TILLAGE

Periodic Response of Soybean Yields and Economic Returns to Long-Term No-Tillage

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ABSTRACT

Farmers have been encouraged to adopt no-tillage (NT) because of its positive environmental effects compared with other conservation tillage systems. Nevertheless, poor crop performance under NT management has been reported in both short- and long-term experiments. This study was conducted on six different soils (a poorly drained Taintor soil near Burlington, a moderately well-drained Kenyon soil near Nashua, a well-drained Clarion soil near Newell, a well-drained Galva soil near Sutherland, and a well-drained Nira soil and a poorly drained Kalona soil near Crawfordsville) in Iowa during 1978 to 2001. Soybean [*Glycine max* (L.) Merr.] response to long-term NT management was evaluated by 5-yr periods and on the average over the entire study in terms of grain yields and economic returns. The design of the field experiments was a randomized complete block or split plot. Eight tillage systems, including NT, moldboard plow, chisel plow, ridge tillage, alternative tillage, reduced tillage, field cultivation, and tillage-plant were investigated in a corn (*Zea mays* L.)–soybean rotation. Differences between NT and other tillage systems in both soybean grain yields and economic returns remained the same over the entire period of each study, ranging from 8 to 15 yr. No-tillage generally had less than 5% yield decrease and equal or greater economic returns compared with other tillage systems on well-drained soils during each 5-yr period and when averaged over the entire study. Therefore, economic returns favor the adoption of NT for soybean production from both short- and long-term perspectives for well-drained soils in Iowa.

Conservation tillage systems, in general, offer pronounced advantages over moldboard plow (MP) in conserving soil and water, sustaining soil productivity, and reducing labor and energy requirements (Unger and McCalla, 1980; Conserv. Tillage Inf. Cent., 1983). No-tillage possesses a greater advantage than other conservation tillage systems because it results in less soil disturbance and greater residue coverage on the soil surface.

No-tillage production for all crops has almost doubled in the United States during the last decade. In 2002, nearly 20% of cropland was planted under NT (Conserv. Technol. Inf. Cent., 2003). Although 33% of soybean fields in the United States were under NT management in 2002, which is greater than the NT corn percentage (18%), there is still a potential to increase NT soybean acreages. Even with the stated advantage of NT, some notable difficulties remain that have hampered the adoption of NT practices for soybean production (Nowak, 1983). One of the main concerns is the perception that NT will reduce soybean grain yields and economic returns, particularly during the first few years of adoption.

Soybean grain yield response to NT systems depends mainly upon soil drainage and previous crop characteristics (Dick and van Doren, 1985; Guy and Oplinger, 1989). In general, well-drained soils, crop rotation, and more southern latitudes provide significant benefit to NT soybean production compared with poorly drained soils, continuous cropping, and northern latitudes (Griffith and Wollenhaupt, 1994). Chase and Duffy (1991), in a 10-yr Iowa tillage study, reported that NT and MP produced similar soybean grain yields in a corn–soybean rotation on a moderately well-drained and moderately permeable loam soil. Brown et al. (1989) found that soybean grain yields did not differ between NT and MP when averaged over an 8-yr tillage study on a silt clay loam soil in Iowa. In two 3-yr tillage studies in Wisconsin, NT and MP produced similar soybean grain yields on silty loam soils in a corn–soybean or corn–soybean–wheat (*Triticum aestivum* L.) rotation (Meese et al., 1991; Lund et al., 1993). However, West et al. (1996) reported an 8% reduction in soybean grain yields under NT compared with MP in a corn–soybean rotation averaged over a 20-yr study on a poorly drained silty clay loam soil in Indiana. McIsaac et al. (1990) found, in a 9-yr tillage study on a poorly drained soil in Illinois, that NT soybean grain yields were less than yields with other tillage systems. Delayed crop growth and development and increased difficulties in soil and pest management have been cited as the cause for less-than-desirable or inconsistent soybean yield performance under NT management.

The magnitude of economic returns for various tillage systems is the most important evidence of the viability and superiority of one tillage system over another. Acceptance of NT for soybean production compared with MP and other conservation tillage systems depends more on its profitability than just grain yields. Soybean profitability depends on the revenue (soybean grain yields × price for soybean grain) and total production cost. In general, NT systems have reduced costs of labor, fuel, and machinery inputs but increased costs of pesticides and increased management to maintain or increase yields. Economic returns for NT compared with other tillage systems vary with many factors, such as management practices, crop rotation, and labor costs (Duffy and Hanthorn 1984; Chase and Duffy, 1991). Liu and Duffy (1996) found that NT resulted in greater eco-

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Abbreviations: AL, alternative tillage; CP, chisel plow; FC, field cultivation; MP, moldboard plow; NT, no-tillage; RDT, reduced tillage; RT, ridge tillage; TP, tillage-plant.

nomic returns than conventional tillage on soybean, primarily a result of different operating costs, but NT and ridge tillage (RT) had similar economic returns after analyzing the survey data from Iowa Max Program participants. In contrast, Duffy and Hanthorn (1984) compared the economic returns of soybean under three tillage systems [NT, reduced tillage (RDT), and MP] for the Midwest region and found NT had economic returns less than MP but similar to RDT.

Differences in both soybean grain yields and economic returns between NT and other tillage systems over time since tillage adoption are complex and often variable. Dick et al. (1991), in Ohio, reported that after 18 yr of continuously applying specific tillage practices, the negative impact of NT on soybean yields on a poorly drained silty clay loam soil was greatly decreased compared with that found in earlier years; whereas the soybean yield advantage associated with NT relative to MP on a well-drained silty loam soil became even more pronounced. Dickey et al. (1994) found that soybean yields under NT were equal to yields with MP in a soybean–grain sorghum [*Sorghum bicolor* (L.) Moench] rotation at the beginning of the study and greater than yields with MP for the last 5 yr on a silty clay loam soil in an 8-yr Nebraska tillage study. However, Chase and Duffy (1991) reported that there was no improvement in soybean yields with time in a 10-yr Iowa tillage study. After reviewing 18 locations throughout the United States, Johnson (1994) concluded that soybean yield response to NT did not improve with time.

Responses of soybean yields and economic returns to NT management have been predominantly evaluated by analyzing individual-year results or data averaged over the entire study period (Chase and Duffy, 1991; Dick et al., 1991; Dickey et al., 1994). Little is done to analyze the periodic responses of soybean yields and economic returns to NT compared with other tillage systems within long-term experiments. The objective of this study was to evaluate the 5-yr periodic responses of soybean grain yields and economic returns to NT relative to MP, RT, chisel plow (CP), and other tillage systems in several long-term experiments throughout Iowa.

MATERIALS AND METHODS

Site Description

Six tillage studies were conducted near Burlington, Nashua, Newell, Sutherland, and Crawfordsville, respectively, throughout Iowa with different experimental designs and for various lengths of time. The Burlington study was conducted from 1980 to 1992 on a poorly drained and moderately slowly permeable Taintor soil (fine, montmorillonitic, mesic Typic Argiaquolls). This soil had a silty clay loam texture, formed on loess, with slope of 0 to 1%. The experiment at the Nashua site was conducted at the Iowa Experiment Station Research Farm from 1978 to 1992 on a Kenyon soil (fine-loamy, mixed, mesic Typic Hapludolls). This soil was a moderately well-drained and moderately permeable loam soil, formed on friable loamy erosion sediments overlying firm loamy glacial till and had a slope in the range of 2 to 5%. The study at the Newell site was conducted from 1980 to 1986 on a well-drained, moderately permeable Clarion loam soil (fine-loamy, mixed, mesic Typic Hapludolls). This soil formed on loamy, calcareous glacial till or sediment derived from glacial till, with a slope ranging from 2 to 5%. The Sutherland experiment was performed on the Iowa Northwest Research Farm from 1994 to 2001 on a well-drained and moderately permeable Galva soil (fine-silty, mixed, mesic Typic Hapludolls) with a silty clay loam texture. This soil formed on loess and had slope in the range of 2 to 5%. The study at the Crawfordsville site was conducted from 1990 to 2001 on Nira (fine-silty, mixed, mesic Typic Hapludolls) and Kalona (fine-silty, montmorillonitic, mesic Typic Haplaquolls) soils. The Nira soil was silty clay loam, moderately well drained, and moderately permeable. It formed on deoxidized loess, with a slope ranging from 5 to 9%. The Kalona soil was silty clay loam, poorly drained, and moderately slowly permeable. It formed on loess, with a slope of 0 to 2%. The native vegetation at all locations was primarily prairie grasses.

Experimental Design

A randomized complete block design with three to six replicates (varying with location) was used at the Burlington, Nashua, Newell, and Crawfordsville sites. Tillage systems were the treatments. At the Burlington site, NT, RDT, and MP tillage systems were evaluated each season. At the Nashua site, NT, RT, CP, and MP tillage systems were tested every year. Five tillage systems, including NT, CP, MP, field cultivation (FC), and tillage-plant (TP) were investigated at the Newell site. At the Crawfordsville site, NT, RT/alternative tillage (AL; consisting of NT-drilled soybean and FC ahead of corn in a corn–soybean rotation), and CP tillage systems were evaluated. The RT treatment at this site was changed to AL in the sixth year of the experiment. A randomized complete block split-plot design was used for the Sutherland site where tillage systems (NT, RT, and CP) were randomly assigned to the main plots and lime rates (0, 560, 1120, 2240, 4480, and 6720 kg ha^{-1}) were assigned to the split plots. Soybean was planted in a corn–soybean rotation at all locations. Two adjacent areas in the same field were used simultaneously every year at each location so that both soybean and corn were evaluated in each year.

Field Operations

The field operations and the time of the year they were performed for each tillage system at each location are presented in Table 1. Typically, NT was defined as no preplant tillage. Soybean under NT was planted using a planter with a single coulter to cut through residues and loosen soil ahead of standard planter units. There was no postplant tillage under NT at any location except at the Nashua site where two field cultivations were performed. Use of two field cultivations was not common for NT systems. The original intent of the Nashua study was to analyze tillage effect on insect populations. The purpose of the cultivations was to allow the use of essentially identical herbicide programs among different tillage systems. Therefore, the only disturbance to the soil under NT was due to planting and fertilizer applications, except at the Nashua study. In Table 1, primary tillage operations represent fall stalk chopping and fall or spring tillage while secondary tillage operations include spring tillage before planting and spring or summer field cultivations as noted for each tillage system and site in Table 1.

The following tillage practices were performed for the soybean crop in these studies. Chisel plow was conducted predominately to 20 cm deep in the fall, with or without one field

Table 1. Field operations by tillage system at each location.

Location and operation	Tillage treatments†							
	NT	RT	CP	MP	RDT	FC	TP	AL
Burlington								
Primary tillage (plow, disk)				F‡	Sp§			
Secondary tillage (FC)				Sp	Sp			
Planting	Sp			Sp	Sp			
Herbicide	2Sp¶			Sp	Sp			
Fertilizer	F			F	F			
Harvest	F			F	F			
Nashua								
Primary tillage (chisel, plow)			F	F				
Secondary tillage (FC, disk, harrow)	2Su#	2Su	Sp + 2Su	Sp + 2Su				
Planting	Sp	Sp	Sp	Sp				
Herbicide	Sp	Sp	Sp	Sp				
Harvest	F	F	F	F				
Newell								
Primary tillage (chop stalk, chisel, plow, disk)	FCS††		FCS + F	FCS + F		FCS + Sp	FCS	
Secondary tillage (disk, FC)			Sp + Su	Sp + Su‡‡		Sp + Su		
Planting	Sp		Sp	Sp		Sp	Sp	
Herbicide	2Sp		2Sp	2Sp		2Sp	2Sp	
Fertilizer	F		F	F		F	F	
Harvest	F		F	F		F	F	
Sutherland								
Primary tillage (disk, chisel)			F					
Secondary tillage (disk)		2Su						
Planting	Sp	Sp	Sp					
Herbicide	Sp	Sp	Sp					
Fertilizer	Sp	Sp	Sp					
Harvest	F	F	F					
Crawfordsville								
Primary tillage (disk, chisel)			F					
Secondary tillage (disk)		2Su						
Planting	Sp	Sp	Sp					Sp
Herbicide	Sp	Sp	Sp					Sp
Fertilizer	Sp	Sp	Sp					Sp
Harvest	F	F	F					F

† NT, no-tillage; RT, ridge tillage; CP, chisel plow; MP, moldboard plow; RDT, reduced tillage; FC, field cultivation; TP, tillage-plant; AL, alternative tillage.
‡ F, fall.
§ Sp, spring.
¶ 2Sp indicates the operation was applied twice in the spring of each season.
# 2Su represents the operation was applied twice in the summer of each season.
†† FCS, fall chopping stalks.
‡‡ Su, summer.

cultivation to about 10 cm deep in the spring before planting. Ridge tillage was performed with a ridge-till cultivator (large sweeps or disks) in the fall after corn harvest or during the soybean season to reform the ridges during in-season cultivation. Typical tillage operations for MP were moldboard plowing to approximately 20 cm deep in the fall and one field cultivation to 10 cm deep in the spring before planting. Reduced tillage included tandem disking and field cultivation in the spring. Field cultivation included one operation in the spring. Tillage-plant was performed with a sweep, double disk, or flat disk mounted on the planter for a one-pass tillage-planting operation.

Within each location, soybean was planted on the same day for different tillage treatments each year. Soybean cultivars Pioneer 9381, Pioneer 3541, Williams, Merschman Truman II, Cheyenne III, Washington VI, Eisenhower II, Kenwood, SOI 237, etc., were used in these studies at a seeding rate ranging from 315 000 to 435 000 seeds ha^{-1}. The seeding rate was the same for all the tillage treatments each year at each location. The planting date varied with year and location, ranging from 8 May to 18 June. The plot size was different from one location to another. For example, at the Burlington site, the plot was 38 m wide and 381 m long, but the plot size was 6 by 31 m for the Sutherland site. All tillage treatments, except TP, were planted with the same planter each year at each location. The TP treatment was planted with a Buffalo Till planter.

The center three to five rows of each plot (or split plot, if applicable) were harvested with a plot combine for grain yield determination at each location. Grain samples were collected from the yield samples for the determination of moisture content. Soybean yields were adjusted to moisture content of 130 g kg^{-1}. Daily rainfall and air temperature for each growing season were recorded on site or obtained from the nearest weather station. Growing degree days from May to September using 10°C as the base temperature and precipitation from October of the previous year to September of the current year were calculated for each growing season at all locations.

Fertilizer and Herbicide Programs

The fertilizer program was identical among the tillage treatments within a given year and location but varied considerably across years and locations. At the Burlington site, 22 to 50 kg N ha^{-1}, 25 to 57 kg P ha^{-1}, and 93 to 168 kg K ha^{-1} were applied each season, except 1989 when soybean was not fertilized. At the Nashua site, soybean was not fertilized in any of the years but relied on the residual effects of fertilizers that were applied to the previous year corn. Corn received 164 to 174 kg N ha^{-1}, 47 to 73 kg P ha^{-1}, and 112 to 170 kg K ha^{-1} each season at the Nashua site. At the Newell site, 0 kg N ha^{-1}, 20 kg P ha^{-1}, and 37 kg K ha^{-1} were applied in 1981 and 1982. In 1983, soybean received 17 kg N ha^{-1}, 20 kg P ha^{-1}, and 37 kg K ha^{-1}. In 1984, 50 kg N ha^{-1}, 59 kg P ha^{-1}, and 112 kg K ha^{-1} were applied. For 1985 and 1986, no fertilizer was applied to soybean. At the Sutherland site, 40 to 67 kg N ha^{-1} was applied each season. But P and K were only applied in 1994 and 1997 at 49 kg P ha^{-1} and 46 kg K ha^{-1}. At the Crawfordsville site, soybean was fertilized with 17 kg P ha^{-1} and 65 kg K ha^{-1}, averaged over the growing seasons.

Herbicide programs varied from one year to another and from one location to another, depending on weather conditions, weed pressure, and the introduction of new products. Herbicides used in all these studies followed the recommended guidelines for use. The timing of herbicide applications for each tillage system at each location is presented in Table 1. In general, the herbicides used each year varied among the tillage treatments within each location. No-tillage, RT, and TP systems usually had a more intensive herbicide program than other tillage systems. For example, at the Burlington site, imazethapyr {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} plus pendimethalin [*N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] (or clomazone {2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone} plus trifluralin [2,6-dinitro-*N,N*-dipropyl-4-(trifluoromethyl)benzenamine] and imazaquin {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-quinolinecarboxylic acid}) and chloramben (3-amino-2,5-dichlorobenzoic acid) were applied to the RDT and MP treatments. For NT, however, 2,4-D [(2,4-dichlorophenoxy)acetic acid], chlorimuron ethyl {2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]-carbonyl]amino]sulfonyl]benzoic acid} + metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one], metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide], and chloramben were applied before soybean planting; sethoxyim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} and bentazon [3-(1-methylethyl)-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide] (or thifensulfuron methyl {3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid}, chlorimuron ethyl, and quizalofop {2-[4-[(6-chloro-2-quinoxalinyl)oxy]phenoxy]propanoic acid}) were applied after planting. At the Nashua site, alachlor [2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl)acetamide] and metribuzin were applied to CP and MP. Alachlor, metribuzin, and paraquat (1,1′-dimethyl-4,4′-bipyridinium) were used for the NT and RT systems. At the Newell site, alachlor and metribuzin were applied to the CP, MP, and FC systems. Alachlor, metribuzin, and glyphosate [*N*-(phosphonomethyl) glycine] were used for NT and TP.

Input Costs

Economic returns in this article refer to the difference between the revenue of soybean production and the total input cost (excluding land cost) per land unit. The revenue of soybean production is the product of soybean grain yields per land unit × price for soybean grain. Economic returns were calculated by using a soybean grain price of \$196.66 Mg^{-1}. The total input cost included the expenses on machinery, seed, fertilizer, herbicide, crop insurance, and interest on the investment (Table 2).

The machinery costs on a yearly basis consisted of both fixed and variable components. Fixed costs included depreciation, interest on the investment, taxes, insurance, and housing. Variable costs included repairs and maintenance, fuel, and lubrication. These components of machinery costs were estimated

Table 2. Average production costs by tillage system at each location.†

Location and category	Tillage treatments‡							
	NT	RT	CP	MP	RDT	FC	TP	AL
	\$ ha^{-1}							
Burlington								
Machinery	77.19			108.91	90.17			
Seed and fertilizer	136.00			136.00	136.00			
Herbicide	86.42			76.54	76.54			
Labor	9.48			15.80	13.43			
Miscellaneous	37.83			37.85	37.48			
Total cost	346.92			375.10	353.62			
Nashua								
Machinery	80.27	80.27	100.84					
Seed and fertilizer	59.26	59.26	59.26					
Herbicide	86.42	86.42	76.54					
Labor	14.02	14.02	20.15					
Miscellaneous	34.07	34.07	33.85					
Total cost	274.04	274.04	290.64					
Newell								
Machinery	93.48		122.25	138.05		110.49	102.30	
Seed and fertilizer	101.98		101.98	101.98		101.98	101.98	
Herbicide	86.42		76.54	76.54		76.54	86.42	
Labor	14.02		21.73	22.52		20.15	14.02	
Miscellaneous	36.40		36.32	36.62		36.12	36.54	
Total cost	332.30		358.82	375.71		345.28	341.26	
Sutherland								
Machinery	73.16	90.79	84.91					
Seed and fertilizer	103.33	103.33	103.33					
Herbicide	86.42	86.42	76.54					
Labor	9.48	14.22	13.43					
Miscellaneous	36.12	36.40	35.83					
Total cost	308.51	331.16	314.04					
Crawfordsville								
Machinery	73.16	90.79	84.91					73.16
Seed and fertilizer	103.33	103.33	103.33					103.33
Herbicide	86.42	86.42	76.54					76.54
Labor	9.48	14.22	13.43					9.48
Miscellaneous	36.12	36.40	35.83					35.63
Total cost	308.51	331.16	314.04					298.14

† More details regarding each category for each tillage system were stated in the Input Costs subsection in Materials and Methods.

‡ NT, no-tillage; RT, ridge tillage; CP, chisel plow; MP, moldboard plow; RDT, reduced tillage; FC, field cultivation; TP, tillage-plant; AL, alternative tillage.

based on power units of average size and implements needed to accomplish the operations. Machinery costs per field operation were obtained from Duffy and Smith (2002). Possible size differences in power units and implements among tillage systems each year were not taken into consideration within each location, neither were the machine size differences of each operation among years during the entire study period at each location. Because the same kind of tillage system (such as NT) may consist of different field operations (tillage, fertilization, and herbicide applications) at different locations, the costs of machinery for the same kind of tillage system varied with location.

Costs of seed and fertilizer included the expenses of seed; N, P, and K fertilizers; and lime. Seed and lime costs were estimated from soybean production in Iowa (Duffy and Smith, 2002) while fertilizer costs were calculated based on the average rates of fertilizers actually used in each season at each location. The costs of herbicide were estimated from soybean production in Iowa (Duffy and Smith, 2002). Because the fertilizer and herbicide programs varied with location, the costs on these items were different from one location to another.

Labor costs included expenses of labor used for all the field operations. Labor costs were calculated according to actual field operations (such as tillage, fertilization, and herbicide applications). The time required for each field operation was estimated according to Hanna (2001) by using machine sizes of intermediate field capacity. The labor costs covered not only the actual fieldwork, but also the time for machine maintenance, travel, and other activities related to crop production. The labor cost rate used was \$8.00 h^{-1} (Duffy and Smith, 2002). Because the same kind of tillage system may include different field operations at different locations (Table 1), the labor costs for the same kind of tillage system may be different among different locations (Table 2). Miscellaneous costs included crop insurance, interest on preharvest variable costs, etc. Costs on crop insurance were estimated from Duffy and Smith (2002). Interest on preharvest variable costs was calculated based on the assumption that the loan was used for eight months each season at an interest rate of 7.5% (Duffy and Smith, 2002).

Statistical Analysis

All statistical analyses in this article were conducted separately for each location by using the SAS System for Windows version 8 (SAS Inst., 2002). Soybean grain yields and economic returns were analyzed across years of the entire study period within each location to examine the general trend of soybean response to NT compared with other tillage systems. For the data sets averaged over years, an appropriate analysis of variance was conducted using a split-plot design for the Burlington, Nashua, Newell, and Crawfordsville sites where years were treated as the main factor and tillage treatments were treated at the split factor. At the Sutherland site, however, the analyses were performed based on a split-split plot design where years, tillage systems, and lime rates were treated as the main, split, and split-split factors, respectively.

In addition, soybean grain yields of each individual year were analyzed separately at each location by using an analysis of variance appropriate for a complete randomized block design for the Burlington, Nashua, Newell, and Crawfordsville sites. But the analyses for the Sutherland site data were performed based on a split-plot design by treating tillage systems and lime rates as the main and split factors, respectively.

To evaluate the periodic response of soybean yields and economic returns to NT, the first 5-yr period after tillage adoption was referred to as the beginning period, the second 5-yr period represented the intermediate period, and the third 5-yr period was referred to as the final period. The use of 5 yr for each period was based on the tradition of determining yield goal for management recommendations (i.e., fertilizer recommendations) by using 5-yr yield average in the Midwest and elsewhere. There was 1-yr overlap between two adjacent 5-yr periods in each study. For the last 5-yr period of each study, some may have less than 5 yr, depending on the total length of each study. The beginning period for the Burlington, Nashua, Sutherland, and Crawfordsville sites was 1980–1984, 1978–1982, 1994–1998, and 1990–1994, respectively. The intermediate period for the Burlington, Nashua, Sutherland, and Crawfordsville sites was 1984–1988, 1982–1986, 1998–2001, and 1994–1998, respectively. The final period for the Burlington, Nashua, and Crawfordsville sites was 1988–1992, 1986–1989, and 1998–2001, respectively. Because the Nashua study was conducted from 1978 to 1992, totaling 15 yr, it had the fourth 5-yr period of 1989–1992. All other studies only had three 5-yr periods. At each location, data of soybean grain yields and economic returns were grouped according to these periods, and statistical analyses were conducted separately for each of these data groups. For these periodic data sets, an appropriate analysis of variance was conducted for each location by using the same experimental design as those used for the analyses averaged over years. No statistical analysis on periodic response was conducted for the Newell site because this location lasted for 6 yr only.

If the treatment effects were statistically significant at $\alpha = 0.05$ according to the F test, then means for the treatment effects were separated using Fisher's protected least significant difference (LSD) test at $\alpha = 0.05$. Otherwise, no mean separation was performed, and the differences among the treatment means were presumed statistically identical.

Linear regression analysis using actual annual soybean yields as the dependent variable and the length of time (number of years) since tillage adoption as the independent variable was conducted to examine the stability of yields in each tillage system with time. This kind of analysis was conducted for each tillage system within each location.

RESULTS

Presentation of the results in this section is based on the order of statistical significance, which ranges from the highest-level interaction to the main effect of treatments. If there was a statistically significant interaction of treatments, then the main effect of the treatments that were involved in this interaction was not reported. Otherwise, only the main effect was presented. Because no statistically significant interaction (yr $\times$ tillage, tillage $\times$ lime rate, or yr $\times$ tillage $\times$ lime rate) was observed for either yields or economic returns in any of these studies, all the results reported in this section are based on the main effect of treatments.

Average No-Tillage Yields and Economic Returns

Results from the Burlington site showed that NT produced soybean yields 8.2% less than MP averaged over 13 yr (Table 3). Soybean yields under NT were close to those under MP although statistically significant at the Nashua site. At the Newell site, the yield difference between NT and MP was only 5.4% although NT yielded statistically less. Economic returns of NT were

Table 3. Soybean yields and economic returns under no-tillage compared with other tillage systems averaged over the entire study period.

Location	No. of years	Tillage†	Yields	Returns
			Mg ha^{-1}	\$ ha^{-1} yr^{-1}
Burlington	13	NT	2.69c‡	181.85b
		RDT	2.80b	197.10a
		MP	2.93a	200.83a
		F test	***	**
Nashua	15	NT	2.60b	236.43a
		RT	2.49c	215.89b
		CP	2.64ab	228.62a
		MP	2.69a	213.36b
		F test	***	***
Newell	6	NT	2.61bc	181.21b
		CP	2.71ab	174.15b
		FC	2.79a	202.65a
		TP	2.57c	163.19b
		MP	2.76a	166.33b
		F test	***	**
Sutherland	8	NT	2.92a	264.80a
		RT	2.90a	239.22b
		CP	2.95a	265.39a
		F test	ns§	***
Crawfordsville	12	NT	3.00ab	280.71a
		RT/AL	2.94b	266.96b
		CP	3.04a	283.44a
		F test	*	*

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NT, no-tillage; RDT, reduced tillage; MP, moldboard plow; RT, ridge tillage; CP, chisel plow; FC, field cultivation; TP, tillage-plant; AL, alternative tillage.
‡ Means in a column within each location followed by different letters are significantly different at $P = 0.05$ according to Fisher's protected LSD test.
§ ns, not significant at the 0.05 level.

\$18.98 ha^{-1} yr^{-1} less at the Burlington site, but \$23.07 ha^{-1} yr^{-1} greater at the Nashua site, compared with those under MP. There was no significant difference in economic returns between NT and MP at the Newell site. It was apparent that NT had equal or greater economic returns than MP at all locations except the Burlington site where the soil was poorly drained.

Ridge tillage and CP are two other conservation tillage systems used in these studies. At all sites, NT had yields that were equal or greater than those for RT (or RT/AL) (Table 3), and economic returns for NT were significantly greater than those under RT (or RT/AL) (Table 3). No-tillage consistently produced statistically identical yields and economic returns as CP at all locations that included CP (Table 3). In addition, yields under NT were significantly less than those under RDT (Burlington site) and FC (Newell site) but similar to yields with TP (Newell site). Economic returns of NT were approximately \$15 ha^{-1} yr^{-1} less than the returns with RDT and \$21 ha^{-1} yr^{-1} less than those with FC but did not differ from those with TP.

Yearly No-Tillage Yield Response

Soybean yields of years in which NT had significant yield differences from other tillage systems are presented in Table 4. The data from the growing seasons in which no yield differences were observed between NT and other tillage systems were not presented.

In 5 out of 13 growing seasons, NT yielded less than MP at the Burlington site; the yield reductions due to NT ranged from 8.8% in 1983 to 13.9% in 1991 (Table 4). No-tillage when compared with MP showed significantly less grain yields in 4 out of 15 seasons at the Nashua site and one out of six growing seasons at the Newell site compared with MP.

Three out of the 15 seasons had significantly greater yields with NT compared with RT at the Nashua site (Table 4); the other 12 seasons yielded similarly between NT and RT. Soybean planted with NT yielded significantly less than RT soybean at the Sutherland site only in 1 out of 8 yr. There was no significant difference in yields when NT was compared with RT/AL in any year at the Crawfordsville site. Therefore, NT had yearly yields equal to or greater than RT or RT/AL regardless of location.

No-tillage caused significant yield reduction in only 1 out of 15 yr compared with CP at the Nashua site

Table 4. Soybean yields of years in which no-tillage had significant yield differences from other tillage systems.

Location	Year	Significance	Yields† NT	RT	CP	MP	RDT	FC	TP
			Mg ha^{-1}						
Burlington	1983	**	2.69b‡			2.95a	2.90a		
	1988	***	2.58c			2.93a	2.76b		
	1990	**	2.93b			3.22a	3.13a		
	1991	**	2.90c			3.37a	3.22b		
	1992	***	3.21b			3.62a	3.17b		
Nashua	1980	**	2.44b	2.26c	2.57ab	2.69a			
	1982	*	2.45b	2.47b	2.58ab	2.66a			
	1983	***	2.87a	2.39b	2.93a	2.87a			
	1987	*	2.67b	2.65b	2.69b	2.87a			
	1991	*	3.11a	2.73b	3.18a	3.13a			
	1992	*	2.91c	3.03bc	3.21ab	3.44a			
Newell	1981	*	3.34bc		3.32c	3.41bc		3.52a	3.44ab
	1984	**	2.15b		2.46a	2.36a		2.45a	2.05b
	1986	*	2.98bc		3.13a	3.11ab		3.17a	2.92c
Sutherland	1994	*	2.39a	2.22b	2.41a				
	1999	*	3.04b	3.17a	3.20a				

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NT, no-tillage; RT, ridge tillage; CP, chisel plow; MP, moldboard plow; RDT, reduced tillage; FC, field cultivation; TP, tillage-plant.
‡ Means in a row followed by different letters are significantly different at $P = 0.05$ according to Fisher's protected LSD test.

(Table 4). Yields under NT were less than those with CP in 2 out of 6 yr at the Newell site and one out of eight seasons at the Sutherland site. At the Crawfordsville site, no significant yearly yield difference between NT and CP was observed in any of the 12 seasons. In general, NT could produce similar yields as CP regardless of location. In addition, NT had 4 out of 13 yr with less yields than RDT at the Burlington site and three out of six seasons with less yields than FC but no season with less yields than TP at the Newell site (Table 4).

The yearly soybean yields and seasonal growing degree days and annual precipitation are presented in Fig. 1 and 2, respectively. No-tillage may have poorer yield performance relative to MP, RT, or CP during

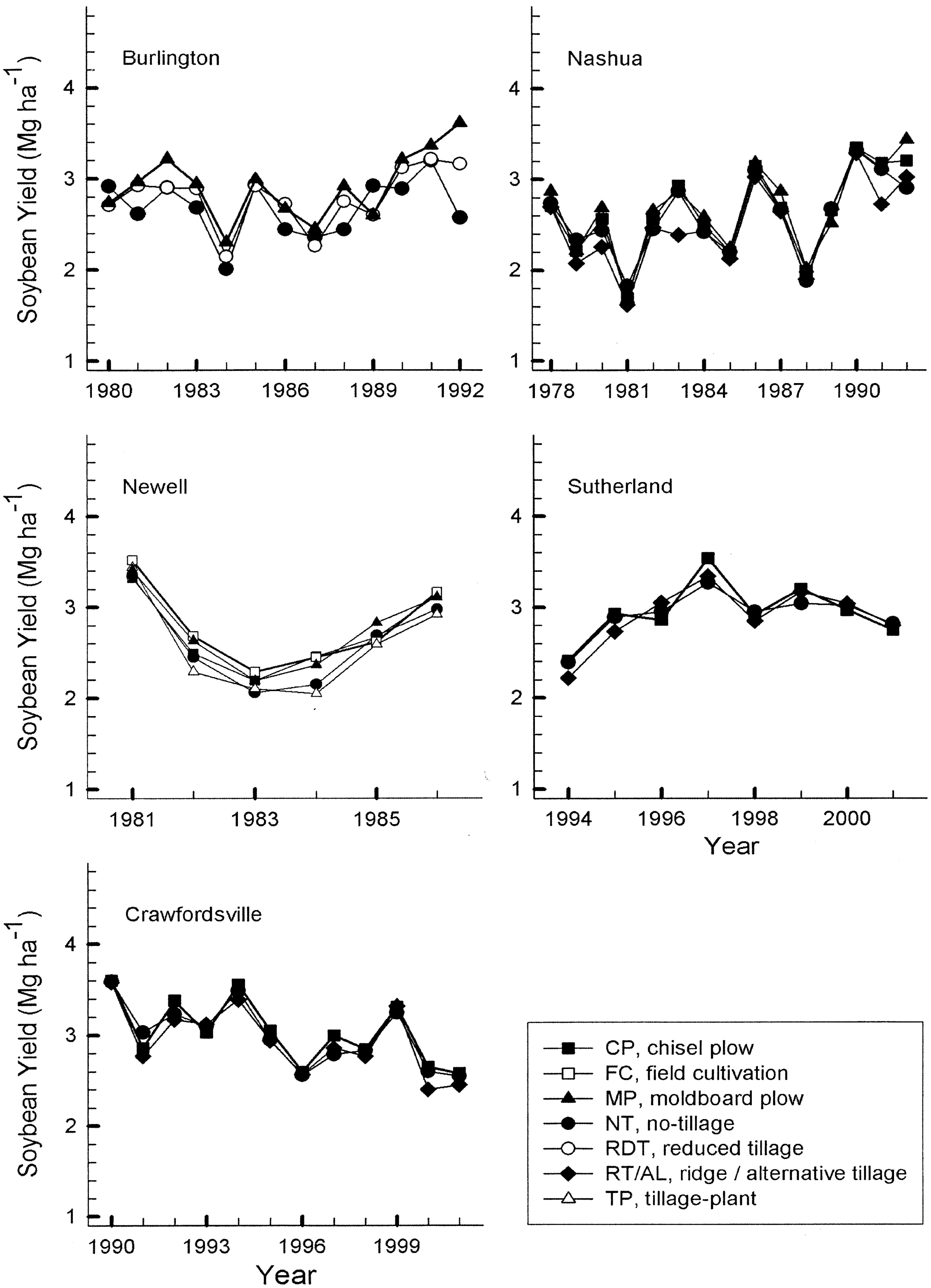

Fig. 1. Seasonal soybean yields under different tillage systems at all locations.

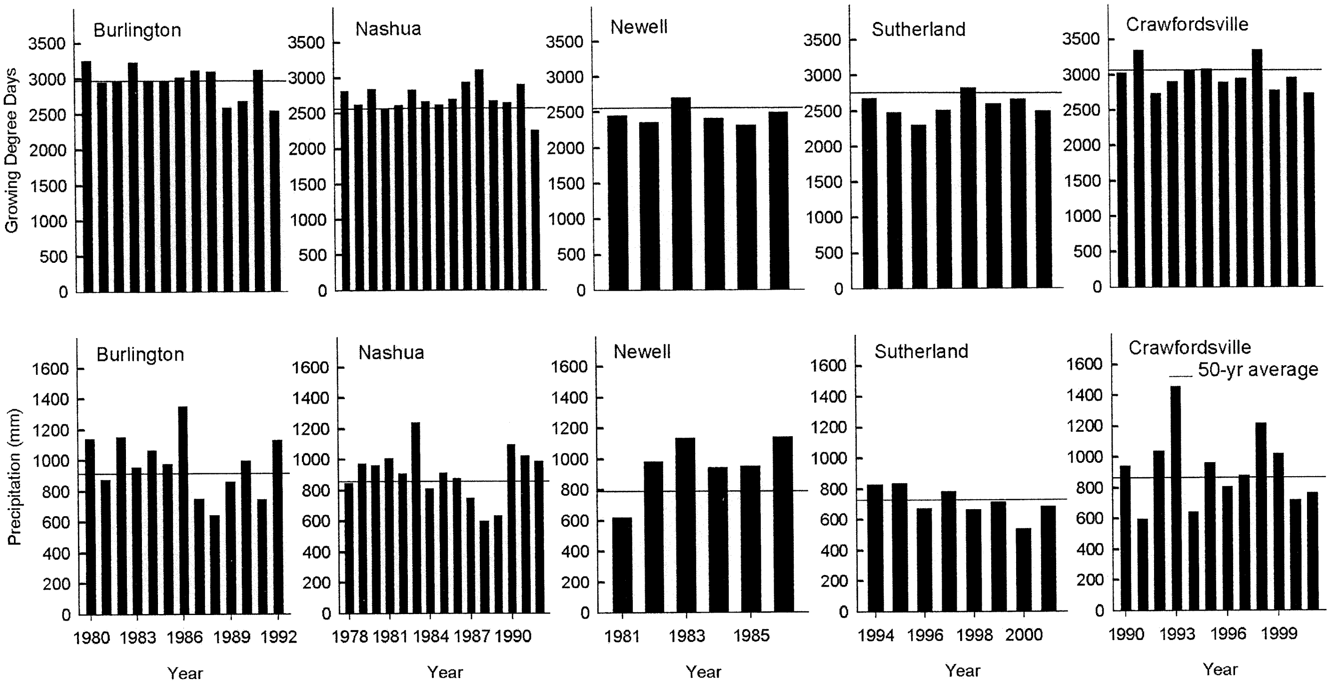

Fig. 2. Seasonal growing degree days and annual precipitation at all locations.

wet seasons. This trend was observed in the 1992 season at both Nashua and Burlington sites and in the 1986 season at the Newell site (Fig. 1 and 2). This observation is reasonable because NT during wet seasons, particularly early spring wet conditions, can delay soybean emergence and early-season soybean growth and promote soil-borne diseases that may have significant impact on yields (Meese et al., 1991). However, there were some dry years, such as 1988 and 1991 at the Burlington site, in which NT soybean yielded significantly less than other tillage systems (Fig. 1 and 2). These moisture conditions of excessive wetness or drought play a significant role in yield performance under different tillage systems (West et al., 1996).

Periodic No-Tillage Yields and Economic Returns

Beginning Period (First Five Years)

When soybean yield data in the beginning period were combined and analyzed for each location, NT had yields 7.4% less than MP at the Burlington site (Table 5). At the Nashua site, the yield difference between NT and MP was not significant. Compared with RT, NT produced equal or even greater yields regardless of location. No significant yield difference between NT and CP was observed at any location. Economic returns for NT soybean were statistically identical to those under MP at the Burlington site (Table 5). At the Nashua site, NT resulted in economic returns \$28.21 ha^{-1} yr^{-1} greater than MP. No-tillage had an advantage of \$25.90 to 39.54 ha^{-1} yr^{-1} over RT regardless of location. Economic returns under NT and CP did not differ statistically at any location. The results for the beginning period since tillage adoption showed that NT was generally competitive with MP and consistently comparable with RT and CP in terms of both yields and economic returns.

Intermediate Period (Second Five Years)

The results of the intermediate period showed that NT produced yields 7.8 and 3.7% less than MP at the

Table 5. Soybean yields and economic returns under no-tillage compared with other tillage systems averaged over the beginning period (first 5 yr).†

Location	*F* test	NT	RT	CP	MP	RDT	*F* test	NT	RT	CP	MP	RDT
		Yields‡						Economic returns				
		Mg ha^{-1}						\$ ha^{-1} yr^{-1}				
Burlington	*	2.63b§			2.84a	2.72ab	ns¶	169.92a			183.08a	181.12a
Nashua	***	2.36a	2.23b	2.35a	2.42a		**	189.43a	163.53b	172.23ab	161.22b	
Sutherland	*	2.89ab	2.84b	2.93a			***	259.76a	227.13b	262.35a		
Crawfordsville	ns	3.29a	3.21a	3.29a			**	338.32a	298.78b	331.84a		

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† Time period for the Burlington, Nashua, Sutherland, and Crawfordsville sites was 1980–1984, 1978–1982, 1994–1998, and 1990–1994, respectively.
‡ NT, no-tillage; RT, ridge tillage; CP, chisel plow; MP, moldboard plow; RDT, reduced tillage.
§ Means in a row within yields or economic returns followed by different letters are significantly different at $P = 0.05$ according to Fisher's protected LSD test.
¶ ns, not significant at the 0.05 level.

Table 6. Soybean yields and economic returns under no-tillage compared with other tillage systems averaged over the intermediate period (second 5 yr).†

	Yields‡						Economic returns					
Location	*F* test	NT	RT/AL	CP	MP	RDT	*F* test	NT	RT/AL	CP	MP	RDT
		Mg ha^{-1}						\$ ha^{-1} yr^{-1}				
Burlington	**	2.47b§			2.68a	2.57b	ns¶	137.96a			150.93a	151.11a
Nashua	***	2.61b	2.49c	2.67ab	2.71a		***	238.71a	215.21b	233.90a	217.65b	
Sutherland	ns	2.96a	2.97a	2.96a			***	273.04a	252.09b	268.11a		
Crawfordsville	ns	2.92a	2.91a	3.01a			ns	266.28a	266.79a	278.02a		

** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† Time period for the Burlington, Nashua, Sutherland, and Crawfordsville sites was 1984–1988, 1982–1986, 1998–2001, and 1994–1998, respectively.
‡ NT, no-tillage; RT, ridge tillage; AL, alternative tillage; CP, chisel plow; MP, moldboard plow; RDT, reduced tillage.
§ Means in a row within yields or economic returns followed by different letters are significantly different at $P = 0.05$ according to Fisher's protected LSD test.
¶ ns, not significant at the 0.05 level.

Burlington and Nashua sites, respectively (Table 6). However, NT yields were similar to or even greater than those under RT or AL regardless of location. No-tillage had similar yields to CP at all locations. Economic returns under NT were equal or greater than under MP, RT, and AL in this period (Table 6). The difference in economic returns was negligible between NT and CP regardless of location. In general, NT performance relative to MP, RT, and CP systems was not different in the intermediate period compared with the beginning period, in terms of either yields or economic returns.

Final Period (Third Five Years)

Yield and economic return trends of the final period (the third 5 yr) were similar to those observed in the beginning and intermediate periods at each location (Table 7). No grain yield differences between NT and MP, RT, AL, or CP were observed at any location except at the Burlington site in the third 5-yr period where NT produced yields 10.8% less than MP. Decreased yields with NT compared with MP at the Burlington site were probably related to the poor drainage of the soil. Economic returns for NT soybean were \$38.01 ha^{-1} yr^{-1} less than that for MP at the Burlington site but \$27.84 ha^{-1} yr^{-1} greater at the Nashua site (Table 7). Our results suggest that NT may perform poorly in both yield and economic returns compared with other tillage systems, especially MP, on poorly drained soils. This was evident in the Burlington experiment but not in the Crawfordsville experiment. Economic returns with NT did not differ from those under RT, AL, or CP at any location. Similar trends to those observed in the third 5-yr period were observed in the fourth 5-yr period for both yields and economic returns at the Nashua site (Table 7).

In addition, when the annual yields in each tillage system were linearly regressed with the length of time (number of years) since tillage adoption, soybean grain yields did not show any trend of change (either increase or decrease) with time under any tillage system at the Burlington, Newell, or Sutherland sites (data not presented). However, soybean yields slightly increased at the Nashua site under RT and CP but slightly decreased at the Crawfordsville site regardless of tillage system with time. This finding suggests that the length of tillage implementation generally does not significantly influence soybean yield stability over time in these studies. This finding also agrees with the periodic yield analysis, indicating that the NT soybean yields and economic returns relative to other tillage systems are the same in different periods of long-term management.

In summary, neither soybean grain yields nor economic returns showed any significant change under NT relative to MP, RT, CP, or other tillage systems with time over the 8 to 15 yr of these studies. No-tillage grain yields and economic returns during the beginning period were similar to grain yields and economic returns in later periods. The grain yield differences between NT

Table 7. Soybean yields and economic returns under no-tillage compared with other tillage systems averaged over the final period (third 5 yr).†

	Yields‡						Economic returns					
Location	*F* test	NT	RT/AL	CP	MP	RDT	*F* test	NT	RT/AL	CP	MP	RDT
		Mg ha^{-1}						\$ ha^{-1} yr^{-1}				
Burlington	***	2.81c§			3.15a	2.98b	***	206.34c			244.35a	231.86b
Nashua	ns¶	2.58a	2.56a	2.62a	2.65a		**	233.76a	229.98a	224.96a	205.92b	
Crawfordsville	ns	2.80a	2.73a	2.85a			ns	243.00a	239.63a	245.70a		
Nashua#	*	3.00ab	2.93b	3.10a	3.10a		ns	317.02a	302.29a	318.55a	295.35a	

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† The third time period for the Burlington, Nashua, and Crawfordsville sites was 1988–1992, 1986–1989, and 1998–2001, respectively. The fourth period was for the Nashua site only: 1989–1992.
‡ NT, no-tillage; RT, ridge tillage; AL, alternative tillage; CP, chisel plow; MP, moldboard plow; RDT, reduced tillage.
§ Means in a row within yields or economic returns followed by different letters are significantly different at $P = 0.05$ according to Fisher's protected LSD test.
¶ ns, not significant at the 0.05 level.
# This row contains the fourth 5-yr period results for the Nashua site.

and MP, RT, CP, or other tillage systems were usually less than 5% at all locations except at the Burlington site. Economic returns for NT soybean were consistently equal to or greater than those under MP, RT, CP, or other tillage systems in different periods at all locations except at the Burlington site. This trend is encouraging to those soybean producers who are concerned about poor NT soybean performance during the first few years after tillage adoption and to those who are only willing to use NT for a short period of time, i.e, 5 yr or less.

DISCUSSION

Periodic responses (Tables 5–7) showed neither significant improvement nor deterioration in grain yields or economic returns of NT soybean compared with soybean under other tillage systems. Our results suggest that the differences in yields and economic returns between NT and other tillage systems were stable with time, which disagrees with those reported by Dick et al. (1991) from Ohio where after 18 yr of different tillage implementation, the negative impact of NT on soybean yields on a poorly drained soil was greatly decreased over time; and the soybean yield advantage associated with NT relative to MP on a well-drained soil became even more pronounced. This disagreement is reasonable because the duration of the experiments in our study were much shorter than that reported by Dick et al. (1991). In addition, most sites in our study were well drained, which contributed to the stability of yield over time. It was surprising that soybean yields did not show significant increases over time, regardless of tillage system and location in our studies, despite continuous improvement in soybean cultivar, management practices, and farming equipment.

In general, the difference in soybean grain yields between NT and MP was less at the Nashua and Newell sites than at the Burlington site (Tables 3 and 4). These NT yield performance differences can be attributed to the soil and climatic characteristics where the Nashua and Newell sites had well-drained soils while the Burlington site had a poorly drained soil. Dick and van Doren (1985) reported a similar trend that soybean yields under NT were better on a well-drained soil than poorly drained soil compared with MP.

It was unexpected in our studies that significant yield reduction in NT systems occurred in some dry seasons. However, West et al. (1996) observed poor yields of soybean under NT compared with other tillage systems in a corn–soybean rotation during some drought years of their study in Indiana. This outcome was ascribed to the possibility that NT soybean did not respond to the extra soil moisture available at the lower depths because plant deep rooting may be delayed under NT.

Soybean economic returns are affected not only by yields, but also by the input cost on seed, herbicide, fertilizer, machinery, and labor. Therefore, increase in grain yields do not necessarily represent increase in economic returns, and a significant yield reduction caused by NT may not result in a significant decrease in economic returns with NT. For example, NT usually has a total soybean production cost of \$30 to 40 ha^{-1} yr^{-1} less than MP soybean production. Therefore, even though NT produces soybean yields 0.20 Mg ha^{-1} yr^{-1} less than MP, the economic returns for the two tillage systems are still similar.

Our results are generally in agreement with those based on the Iowa MAX program participants' survey data reported by Liu and Duffy (1996). No-tillage resulted in greater economic returns than MP in well-drained soils. The primary reason for greater economic returns with NT was its lower input cost (including machinery, energy, and labor).

Producers always play a very important role in NT soybean production because converting MP, RT, CP, or other tillage systems to NT requires learning and adopting new farming technologies. Different producers may obtain considerably different yields and economic returns from NT because they may have different production environments and may adopt different crop and soil management practices. The adoption of NT will most likely be increased rapidly as producers become familiar with NT management requirements and if labor costs increase significantly.

CONCLUSIONS

Differences in soybean grain yields and economic returns between NT and MP, RT, CP, or other tillage systems did not change considerably with time under long-term management ranging from 8 to 15 yr. Therefore, the differences in yields and economic returns between NT and MP, RT, CP, or other tillage systems in the early years (5 yr) after tillage adoption were the same as those 8 to 10 yr later. Soybean yield performance was stable with time regardless of tillage system.

No-tillage soybean grain yields were similar to those under MP, RT, CP, or other tillage systems on well-drained soils. Soybean grain yield differences between NT and MP, RT, CP, or other tillage systems were usually within 5%. No-tillage generally had equal or greater economic returns than other tillage systems. The primary reason for greater economic returns with NT than other tillage systems was the decreased cost of machinery, energy, and labor with NT. Our results suggest that the use of NT in soybean production can be accomplished without lowering economic returns from both short- and long-term perspectives.

Because economic returns are affected not only by soybean grain yields but also by the costs on machinery, fertilizer, and labor, the increase in yields does not necessarily represent an increase in economic returns. Also, a significant grain yield reduction with NT relative to MP, RT, CP, or other tillage systems does not always mean a remarkable decrease in economic returns with NT. Different producers may obtain different soybean yields and economic returns in NT because they have different production environments and may adopt different crop and soil management practices.

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