product does not imply preferential treatment or recommendation.

Acknowledgement

The authors would like to acknowledge the following people for hosting a Monsanto Centers of Excellence site: Ron Allen, Blaine Baker, Roy Bardole, Neil Clark, Steve Claussen, Keith Gorrell, Paul Harrison, Kyle Kimpling, Tim Maloney, Steve Monroe, Jeff and Jon Olson, Roger and Mark Rekeweg, Ray Rauenhorst, and the University of Missouri.

The authors would like to acknowledge the following people for data collection at the Monsanto Centers of Excellence sites: Chad Becker, Phil Boeve, Dan Childs, Mark Dostal, Erika Ehler, Curt Fettig, Doug Gray, Steve Griffith, Pete Hill, Jeff Hinen, Phil Holman, Doug Johansen, John Kaufmann, Rob Kauffman, Kyle Kimpling, Hans Kok, Greg Lake, Tom Larson, Bruce Magnus, Tim Maloney, Larry Martin, Dave Mayonado, Bill McKibben, William Parker, Tom Perlick, Tim Reinbott, Aron Robinson, Tami Craig-Schilling, Jim Schneider, Terry Semmel, Steve Spangler, Paul Sprankle, Lance Tarochione, Carl Urwin, Tom Van Wagner, Stacy Ward, Harmon Wilts, and John Woerner.

References Cited

Adams, J.E. 1966. Influence of mulches on runoff, erosion, and soil moisture depletion. Soil Science Society of America Proceeding 30:110-114.

Al-Kaisi, M.M. 2002. Considerations in Selecting No-Till. Publication PM 1901d. Iowa State University Extension, Ames, Iowa.

Andrews, S.S., D.L. Karlen, and J.P. Mitchell. 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agriculture Ecosystem Environment 90:25-45.

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Science Society of America Journal 68:1945-1962.

Arshad, M.A., B. Lowery, and R. Grossman. 1996. Physical test for monitoring soil quality. Pp. 123-141. *In:* J.W. Doran and A.J. Jones. (ed.) Methods for Assessing Soil Quality. Soil Science Society of America Special Publication 49. Soil Science Society of America, Madison, Wisconsin.

Azooz, R.H. and M.A. Arshad. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Canadian Journal of Soil Science 76:143-152.

Benoit, G.R. and M.J. Lindstrom. 1987. Interpreting tillage-residue management effects. Journal Soil and Water Conservation 42(2):87-90.

Blair, J.M., P.J. Bohlen, and D.W. Freckman. 1996. Soil Invertebrates as Indicators of Soil Quality. Pp. 283-284. *In:* J.W. Doran and A.J. Jones. (ed.) Methods for Assessing Soil Quality. Soil Science Society of America Special Publication 49. Soil Science Society of America, Madison, Wisconsin.

Blake, G.R. and K.H. Hartge. 1986. Bulk density. Pp. 363-375. *In:* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd edition Agronomy Monogram 9. American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin.

Cambardella, C.A. and E.T. Elliott. 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Science Society of America Journal 56:777-783.

Cambardella, C.A. and E.T. Elliott. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Science Society of America Journal 57:1071-1076.

Cambardella, C.A., T.B. Moorman, S.S. Andrews, and D.L. Karlen. 2004. Watershed-scale assessment of soil quality in the Loess Hills of Southwest Iowa. Soil and Tillage Research 78:237-247.

Conservation Technology Information Center (CTIC). 2000. National Crop Residue Management Survey. <http://www.ctic.purdue.edu/CTIC/CTIC.html> Accessed July 2002.

Conservation Technology Information Center (CTIC). 2002a. Tillage Type Definitions. 1220 Potter Dr., West Lafayette, Indiana.

Conservation Technology Information Center (CTIC). 2002b. National crop residue management survey results. 1220 Potter Dr., West Lafayette, Indiana.

Conservation Technology Information Center (CTIC). 2003. Economic benefits with environmental protection. 1220 Potter Dr., West Lafayette, Indiana.

Duffy, M. and D. Smith. 2004. Estimated Cost of Crop Production in Iowa—2004. Publication FM 1712. Iowa State University Extension, Ames, Iowa.

Edwards, C.A. 1983. Earthworm ecology in cultivated soils. Pp. 205-230. *In:* C.A. Francis, C.B. Flora, and L.D. King (eds). Sustainable Agriculture in Temperate Regions. Wiley, New York, New York.

Golabi, M.H., D.E. Radcliffe, W.L. Hargrove, E.W. Tollner, and R.L. Clark. 1988. Influence of long-term no-tillage on the physical properties of an Ultisol. *In:* K.H. Remy (ed). Conservation farming: Focus on a better future. Proceedings of the Southern Convservation Tillage Conference, Tupelo, Mississippi.

Hill, P.R. 1998. Fall Strip-till Systems for Corn Production. Integrated Crop Management, Iowa State University Extension, Ames, Iowa.

Hill, P.R. 2001. Use of continuous no-till and rotational tillage systems in the central and northern Corn Belt. Journal Soil and Water Conservation 56(4):286-290.

Hoeft, R.G., E.D. Nafziger, L.C. Gonzini, J.J. Waren, E.A. Adee, L.E. Paul, and R.E. Dunker. 2000. Strip Tillage, N Placement, and Starter Fertilizer Effects on corn Growth and Yield. Illinois Fertilizer Conference Proceedings. University of Illinois Urbana-Champaign, Champaign, Illinois.

Karlen, D.L. and D.E. Stott. 1994. A framework for evaluating physical and chemical indicators of soil quality. Pp. 53-72. *In:* Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (eds.), Defining soil quality for a sustainable environment. Soil Science Society of America Special Publication No. 35. Soil Science Society of America, Madison, Wisconsin.

Kaspar, T.C., S.D. Logsdon, and M.A. Prieksat. 1995. Traffic pattern and tillage system effects on corn root and shoot growth. Agronomy Journal 87:1046-1051.

Kladivko, E.J. 2001. Earthworms and Crop Management. 17th Annual Workshop. Manitoba-North Dakota Zero Tillage Farmer Association. Online manual at: http://www.mandakzerotill.org/book17/worms.html.

Kladivko, E.J., D.R. Griffith, and J.V. Mannering. 1986. Conservation Tillage effects on soil properties and yield of corn and Soya Beans in Indiana. Soil Tillage Research 8:277-287.

Kramer, L.A. and L.D. Meyer. 1969. Small amounts of surface mulch reduce soil erosion and runoff velocity. Transaction American Society of Agricultural Engineers 12:638-645.

Logsdon, S.D., R.R. Allmaras, W.W. Nelson, W.B. Voorhees. 1992. Persistence of subsoil compaction from heavy axle loads. Soil Tillage Research 23:95-110.

Logsdon, S.D. and C.A. Cambardella. 2000. Temporal changes in small depth incremental soil bulk density. Soil Science Society of America Journal 64:710-714.

Lowery, B. and R.T. Schuler. 1991. Temporal effects of subsoil compaction on soil strength and plant growth. Soil Science Society of America Journal 55:571-575.

Lowery, B., W.J. Hickey, M.A. Arshad, and R. Lal. 1996. Soil water parameters and soil quality. Pp. 148-150. *In:* J.W. Doran and A.J. Jones. (ed.) Methods for Assessing Soil Quality. Soil Science Society of America Special Publication 49. Soil Science Society of America, Madison, Wisconsin.

Mannering, J.V. and D.L. Meyer. 1963. Effects of various rates of surface mulch on infiltration and erosion. Soil Science Society of America Proceedings 27:84-86.

Mehlich, A. 1984. Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. Comm. Soil Science and Plant Analysis 15:1409-1416.

Meyer, L.D., W.J. Wischmeier, and G.A. Foster. 1970. Mulch rates required for erosion control on steep slopes. Soil Science Society of America Proceedings 34:928-931.

Neter, J., W. Wasserman, and M.H. Kutner. 1985. Applied Linear Statistical Models. Pp.574-579. Richard D. Irwin Inc, Homewood, Illinois.

Nowak, P. and F.J. Pierce. 2000. Iowa Residue Management Survey 2000; Report to the Iowa Residue Management Partnership.

Randall, G.W., N.B. Senjem, L.M. Busman, T.L. Wagar, and J.F. Moncrief. 2002. Tillage Best Management practices for water quality protection in southeastern Minnesota. Publication BU-07694. University of Minnesota Extension, St. Paul, Minnesota.

Rhoades, J.D. 1982. Soluble salts. *In:* A.L. Page, R.H. Miller, and D.R. Keeney (eds.). Methods of Soil Analysis Part 2. 2nd edition Agronomy Monogram 9. American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin.

SAS Institute. 1992. SAS/STAT guide for personal computers. Pp. 335-355. Version 6.03. SAS Institute, Cary, North Carolina.

Sauer, T.J., B.E. Clothier, and T.C. Daniel. 1990. Surface measurements of the hydraulic character of tilled and untilled soil. Soil Tillage Research 15:359-369.

Sawyer, J.E., A.P. Mallarino, and R. Killorn. 2003. Interpretation of soil test results. PM-1310. Iowa State University, Cooperative Extension Service, Ames, Iowa. http://www.extension.iastate.edu/Publications/PM1310 (verified 1-16-04)

Shelton, D.P., R. Kanable, and P.J. Jasa. 1993. Estimating percent cover using the line-transect method. Pp. 1-5. G93-113. Cooperative Extension, University of Nebraska, Lincoln, Nebraska.

Siddoway, F.H., W.S. Chepil, and D.V. Armbrust. 1965. Effect of kind, amount, and placement of residue on wind erosion control. Transaction American Society of Agricultural Engineers 8:327-331.

Vetsch, J.A. and G.W. Randal. 2002. Corn production as affected by tillage system and starter fertilizer. Agronomy Journal 94:532-540.

Voorhees, W.B., J.F. Johnson, G.W. Randall, and W.W. Nelson. 1989. Corn growth and yield as affected by surface and subsoil compaction. Agronomy Journal 81:294-303.

Watson, M.E. and J.R. Brown. 1998. pH and Lime Requirement. Pp. 13-16. *In:* J.R. Brown (ed.) Recommended chemical soil test procedures for the North Central region. NCR Publ. No. 221 (Revised). Missouri Agricultural Experiment Station, Columbia, Missouri.

Whitney, D.A. 1998. Micronutrients: Zinc, Iron, Manganese and Copper. Pp. 41-44. *In:* J.R. Brown (ed.) Recommended chemical soil test procedures for the North Central region. NCR Publication No. 221 (Revised). Missouri Agricultural Experiment Station, Columbia, Missouri.