Published March, 2012

Effects of No-Till on Yields as Influenced by Crop and Environmental Factors

Dustin K. Toliver,* James A. Larson, Roland K. Roberts, Burton C. English, Daniel G. De La Torre Ugarte, and Tristram O. West

ABSTRACT

This research evaluated differences in yields and associated downside risk from using no-till and tillage practices. Yields from 442 paired tillage experiments across the United States were evaluated with respect to six crops and environmental factors including geographic location, annual precipitation, soil texture, and time since conversion from tillage to no-till. Results indicated that mean yields for sorghum [*Sorghum bicolor* (L.) Moench] and wheat (*Triticum aestivum* L.) with no-till were greater than with tillage. In addition, no-till tended to produce similar or greater mean yields than tillage for crops grown on loamy soils in the Southern Seaboard and Mississippi Portal regions. A warmer and more humid climate and warmer soils in these regions relative to the Heartland, Basin and Range, and Fruitful Rim regions appear to favor no-till on loamy soils. With the exception of corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) in the Southern Seaboard region, no-till performed poorly on sandy soils. Crops grown in the Southern Seaboard were less likely to have lower no-till yields than tillage yields on loamy soils and thus had lower downside yield risk than other farm resource regions. Consistent with mean yield results, soybean [*Glycine max* (L.) Merr.] and wheat grown on sandy soils in the Southern Seaboard region using no-till had larger downside yield risks than when produced with no-till on loamy soils. The key findings of this study support the hypothesis that soil and climate factors impact no-till yields relative to tillage yields and may be an important factor influencing risk and expected return and the adoption of the practice by farmers.

Conservation tillage practices, like no-till, are not new. The Incas and ancient Egyptians used a form of no-till by using a stick to make a hole in the soil for the seed and covering the hole with dirt using their feet (Derpsch, 2004). No-till as we know it today, however, did not occur until the late 1940s following the invention of the herbicide 2,4-D (2-4 dichlorophenoxyacetic acid) and later the herbicides atrazine (2-chloro-4-ethylamine-6-isopropylamino-*S*-triazine) and paraquat (1′-dimethyl-4,4′-bipyridunium) (Derpsch, 2004). Herbicides made it possible to control weeds with chemicals, which substituted for manual labor and mechanical tillage. In addition, improvements in no-till planting technology and the introduction of herbicide-tolerant crops in the 1990s that allowed over-the-top application of herbicides during the growing season have positively influenced the adoption of conservation tillage practices such as no-till (Fernandez-Cornejo, and McBride. 2000; Derpsch, 2004; Roberts et al., 2006). Thus, the area under no-till for major crops in the United States has grown to an estimated 24 million ha in 2007 (Larson et al., 2010). In 1984, then Secretary of Agriculture John Block predicted that 95% of all U.S. cropland would be under no-till by 2010 (McWhorter, 1984) and others predicted 65% by 2000 (Phillips et al., 1980). Only 24% of cropland in the United States is currently under no-till, however, and the percentage declines for all cropland worldwide (Conservation Technology Information Center, 2009). With a wide range of reported advantages of no-till (Young, 1982; Bremer et al., 2001; Lankoski et al., 2004; DeFelice et al., 2006), why has the practice not been more universally adopted?

Profit is probably the most important factor influencing whether farmers adopt conservation practices such as no-till (Cary and Wilkinson, 1997). This study addressed the crop yield component of profit as influenced by tillage and no-till practices. Farmers are “passionately interested” in crop yields and the influence that alternative production practices have on yields because of their large impacts on profits (Lowenberg-DeBoer, 1999, p. 276). With farmers being price takers, tillage practices can be ranked in terms of revenue by considering differences in yields and the probability that no-till yields will fall below tillage yields (downside yield risk). Evidence about whether no-till yields are different from tillage yields is not clear. Many researchers have indicated higher yields with the use of no-till compared with tillage (Endale et al., 2008; Smiley, and Wilkins, 1993; Wagger and Denton, 1989), while others have reported the opposite (Graven and Carter, 1991; Halvorson et al., 2006; Hammel, 1995). Still others found no significant difference between tillage and no-till yields (Archer and Reicosky, 2009; Barnett, 1990; Kapusta et al., 1996). The soils on which a crop is grown using no-till or tillage practices and climate may influence the differences in yields observed with the two practices (DeFelice et al., 2006). Previous studies have also found that different crops respond differently to no-till (Shapiro et al., 2001; Wilhelm, and Wortmann, 2004). These yield differences may affect the risk and return from converting to no-till and thus farmers’ willingness to adopt no-till (Larson et al., 2001; Ribera et al., 2004).

D.K. Toliver, J.A. Larson, R.K. Roberts, B.C. English, and D.G. De La Torre Ugarte, Agricultural and Resource Economics Dep., Univ. of Tennessee, Knoxville, TN 37996; and T.O. West, Pacific Northwest National Lab., Richland, WA 99352, and Global Change Research Inst., Univ. of Maryland, College Park, MD 20740. Received 8 Sept. 2011 *Corresponding author (dtoliver@utk.edu).

Published in Agron. J. 104:530–541 (2012)
Posted online 7 Feb 2012
doi:10.2134/agronj2011.0291

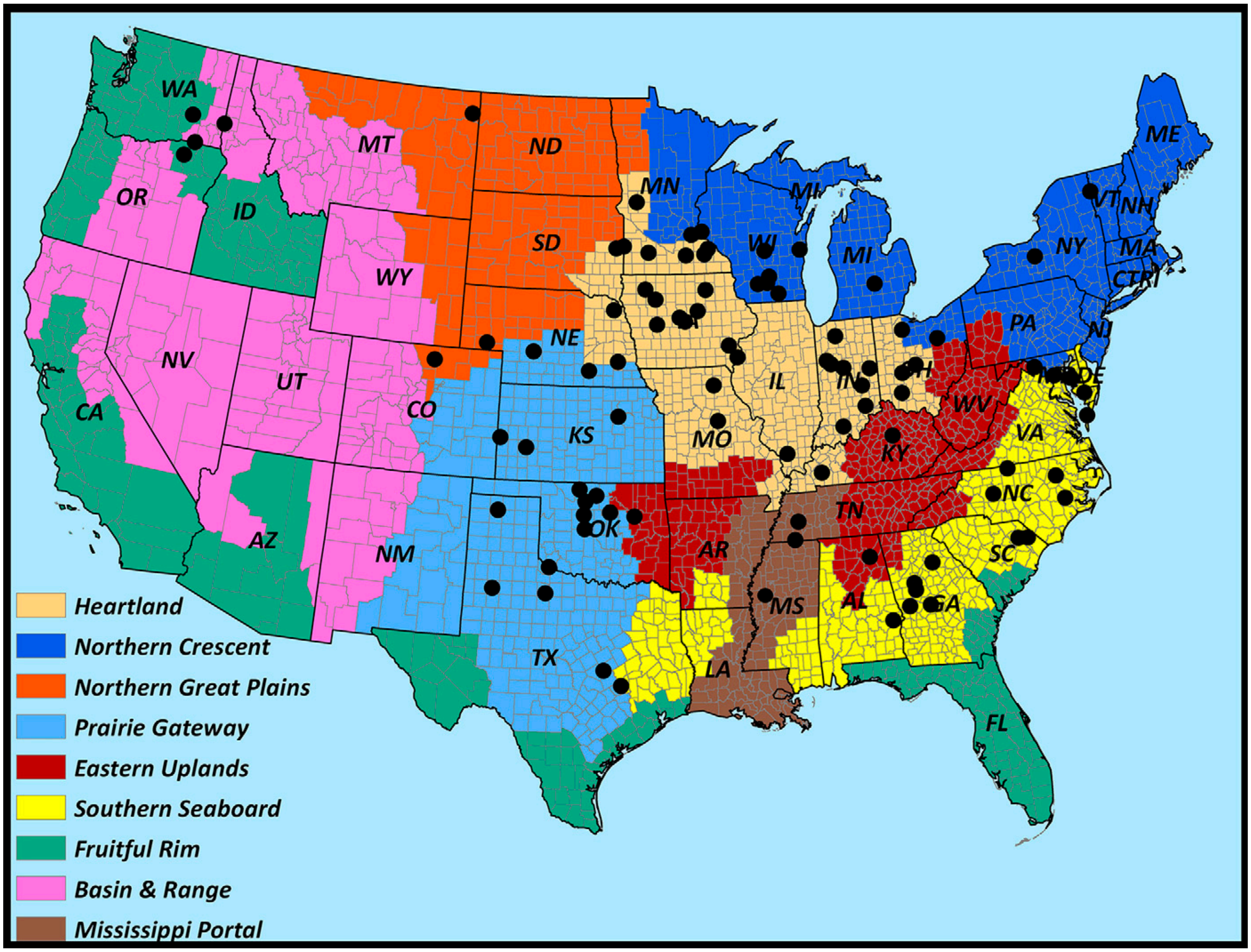

Fig. 1. Experiment locations used in analysis and mapped according to their USDA Economic Research Service farm resource region.

The objective of this research was to evaluate the impacts on expected crop yields and risk after converting from tillage (conventional tillage, strip tillage, ridge tillage, or mulch tillage) to no-till practices. The impacts were explored in relation to the year the conversion took place, the crop produced, annual precipitation, soil texture, and geographic location in the United States. The only other regional analysis of tillage intensity and crop yields (DeFelice et al., 2006) evaluated mean corn and soybean yields using data from experiments located in the midwestern and eastern United States and southern Canada. Our study differed by evaluating the yields of six crops in addition to evaluating the differences in downside yield risk from converting from tillage to no-till using experiments from across the United States. We measured downside risk as the probability of having lower yields with no-till than tillage after conversion. We also evaluated a wider range of potential growing environments and location factors that may influence differences in yields and downside risk.

DATA

Data from 686 paired tillage and no-till experiments published in *Soil and Tillage Research* were compiled by Kunda and West (2006). Of these 686 paired experiments, the 161 experiments pertaining to the 48 contiguous United States were analyzed. The data set was updated to include four paired experiments reported in that journal between July 2006 and December 2009. The data set was further augmented by adding 173 paired experiments published in *Agronomy Journal* from 1980 through 2009 to maintain temporal consistency with the previous data set. The data set was expanded a third time with 104 paired experiments found in the *Journal of Production Agriculture* from its inception in 1988 until it was absorbed into *Agronomy Journal* in 1999. These additions increased the data set to a total of 442 paired tillage experiments across 92 locations in the 48 contiguous United States.

Of these experiments, 66% used a randomized complete block experimental design, 25% a split-plot design, 7% another design (i.e., strip plot, strip-split, or unique companion plots), and 2% did not report the experimental design. When researchers used different fertilizer rates or other treatments in the experiments, yields were averaged across these treatments for each tillage method. The crops analyzed included sorghum, corn, soybean, oat (*Avena sativa* L.), cotton, and wheat. It should be noted, however, that data for oat in this data set are few and limited to one experiment in Ohio in the eastern part of the Heartland farm resource region as defined by the USDA Economic Research Service (2000; Fig. 1). Other data for all experiments included the year each experiment began, each individual year of the experiment, soil texture, geographic location, and annual precipitation. The soil texture at each

Table 1. Variable names and definitions for the statistical models comparing no-till yields with tillage yields.

Variable name	Variable definition	Mean	Hypothesized sign
Dependent variables			
ln(RR)	natural logarithm of the ratio of no-till to tillage yields	–0.038	
NTPROB	= 1 if no-till yields < tillage yields; 0 otherwise	0.63	
	Explanatory variables		
TECH	natural logarithm of the year the experiment began	2.81	–
LOGYR	natural logarithm of each year of the experiment	1.41	+
RAIN	actual annual rainfall at experiment location, cm	76.96	+/–
	Crop variables		
SORG	= 1 if sorghum; 0 otherwise	0.07	+/–
WHEAT	= 1 if wheat; 0 otherwise	0.22	+/–
CORN†	= 1 if corn; 0 otherwise	0.50	+/–
SOY	= 1 if soybean; 0 otherwise	0.16	+/–
OAT	= 1 if oat; 0 otherwise	0.01	+/–
COTT	= 1 if cotton; 0 otherwise	0.04	+/–
	Tillage variables		
TILL	= 1 if comparing conventional tillage to no-till; 0 for comparing reduced tillage to no-till	0.61	+/–
	Soil texture variables		
SAND	= 1 if sandy soil; 0 otherwise	0.09	+
SILT	= 1 if silty soil; 0 otherwise	0.01	–
CLAY	= 1 if clay soil; 0 otherwise	0.03	–
LOAM†	= 1 if loamy soil; 0 otherwise	0.87	–
	Farm resource region		
HEART†	= 1 if Heartland region; 0 otherwise	0.39	+/–
NCRES	= 1 if Northern Crescent region; 0 otherwise	0.13	–
NGP	= 1 if Northern Great Plains region; 0 otherwise	0.07	–
PGATE	= 1 if Prairie Gateway region; 0 otherwise	0.20	+/–
EASTU	= 1 if Eastern Upland region; 0 otherwise	0.02	+/–
SOSEA	= 1 if Southern Seaboard region; 0 otherwise	0.11	+
FRIM	= 1 if Fruitful Rim region; 0 otherwise	0.02	+/–
BANDR	= 1 if Basin and Range region; 0 otherwise	0.04	+/–
MISS	= 1 if Mississippi Portal region; 0 otherwise	0.02	+

† Reference dummy variables excluded from the regression models.

experimental location was usually provided. When the soil texture was provided as percentages, the USDA soil texture triangle was used to estimate the soil texture classification (Soil Survey Division Staff, 1993). As with oat, observations for silt-textured soils were limited to a wheat experiment in the upper part of the Basin and Range farm resource region (USDA Economic Research Service, 2000; Fig. 1). Annual precipitation in centimeters for each year of each experiment was added to the data set (National Climatic Data Center, www.ncdc.noaa.gov/oa/climate/stationlocator.html, accessed 2009).

Each experiment was located within one of the nine farm resource regions defined by the USDA Economic Research Service (2000; Fig. 1). These regions represent areas with similar types of farms as well as similar climatic, physiographic, and soil characteristics (Fernandez-Cornejo and McBride, 2000). Geographic locations for the experiments are provided in Fig. 1. Four observations were omitted because of human error, resulting in little to no yield. Three additional observations were omitted because of zero yield readings from a plot digitizer. The total number of usable paired no-till and tillage yield observations from the 442 experiments at 92 locations in the augmented data set was 1546. Table 1 contains the variable names, means, and their definitions.

METHODS AND PROCEDURES

Conceptual Framework

Profit from producing a crop using alternative tillage practices can be modeled using the following equation (Nicholson, 2005):

$$\pi_i = PY_i - \mathrm{VC}_i - \mathrm{FC}_i \qquad [1]$$

where π is profit, P is crop price, Y is crop yield, VC is the variable costs of production, FC is the fixed costs of production, and subscript i denotes the particular tillage practice (conventional tillage, no-till, strip tillage, ridge tillage, or mulch tillage). Crop yield Y can be used to rank tillage practices by their revenue outcomes (PY_i) because the crop price is fixed for the price-taking farmer. The costs of production also affect profit ($\mathrm{VC}_i + \mathrm{FC}_i$) but were not investigated in this study. Yields for the ith tillage practice are uncertain due the unpredictable impacts of weather, soil, other production environment factors, and location (Graven, and Carter, 1991; Hairston et al., 1990; Lueschen et al., 1992; Smith et al., 1992). The influence of alternative tillage practices on crop yields can be evaluated using the moments of the yield probability distribution (Anderson et al., 1977; Chavas et al., 2009). The first moment is the mean yield:

$$\mathrm{E}\left[Y_i\right] = \mathrm{E}\left[F\left(\mathbf{v}_i | \mathbf{x}_i\right)\right] \qquad [2]$$

where E[·] is the expectation operator, **v** is a vector of the production environment factors affecting production, and **x** is a vector of production inputs used with the *i*th tillage method. Mean yield, and thus mean revenue, varies with the *i*th tillage practice as influenced by the production environment and location factors.

Many farmers are concerned about the risk of yield variability or change associated with the *i*th tillage practice. Risk-averse farmers are most often concerned about deviations in yields below the mean or some other target value (Binswanger, 1981; Selley, 1984; Antle, 1987; Chavas, 2004). Downside risk below a target or comparison value can be modeled using the lower partial moment (LPM) (Fishburn, 1977). The equation for the LPM in the context of the tillage decision problem is

$$\mathrm{E}[\mathrm{LPM}]_i = \mathrm{E}\left[\left\{\min(Y_i - Z), 0\right\}^n\right] \qquad [3]$$

where Z is some yield reference point for the *i*th tillage practice to be evaluated against and n is the degree of the moment. Thus, the LPM is a measure of the expected deviation below the comparison or target level. The common classifications of n are: $n = 0$ is the probability of a loss, $n = 1$ is the target shortfall, $n = 2$ is the target semivariance, and $n = 3$ is the target skewness.

Meta-analysis is a quantitative method for summarizing the results of independent studies to allow the testing of hypotheses that cannot be addressed in a single experiment (Hedges and Olkin, 1985; Cooper and Hedges, 1994; Miguez and Bollero, 2005). For this study, the hypotheses related to the effects of weather, soils, and other production environment factors on mean yields and downside yield risk for no-till (i = NT) relative to tillage (conventional, strip, ridge, or mulch tillage; i = TILL) were evaluated. A response ratio (RR) was created to evaluate the relative no-till and tillage yields (Hedges et al., 1999):

$$\mathrm{RR} = \frac{Y_{\mathrm{NT}}}{Y_{\mathrm{TILL}}} \qquad [4]$$

With the natural logarithm of the response ratio [ln(RR)] as the dependent variable (Miguez, and Bollero, 2005), a mixed linear model was used to evaluate which production environmental and location factors affect the relative mean crop yields:

$$\ln(\mathrm{RR}) = \mathbf{W}\boldsymbol{\alpha} + \mathbf{U}\boldsymbol{\beta} + \varepsilon \qquad [5]$$

where $\boldsymbol{\alpha}$ is a vector of unknown fixed effects, $\boldsymbol{\beta}$ is a vector of random effects, $\boldsymbol{\varepsilon}$ is a vector of random residuals, and **W** and **U** are given known and incidence matrices, respectively (Harville and Mee, 1984; McLean et al., 1991). The factors influencing the differences in mean yields for no-till vs. tillage practices were determined by the sign and significance of the parameter estimates.

Setting $n = 0$ in Eq. [3] (probability of a loss below a comparison level) and using the response ratio in Eq. [4], a mixed logit model was specified to evaluate the probability of no-till yields being lower than tillage yields as influenced by the production environment and location factors. The dependent variable NTPROB was defined as follows: if RR < 1, then NTPROB = 1; otherwise, NTPROB = 0. Thus, downside risk in this case is defined as the probability of no-till yields being lower than tillage yields after conversion from tillage to no-till.

The mixed logit model specifies the probability of downside production risk when converting from tillage to no-till:

$$\mathrm{NTPROB}(a=1) = \frac{\exp(\theta)}{1+\exp(\theta)} \qquad [6]$$

where $a = 1$ if no-till yield is less than tillage yield, otherwise 0; $\theta = \mathbf{W}\boldsymbol{\gamma} + \mathbf{U}\boldsymbol{\eta} + \boldsymbol{\tau}$, $\boldsymbol{\gamma}$ is a vector of fixed effects, $\boldsymbol{\eta}$ is a vector of random effects, and $\boldsymbol{\tau}$ is a vector of random residuals. The probability of no downside risk when converting to no-till is determined as

$$\mathrm{NTPROB}(a=0) = 1 - P(a=1) = \frac{1}{1+\exp(\theta)} \qquad [7]$$

Identification of the factors influencing the probability of lower no-till yields was determined by the sign and significance of the parameter estimates.

Empirical Models

The empirical model used to evaluate mean yield differences between no-till and tillage was specified as

$$\begin{aligned}
\ln\left(\hat{\mathrm{RR}}\right) = {} & \\
& \hat{\alpha}_0 + \sum_{i=1}^{5} \hat{\alpha}_i \mathrm{CROP}_i + \sum_{j=6}^{8} \hat{\alpha}_j \mathrm{SOIL}_j \\
& + \sum_{k=9}^{16} \hat{\alpha}_k \mathrm{ERS}_k + \hat{\alpha}_{17}\mathrm{TILL} + \hat{\alpha}_{18}\mathrm{TECH} \\
& + \hat{\alpha}_{19}\mathrm{LOGYR} + \hat{\alpha}_{20}\mathrm{RAIN} \\
& + \sum_{i=1}^{5}\sum_{j=6}^{8} \hat{\alpha}_{ij}(\mathrm{CROP}_i)(\mathrm{SOIL}_j) \\
& + \sum_{i=1}^{5} \hat{\alpha}_{i18}(\mathrm{CROP}_i)(\mathrm{TECH}) \\
& + \sum_{i=1}^{5} \hat{\alpha}_{i19}(\mathrm{CROP}_i)(\mathrm{LOGYR}) \\
& + \sum_{i=1}^{5} \hat{\alpha}_{i20}(\mathrm{CROP}_i)(\mathrm{RAIN})
\end{aligned} \qquad [8]$$

where $\ln(\hat{\mathrm{RR}})$ is the estimate of ln(RR), $\hat{\alpha}$ is an estimated coefficient, CROP represents one of five crops (i = sorghum, wheat, soybean, cotton, or oat); SOIL represents one of three soil textures (j = sand, silt, or clay), and ERS represents one of eight USDA-ERS farm resource regions (k = Northern Crescent, Northern Great Plains, Prairie Gateway, Eastern Uplands, Southern Seaboard, Fruitful Rim, Basin and Range, or Mississippi Portal). The reference categories for CROP, SOIL, and ERS in Eq. [8] are corn (CORN), loam soil (LOAM), and the Heartland (HEART) region. The ERS variables were included to capture differences across latitudes, longitudes, and other unique regional and environmental factors that affect crop yields. The TILL variable is a binary dummy variable with a value of 1 for a comparison of conventional tillage with no-till or 0 for a comparison of reduced tillage (strip tillage, ridge tillage, or mulch tillage) with no-till. The variable TECH is a continuous variable used to capture improvements in technology with time. It represents the natural logarithm of the year in which the experiment was initiated, with 1964 = ln(1), 1965 = ln(2), ..., 2005 = ln(42). The variable LOGYR is a continuous variable that represents the natural logarithm of the year of the experiment; for example, for Exp. A conducted between 1981 and 1985, 1981 = ln(1), 1982 = ln(2), ..., 1985 = ln(5), and for

Exp. B conducted in 1995 and 1996, 1995 = ln(1) and 1996 = ln(2). The value of LOGYR was used to test whether a yield lag existed when converting from tillage to no-till, as much anecdotal evidence suggests, and to see if no-till yields increased with time relative to tillage yields through soil improvement. The continuous variable RAIN is the mean annual precipitation for the location and year of each experiment. No interactions were specified between CROP and ERS because not all crops were present in each farm resource region. For example, the Fruitful Rim and Basin and Range regions had observations for only two and one crops, respectively. It should be noted that there were no observations for sorghum, soybean, oat, or cotton on a silt-textured soil and no observations for oat on sand- or clay-textured soils; therefore, no interactions were specified between those specific crops and soil textures.

The following logit model was specified to evaluate the probability of no-till yields being less than tillage yields after conversion to no-till:

$$\begin{aligned}\widehat{\mathrm{NTPROB}} = {} & \hat{\gamma}_0 + \sum_{i=1}^{5} \hat{\gamma}_i \mathrm{CROP}_i + \sum_{j=6}^{8} \hat{\gamma}_j \mathrm{SOIL}_j \\ & + \sum_{k=9}^{16} \hat{\gamma}_k \, \mathrm{ERS}_k + \hat{\gamma}_{17}\mathrm{TILL} + \hat{\gamma}_{18}\mathrm{TECH} \\ & + \hat{\gamma}_{19}\mathrm{LOGYR} + \hat{\gamma}_{20}\mathrm{RAIN} \\ & + \sum_{i=1}^{5}\sum_{j=6}^{8} \hat{\gamma}_{ij}\left(\mathrm{CROP}_i\right)\left(\mathrm{SOIL}_j\right) \\ & + \sum_{i=1}^{5} \hat{\gamma}_{i18}\left(\mathrm{CROP}_i\right)\left(\mathrm{TECH}\right) \\ & + \sum_{i=1}^{5} \hat{\gamma}_{i19}\left(\mathrm{CROP}_i\right)\left(\mathrm{LOGYR}\right) \\ & + \sum_{i=1}^{5} \hat{\gamma}_{i20}\left(\mathrm{CROP}_i\right)\left(\mathrm{RAIN}\right)\end{aligned} \qquad [9]$$

where $\widehat{\mathrm{NTPROB}}$ is the estimate of NTPROB that is the downside risk-dependent variable equal to one if the no-till crop yield was less than the tillage yield and zero otherwise, and $\hat{\gamma}$ is an estimated coefficient.

Statistical Analysis

Equation [8] was estimated using the MIXED procedure in SAS (SAS Institute, 2004) to test the null hypothesis that the yield means do not differ with tillage practice (Littell et al., 1996). Equation [9] was estimated using the GLIMMIX procedure in SAS (SAS Institute, 2006) to test the null hypothesis that the downside yield risk does not differ with tillage practice (Schabenberger, 2005). The null hypothesis of constant yield variances across experiment locations was tested using two general tests for heteroskedasticity: the White test and the Breusch–Pagan test. These tests were performed using the residuals from the models estimated without a random effects statement in SAS (Judge et al., 1985). Heteroskedasticity was detected, so the location of the experiment was specified as a random effect and modeled using an unstructured covariance matrix (SAS Institute, 2006). Akaike information criteria were used to determine whether the models with the random effects specification provided a better fit for the data (Dayton, 2003). Variance inflation factors were used for multicollinearity diagnosis (Chatterjee and Price, 1991).

RESULTS

Heteroskedasticity and Multicollinearity

The White test and Breusch–Pagan test both indicated that heteroskedasticity was present in the models. The models corrected for heteroskedasticity had Akaike information criteria closer to zero than the models estimated without random effects, suggesting a better fit for this specification (Dayton, 2003). Evidence of multicollinearity was not found.

Mean Yield Differences

In the following discussion, results from Table 2 are presented as the effects of a variable on the natural logarithm of the ratio of no-till to tillage yields relative to the ratio of no-till to tillage yields for corn produced on a loam soil in the Heartland region. A larger ratio can be interpreted as a larger difference between no-till and tillage yields. A positive (negative) coefficient for a variable indicates that the ratio of yields is larger (smaller) than the ratio of yields for corn on a loam soil in the Heartland region, indicating that no-till yields are higher (lower) than tillage yields relative to corn on a loam soil in the Heartland region. In the discussion, one or more of the reference categories for the dummy variables (corn, loam, Heartland) may be implied for ease of exposition.

Crops reacted differently to no-till and tillage methods. Differences between no-till and tillage sorghum (SORG) and wheat (WHEAT) yields were larger than the difference between no-till and tillage corn yields with all other factors being equal. Increased soil moisture, or soil water content, from the residues left in the field was by far the most common explanation for increased no-till sorghum and wheat yields from the studies used in this analysis (Dao and Nguyen, 1989; Douglas et al., 1994; Norwood, 1992; Tarkalson et al., 2006; Wiese et al., 1998; Winter and Unger, 2001). Even though the coefficient for oat was negative and significant, it is difficult to draw any conclusions about differences in yields for OAT without including the OAT × LOGYR and OAT × RAIN coefficients because the data were from a single experiment.

The difference between no-till and tillage yields in a silt soil (SILT) was smaller than the difference between no-till and tillage yields in a loam soil. This result coincides with previous research showing that no-till performs better on well-drained soils but does not produce as well on finely textured or poorly drained soils such as silty soils (DeFelice et al., 2006; Hairston et al., 1990). This result may not give a full representation of no-till's effectiveness on a silt-textured soil, however, due to the limited number of silt observations in the data set. Differences between no-till and tillage yields on clay and sandy soils were not statistically different from those on loam soils, all other factors being equal. Several significant interactions were found between soil texture and crop. The interactions SORG × SAND, WHEAT × SAND and SOY × SAND were significant and negative, suggesting that no-till yields for sorghum, wheat, and soybean produced on a sandy-textured soil were less than the yields for corn produced on a loam soil. A potential explanation generally given for lower yields under sandy soils in the studies used in this analysis was lower water holding capacity or lower soil moisture under sandy soils, which is exacerbated in dry years (Busscher et al., 2005; Hilfiker and Lowery, 1988; Lowery et al., 1998). Other reasons given were N insufficiency due to leaching (Evanylo, 1991) and reduced root length under no-till (Hilfiker and Lowery, 1988; Karlen et al., 1991). Sandy soils leach nutrients more readily, reducing the amount available to the plants (North Carolina Department of Agriculture, 2010). Reduced root length on a plant causes more stress on the plant under low rainfall and high temperatures (Karlen et al., 1991). Sandy soils tend to compact and some recommend deep or slit tillage to loosen the soil, which has been shown to increase root length and yields over no-till (Busscher et al., 2006; Karlen et al., 1991).

The hypothesis of no-till performing better relative to tillage in warmer climates was confirmed. The Southern Seaboard (SOSEA) and Mississippi Portal (MISS) regions, which represent a majority of the southern and southeastern United States, had positive and significant coefficients. These regions had, on average, higher no-till yields relative to tillage yields compared with the Heartland region. These results concur with previous research (DeFelice et al., 2006), where no-till was found to have higher yields in the southern United States and lower yields in the northern United States than tillage. The Fruitful Rim (FRIM) and Basin and Range (BANDR) regions, which cover much of the western and northwestern parts of the country, had smaller ratios of no-till to tillage yields than the Heartland region. This result could be explained by all experiments in the data set from these two regions originating from the Upper Northwest United States. That area receives large amounts of precipitation from October to March and experiences cold weather. It is common for the soil to freeze to a depth of 40 cm or greater (Papendick, 1987). Wet years and cold climates have been found to cause reduced yields under no-till compared with tillage (Graven and Carter, 1991; Eckert, 1984; Herbek et al., 1986).

The significant and negative interactions between the variable for technology and sorghum and wheat, SORG × TECH and WHEAT × TECH, suggest that as the year in which the experiment was initiated increased, the differences between no-till and tillage yields decreased for sorghum and wheat compared with differences in corn yields. Seed and no-till technology have advanced with time. With the United States being the largest producer of corn in the world, technological advances related to corn have increased at a faster rate than for sorghum or wheat. Initial efforts to genetically modify crops were primarily focused on corn, soybean, cotton, canola (*Brassica napus* L. var. *napus*) and potato (*Solanum tuberosum* L.) (Harlander, 2002). In fact, one of the first genetically modified crops was insect-resistant corn: *Bacillus thuringiensis* (Bt) corn (Harlander, 2002). The Bt corn provides protection against the European corn borer, which is noted as the most damaging insect in corn production in the United States and Canada (Witkowski et al., 2002). To get a better view of how much more technology was focused on corn than wheat or sorghum from 1987 to 2011, 7267 applications were approved for field testing of genetically engineered corn by the USDA Animal and Plant Health Inspection Service (Information Systems for Biotechnology, 2010). By comparison, for the same time period, only 431 were approved for wheat, while sorghum was not mentioned (Information Systems for Biotechnology, 2010). Another benefit to no-till was the breeding of herbicide-tolerant crops. These herbicide-tolerant crops have increased the trend of no-till by allowing easier control of

Table 2. Empirical mean yield regression model comparing no-till yields with tillage yields. The dependent variable is the natural logarithm of the ratio of no-till to tillage yields.

Explanatory variable†	Coefficient	*t* value
INTERCEPT	–0.005370	–0.11
SORG	0.444500**	5.33
WHEAT	0.222500**	2.62
SOY	–0.169500	–1.01
OAT	–0.518700*	–2.47
COTT	–1.019900	–1.59
SAND	0.001908	0.07
SILT	–0.122800‡	–1.83
CLAY	0.009623	0.20
TILL	–0.002650	–0.28
TECH	0.004154	0.34
LOGYR	–0.022690**	–2.67
RAIN	–0.000200	–0.92
NCRES	–0.006180	–0.39
NGP	–0.039590	–1.13
PGATE	0.003242	0.18
EASTU	0.038120	1.19
SOSEA	0.071550**	2.72
FRIM	–0.097470**	–2.77
BANDR	–0.107100*	–2.46
MISS	0.085000‡	1.68
SORG × SAND	–0.219500*	–2.57
SORG × CLAY	0.022640	0.29
SORG × TECH	–0.074340**	–3.60
SORG × LOGYR	0.025760	1.06
SORG × RAIN	–0.003000**	–4.62
WHEAT × SAND	–0.211600**	–4.49
WHEAT × CLAY	–0.098090	–1.08
WHEAT × TECH	–0.049200*	–2.21
WHEAT × LOGYR	–0.001380	–0.08
WHEAT × RAIN	–0.000700	–1.48
SOY × SAND	–0.206300**	–4.16
SOY × CLAY	0.002139	0.03
SOY × TECH	0.046260	0.98
SOY × LOGYR	0.023290	1.36
SOY × RAIN	0.000340	0.65
OAT × LOGYR	0.151500	1.48
OAT × RAIN	0.009060*	2.58
COTT × SAND	0.155300	1.43
COTT × CLAY	0.012990	0.10
COTT × TECH	0.249700	1.26
COTT × LOGYR	0.168900**	3.40
COTT × RAIN	0.000510	0.65
n	1546	
–2 Residual log likelihood	–811.1	
Akaike information criterion	–807.1	
Sample-size-corrected Akaike information criterion	–807.1	
Bayesian information criterion	–811.1	

* Significant at the 0.05 confidence level.

** Significant at the 0.01 confidence level.

† INTERCEPT contains the reference categories of corn crop, loam texture, and Heartland region; SORG, sorghum crop; WHEAT, wheat crop; SOY, soybean crop; OAT, oat crop; COTT, cotton crop; SAND, sand texture; SILT, silt texture; CLAY, clay texture; TILL, comparison of tillage; TECH, natural logarithm of year experiment began; LOGYR, natural logarithm of each year of experiment; RAIN, actual rainfall at location; NCRES, Northern Crescent region; NGP, Northern Great Plains region; PGATE, Prairie Gateway region; EASTU, Eastern Upland region; SOSEA, Southern Seaboard region; FRIM, Fruitful Rim region; BANDR, Basin and Range region; MISS, Mississippi Portal region.

‡ Significant at the 0.10 confidence level.

weeds without tillage by applying a post-emergent herbicide over the crop (Fernandez-Cornejo and McBride, 2002).

The year of the experiment (LOGYR) was hypothesized to have a positive sign in the hope of capturing any yield lag in the first few years after conversion from tillage to no-till. Contrary to expectations, the variable was significant and negative. Thus, with each additional year after conversion, no-till corn yields decreased slightly compared with tillage corn yields. The negative effects might be explained by most experiments lasting between 3 and 5 yr, which may not be sufficient time for no-till fields to reach their full potential in building soil tilth, porosity, and organic matter. Given that most of the experiments lasted between 3 to 5 yr, other factors could also have caused this result, such as disease or pest pressure or, as in some cases of early no-till experiments, unfamiliarity with the practice. Interactions of LOGYR with the crop dummy variables were not significant except for cotton. The sum of the coefficients for LOGYR and the COTT × LOGYR interaction suggests that cotton no-till yields increased relative to tillage yields with each year after conversion from tillage to no-till compared with the difference between no-till and tillage corn yields.

Rainfall did not significantly affect the ratio of no-till to tillage yields for corn; however, RAIN was significant in two interactions, SORG × RAIN and OAT × RAIN. Compared with corn, increases in the amount of precipitation decreased the ratio of sorghum no-till to tillage yields. This has been found in other work where no-till performed better than tillage during dry years but yielded less during wet years (Anderson, 1986; Blevins et al., 1971). One reason for lower no-till yields with increased rainfall is that wetter soils require more time for the soil temperatures to increase. This problem is further exacerbated under cold temperatures when crop residues are present. The residues act as insulation, keeping the soils cooler as well as reducing moisture evaporation (Herbek et al., 1986). The other significant interaction, OAT × RAIN, was positive, showing that with an increase in rainfall, no-till oat yields increased relative to tillage oat yields compared with the difference between no-till and tillage corn yields.

The coefficients in Table 2 can be used to calculate the ratios of no-till to tillage yields for specific crops, soils, and regions. Corn produced on a loam soil in the Southern Seaboard region (SOSEA), with TECH and LOGYR evaluated at their data set means and RAIN evaluated at its mean for the Southern Seaboard region (TECH = 2.81, LOGYR = 1.41, RAIN = 110.1, TILL = 1), SOSEA = 1, and all other dummy variables equal to zero resulted in

$$\begin{aligned}\ln(\mathrm{RR}) = &-0.00537+(0.004154\ \mathrm{TECH})\\ &+(-0.02269\ \mathrm{LOGYR})\\ &+(-0.0002\ \mathrm{RAIN})\\ &+(-0.00265\ \mathrm{TILL})\\ &+(0.07155\ \mathrm{SOSEA})\\ = &\ 0.02118984\end{aligned} \qquad [10]$$

Taking the antilog of Eq. [10] [exp(0.02118984)] gives 1.021415939 as the ratio of no-till to tillage yields. Taking the antilog of the equation gives a simple proportion of no-till yields over tillage yields. This can then be interpreted as: if the ratio is less (greater) than one, the difference is negative (positive), meaning that no-till yields are less (greater) than tillage yields. In this case, the ratio indicates that mean no-till yields were 2.1% greater than the mean tillage yields for corn produced on a loam soil in the Southern Seaboard region. Another example is that of corn produced on a loam soil in the Heartland region. In this case, all dummy variables, including SOSEA, were set equal to zero and the mean rainfall for the Heartland region (81.5 cm) was used:

$$\begin{aligned}\ln(\mathrm{RR}) = &-0.00537+(0.004154\times 2.81)\\ &+(-0.02269\times 1.41)\\ &+(-0.0002\times 81.5)\\ &+(-0.00265\times 1)\\ = &-0.04464016\end{aligned} \qquad [11]$$

The antilog of Eq. [11] [exp(−0.4464016)] is 0.95634155, indicating that no-till yields for corn grown on a loam soil in the Heartland region are 4.4% lower than tillage yields. The results in Eq. [10] and [11] indicate that no-till produced higher corn yields in the Southern Seaboard region, whereas tillage produced higher corn yields in the Heartland region.

The coefficients from the model in Table 2 can also be used to show how relative yields are affected through time after conversion to no-till. For the Southern Seaboard region, the process would be the same as in Eq. [10], except LOGYR would take on values for the specific years after conversion. As an example, LOGYR would be evaluated at ln(1), ln(3), ln(5), and ln(10) instead of at its mean as in Eq. [10]. The resulting no-till to tillage ratios for Years 1, 3, 5, and 10 after conversion to no-till would be 1.055, 1.029, 1.017, and 1.001, respectively. These results suggest that no-till corn yields would be greater than tillage corn yields produced on a loam soil in the Southern Seaboard region for at least 10 yr after conversion to no-till, but the advantage of no-till would decrease from 5.5 to <1% during those 10 yr. When Eq. [11] is used to estimate relative yields after conversion to no-till for corn grown on a loam soil in the Heartland region, the results show that no-till yields are 1.3, 3.7, 4.8, and 6.3% lower than tillage yields in Years 1, 3, 5, and 10 after conversion, respectively.

The predicted no-till yields as a percentage of tillage yields using all of the available data for the United States are given in Table 3. The predictions were calculated in the same manner as the examples using the estimated coefficients in Table 2 and sample means for TECH (2.81), LOGYR (1.41), RAIN (using the sample averages for each farm resource region), and the dummy variable TILL = 1. While not all of the estimated coefficients in Table 2 are significant, they are the best linear unbiased estimates of yield differences due to tillage practice. No-till tended to produce similar or greater mean yields than tillage for crops grown on loamy soils in the Southern Seaboard and Mississippi Portal regions. For the Southern Seaboard region, no-till yields outperformed tillage yields on average on loam soils when producing soybean (5.3% higher), corn (2.1% higher), or wheat (2.7% higher). A warmer and more humid climate and warmer soils in these regions relative to the Heartland, Basin and Range, and Fruitful Rim regions appear to favor no-till on loamy textured soils. By comparison, the results on sandy textured soils in the Southern Seaboard region were mixed, with higher mean no-till yields for corn and cotton but

Table 3. Predicted no-till yields as a percentage of tillage yields by USDA Economic Research Service farm resource region (Fig. 1) and soil texture.

USDA-ERS region	Annual precipitation	Soil texture	No-till yield increase†					
			Corn	Sorghum	Cotton	Soybean	Wheat	Oat
	cm		%					
Heartland	81.5	loam	95.63	98.29	–‡	97.67	–	147.50
		clay	96.56	–	–	98.82	–	–
Northern Crescent	71.9	loam	95.23	–	–	96.94	98.32	–
		sand	95.41	–	–	–	–	–
Northern Great Plains	38.4	loam	–	–	–	–	98.00	–
Prairie Gateway	64.8	loam	96.27	104.03	91.84	97.76	99.89	–
		clay	98.46	107.44	93.94	–	91.43	–
Eastern Upland	96.7	loam	99.05	–	–	101.68	100.51	–
Southern Seaboard	110.1	loam	102.14	–	99.73	105.33	102.68	–
		sand	102.34	77.51	116.70	85.86	83.25	–
Fruitful Rim	34.1	loam	–	–	–	–	92.85	–
		sand	87.75	–	–	–	–	–
Basin and Range	22.0	loam	–	–	–	–	92.97	–
		silt	–	–	–	–	82.22	–
Mississippi Portal	132.8	loam	–	–	101.79	107.10	–	–
		clay	–	–	–	108.37	93.33	–

† Predictions were calculated using the estimated regression coefficients in Table 2, sample means for TECH (2.81), LOGYR (1.41), and RAIN for each farm resource region, and TILL = 1.

‡ Crop yield data were not available for the farm resource region and soil texture classification.

lower mean no-till yields for sorghum, soybean, and wheat. Lower mean no-till yields on sandy textured soils were also estimated for corn in the Fruitful Rim and Northern Crescent region. The estimates for oat on a loamy textured soil in the Heartland region and wheat on a silt-textured soil in the Basin and Range region should be viewed with caution due to the limited number of observations for both in the data set used for the meta-analysis. The results in Table 3 also indicate the potential gaps in knowledge about the performance of no-till relative to tillage for alternative crops and soils. For example, data based on the available refereed literature about the performance of no-till and tillage practices for corn and sorghum on loam-, clay-, silt-, and sand-textured soils were not available for the Mississippi Portal Region.

Downside Risk

The downside risks for wheat (WHEAT), soybean (SOY), oat (OAT), and cotton (COTT) were not different from corn, but sorghum (SORG) had a smaller probability than corn of having lower no-till yields than tillage yields after conversion to no-till, all other factors being equal (Table 4). Soil texture (SAND, SILT, or CLAY) did not significantly affect the downside risk compared with a loam (LOAM) soil texture. Alternatively, wheat and soybean grown on sandy soils (WHEAT × SAND and SOY × SAND) increased the probability of producing lower no-till yields than tillage yields relative to corn produced on a loam soil. This is probably due to sandy soils having lower moisture holding capacity, greater leaching potential, or reduced root length due to soil compaction (Busscher et al., 2005; Evanylo, 1991; Hilfiker and Lowery, 1988; Karlen et al., 1991; Lowery et al., 1998). The lower mean yields and higher downside risk may indicate that no-till on sandy-textured soils for wheat and soybean may not be a risk-efficient practice and may impede the adoption of no-till for these crops on these soils.

The Southern Seaboard (SOSEA) was the only farm resource region that had significantly reduced chances of having lower no-till yields than tillage yields. The rest of the regions were not significantly different from the Heartland region (HEART) in affecting downside risk. Because the Southern Seaboard covers much of the southeastern United States, this result compares favorably to a study by DeFelice et al. (2006), who found that no-till corn and soybean yields were greater in the southern United States and lower in the northern United States. Their results were mainly attributed to soil moisture, drainage, and climate (DeFelice et al., 2006). The results indicate that the potential positive risk management benefits of no-till through higher mean yields and lower downside risk may be a positive factor in the adoption of the technology in the region, all other factors being equal.

The variable LOGYR was significant, showing that the longer the amount of time that no-till is used, the higher the probability of having lower no-till corn yields than tillage corn yields. A possible explanation could be increased weeds, insects, and disease with the use of no-till as a result of the increased residues. Some previous work has shown no-till to have reduced yields compared with tillage due to weed infestations (Buhler and Mester, 1991; Cardina et al., 1995). The residue could also be keeping the soil too cold and moist, delaying crop emergence and diminishing yields. One study in Minnesota did report a gradual decrease in corn yields with time with the use of no-till. This was attributed in part to wet and cold soil (Linden et al., 2000). When LOGYR was interacted with soybean and cotton, just the opposite occurred. When interacted with soybean (SOY × LOGYR) and cotton (COTT × LOGYR), there is a lower probability of having lower yields with no-till than with no-till corn. Thus the production of soybean and cotton using no-till becomes less risky relative to tillage as the time after conversion increases.

The year each experiment was initiated (TECH) was not significant and was not significant in any interactions. This result is a little surprising. We hypothesized that increases in technology with time would decrease the probability of downside risk with no-till; however, the probability of downside risk throughout the years did not significantly increase for no-till either.

The amount of precipitation (RAIN) was significant in affecting the probability of corn having diminished yields with no-till relative to tillage. Each centimeter increase in precipitation increased the probability of lower no-till corn yields relative to tillage corn yields. Previous research has shown that no-till outperforms tillage during dry years because no-till conserves water, but no-till yields are less with increased amounts of rainfall (Eckert, 1984; Herbek et al., 1986). This could be caused by the decaying wet residue increasing weeds and disease. The increased rainfall could also be keeping the soil too cool and moist, delaying crop emergence and decreasing yields (Herbek et al., 1986). When rainfall was interacted with sorghum (SORG × RAIN), a high-residue crop, the probability of having lower no-till yields than tillage yields increased compared with corn; this once again coincides with rainfall negatively affecting no-till yields when high amounts of crop residue are present on the soil. Increases in rainfall, however, decreased the likelihood of lower relative no-till yields when producing soybean (SOY × RAIN), wheat (WHEAT × RAIN), or cotton (COTT × RAIN) compared with corn. Because soybean, wheat, and cotton do not provide as much crop residue as corn, they may not affect soil moisture and temperature as much as a dense-residue crop such as corn. Therefore, crop emergence is not delayed and diminished yields are less likely to occur.

The coefficients in Table 4 can be used to calculate the probability of no-till yields being less than tillage yields for specific crops, soils, and regions. Corn produced on a loam soil in the Southern Seaboard region (SOSEA), with TECH and LOGYR evaluated at their data set means and RAIN evaluated at its mean for the Southern Seaboard region (TECH = 2.81, LOGYR = 1.41, RAIN = 110.1, TILL = 1), SOSEA = 1, and all other dummy variables equal to zero results in

$$\begin{aligned}\mathrm{ODDS} = \exp\Big[&\big(-0.6474 + 0.2853\ \mathrm{TECH}\big)\\ &+\big(0.2318\ \mathrm{LOGYR}\big)\\ &+\big(0.01057\ \mathrm{RAIN}\big)\\ &+\big(-0.1015\ \mathrm{TILL}\big)\\ &+\big(-0.9159\ \mathrm{SOSEA}\big)\Big]\\ = 1.&87289994\end{aligned} \qquad [12]$$

where ODDS is the odds ratio. The ratio indicates that no-till corn yields were about 1.9 times as likely to be lower than tillage corn yields on a loam soil in the Heartland region. The downside yield risk probability calculated using the odds ratio is

$$\begin{aligned}\mathrm{NTPROB}(a=1) &= \frac{\mathrm{ODDS}}{1+\mathrm{ODDS}}\\ &= \frac{1.87289994}{1+1.87289994}\\ &= 0.651919656\end{aligned} \qquad [13]$$

This indicates that there was a 65% probability that no-till corn yields would be lower than tillage corn yields. Using Eq. [12], the probability of no-till yields being lower than tillage yields for corn on a loam soil in the Heartland region can be calculated by setting SOSEA = 0 and RAIN = 81.5, producing

Table 4. Estimated logit model predicting the probability of no-till yields lower than tillage. The dependent variable is 1 if no-till yields < tillage yields, 0 otherwise.

Explanatory variable†	Coefficient	t value
INTERCEPT	–0.64740	–0.74
SORG	–4.77400*	–2.40
WHEAT	–1.33500	–0.84
SOY	3.24960	1.40
OAT	6.19830	1.36
COTT	15.43730	1.64
SAND	–0.77000	–1.47
SILT	5.99220	0.79
CLAY	–0.14550	–0.20
TILL	–0.10150	–0.73
TECH	0.28530	1.16
LOGYR	0.23180‡	1.83
RAIN	0.01057**	∞
NCRES	–0.35170	–0.98
NGP	–0.98830	–1.30
PGATE	–0.56220	–1.36
EASTU	–0.29090	–0.46
SOSEA	–0.91590*	–2.05
FRIM	0.76980	0.99
BANDR	–0.22560	–0.21
MISS	–0.89940	–1.05
SORG × SAND	5.74460	0.46
SORG × CLAY	–0.38470	–0.32
SORG × TECH	0.25120	0.51
SORG × LOGYR	–0.13440	–0.30
SORG × RAIN	0.05326**	∞
WHEAT × SAND	2.62090**	3.17
WHEAT × CLAY	0.86650	0.70
WHEAT × TECH	0.42720	0.96
WHEAT × LOGYR	0.08420	0.37
WHEAT × RAIN	–0.00740**	–∞
SOY × SAND	3.3580**	4.42
SOY × CLAY	0.78220	0.70
SOY × TECH	–0.86690	–1.32
SOY × LOGYR	–0.41300‡	–1.81
SOY × RAIN	–0.01580**	–∞
OAT × LOGYR	–2.25860	–1.25
OAT × RAIN	–0.10030	–1.43
COTT × SAND	–6.14070	–0.57
COTT × CLAY	4.99320	0.31
COTT × TECH	–4.26560	–1.48
COTT × LOGYR	–1.38340‡	–1.82
COTT × RAIN	–0.00830**	–∞
n	1546	
–2 log likelihood	1719.07	
Akaike information criterion	1807.07	
Bayesian information criterion	1915.06	
Sample-size-corrected Akaike information criterion	1809.71	

* Significant at the 0.05 confidence level.

** Significant at the 0.01 confidence level.

† INTERCEPT contains the reference categories of corn crop, loam texture, and Heartland region; SORG, sorghum crop; WHEAT, wheat crop; SOY, soybean crop; OAT, oat crop; COTT, cotton crop; SAND, sand texture; SILT, silt texture; CLAY, clay texture; TILL, comparison of tillage; TECH, natural logarithm of year experiment began; LOGYR, natural logarithm of each year of experiment; RAIN, actual rainfall at location; NCRES, Northern Crescent region; NGP, Northern Great Plains region; PGATE, Prairie Gateway region; EASTU, Eastern Upland region; SOSEA, Southern Seaboard region; FRIM, Fruitful Rim region; BANDR, Basin and Range region; MISS, Mississippi Portal region.

‡ Significant at the 0.10 confidence level.

a higher odds ratio of 3.45936830 and a higher downside yield risk probability of 78%. Consistent with the mean yield results, the downside yield risk under no-till was less in the Southern Seaboard region than in the Heartland region. Evaluation of the estimated coefficients in the logit model also indicated that downside yield risks under no-till for soybean production were lower than for corn production. The estimated soybean downside yield risk probability for the Heartland region (SOY = 1, TECH = 2.81, LOGYR = 1.41, RAIN = 81.5, TILL = 1) is

$$\begin{aligned}\mathrm{ODDS} = \exp\big[&-0.6474+(3.2496\ \mathrm{SOY})\\ &+(0.2853\ \mathrm{TECH})\\ &+(0.2318\ \mathrm{LOGYR})\\ &+(0.01057\ \mathrm{RAIN})\\ &+(-0.1015\ \mathrm{TILL})\\ &+(-0.8669\ \mathrm{SOY}\times\mathrm{TECH})\\ &+(-0.413\ \mathrm{SOY}\times\mathrm{LOGYR})\\ &+(-0.0158\ \mathrm{SOY}\times\mathrm{RAIN})\big]\\ =1.20281784&\end{aligned}\qquad [14]$$

and

$$\mathrm{NTPROB}(a=1)=\frac{1.20281784}{1+1.20281784}=0.54603600$$

The estimated soybean downside yield risk probability for the Southern Seaboard (SOY = 1, TECH = 2.81, LOGYR = 1.41, RAIN = 110.1, TILL = 1), SOSEA = 1, region is

$$\begin{aligned}\mathrm{ODDS} = \exp\big[&-0.6474+(3.2496\ \mathrm{SOY})\\ &+(0.2853\ \mathrm{TECH})\\ &+(0.2318\ \mathrm{LOGYR})\\ &+(0.01057\ \mathrm{RAIN})\\ &+(-0.9159\ \mathrm{SOSEA})\\ &+(-0.1015\ \mathrm{TILL})\\ &+(-0.8669\ \mathrm{SOY}\times\mathrm{TECH})\\ &+(-0.413\ \mathrm{SOY}\times\mathrm{LOGYR})\\ &+(-0.0158\ \mathrm{SOY}\times\mathrm{RAIN})\\ =0.41444666&\end{aligned}\qquad [15]$$

and

$$\mathrm{NTPROB}(a=1)=\frac{0.41444666}{1+0.41444666}=0.29300975$$

The predicted downside risk probabilities for no-till yields compared with tillage yields using all of the available data are presented in Table 5. The results indicate that crops grown in the Southern Seaboard region were less likely to have lower no-till yields than tillage yields on loamy-textured soils and thus had lower downside yield risk than other farm resource regions. Consistent with mean yield results, soybean and wheat grown on sandy-textured soils in the Southern Seaboard region using no-till had larger downside yield risks than when produced with no-till on loamy-textured soils.

CONCLUSION AND IMPLICATIONS

The objective of this research was to evaluate the impacts on the mean and risk of crop yields of switching from tillage practices to no-till as explained by factors such as the crop species, the year the experiment began, the time since conversion from tillage to no-till, annual precipitation, soil texture, and the location of production. This objective was accomplished by collecting data from 30 yr of refereed journal articles from 442 experiments at 92 locations comparing tillage with no-till. These data included six different crops with locations across the United States. The earliest paired experiment used in this analysis was initiated in 1964, when no-till was in its infancy.

This study was able to corroborate previous work done with no-till. Previous studies found that different crops respond differently to no-till (Shapiro et al., 2001; Wilhelm and Wortmann, 2004). This study found similar results, with sorghum and wheat prospering under no-till methods. Sorghum was also found to reduce the probability of having lower no-till yields than tillage yields. This analysis indicates that no-till does not perform as well as tillage on a sandy-textured soil. For wheat and soybean on a sandy-textured soil, the likelihood of lower no-till yields than tillage yields was larger than on a loamy-textured soil. Thus, no-till may have lower mean yields and greater downside yield risk when wheat and soybean are grown on sandy soils. The length of time that no-till was used after conversion from tillage had positive effects on the mean yields for cotton. The time after the conversion from tillage to no-till also improved the probability of having higher no-till yields when soybean and cotton were produced; therefore, the downside yield risk was reduced with time for cotton and soybean produced with no-till. Annual rainfall increased the probability of reduced no-till yields. Thus, there may be more downside risk associated with no-till crop production in regions where annual rainfall is higher. This research showed that the differences between no-till and tillage yields in the southern regions of the United States were larger than in northern regions. The location of crop production also affected the probability of downside yield risk. No-till crop production on a loamy-textured soil in the Southern Seaboard region was found to decrease the likelihood of lower no-till yields compared with the Heartland region. Consequently, the favorable mean yields and low downside yield risk with no-till provides risk management benefits in the warmer and more humid climates and warmer soils of the Southern Seaboard region.

The key findings of this study support the hypothesis that crop, soil, and climate factors impact no-till yields relative to tillage yields and may be an important factor influencing risk and expected return and the adoption of the practice by farmers. The results of this study also indicate potential gaps in knowledge about the performance of no-till relative to tillage for alternative crops and soils in different farm resource regions. For example, there is a lack of data for corn and sorghum in the Mississippi Portal region to corroborate the findings of positive advantages of no-till that were observed in the Southern Seaboard region. In addition, the results of this study could be used to target incentives to adopt no-till to crops and regions where the mean yield and downside risk tradeoff are not favorable. Given the importance of no-till to the sustainability of crop production in the United States, future research

Table 5. Predicted no-till downside yield risk probabilities relative to tillage yields by USDA Economic Research Service farm resource region (Fig. 1) and soil texture.

USDA-ERS region	Annual precipitation	Soil texture	Predicted no-till downside risk probability†					
			Corn	Sorghum	Cotton	Soybean	Wheat	Oat
	cm							
Heartland	81.5	loam	0.78	0.79	–‡	0.55	–	0.02
		clay	0.75	–	–	0.69	–	–
Northern Crescent	71.9	loam	0.69	–	–	0.47	0.56	–
		sand	0.50	–	–	–	–	–
Northern Great Plains	38.4	loam	–	–	–	–	0.38	–
Prairie Gateway	64.8	loam	0.62	0.42	0.81	0.43	0.50	–
		clay	0.59	0.30	1.00	–	0.67	–
Eastern Upland	96.7	loam	0.75	–	–	0.45	0.59	–
Southern Seaboard	110.1	loam	0.65	–	0.77	0.29	0.45	–
		sand	0.46	1.00	0.00	0.85	0.84	–
Fruitful Rim	34.1	loam	–	–	–	–	0.78	–
		sand	0.68	–	–	–	–	–
Basin and Range	22.0	loam	–	–	–	–	0.87	–
		silt	–	–	–	–	1.00	–
Mississippi Portal	132.8	loam	–	–	0.78	0.27	–	–
		clay	–	–	–	0.41	0.65	–

† Predictions were calculated using the estimated regression coefficients in Table 4, sample means for TECH (2.81) and LOGYR (1.41) for each farm resource region, and TILL = 1.

‡ Crop yield data were not available for the farm resource region and soil texture classification.

should address those gaps in knowledge through strategic long-term experiments and other research.

REFERENCES

Anderson, E.L. 1986. No-till effects on yield and plant density of maize hybrids. Agron. J. 78:323–326. doi:10.2134/agronj1986.00021962007800020022x

Anderson, J.R., J.L. Dillon, and J.B. Hardaker. 1977. Agricultural decision analysis. Iowa State Univ. Press, Ames.

Antle, J.M. 1987. Econometric estimation of producers' risk attitudes. Am. J. Agric. Econ. 69:509–522. doi:10.2307/1241687

Archer, D.W., and D.C. Reicosky. 2009. Economic performance of alternative tillage systems in the northern Corn Belt. Agron. J. 101:296–304. doi:10.2134/agronj2008.0090x

Barnett, K.H. 1990. No-tillage corn production in an alfalfa–grass sod. J. Prod. Agric. 3:71–75.

Blevins, R.L., D. Cook, S.H. Phillips, and R.E. Phillips. 1971. Influence of no-tillage on soil moisture. Agron. J. 63:593–596. doi:10.2134/agronj1971.00021962006300040024x

Binswanger, H.P. 1981. Attitudes toward risk: Theoretical implications of an experiment in rural India. Econ. J. 91:867–890. doi:10.2307/2232497

Bremer, J.E., S.D. Livingston, R.D. Parker, and C.R. Stichler. 2001. Conservation tillage applications. Texas A&M Univ. Coop. Ext., College Station.

Buhler, D.D., and T.C. Mester. 1991. Effect of tillage systems on the emergence depth of giant and green foxtail. Weed Sci. 39:200–203.

Busscher, W.J., P.J. Bauer, and J.R. Frederick. 2006. Deep tillage management for high strength southeastern USA Coastal Plain soils. Soil and Tillage Res. 85:178–185. doi:10.1016/j.still.2005.01.013

Cardina, J., E. Regnier, and D. Sparrow. 1995. Velvetleaf (*Abutilon theophrasti*) competition and economic threshold in conventional and no-tillage corn (*Zea mays*). Weed Sci. 43:81–87.

Cary, J.W., and R.L. Wilkinson. 1997. Perceived profitability and farmers' conservation behaviour. J. Agric. Econ. 48: 13–21. doi:10.1111/j.1477-9552.1997.tb01127.x

Chatterjee, S., and P. Price. 1991. Regression analysis by example. 2nd ed. Wiley-Interscience, New York.

Chavas, J.-P. 2004. Risk analysis in theory and practice. Elsevier, New York.

Chavas, J.-P., J.L. Posner, and J.L. Hedtcke. 2009. Organic and conventional production systems in the Wisconsin Integrated Cropping Systems Trial: II. Economic and risk analysis 1993–2006. Agron. J. 101:288–295. doi:10.2134/agronj2008.0055x

Conservation Technology Information Center. 2009. Conservation tillage facts. CTIC, W. Lafayette, IN. www.conservationinformation.org/?action=learningcenter_core4_convotill (accessed 2 Apr. 2009).

Cooper, H., and L.V. Hedges, editors. 1994. The handbook of research synthesis. Russell Sage Foundation, New York.

Dao, T.H., and H.T. Nguyen. 1989. Growth response of cultivars to conservation tillage in a continuous wheat cropping system. Agron. J. 81:923–929. doi:10.2134/agronj1989.00021962008100060015x.

Dayton, C.M. 2003. Model comparisons using information measures. J. Mod. Appl. Stat. Methods 2:281–292.

DeFelice, M.S., P.R. Carter, and S.B. Mitchell. 2006. Influence of tillage on corn and soybean yield in the United States and Canada. Crop Manage. doi:10.1094/CM-2006-0626-01-RS.

Derpsch, R. 2004. History of crop production, with and without tillage. Leading Edge 3(1):150–154.

Douglas, C.L., D.E. Wilkins, and D.B. Churchill. 1994. Tillage, seed size, and seed density effects on performance of soft white winter wheat. Agron. J. 86:707–711. doi:10.2134/agronj1994.00021962008600040023x.

Eckert, D.J. 1984. Tillage system × planting date interactions in corn production. Agron. J. 76:580–582. doi:10.2134/agronj1984.00021962007600040017x

Endale, D.M., H.H. Schomberg, D.S. Fisher, M.B. Jenkins, R.R. Sharpe, and M.L. Cabrera. 2008. No-till corn productivity in a southeastern United States Ultisol amended with poultry litter. Agron. J. 100:1401–1408. doi:10.2134/agronj2007.0401

Evanylo, G.K. 1991. Potassium fertilization of doublecropped wheat and soybeans under two tillage systems. J. Prod. Agric. 4:555–562.

Fernandez-Cornejo, J., and W.D. McBride. 2000. Genetically engineered crops for pest management in U.S. agriculture: Farm level effects. Agric. Econ. Rep. AER-786. USDA Econ. Res. Serv., Washington, DC.

Fernandez-Cornejo, J., and W.D. McBride. 2002. Adoption of bioengineered crops. Agric. Econ. Rep. AER810. USDA Econ. Res. Serv., Washington, DC.

Fishburn, P.C. 1977. Mean-risk analysis with risk associated with below-target returns. Am. Econ. Rev. 67:116–126.

Graven, L.M., and P.R. Carter. 1991. Seed quality effect on corn performance under conventional and no-tillage systems. J. Prod. Agric. 4:366–373.

Hairston, J.E., W.F. Jones, P.K. McConnaughey, L.K. Marshall, and K.B. Gill. 1990. Tillage and fertilizer management effects on soybean growth and yield on three Mississippi soils. J. Prod. Agric. 3:317–323.

Halvorson, A.D., A.R. Mosier, C.A. Reule, and W.C. Bausch. 2006. Nitrogen and tillage effects on irrigated continuous corn yields. Agron. J. 98:63–71. doi:10.2134/agronj2005.0174

Hammel, J.E. 1995. Long-term tillage and crop rotation effects on winter wheat production in northern Idaho. Agron. J. 87:16–22. doi:10.2134/agronj1995.00021962008700010004x.

Harlander, S.K. 2002. The evolution of modern agriculture and its future with biotechnology. J. Am. Coll. Nutr. 21:161S–165S.

Harville, D.A., and R.W. Mee. 1984. A mixed-model procedure for analyzing ordered categorical data. Biometrics 40:393–408. doi:10.2307/2531393.

Hedges, L.V., J. Gurevitch, and P.S. Curtis. 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80:1150–1156. doi:10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2.

Hedges, L.V., and I. Olkin. 1985. Statistical methods for meta-analysis. Academic Press, New York.

Herbek, J.H., L.W. Murdock, and R.L. Blevins. 1986. Tillage system and date of planting effects on yield of corn on soils with restricted drainage. Agron. J. 78:824–826. doi:10.2134/agronj1986.00021962007800050016x

Hilfiker, R.E., and B. Lowery. 1988. Effect of conservation tillage systems on corn root growth. Soil Tillage Res. 12:269–283. doi:10.1016/0167-1987(88)90016-5

Information Systems for Biotechnology. 2010. Release summary data and charts (1987–present). ISB, Blacksburg, VA. www.isb.vt.edu/release-summary-data.aspx (accessed 12 July 2011).

Judge, G.G., W.E. Griffiths, R.C. Hill, H. Lutkepohl, and T.-C. Lee. 1985. The theory and practice of econometrics. 2nd ed. John Wiley and Sons, New York.

Kapusta, G., R.F. Krausz, and J.L. Matthews. 1996. Corn yield is equal in conventional, reduced, and no tillage after 20 years. Agron. J. 88:812–816. doi:10.2134/agronj1996.00021962008800050021x.

Karlen, D.L., J.H. Edwards, W.J. Busscher, and D.W. Reeves. 1991. Grain sorghum response to slit-tillage on Norfolk loamy sand. J. Prod. Agric. 4:80–85.

Kunda, M., and T. West. 2006. Tillage and yield study. Working Pap. Oak Ridge Natl. Lab., Oak Ridge, TN.

Lankoski, J., M. Ollikainen, and P. Uusitalo. 2004. No-till technology: Benefits to farmers and the environment? Disc. Pap. 1. Univ. of Helsinki. Helsinki, Finland.

Larson, J.A., B.C English, D.G. De La Torre Ugarte, R. Menard, C. Hellwinckel, and T.O. West. 2010. Economic and environmental impacts of the corn grain ethanol industry on the United States agricultural sector. J. Soil Water Conserv. 65:267–279. doi:10.2489/jswc.65.5.267

Larson, J.A., E.C. Jaenicke, R.K. Roberts, and D.D. Tyler. 2001. Risk effects of alternative winter cover crop, tillage, and nitrogen fertilization systems in cotton production. J. Agric. Appl. Econ. 33:445–457.

Linden, D.R., C.E. Clapp, and R.H. Dowdy. 2000. Long-term corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. Soil Tillage Res. 56:167–174. doi:10.1016/S0167-1987(00)00139-2

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Cary, NC.

Lowenberg-DeBoer, J. 1999. Risk management potential of precision farming technologies. J. Agric. Appl. Econ. 31:275–285.

Lowery, B., R.C. Hartwig, D.E. Stoltenberg, K.J. Fermanich, and K. McSweeney. 1998. Groundwater quality and crop-yield responses to tillage management on a Sparta sand. Soil Tillage Res. 48:225–237. doi:10.1016/S0167-1987(98)00148-2

Lueschen, W.E., J.H. Ford, S.D. Evans, B.K. Kanne, T.R. Hoverstad, GW.. Randall, J.H. Orf, and D.R. Hicks. 1992. Tillage, row spacing and planting date effects on soybean following corn or wheat. J. Prod. Agric. 5:254–260.

McLean, R.A., W.L. Sanders, and W.W. Stroup. 1991. A unified approach to mixed linear models. Am. Stat. 45:54–64. doi:10.2307/2685241

McWhorter, C.G. 1984. Future needs in weed science. Weed Sci. 32:850–855.

Miguez, F.E., and G.A. Bollero. 2005. Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Sci. 45:2318–2329.

Nicholson, W. 2005. Microeconomic theory: Basic principles and extensions. 9th ed. Thomson/South-Western, Mason, OH.

North Carolina Department of Agriculture. 2010. Plant nutrients. N.C. Dep. of Agric. and Consumer Serv., Raleigh. www.agr.state.nc.us/cyber/kidswrld/plant/nutrient.htm (accessed July 2010).

Norwood, C.A. 1992. Tillage and cropping system effects on winter wheat and grain sorghum. J. Prod. Agric. 5:120–126.

Papendick, R.I. 1987. Tillage and water conservation: Experience in the Pacific Northwest. Soil Use Manage. 3:69–74. doi:10.1111/j.1475-2743.1987.tb00713.x

Phillips, R.E., G.W. Thomas, R.L. Blevins, W.W. Frye, and S.H. Phillips. 1980. No-tillage agriculture. Science 208:1108–1113. doi:10.1126/science.208.4448.1108

Ribera, L.A., F.M. Hons, and J.W. Richardson. 2004. An economic comparison between conventional and no-tillage farming systems in Burleson County, Texas. Agron. J. 96:415–424. doi:10.2134/agronj2004.0415

Roberts, R.K., B.C. English, Q. Gao, and J.A. Larson. 2006. Simultaneous adoption of herbicide-resistant and conservation-tillage cotton technologies. J. Agric. Appl. Econ. 38:629–643.

SAS Institute. 2004. SAS online doc 9.1.3. SAS Inst., Cary, NC. support.sas.com/onlinedoc/913/docMainpage.jsp (accessed 2004).

SAS Institute. 2006. The GLIMMIX procedure. SAS Inst., Cary, NC.

Schabenberger, O. 2005. Introducing the GLIMMIX procedure for generalized linear mixed models. In: M. Zdeb, editor, Proceedings Northeast SAS Users Group 18th Annual Conference, Portland, ME [CD]. 11–14 Sept. 2005. SAS Inst., Cary, NC.

Selley, R. 1984. Decision rules in risk analysis. In: P.J Barry, editor, Risk management in agriculture. Iowa State Univ. Press, Ames. p. 53–67.

Shapiro, C.A., D.L. Holshouser, W.L. Kranz, D.P. Shelton, J.F. Witkowski, K.J. Jarvi, et al. 2001. Tillage and management alternatives for returning Conservation Reserve Program land to crops. Agron. J. 93:850–862. doi:10.2134/agronj2001.934850x

Smiley, R.W., and D.E. Wilkins. 1993. Annual spring barley growth, yield, and root rot in high- and low-residue tillage systems. J. Prod. Agric. 6:270–275.

Smith, M.A., P.R. Carter, and A.A. Imholte. 1992. No-till vs. conventional tillage for late-planted corn following hay harvest. J. Prod. Agric. 5:261–264.

Soil Survey Division Staff. 1993. Soil survey manual. Agric. Handbk. 18. U.S. Gov. Print. Office, Washington, DC.

Tarkalson, D.D., G.W. Hergert, and K.G. Cassman. 2006. Long-term effects of tillage on soil chemical properties and grain yields of a dryland winter wheat–sorghum/corn–fallow rotation in the Great Plains. Agron. J. 98:26–33. doi:10.2134/agronj2004.0240.

USDA Economic Research Service. 2000. Farm resource regions. Agric. Inf. Bull. 760. U.S. Gov. Print. Office, Washington, DC.

Wagger, M.G., and H.P. Denton. 1989. Tillage effects on grain yields in a wheat, double-crop soybean, and corn rotation. Agron. J. 81:493–498.

Wiese, A.F., T. Marek, and W.L. Harman. 1998. No-tillage increases profit in a limited irrigation–dryland system. J. Prod. Agric. 11:247–252.

Wilhelm, W.W., and C.S. Wortmann. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. Agron. J. 96:425–432. doi:10.2134/agronj2004.0425

Winter, S.R., and P.W. Unger. 2001. Irrigated wheat grazing and tillage effects on subsequent dryland grain sorghum production. Agron. J. 93:504–510. doi:10.2134/agronj2001.933504x

Witkowski, J.F., J.L. Wedberg, K.L. Steffey, P.E. Sloderbeck, B.D. Siegfried, M.E. Rice, et al. 2002. Bt corn and European corn borer: Long-term success through resistance management. Univ. of Minnesota Ext., St. Paul. www.extension.umn.edu/distribution/cropsystems/dc7055.html (accessed 12 July 2011).

Young, H.M., Jr. 1982. No-tillage farming. No-Till Farmer, Brookfield, WI.