Modeling No-Tillage Adoption by Corn and Soybean Producers: Insights into Sustained Adoption

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Keywords: no-tillage, tillage history, continuous adoption, ordered logit, ARMS

JEL Codes: Q12, Q15, Q18, Q24, Q1, Q2

Selected Paper prepared for presentation for the 2015 Agricultural & Applied Economics Association and Western Agricultural Economics Association Annual Meeting, San Francisco, CA, July 26-28.

The views expressed here are those of the authors, and may not be attributed to the Economic Research Service or the U.S. Department of Agriculture.

Abstract

No-till acreage has increased in recent years but many farmers alternate no-till with other tillage practices, effectively limiting both public and private benefits from sustained no-till adoption. Revealed preference data is used in an ordered logit regression analysis to determine the effect of soil characteristics, climate, regions, farm characteristics, and producer demographics on producers' choices to use continuous tillage, alternate no-till systems with tillage systems, or continuously use no-till. The model provides insight into the characteristics and conditions that are conducive to each tillage regime. The attributes found to significantly affect continuous no-till adoption are erodibility classification, drainage, farm size, and precipitation variables.

Introduction

No-till production systems can provide both off-farm (public) and on-farm (private) benefits. Public benefits include less soil erosion and sediment loss to water and higher levels of soil carbon sequestration (West and Post 2002). On-farm benefits include soil moisture conservation (perhaps reducing drought risk), preservation of soil depth, and improved soil health. In terms of soil health, no-till can help increase soil organic matter and available water capacity and improve soil aggregate size and stability among other benefits (USDA-NRCS 2014).

Many of these benefits, however, are fully realized only when no-till is used continuously over a period of years. Under no-till, for example, the soil sequesters carbon slowly over time while soil carbon gains can be wiped out by a single tillage operation (Johnson et al. 2005). Likewise, soil health benefits are largely a function of organic matter accumulation that happens only when no-till in practiced continuously over a period of years (USDA-NRCS 2014). Significant gains in organic matter and related improvements in soil health are unlikely to be realized by producers who alternate no-till with other tillage practices.

No-till acreage has been increasing in recent years but many farmers alternate no-till with other tillage practices, effectively limiting both public and private benefits. Using the Agricultural Resources Management Survey (ARMS) field-level data on production practices, Horowitz, Ebel, and Ueda (2010) found an upward trend in no-till for a number of major crops, including corn, soybeans, and wheat, during the early- and mid-2000's. Data collected in the 2010-11 farm-level portion of ARMS show that no-till or strip-till was used on just under 40% of land in corn (32%), soybeans (46%), wheat (43%), and cotton (33%) (Wade, Claassen, and Wallander 2014).

The ARMS data also show that many farms alternate no-till with other tillage practices. Field-level ARMS data for 2010 (corn) and 2012 (soybeans) provide a four-year history of no-till use (which may include crops other than the target crop). The corn survey shows that roughly 19% of farmers (17% of acres) reported using continuous no-till (CNT) over a four-year period while 28% of farmers (26% of acres) reported alternating no-till (ANT) and 53% of farmers (57% of acres) report continuous tillage (CT) (corn was grown in the survey year but was not necessarily grown in all four years). In the soybean survey, roughly 25% of farmers (23% of acres) reported CNT over a four-year period while 30% of farmers (31% of acres) reported ANT, and 43% of farmers (46% of acres) reported CT. While both surveys show that roughly 50% of producers used no-till during the previous four years, less than half of those farmers reported CNT. The rate of no-till use varies regionally as shown in figure 1.

This study is the first to use data on tillage history as well as current tillage practices to distinguish farms that use no-till continuously from those that alternate no-till with other tillage practices. Revealed preference data is used in an ordered logit regression analysis to determine the effect of land characteristics, climate, farm characteristics, and producer demographics on producer choice among tillage regimes. Our primary objective is to develop a richer understanding of producer no-till adoption decisions. Although the model cannot be used to estimate the difference in profit across the three tillage regimes, it can provide insight into the characteristics and conditions that are conducive to each tillage regime. This knowledge could be useful in designing conservation incentives to encourage CNT.

Attributes found to significantly affect CNT adoption are highly erodible land designation, well-drained soil, farm size, and precipitation variables. Other attributes that affect CNT by corn survey respondents are average temperature and soil productivity. Other attributes that affect the adoption of CNT by soybean survey respondents are irrigation and temperature variability.

Most of these attributes also affect the probability of ANT. The marginal effects on CNT and ANT are usually similar in magnitude and are not statistically distinguishable. Where soil, climate, and other conditions are conducive to no-till, we observe higher rates of both CNT and ANT and lower rates of CT. For the sample of corn producers, for example, our model indicates that well-drained soil increases the probability, on average, of ANT by 0.06 and of CNT by 0.08. While both are significantly different from zero these effects are not significantly different from each other.

One factor that does appear to encourage CNT over both ANT and CT is designation as highly erodible land (HEL). In our sample of corn producers, HEL designation increases the probability of both CNT and ANT but increases the probability of CNT by more. In the sample of soybean producers, our model indicates that HEL designation increases the probability of CNT by 0.25 but has no effect on the probability of ANT. We note that highly erodible fields are defined as fields where the producer has been notified of a USDA highly erodible land designation, made for the purpose of identifying fields subject to soil conservation requirements under Conservation Compliance. The soybean model also shows that soil drainage also has a stronger effect on the probability of CNT than on ANT.

The next section describes the estimation procedure. We then give a detailed description of the data and variable construction followed by the presentation and discussion of the results. The article ends with concluding remarks.

Estimation Procedure

Farmers are hypothesized to make tillage choices that maximize utility. Within a period of four years, a farmer may choose to use tillage every year, alternate no-till with tillage, or use only no-till. We denote the tillage choice of farmer *i* as $T_i = j$, where j = 1, 2, 3 correspond to continuous tillage (CT), alternating no-till (ANT), and continuous no-till (CNT), respectively. Assume that the farmer's utility (or measure of no-till preference), U, is a random function such that

$$U_i = V_i\left(\boldsymbol{\beta}'\boldsymbol{X}_i\right) + \varepsilon_i ,$$

where i = 1,…, n indexes individual farmers, V_i is the portion of utility observed by researchers expressed as the product of $\boldsymbol{X}_i$, a vector of coregressors thought to affect sustained no-till adoption such as soil, farm, climate, regional, and operator characteristics, and $\boldsymbol{\beta}$, a vector of unknown parameters, and ε_i is the unobserved or random portion of utility.

This discrete and ordered dependent variable (T_i) and random utility model lend themselves to an ordered regression model. If the random portion of utility follows a logistic distribution, model parameters can be estimated using an ordered logit model. We define

$T_i = j$ if $\tau_{j-1} < U_i \leq \tau_j$, for j = 1, 2, 3;

where $\boldsymbol{\tau}$ is a vector of unknown thresholds to be estimated by the model, $\tau_0 = -\infty$ and $\tau_j = \infty$. Then the probability that a farmer's utility falls within category j is

$$\begin{aligned}
\Pr\left[T_i = j\right] &= \Pr\left[\tau_{j-1} < U_i \leq \tau_j\right] \\
&= \Pr\left[\tau_{j-1} < \boldsymbol{\beta}'\boldsymbol{X}_i + \varepsilon_i \leq \tau_j\right] \\
&= \Pr\left[\tau_{j-1} - \boldsymbol{\beta}'\boldsymbol{X}_i < \varepsilon_i \leq \tau_j - \boldsymbol{\beta}'\boldsymbol{X}_i\right] \\
&= \Lambda\left(\tau_j - \boldsymbol{\beta}'\boldsymbol{X}_i\right) - \Lambda\left(\tau_{j-1} - \boldsymbol{\beta}'\boldsymbol{X}_i\right),
\end{aligned}$$

where $\Lambda(\cdot)$ is the cdf of the logistic distribution (Cameron and Trivedi 2005, Train 2009). The ordered logit model was used to evaluate the factors that influence the sustained adoption of no-till. Parameters $\boldsymbol{\tau}$ and $\boldsymbol{\beta}$ are estimated using the maximum likelihood procedure with weighted standard errors.

For this initial analysis of continuous no-till, we estimate a reduced form model. There is evidence to suggest that tillage decisions are made in conjunction with crop choice, e.g., some farmers use no-till in soybeans but till when producing corn (Reimer et al. 2012). So the estimated effects of soil, topography, climate, and other factors may affect no-till adoption directly or through the crop choice. Of course, the availability of no-till may also affect the crop. For example, no-till may significantly reduce soil erosion when growing low-residue crops (such as soybeans) on highly erodible cropland. Nonetheless, we focus on the effects of soils, climate, and farm characteristics.

Data Description and Variable Construction

Data on tillage, field, farm, and farmer characteristics are from the Agricultural Resource Management Survey (ARMS) implemented by the USDA's Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS). The Production Practices and Costs Report (PPCR) is a field-level, commodity specific survey that provides data on production practices, including no-till, no-till history, land tenure and some field characteristics. Each survey covers a subset of states which typically account for 90-95 percent of the production for the surveyed crop. The 2010 corn and 2012 soybeans surveys provide usable data on 2,303 and 2,492 fields, respectively. The Costs and Returns Report (CRR) is a farm-level, follow-on survey that provides data on farm size, farm household information, and operator characteristics. To minimize respondent burden, different famers are surveyed each year, so the data do not form a panel. Merging the PPCR and CRR and combining corn and soybean data yields a dataset including 3,480 fields representing approximately 110 million acres.

Dependent variable

The dependent variable is constructed from the no-till and no-till history data and has three categories identifying no-till intensity over a four-year period: CT (or 0 years of no-till), ANT (or 1-3 years of no-till) and CNT. A field is considered tilled if it has a tillage operation in any portion of the crop year. No-till in the survey year is indicated by an absence of tillage operations in the spring (as listed by the respondent) and the previous fall as recalled by the respondent, including situations where a cover-crop, winter crop (e.g., wheat), or no crop was grown. For prior years, we use the same definition of no-till, although no-till during both the spring and the previous fall are based on producer recall. We believe this definition (also used in Uri (2000)) is aligned with how farmers interpret no-till adoption (i.e. they are not tilling) and therefore more consistent with the tillage history data, which is based on the respondent's recollection of the previous three years tillage practices.

Fallow fields are treated as a separate management strategy and are excluded from the tillage analysis (approximately 1.6% of acres). Therefore only those fields that are continuously in production are included. Fallow fields are identified based on typical crop rotations. Perennials and land in CRP (approximately 3.4% of acres) are also excluded from analysis. Like fallow fields, farmers do not have to make a tillage decision on these fields. The dependent variable is a quantitative measure of farmers' preferences/attitudes towards CNT making the ordered logit regression model appropriate.

Independent variables

Soil characteristics. On highly erodible land (HEL), producers who participate in farm programs must apply approved conservation systems or risk losing eligibility (Secchi et al. 2009). In this context, HEL fields are designated as such by the USDA for the purpose of identifying fields subject to soil conservation requirements. The dataset likely contains fields that are eligible to participate in conservation compliance programs and use no-till adoption to meet those requirements. Information on practice adoption to meet conservation compliance is not publically available. Therefore, this analysis does not include information on government cost share to adopt no-till. A field's erodibility status is a binary variable reported by the farm operator in the PPCR. It is expected to positively affect no-till adoption.

Soil drainage is also important to the success of no-till systems as leaving residue on poorly-drained soil increases the likelihood of waterlogging. No-till has potential to increase yields and store soil organic carbon when used on moderate- to well-drained soils (Kumar et al. 2012; Triplett and Dick 2008). Conversely, decreased yields may be noticed when used on poorly-drained soils (Ogle, Swam, and Paustian 2012). This binary variable identifies moderate- to well-drained soils and is derived from the Soil Survey Geographic database majority drainage class code within a 300 meter neighborhood (USDA-NRCS 2014).

The average National Commodity Crop Productivity Index (NCCPI) is used to measure the effect of soil productivity on no-till adoption. Soil productivity may affect no-till adoption if producers perceive a yield penalty associated with no-till. Producers who expect higher yields may be more sensitive to the possibility of a yield penalty. Agronomic studies that investigate the effects of no-till adoption on yield have mixed results (see, e.g., Wilhelm and Wortmann 2004, Toliver et al. 2012,) indicating that there is still uncertainty about how no-till affects crop yields. Although no-till has been used successfully for several years, farmers with high producing fields may perceive risk in using this tillage system. NCCPI ranges from 0 to 100 for low to high producing soil and is expected to negatively affect no-till adoption.

Farm characteristics. Irrigation, farm size, and farm typology are farm characteristics thought to affect tillage adoption. Approximately 12% of corn and 10% of soybean acres are irrigated with 70% of irrigated acres in the Heartland and Prairie Gateway. No-till is less suitable for irrigated fields because the residue left on the field may create uneven surfaces impeding the movement of irrigation machinery and water. Also, because no-till is a soil moisture management technique it may be treated as a substitute to irrigation and not used simultaneously. Irrigated fields tend to have cooler soil; the residue cover as a result of no-till may compound this problem (Ogle, Swam, and Paustian 2012). Having an irrigated field is therefore expected to have a negative effect on no-till adoption. A binary indicator of irrigation is available from PPCR.

Larger farms can spread fixed costs (such as equipment purchases) over more acres making no-till more attractive (Soule, Tegene, and Weibe 2000; Lambert et al. 2007; Robertson et al. 2014). The log of cropland acres is used to capture this effect and is expected to be positively correlated with CNT adoption.

Farm typology is developed by the USDA-ERS and classifies farms based on their gross sales, the primary occupation of the operators, and whether the farms are family farms (Hoppe and MacDonald 2013). The seven category variable is summarized here to indicate whether a farm is a rural residential, intermediate, or commercial farm. Because farm sales are closely related to cropland size, commercial and intermediate farms are expected to be positively correlated with sustained no-till adoption.

Regional indicators and climate characteristics. Regional dummies for each USDA farm resource region (USDA-ERS 2000) are included. All climate regressors are constructed from the

PRISM monthly-average county-level temperature and precipitation data for the most common planting and harvesting dates in the corn and soybeans growing seasons; April through October for corn and May through October for soybeans (USDA-NASS 2010). The climate variables are the 30 year average temperature, average precipitation, variability in monthly temperature, and variability in monthly precipitation. This captures the within season and cross season variability in climate. High average temperatures are expected to be positively correlated with no-till adoption while high levels of average precipitation may negatively affect adoption. This is consistent with no-till operating poorly on cold wet soil (Soule et al. 2000, Ogle, Swam, and Paustian 2012). Uncertainty in temperature and precipitation, captured by their respective variability, may correlate with inconsistent yields making traditional tillage systems more attractive and hence less likely to adopt no-till.

Operator characteristics. Tenure is used often with varying results (see, Prokopy et al. 2008). We capture the owner versus tenant effect with this dummy variable, where 1 indicates the respondent is a full owner and 0 indicates partial ownership or tenant. Like Lambert et al. (2007) we presume that full owners have a long-term interest in the health of the soil and profitability of the field and are therefore more likely to adopt practices that help improve long-term soil health. Being a full owner is therefore expected to increase the likelihood of sustained no-till adoption.

College education has long been thought to improve the adoption of conservation practices (e.g., Rahm and Huffman (1984), Gould, Saupe, and Klemme (1989), Wu and Babcock (1998), Soule, Tegene, and Weibe (2000), D'Emden, Llewellyn, and Burton (2008) and Prokopy et al. (2008)). Graduating from college is therefore expected to positively affect no-till adoption.

Proxies for farmer experience are also used widely with mixed results (see, e.g., Wu and Babcock (1998), Knowler and Bradshaw (2007) and Prokopy et al. (2008)). Here age proxies farm experience. Studies have also postulated that younger farmers are more likely to adopt conservation practices because their longer farming horizons affords them time to recapture the cost of new equipment and training (Baumgart-Getz, Prokopy, and Floress 2012; Lambert et al. 2007). Wu and Babcock (1998) theorize that this negative correlation with conservation tillage adoption is due to long farming tradition and cultural practices. Operator's age is therefore expected to be negatively correlated with no-till adoption.

The analysis uses time invariant variables and variables that change slowly over time (e.g., farm size, operator age, education, etc.) that are not specific to the survey year. Survey specific variables that are likely to have changed annually are avoided because they may not incorporate attributes from the previous three years. For example, grazing affects soil compaction and whether the field is grazed is available in ARMS, however, the field may be grazed in conjunction with the crop that is grown and not annually. Though not examined directly in this analysis, cropping patterns play an important role in the tillage decision. It is known that farmers alternate tillage with specific crops (Robertson et al. 2014); for example, tilled corn is often rotated with no-till soybeans or wheat. During the three-year cropping history, 5% of sampled corn acres and 7% of sampled soybean acres were planted in crops other than corn or soybeans (with farmers in the soybean sample planting soybeans on 86% of cropland and farmers in the corn sample planting soybeans on 69% of cropland). Because cropping history is highly correlated with the dependent variable and because we are interested in the direct impact of the coregressors on sustained no-till adoption we are in favor of using the variables discussed in a reduced form model.

The final samples have 1155 common observations for corn and 1324 for soybeans representing 85 million acres. These acres contain about 52% of U.S. corn and 51% of soybean acres (USDA-NASS 2014). The average field size is 52 acres. Table 1 summarizes the descriptions and provides descriptive statistics of the common observations. All statistics are weighted by state crop acres.

Results

Appendix table A1 provides the ordered logit parameter estimates for our three categories of no-till adoption by crop. Positive coefficient estimates indicate a likely increase in the probability of CNT while negative estimates indicate an increase in the probability of CT. With Wald chi-square statistic of 73.28 for the corn sample and 170.65 for soybeans (p-values< 0.001), we reject the hypothesis that the specification with only cut-points is not significantly different from the present models. T-tests indicate that the cut-points, $\boldsymbol{\tau}$, are statistically different from each other in the corn at the 0.01% level. Therefore, the model identifies statistically distinct levels of no-till intensity. Designating the largest of the three predicted probabilities as the predicted outcome, there are 55% correct predictions for corn and 53% for soybeans. The rate of correct predictions does not seem low considering we observe several levels of no-till intensity (Wang, Young, and Camera 2000). Estimates for the ordered probit model using the identical specification are virtually identical to the ordered logit model in terms of number of correct predictions, predicted probabilities, log likelihood, Bayesian information criterion (BIC), and Akaike information criterion (AIC).

Predicted probabilities closely mirror sample proportions for both the corn and soybean samples (table 2). In both cases, the adoption rate for CNT is substantially less than that of ANT or CT. In the corn survey 54% of respondents reported continuous use of tillage over the four-year period considered in the survey. Just under 30% reported alternating tillage with no-till (using no-till in at least one of the four years) while only 17% said they used no-till continuously. In the soybean survey, 45% indicate continuous tillage, while just under 30% indicated ANT and 25% used CNT. For the regions heavily represented in the sample (Heartland, Northern Crescent, Northern Great Plains, and Prairie Gateway), respondents in the Prairie Gateway report a much higher rate of CNT (24% and 50% in the corn and soybean surveys, respectively).

The estimates reveal that adoption probabilities vary widely across soil properties, farm size (cropland acreage), and climate. The attributes found to significantly affect the adoption of CNT in both models are HEL, well-drained soil, total cropland acres, and precipitation variables. Attributes that affect CNT adoption by corn growers are being an intermediate farm, average temperature, and NCCPI. Other attributes that affect the adoption of CNT by soybean growers are irrigation and temperature variability.

Marginal effects for corn producers

Soil characteristics. A marginal increase in NCCPI is estimated to increase the probability of adopting CT by 0.0025, decrease the probability of ANT by 0.0011, and decrease the probability of CNT adoption by 0.0014. NCCPI is defined over a range of 0-100 but most land in our sample has values between 20 and 80. A simple approximation, using the average marginal effects indicates that the probability of CT would be roughly 0.15 higher at the upper end of the range (NCCPI=80) than at the lower end (NCCPI=20). Decreasing NCCPI by 60 units reduces the probability of ANT and CNT by 0.066 and 0.084, respectively. These effects are not statistically different, so land productivity affects ANT and CNT to a similar extent.

Assuming that NCCPI is positively correlated with corn yields, the role of NCCPI may be explained by the perceived risk of using no-till or perceived no-till yield penalty in corn (Ogle, Swan, and Paustian 2012, Reimer, Weinfauf, and Prokopy 2012). Although many crops other than corn appear in crop history, 95% of respondents planted corn in the same field at least once in the previous three years and 18% planted corn in each of the previous three years.[1] If higher corn yields results in a larger yield penalty for corn in no-till, the cost of revenue loss due to no-till adoption could be higher where NCCPI is higher. If the yield penalty is larger in some years (e.g., when cool, wet spring weather delays planting) no-till may also increase yield variability, particularly where NCCPI is high, making no-till less appealing to more risk averse farmers.

Highly erodible designation is, perhaps, the single most important factor in determining whether producers use CNT. HEL designation increases the probability of CNT adoption by 0.17, on average, and increases the probability of ANT by 0.06, on average (1% level of significance for both). Moreover, these estimates are statistically significantly different from each other, indicating that conditions on highly erodible land clearly favor CNT over ANT.

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[1] Issues related to residue management, crop diseases such as gray leaf spot, pest management, and weed management (Bullock 1992, Soane et al. 2012) are possible reasons why farmers who plant monocultures are less likely to use no-till systems. Increasing demand for corn could make continuous corn attractive on cropland that can sustain profitable corn intensive rotations and make no-till less likely on these fields.

Well-drained soils are also more likely to be in CNT than soils that tend to drain slowly. For the corn sample, we estimate that the probability of CNT is roughly 0.08 higher and the probability of ANT is roughly 0.06 higher on moderately-well and well-drained soils. These estimates are not statistically significantly different from each other, indicating that soil drainage increases the probability of both CNT and ANT to the same degree. We also note that the effect of soil drainage on the probabilities of ANT and CNT are slightly smaller than our estimate of the effect of a large difference in soil productivity (NCCPI).

To further explore the marginal effects of soil properties we graphed the estimated probabilities of CT, ANT, and CNT as a function of NCCPI for four categories of land. Panel (a) of figure 2 shows the effect of NCCPI for non-HEL cropland with well-drained soils. Panel (b) shows the effect of NCCPI on the predicted probabilities for HEL cropland that is also well-drained. Panels (c) and (d) show the corresponding effect of NCCPI on the predicted probabilities for HEL and non-HEL cropland that is poorly drained. In each graph, we assume non-irrigated production and all other variables are held at the mean of the data. The distribution of acreage by NCCPI is also included in each panel (right-hand scale) to help interpret the importance of estimated probabilities for any given level of NCCPI.

On non-HEL soil, predicted probabilities suggest that famers, on average, view CNT as less profitable option than CT or ANT. For well-drained, non-HEL fields, the estimated probability of CNT is less than the probability of CT at all levels of NCCPI (see figure 2, panel a). On low productivity land (NCCPI=20), the estimated probability of CNT (0.23) lags well behind that of CT (0.41) or ANT (0.36). When soil productivity is high (NCCPI=80) the estimated probability of CNT drops to 0.13 (a decline of 0.10) while ANT drops to 0.30 (a decline of 0.06) and CT rises to 0.57 (an increase of 0.16). These results indicate that while the probability of CNT is low, the probability that no-till is used at least once over the four-year period ranges from 0.59 on low productivity land (NCCPI=20) to 0.43 on high productivity land (NCCPI=80). On poorly-drained, non-HEL soils (figure 2, panel c), the gap between the probabilities for the three tillage regimes is larger. The probability of CT is 0.5 or larger for all levels of NCCPI on non-HEL land that is also poorly drained.

The likelihood of CNT is significantly higher on HEL cropland at all levels of NCCPI, although the increase is slightly larger for low productivity land. For well-drained HEL cropland (figure 2, panel b) with NCCPI<50, CNT is the most likely of the three tillage options for our average farm. On more productive land (NCCPI>50), which accounts for most HEL in the corn sample, the model predicts that ANT, CNT, and CT will command similar shares although the probability of CT rises and the probability of CNT falls as NCCPI rises. The probability that no-till is used at least once over the four-year period ranges from 0.80 on low productivity land (NCCPI=20) to 0.70 on high productivity land (NCCPI=80).

On poorly-drained HEL the probability of CNT is also much larger than for non-HEL that is also poorly drained (figure 2, panel d). Even after the shift, however, the probability of CNT lags well behind the probabilities of CT or ANT, particularly for NCCPI>50 which accounts for most of the poorly drained HEL soils.

Our results suggest that both CNT and (to a slightly lesser extent) ANT have a higher probability of being adopted on highly erodible land than on non-highly erodible land. The return to these practices may include the value of applying a soil conservation system to reduce soil productivity damage and avoid conservation compliance sanction. Conservation compliance requires that producers apply approved soil conservation plans on highly erodible cropland to maintain eligibility for most federal farm-related payments including commodity support payments, crop insurance premium subsidies, and conservation program payments. The actual effect of conservation compliance, however, is difficult to understand without more complete information on the conservation systems approved for use within individual fields. A range of soil conservation practices, including no-till and other forms of conservation tillage, could be used alone or in conjunction with other practices to satisfy conservation compliance requirements. To the extent that no-till is required by approved soil conservation plans, the higher probability of CNT and ANT could be accounted for by the potential cost of non-compliance and the cost of other options for controlling soil erosion.

Farm characteristics. On non-HEL cropland, the probability of each tillage regime varies significantly with cropland acreage, holding all other variables at the mean of the data. For farms with 250 cropland acres, the probability of CT is 0.62, ANT is 0.26 and CNT is 0.12; for farms that are 1,000 acres the probability of CT is 0.54, ANT is 0.29, and CNT is 0.17; for farms that are 3,000 acres, the probability of CT is 0.47, ANT is 0.32, and CNT is 0.21. For HEL cropland, farms that are 3,000 acres are more likely to adopt CNT (0.40) than CT (0.25). Most farms in this study have cropland acreage between 150 acres and 3,000 acres.

Regional indicators and climate characteristics. The effects of the climate variables are similar to those found in binary analysis presented in Pautsch et al. (2001). We find higher average temperatures and precipitation are positively correlated with no-till adoption. On average, the majority of corn sample respondents are located in areas that receive between 80mm and 110mm of precipitation and have average temperature between 15°C and 20°C during the growing season. Using the average marginal effects, the model predicts that a 30mm increase in average precipitation, *ceteris paribus*, increases the probabilities of CNT by 0.21 and ANT by 0.16 and therefore decreases the probability of CT by 0.37; a 5°C increase in average temperature increases the probabilities of CNT by 0.17 and ANT by 0.12 and decreases the probability of CT by 0.29. These results are consistent with no-till being more attractive in warmer regions and with conservation tillage becoming more popular in areas where heavy precipitation causes soil erosion (Holland 2004, Zhang 2012). The statistically significant negative effect of the variability of precipitation is an indication that fields that experience more variable precipitation are less likely to adopt no-till. Increased variability makes it difficult to plan using moisture and temperature sensitive methods such as no-till. It is also consistent with a higher need for adequate soil drainage under reduced tillage systems (Pautsch et al. 2001).

In many regions the probability of CT is much larger than probabilities of CNT or ANT when average precipitation is low (for the region). When average precipitation is high, however, the probabilities of CT, ANT, and CNT fall within a relatively narrow range. For example, on well-drained, non-irrigated non-HEL fields in the Heartland (figure 3), when average precipitation is relatively low (71mm), the probability of adopting CT is 0.80, the probability of ANT is 0.15, and the probability of adopting CNT is 0.05. When average precipitation is relatively high (114mm) the probability of adopting CT is 0.28, the probability of ANT is 0.37, and the probability of adopting CNT is 0.35. Differences in precipitation have similar effects in the Northern Crescent and Northern Great Plains regions. The Prairie Gateway (figure 4) has the most variation in average precipitation and also the most variation in probabilities among the tillage regimes. When average precipitation is low (55mm) the probability of adopting CT is 0.75 and the probability of adopting ANT and CNT are 0.19 and 0.06, respectively. When average precipitation is high (115mm), however, the predicted probability of CNT (0.65) is almost seven times that of CT (0.10) and more than twice that of ANT (0.25).

The figures also highlight the large effect HEL designation has on no-till adoption. On HEL cropland in the Heartland, when average precipitation is 71mm, the probability of CT (0.59) is much larger than ANT (0.29) and CNT (0.12). When average precipitation is 114mm, the situation is reversed: the probability of CNT (0.60) is increased dramatically, while the probability of CT (0.12) declines dramatically and ANT (0.28) is almost the same. In the Prairie Gateway, when average precipitation is 71mm there are small differences among the probabilities (the probabilities of CT, ANT, and CNT are 0.30, 0.38, and 0.32, respectively); however, when average precipitation is 114mm, the probability of CNT (0.83) far exceeds the probabilities of ANT (0.13) and CT (0.14).

The effect of average temperature in the Heartland is shown in figure 5. Over the full range of temperatures observed in the Heartland region, we see large changes in the probability of no-till adoption. When average temperature is 2.5 degrees less than average (14°C), the predicted probability of CT (0.73) is more than 10 times that of CNT (0.07) and 0.53 points higher than ANT (0.20). When average temperature is 2.5 degrees above average (20°C), all other things equal, the predicted probability of CT (0.37) is equivalent to that of ANT (0.37) and 0.12 points higher than CNT (0.25). Though the Prairie Gateway shows more variation in growing season average temperatures (figure 6), the probabilities at 14°C and 20°C are almost identical to the Heartland: the probabilities of CT, ANT, and CNT at 14°C are 0.76, 0.18, and 0.06, respectively, and the probabilities of CT, ANT, and CNT at 20°C are 0.41, 0.36, and 0.23, respectively.

On HEL fields, when average temperature in the Heartland is 14°C the predicted probability of CNT (0.17) is well below the probabilities of ANT (0.33) and CT (0.50) (figure 5, panel (b)). When average temperature is 20°C, the predicted probabilities in the Heartland for CNT, ANT, and CT are 0.49, 0.33, and 0.18, respectively. When average temperature is 14°C in the Prairie Gateway the predicted probabilities of CNT, ANT, and CT are 0.15, 0.32, 0.53, respectively (figure 6, panel (b)). In the Prairie Gateway when average temperatures are 20°C these values are 0.45 for CNT, 0.35 for ANT, and 0.20 for CT. Both regions show dramatic differences in the probabilities of CNT and CT for high and low temperatures but little change in the probability of ANT. Other regions in the study show tends similar to the Heartland.

Differences in the model inputs such as HEL, drainage, productivity, temperature, and precipitation could play a role in the regional differences in the probability of CNT adoption. For example, the most productive cropland are observed in the Heartland (average NCCPI is 66) where NCCPI is relatively high compared to the Prairie Gateway (average NCCPI is 45) and Southern Seaboard (average NCCPI is 55), but this is not the only driving force in high probabilities of CNT adoption where productivity is low (figure 7). We observe much higher probabilities of CNT in the Southern Seaboard where growing season average temperature is 22°C and precipitation is 114mm. Average temperature in the Southern Seaboard is 4°C lower in the Heartland and 3°C lower in the Prairie Gateway, while average precipitation is 20mm lower in the Heartland and 24mm lower in the Prairie Gateway (see appendix table A2 for region averages of coregressors). That the range of predicted probabilities in the Heartland and Prairie Gateway are relatively similar (the probability of CNT ranges from 0.28 to 0.11 in the Heartland and 0.31 to 0.13 in the Prairie Gateway for NCCPI values of 0 to 100, respectively) is likely due to their similarities in farm size (6.6 units for the Heartland and 7.0 units for the Prairie Gateway), temperature (18°C for the Heartland and 19°C for the Prairie Gateway), and precipitation (94mm for the Heartland and 80mm for the Prairie Gateway). The Prairie Gateway's high proportion of cropland that is well-drained (93% of acres) likely contributes to the higher probability of no-till adoption in this region: the average probability that no-till is adopted at least once during the four-year period is 0.30 on the Prairie Gateway, 0.26 in the Heartland, and 0.41 in the Southern Seaboard[2]. These regional differences may also be responsible for trends in the probability of no-till adoption on HEL cropland (figure 8).

Marginal effects for soybean producers

Soil characteristics. Unlike corn, NCCPI is not found to have a significant effect on no-till adoption. This may be due to the lack of yield penalty associated with no-till soybeans (Yin and Al-Kaisi 2004). While there are many crops in the yield histories in the soybean survey, a large proportion of fields were planted soybeans in previous years: 93% of soybean acres planted soybeans at least once in the previous three years while only 74% of corn acres were in soybeans at least once in the previous three years. This difference reflects the regions sampled. The soybean sample draws more heavily on Southeastern states where soybeans are more likely than corn and warm, moist conditions are more conducive to no-till.

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[2] It should be noted that of the ten states included in the Southern Seaboard only Georgia, Texas, and North Carolina were included in this study.

Consistent with the agronomic and economic literature, highly erodible land and well-drained land are more likely to be in no-till (see, e.g., Soule, Tengene, and Wiebe 2000, Prokopy et al. 2008, and Soane et al. 2012). HEL designation increases the probability of CNT by 0.25 but does not significantly increase the probability of ANT. The larger impact of HEL designation could be due to the higher proportion of soybeans grown in previous years on fields in the soybean survey. Producers who are concerned about soil erosion may see no-till, particularly on soybeans, as an important component of their overall soil conservation plan. Well-drained land increases the probability of CNT by 0.11 and the probability of ANT by 0.04—a much smaller and statistically different result.

Figure 9a illustrates the changes in average predicted probabilities when interchanging drainage and tillage characteristics (assuming non-irrigated cropland and holding all other variables at their means). Moving from non-HEL, poorly-drained soil to HEL, well-drained soil, we see the average predicted probabilities for field conditions that are poorly suited for no-till to those that are well suited for no-till. Only considering well-drained cropland (the second and fourth cluster in figure 9a), we see that on average, HEL designation increases the probability of CNT from 0.25 to 0.55 and decreases the probability of ANT from 0.35 to 0.30. Only considering poorly-drained cropland (clusters one and three), HEL designation increases the probability of CNT from 0.14 to 0.38 and increases the probability of ANT from 0.28 to 0.35. For non-HEL, well-drained cropland, the probability of CT exceeds the probability of CNT by 0.15 points and exceeds the probability of ANT by 0.05 points. The inverse is seen for poorly-drained, HEL cropland: the probability of CNT exceeds the probability of CT by 0.12 points and exceeds the probability of ANT by 0.03 points.

Farm characteristics. Irrigation is found to significantly increase the probability of adopting CT by 0.14 and decrease the probability of adopting CNT by 0.09. While the decreases in ANT and CNT are small for the irrigation dummy, their difference relative to the total effect is large. And while some irrigation systems use no-till (15% of irrigated acres use CNT and 25% ANT) farmers likely perceive a risk of obstructing irrigation machinery with residue left on the soil surface.

Figure 9b shows the averaged predicted probabilities for combinations of HEL and drainage classifications assuming irrigated cropland and holding all other variables at their means. As expected, the average predicted probabilities for irrigated cropland shows similar trends to those of non-irrigated cropland with larger differences between CT and those who use no-till at least once during the four-year period. For example, for non-HEL, poorly-drained cropland, the difference between CT and CNT on non-irrigated fields (figure 9a) is 0.43 while this difference is 0.64 on irrigated cropland. For CT, the predicted probabilities for irrigated cropland are 0.10 to 0.16 points higher than those on non-irrigated cropland, while the predicted probabilities for CNT are 0.06 to 0.16 points lower on irrigated cropland than on non-irrigated cropland, on average. As suggested by the average marginal effects in table 4, there is relatively little change in the average probabilities of ANT when varying HEL and drainage classifications. Only on HEL, well-drained cropland do we predict that the average probability of ANT is greater on irrigated fields (0.35) than on non-irrigated fields (0.30).

Like corn fields, the results also suggest that larger farms have a higher probability of adopting CNT. For non-HEL, well-drained fields, we find that small farms (150 acres, holding all other variables at the mean of the data) are much more likely to use CT (0.50) than either ANT

(0.32) or CNT (0.18). As farm size increases, the probability of both ANT and CNT rise in relation to CT. Farms that have 500 acres (i.e. where the log of cropland is about 6.2 units) are almost twice as likely to adopt CT (0.42) as CNT (0.23). On a 3,000 acre farm, the probabilities of CNT (0.32), ANT (0.36), and CT (0.32) are roughly equal. For HEL cropland, the probability of CNT is greater than the probability of ANT and CT (for our otherwise "average" farm) for all but the very smallest farms (farms of roughly 40 acres or less). On most farms, CNT is the dominant tillage regime. When cropland is 500 acres, for example, the probability of CNT (0.53) is more than three times that of CT (0.16) and is 0.22 points higher than ANT (0.31). All observed HEL acres are located on fields where the predicted probability of CNT is greater than the probability of ANT or CT.

Regional indicators and climate characteristics. The changes in probabilities due to changes in precipitation are similar to those of corn with corn fields showing slightly more sensitivity to precipitation levels than soybeans. Though small, the average marginal change in the probability of adopting CNT is three-times larger than that of ANT (table 4). This is evidence that expected precipitation levels play a small but significant role in CNT adoption for soybeans. Like corn, most of the soybean sample observes average precipitation between 80mm and 110mm. Using average marginal effects, an increase of 30mm in average precipitation suggests that the probability of ANT will increase by 0.06 and increase the probability of CNT by 0.18.

All regions show similar trends in no-till adoption for well-drained, non-irrigated, non-HEL cropland. The probability of both CNT and ANT rise as precipitation rises, ceteris paribus. In the Heartland, for example (figure 10), when average precipitation is low, say 75mm, the probability of adopting CT (0.59) is more than four times greater than the probability of CNT

(0.13) and twice that of ANT (0.27). When average precipitation is high, say 114mm, the probability of adopting CNT (0.39) is only 0.04 points higher than ANT (0.35) but both are 0.09 or more points higher than CT (0.26). Trends are similar in the Northern Crescent and Mississippi Portal. In the Prairie Gateway (figure 11), if average precipitation should fall to 81mm, the probability of CNT (0.33) is almost equal to the predicted probability of CT (0.31) and ANT (0.36). However, if average precipitation rises to 113mm, the probability of CNT (0.62) is more than twice that of ANT (0.26) and five times that of CT (0.12). Though both regions show that no-till adoption is likely at high levels of average precipitation, CT is more likely than ANT and CNT on 97% of acres in the Heartland and only 8% in the Prairie Gateway. No-till will likely be used at least once during the four-year period when average precipitation levels are above 87mm in Heartland and 61mm in the Prairie Gateway.

Results for the soybean survey vary from those based on the corn survey in the sense that the probability of CNT exceeds that of ANT or CT for almost all non-irrigated, well-drained, HEL fields. It is clear that CNT is the preferred practice on highly erodible soybean fields but also that CNT adoption is more likely in the Prairie Gateway. In this region, the probability of CNT exceeds that of ANT and CT for all levels of average precipitation examined.

Conclusion

This article examines the attributes thought to affect the continuous adoption of no-till. It is a national study of field-level tillage intensity using farmers past behavior over a four-year period as revealing their preferences towards no-till and measures this preference in three ordered groups: CT, ANT, and CNT. The ordered logit regression analysis was therefore used to estimate the effect soil, climate, regional, farm, and farmer characteristics have on farmers' adoption of continuous no-till.

The regression results show a clear picture of how regions, soil, and climate affect the predicted probabilities of each tillage category. For relatively low values of average precipitation, corn and soybean producers are more likely to use CT on non-HEL fields, and are indifferent to ANT and CNT use when average precipitation is relatively high. The same is true for relatively low and high values of average temperature on non-HEL corn fields. The varied temperatures and precipitation levels in the Prairie Gateway implies that this region has more opportunities to adopt no-till than other regions.

Both agronomic studies and the evidence presented indicate that corn and soybeans farmers rotate no-till. CNT adoption has the potential to significantly increase carbon sequestration in cropland as well as improve soil health, mitigate sediment and nutrient losses, but fields need more than five years of continuous no-till to reach their full potential for building organic matter (Toliver et al. 2012). If it is not economically feasible for farmers to use CNT (due to weed management or yield reductions) then policymakers hoping to increase no-till acreage may need to better understand the economic drivers of new or non-adopters and factors that influence transitions from ANT to CNT adoption. A key question for future research is the cost associated with sustained adoption. It may be possible to convince farmers to switch to CNT where the probability of ANT is close to the probability of CNT.

Future research may also consider constructing panels, using more years of no-till choice data and incorporating other farmer attributes such as attitudes towards conservation, stewardship, whether the farmer received no-till payments, and other characteristics that may help explain what motivates farmers to transition into CNT. In addition, farmers make decisions to till before each planting season. Weather, soil moisture, temperature, nutrient needs, equipment availability, and issues with suppliers are some of the factors considered at the beginning of each season that could lend insight into the challenges that farmers face with sustained adoption.

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Table 1. Descriptions of variables and summary statistics

		Corn		Soybean	
Variable	Description	Mean	Std. Dev.	Mean	Std. Dev.
No-Till Intensity	*Dependent Variable*: 1-Continuous tillage; 2-alternating no-till; 3-continuous no-till				
NCCPI	Mean of the National Commodity Crop Productivity Index within 300m	57.4	20.4	58.6	18.8
Highly Erodible Land	1-Land is classified as highly erodible by NRCS; 0-otherwise	0.109	0.311	0.143	0.351
Well-Drained Soil	1-Soil is excessively to moderately well drained; 0-otherwise	0.627	0.484	0.578	0.494
Irrigated Field	1-Any portion of the field is irrigated; 0-otherwise	0.061	0.240	0.079	0.270
Log of Cropland	Natural log of the total cropland	6.51	1.11	6.53	1.20
Residence Farm	1-Farm is a residential or lifestyle farm; 0-otherwise	0.102	0.302	0.120	0.325
Intermediate Farm	1-Farm is an intermediate farm; 0-otherwise	0.183	0.387	0.226	0.418
Commercial Farm	1-Farm is a commercial farm; 0-otherwise	0.715	0.452	0.654	0.476
Heartland	1-Field is in the Heartland; 0-otherwise	0.608	0.488	0.581	0.494
Northern Crescent	1-Field is in the Northern Crescent; 0-otherwise	0.216	0.412	0.151	0.358
Northern Great Plains	1-Field is in the Northern Great Plains; 0-otherwise	0.035	0.184	0.043	0.204
Prairie Gateway	1-Field is in the Prairie Gateway; 0-otherwise	0.095	0.294	0.066	0.249
Eastern Uplands	1-Field is in the Eastern Uplands; 0-otherwise	0.019	0.136	0.029	0.167
Southern Seaboard	1-Field is in the Southern Seaboard; 0-otherwise	0.022	0.148	0.022	0.145
Fruitful Rim	1-Field is in the Fruitful Rim; 0-otherwise	0.0043	0.0657		
Mississippi Portal	1-Field is in the Mississippi Portal; 0-otherwise			0.108	0.311
Average Temperature	County average of monthly temperature during the crop growing season (°C)	17.41	2.08	19.33	2.19

Temperature Variability	County variance of monthly temperature during the crop growing season	26.71	4.06	18.98	3.19
Average Precipitation	County average of monthly precipitation during the crop growing season (mm)	91.7	11.8	94.5	10.1
Precipitation Variability	County variance of monthly precipitation during the crop growing season	2597	835	2812	882
Age	Operator’s age (years)	55.3	11.3	57.1	11.1
Tenure	1-Operator is a full-owner; 0-otherwise	0.522	0.500	0.470	0.499
College Graduate	1-Primary operator graduated from college; 0-otherwise	0.210	0.407	0.237	0.425

Table 2. Share of fields and predicted probabilities by tillage category and region

	Continuous Tillage			Alternating No-Till			Continuous No-Till		
	Share	Estimate		Share	Estimate		Share	Estimate	
Corn	0.5374	0.5367	(0.0199)	0.2937	0.2936	(0.0197)	0.1689	0.1697	(0.0170)
Heartland	0.5636	0.5646	(0.0237)	0.2899	0.2842	(0.0207)	0.1465	0.1511	(0.0164)
Northern Crescent	0.5333	0.5328	(0.0550)	0.2867	0.3012	(0.0272)	0.1800	0.1660	(0.0370)
Northern Great Plains	0.5563	0.5681	(0.0618)	0.3249	0.2917	(0.0359)	0.1188	0.1402	(0.0323)
Prairie Gateway	0.4145	0.4126	(0.0493)	0.3444	0.3382	(0.0265)	0.2411	0.2492	(0.0408)
Eastern Uplands	0.5452	0.5456	(0.1442)	0.3220	0.2970	(0.0694)	0.1327	0.1574	(0.0784)
Southern Seaboard	0.3104	0.2436	(0.0767)	0.1872	0.3104	(0.0414)	0.5024	0.4460	(0.1115)
Fruitful Rim	0.7689	0.7816	(0.1363)	0.2311	0.1635	(0.0948)	n/a	0.0549	(0.0423)
Soybeans	0.4521	0.4544	(0.0160)	0.2932	0.2932	(0.0157)	0.2547	0.2524	(0.0144)
Heartland	0.4393	0.4426	(0.0207)	0.3116	0.3049	(0.0175)	0.2491	0.2526	(0.0167)
Northern Crescent	0.5387	0.5374	(0.0457)	0.2896	0.2853	(0.0232)	0.1717	0.1773	(0.0287)
Northern Great Plains	0.5410	0.5587	(0.0485)	0.3420	0.2857	(0.0264)	0.1170	0.1556	(0.0273)
Prairie Gateway	0.1794	0.2086	(0.0355)	0.3283	0.2941	(0.0227)	0.4923	0.4973	(0.0504)
Eastern Uplands	0.1724	0.1986	(0.0722)	0.3105	0.2967	(0.0391)	0.5171	0.5047	(0.1074)
Southern Seaboard	0.1450	0.2276	(0.0714)	0.4594	0.2977	(0.0330)	0.3956	0.4747	(0.0992)
Mississippi Portal	0.6667	0.6241	(0.0588)	0.1201	0.2417	(0.0264)	0.2133	0.1342	(0.0359)

Standard errors in parentheses.

Table 3. Ordered logit average marginal effects estimates for corn

	Continuous Tillage		Alternating No-Till		Continuous No-Till	
NCCPI	0.0025	(0.0013)**	-0.0011	(0.0005)**	-0.0014	(0.0007)*
Highly Erodible Land	-0.2314	(0.0558)***	0.0645	(0.0134)***	0.1669	(0.0499)***
Well-Drained Soil	-0.1402	(0.0390)***	0.0634	(0.0188)***	0.0767	(0.0220)***
Irrigated Field	0.0128	(0.0704)	-0.0055	(0.0307)	-0.0073	(0.0397)
Log of Cropland	-0.059	(0.0236)**	0.0249	(0.01)**	0.0341	(0.0142)**
Intermediate Farm	-0.1154	(0.0651)*	0.0431	(0.0281)	0.0723	(0.0390)*
Commercial Farm	-0.0041	(0.0745)	0.0019	(0.0337)	0.0023	(0.0408)
Northern Crescent	-0.0387	(0.0714)	0.0169	(0.0297)	0.0218	(0.0418)
Northern Great Plains	-0.124	(0.0971)	0.0463	(0.0296)	0.0777	(0.0684)
Prairie Gateway	-0.0946	(0.0930)	0.0375	(0.0325)	0.0571	(0.0610)
Eastern Uplands	0.0479	(0.1435)	-0.0234	(0.0737)	-0.0245	(0.0699)
Southern Seaboard	-0.2839	(0.1169)**	0.0602	(0.0207)***	0.2236	(0.1297)*
Fruitful Rim	0.2158	(0.1711)	-0.1231	(0.1116)	-0.0927	(0.0604)
Average Temp	-0.0572	(0.0212)***	0.0241	(0.0093)**	0.0331	(0.0125)***
Temp Variability	-0.0117	(0.0093)	0.0049	(0.0039)	0.0067	(0.0055)
Average Precip	-0.0123	(0.0034)***	0.0052	(0.0015)***	0.0071	(0.0021)***
Precip Variability	0.00015	(0.00005)***	-0.00006	(0.00002)***	-0.00009	(0.00003)***
Age	-0.0018	(0.0016)	0.0008	(0.0007)	0.0010	(0.0009)
Tenure	-0.0254	(0.0400)	0.0108	(0.0168)	0.0147	(0.0232)
College Graduate	-0.0082	(0.0439)	0.0034	(0.0183)	0.0048	(0.0256)

Note: Marginal effects for factor levels is the discrete change from the base level. Standard errors in parentheses. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table 4. Ordered logit average marginal effects estimates for soybeans

	Continuous Tillage		Alternating No-Till		Continuous No-Till	
NCCPI	-0.0005	(0.0010)	0.0001	(0.0002)	0.0004	(0.0007)
Highly Erodible Land	-0.2628	(0.0389)***	0.0090	(0.0131)	0.2537	(0.0479)***
Well-Drained Soil	-0.1495	(0.0331)***	0.0398	(0.0097)***	0.1097	(0.0249)***
Irrigated Field	0.1370	(0.0558)**	-0.0453	(0.0223)**	-0.0917	(0.0340)***
Log of Cropland	-0.0542	(0.0214)**	0.0131	(0.0056)**	0.0411	(0.0161)**
Intermediate Farm	0.0838	(0.0604)	-0.0142	(0.0092)	-0.0696	(0.0531)
Commercial Farm	0.0993	(0.0669)	-0.0182	(0.009)**	-0.0811	(0.0587)
Northern Crescent	0.092	(0.0582)	-0.0292	(0.0219)	-0.0628	(0.0367)*
Northern Great Plains	-0.1012	(0.0691)	0.0155	(0.0058)***	0.0856	(0.0654)
Prairie Gateway	-0.2651	(0.0461)***	-0.0191	(0.023)	0.2842	(0.0654)***
Eastern Uplands	-0.0934	(0.1067)	0.0151	(0.0088)*	0.0783	(0.0988)
Southern Seaboard	-0.0971	(0.1083)	0.0153	0.0086)*	0.0818	(0.1006)
Mississippi Portal	0.1368	(0.1176)	-0.0475	(0.0503)	-0.0893	(0.0677)
Average Temp	-0.0073	(0.0196)	0.0018	(0.0048)	0.0055	(0.0149)
Temp Variability	0.0202	(0.0120)*	-0.0049	(0.003)	-0.0153	(0.009)*
Average Precip	-0.0078	(0.0035)**	0.0019	(0.0008)**	0.0059	(0.0027)**
Precip Variability	0.00013	(0.00004)***	-0.00003	(0.00001)***	-0.00010	(0.00003***
Age	-0.0014	(0.0014)	0.0003	(0.0004)	0.0010	(0.0011)
Tenure	0.0308	(0.0313)	-0.0075	(0.0077)	-0.0233	(0.0237)
College Graduate	0.0150	(0.0364)	-0.0037	(0.0093)	-0.0113	(0.0271)

Note: Marginal effects for factor levels is the discrete change from the base level. Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01

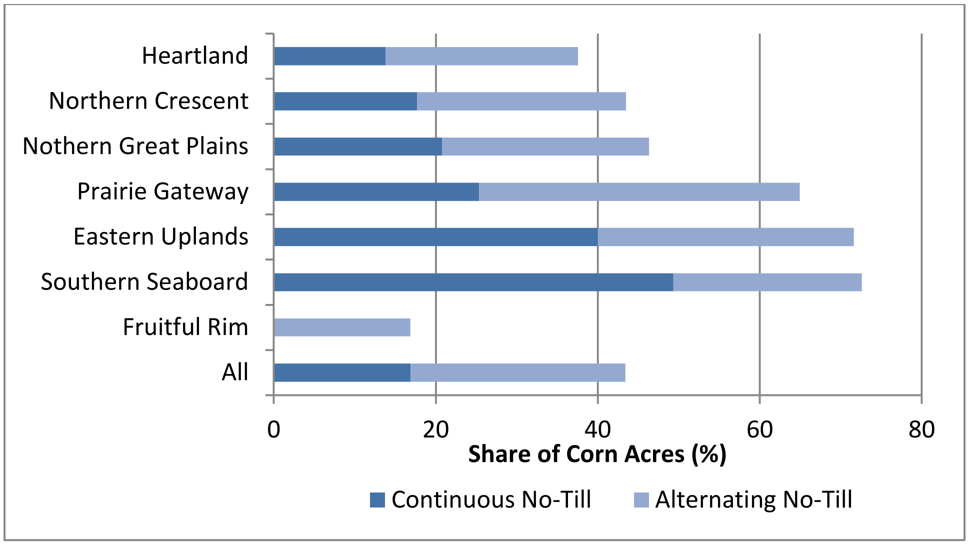

Figure 1a: Tillage adoption for corn acres by USDA, Economic Research Service farm resource regions

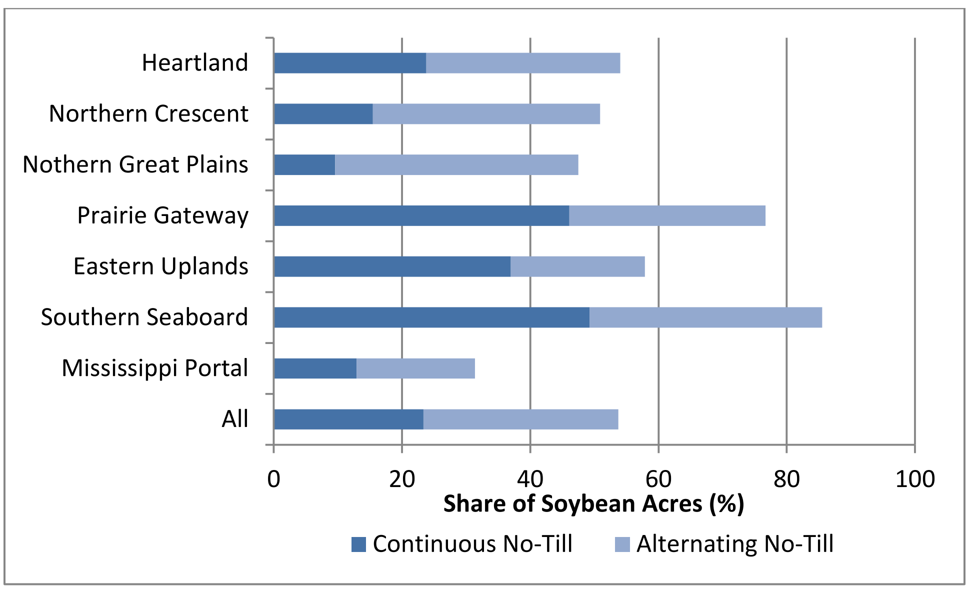

Figure 1b: Tillage adoption for soybean acres by USDA, Economic Research Service farm resource regions

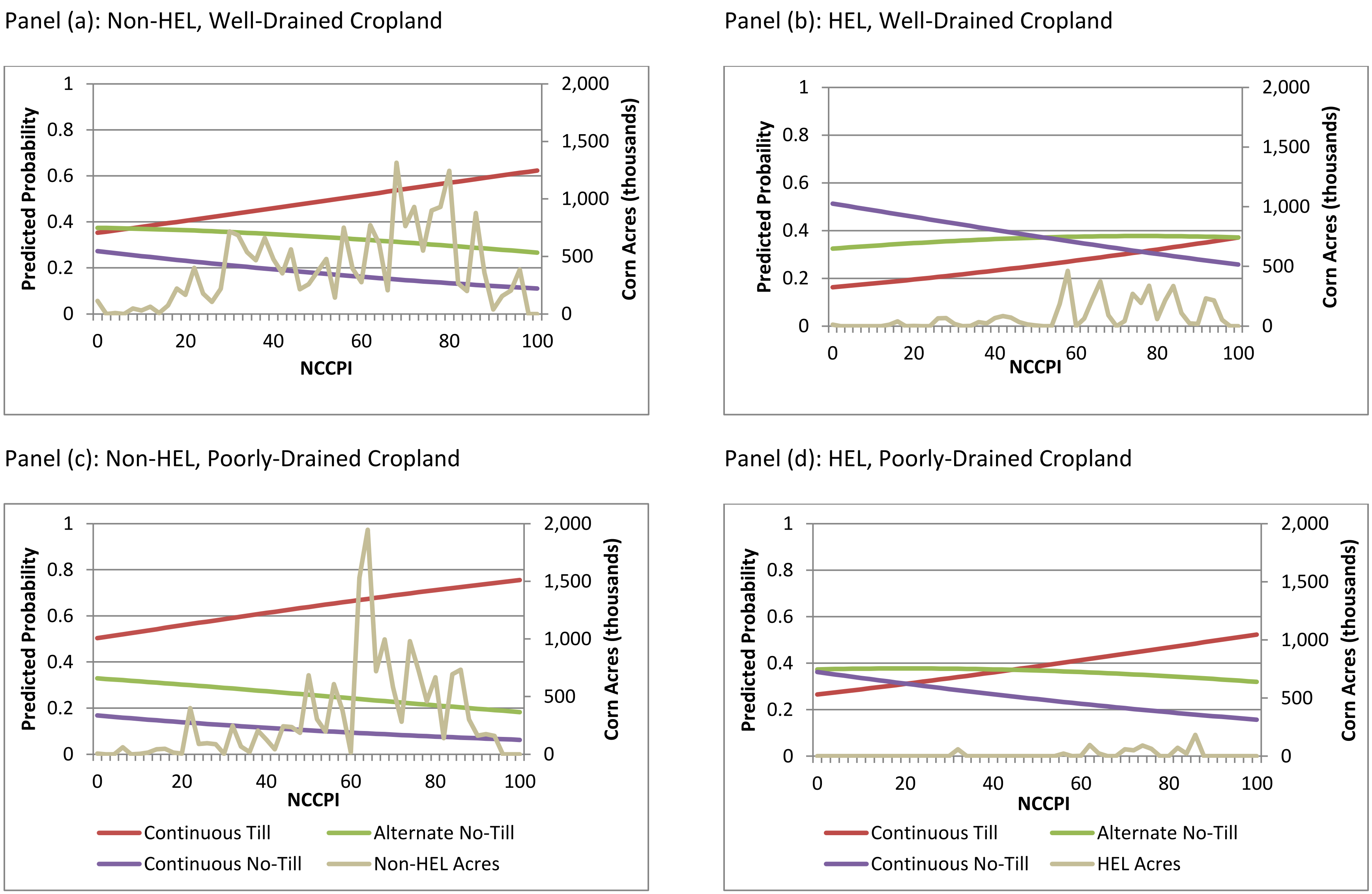

Figure 2. Predicted probabilities as NCCPI increases for non-irrigated corn fields

Panel (a): Non-HEL Cropland in the Heartland

Panel (b): HEL, Well-Drained Cropland in the Heartland

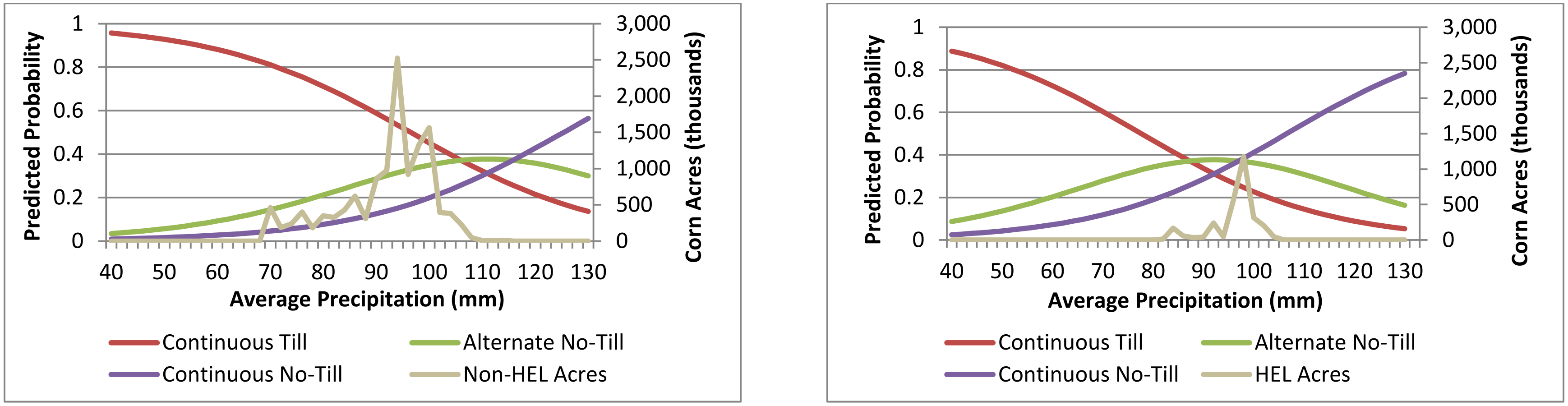

Figure 3. Predicted probabilities as average precipitation increases for non-irrigated, well-drained corn acres

Panel (a): Non-HEL Cropland in the Prairie Gateway

Panel (b): HEL Cropland in the Prairie Gateway

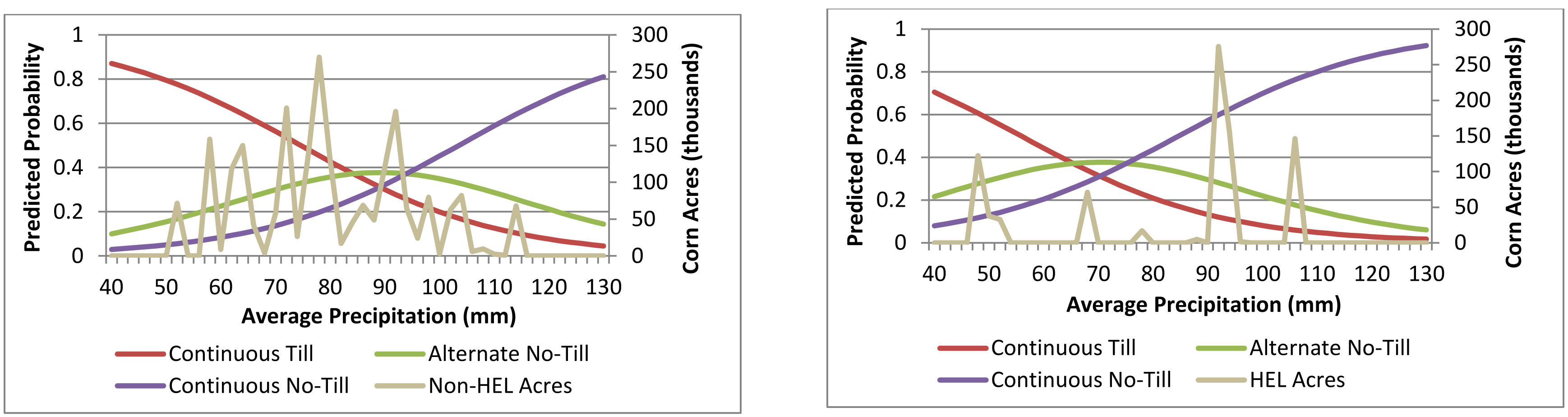

Figure 4. Predicted probabilities as average precipitation increases for non-irrigated, well-drained corn fields

Panel (a): Non-HEL Cropland in the Heartland

Panel (b): HEL Cropland in the Heartland

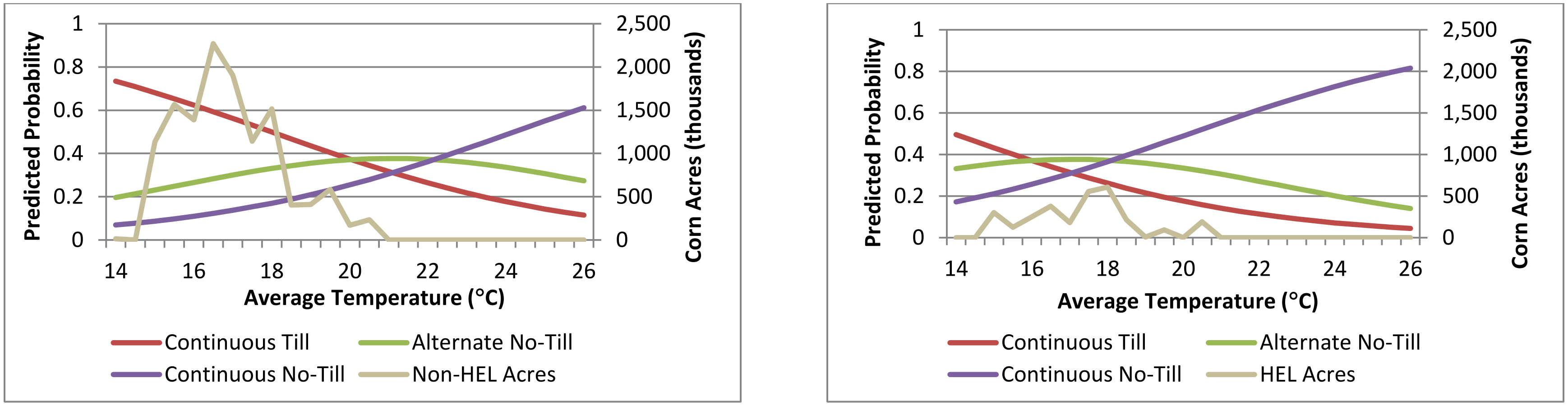

Figure 5. Predicted probabilities as average temperature increases for non-irrigated, well-drained corn fields

Panel (a): Non-HEL Cropland in the Prairie Gateway

Panel (b): HEL Cropland in the Prairie Gateway

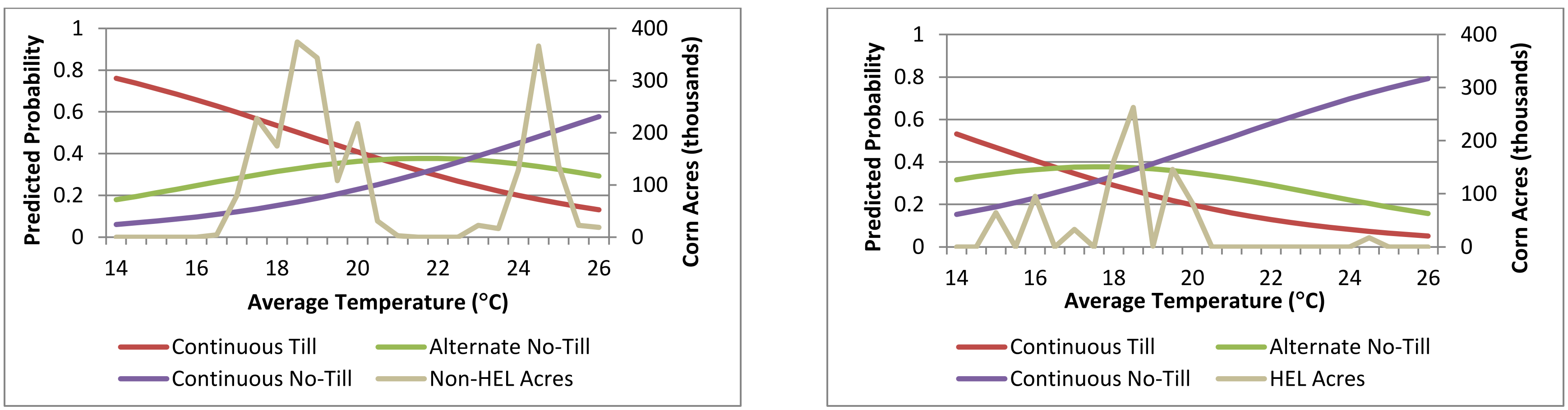

Figure 6. Predicted probabilities as average temperature increases for non-irrigated, well-drained corn fields

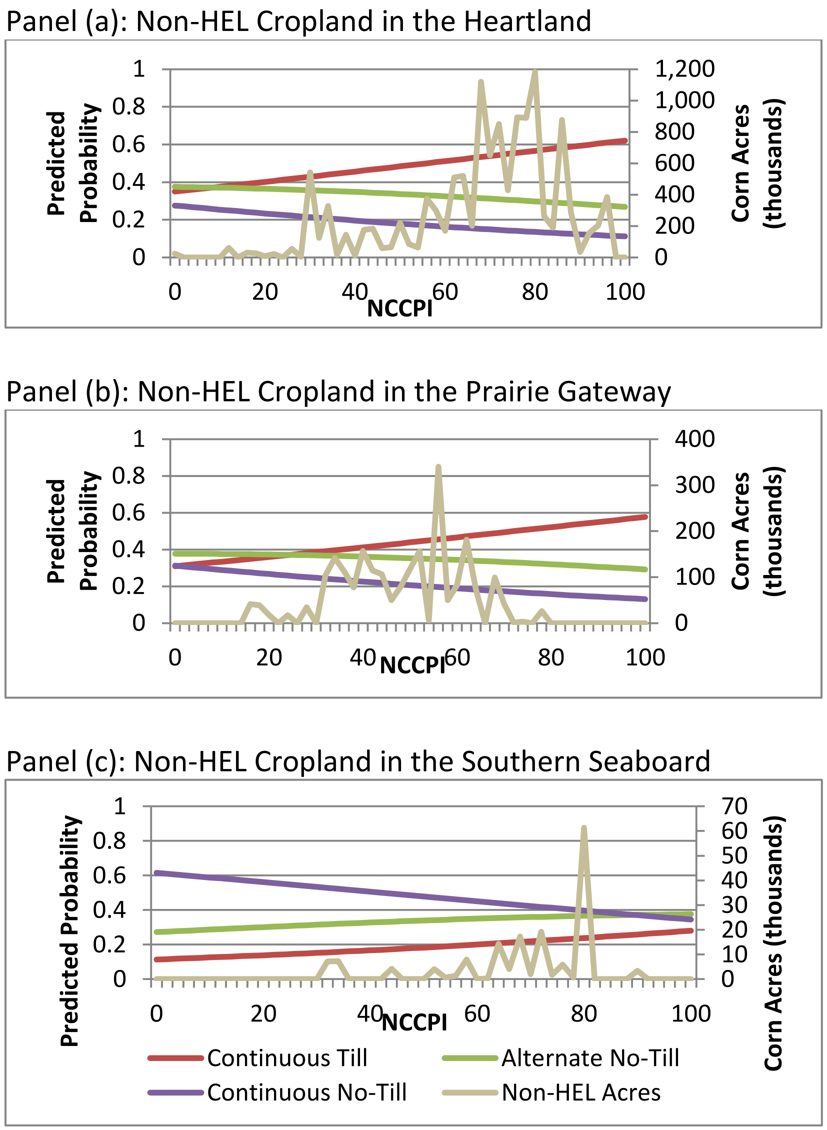

Figure 7. Predicted probabilities as NCCPI increases for non-HEL, well-drained, non-irrigated corn fields by region

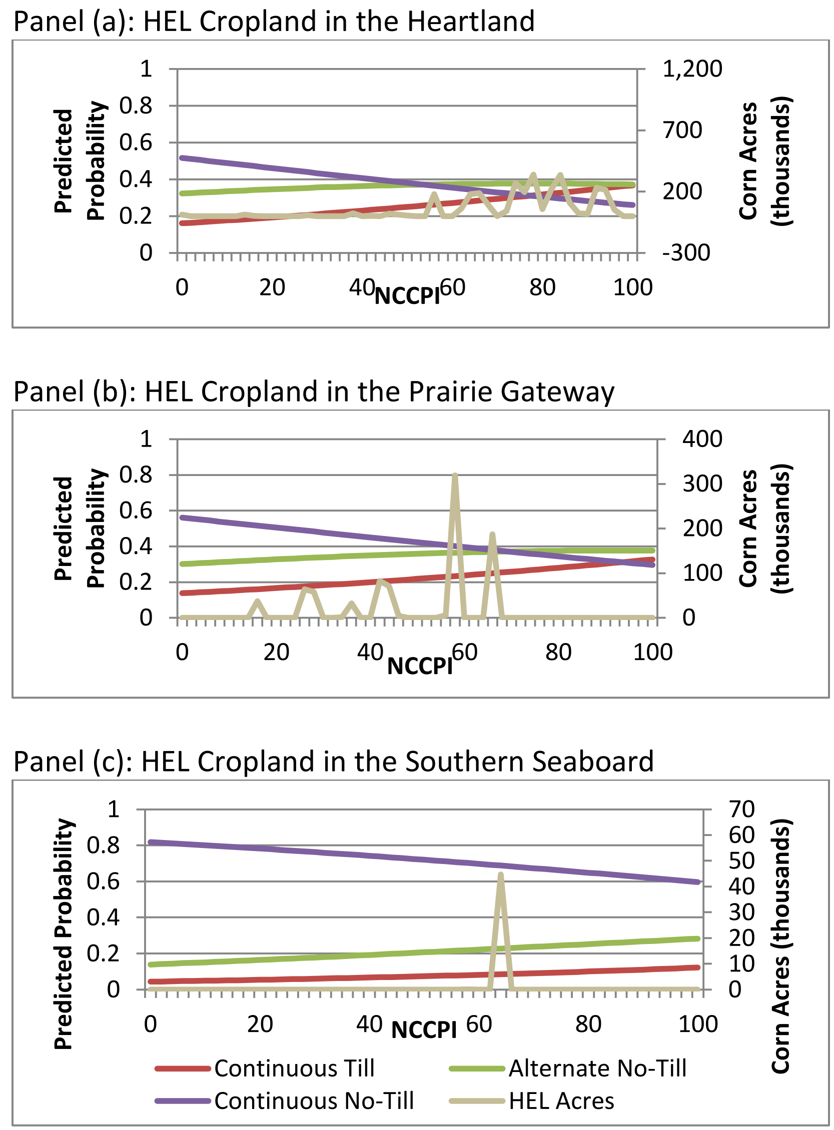

Figure 8. Predicted probabilities as NCCPI increases for HEL, HEL classification for irrigated corn fields

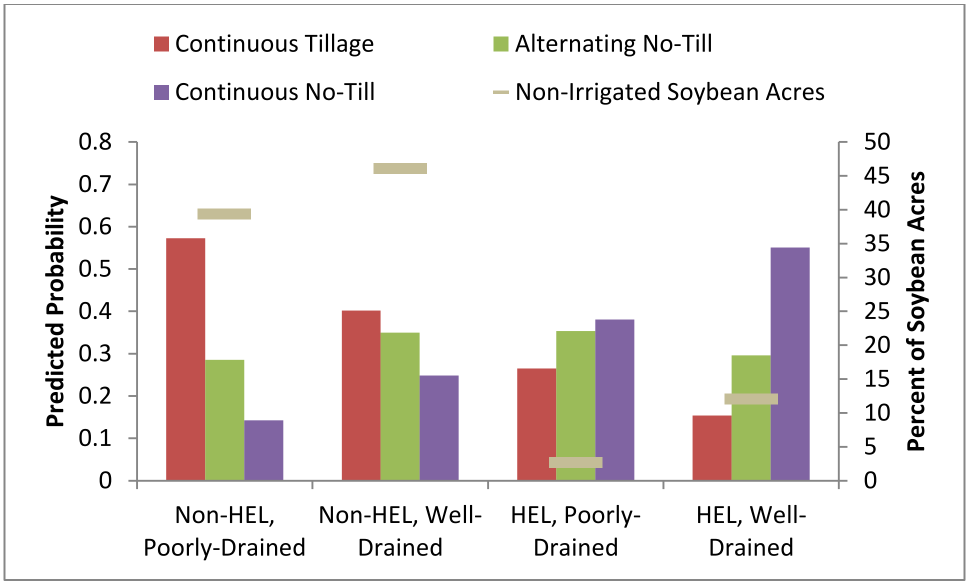

Figure 9a. Average predicted probabilities by drainage and HEL classification for non-irrigated cropland

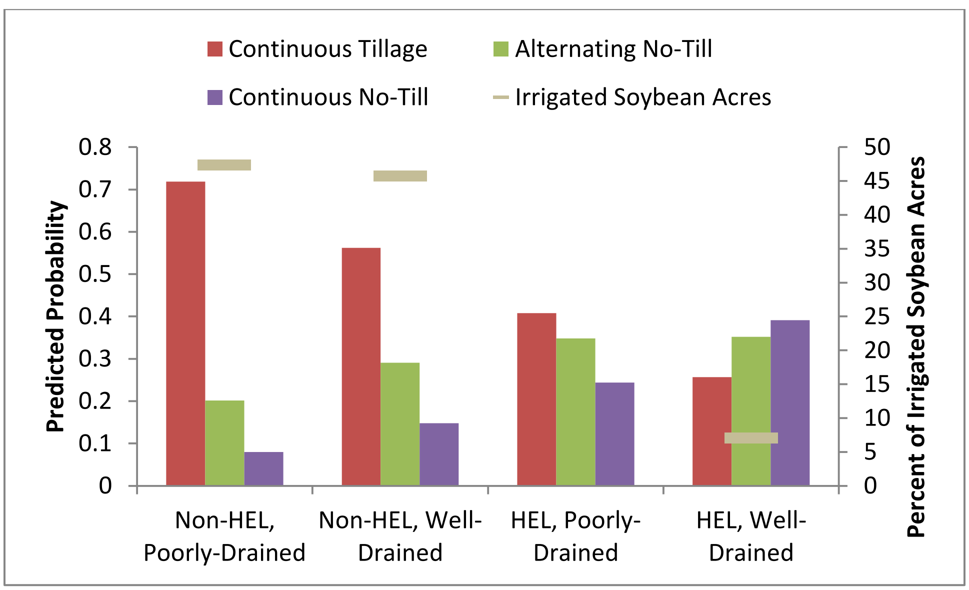

Figure 9b. Average predicted probabilities by drainage and HEL classification for irrigated cropland

Panel (a): Non-HEL Cropland in the Heartland

Panel (b): HEL Cropland in the Heartland

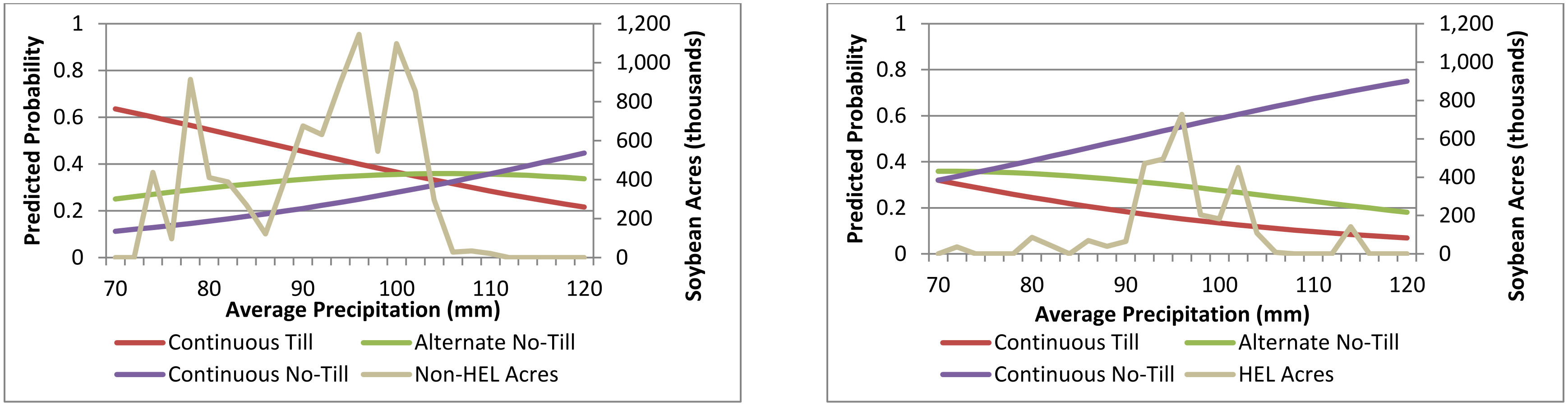

Figure 10. Predicted probabilities as average precipitation increases for non-irrigated, well-drained soybean fields

Panel (a): Non-HEL Cropland in the Prairie Gateway

Panel (b): HEL Cropland in the Prairie Gateway

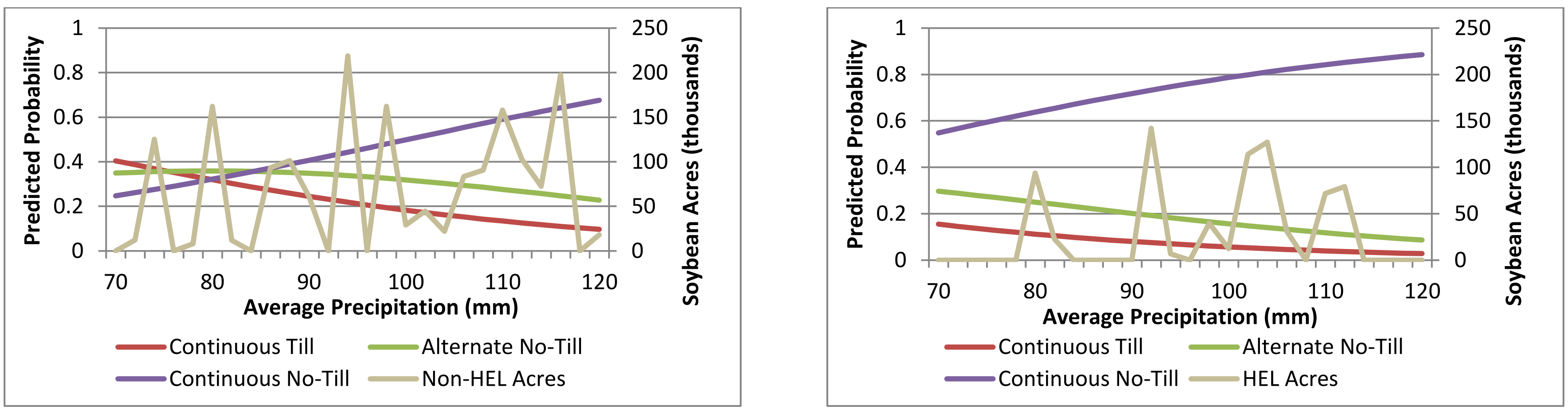

Figure 11. Predicted probabilities as average precipitation increases for non-irrigated, well-drained soybean fields

Appendix

Table A1. Ordered logit parameter by crop

	Corn		Soybean	
Soil:				
NCCPI	-0.0111	(0.0056)**	0.0023	(0.0046)
Highly Erodible Land	1.0323	(0.2697)***	1.3111	(0.2261)***
Well-Drained Soil	0.6206	(0.1764)***	0.6888	(0.1521)***
Farm Characteristics:				
Irrigated Field	-0.0573	(0.3152)	-0.6448	(0.2654)**
Log of Cropland	0.2629	(0.1064)**	0.2567	(0.1024)**
Intermediate Farm	0.5117	(0.2910)*	-0.404	(0.2956)
Commercial Farm	0.0186	(0.3339)	-0.477	(0.3282)
Region and Climate:				
Northern Crescent	0.1703	(0.3137)	-0.4219	(0.2692)
Northern Great Plains	0.5444	(0.4320)	0.4781	(0.3428)
Prairie Gateway	0.4148	(0.4081)	1.4199	(0.3112)***
Eastern Uplands	-0.2159	(0.6583)	0.4398	(0.5173)
Southern Seaboard	1.3063	(0.6154)**	0.4583	(0.5287)
Fruitful Rim	-1.0914	(1.0514)		
Mississippi Portal			-0.6311	(0.5540)
Average Temperature	0.2547	(0.0967)***	0.0346	(0.0930)
Temperature Variability	0.052	(0.0418)	-0.0956	(0.0572)*
Average Precipitation	0.0549	(0.0158)***	0.037	(0.0164)**
Precipitation Variability	-0.0007	(0.0002)***	-0.0006	(0.0002)***
Operator Characteristics:				
Age	0.0079	(0.0071)	0.0065	(0.0068)
Tenure	0.1131	(0.1776)	-0.1456	(0.1482)
College Graduate	0.0364	(0.1951)	-0.071	(0.1721)
τ_1	11.591	(3.2011)***	2.6461	(3.1618)
τ_2	13.178	(3.2134)***	4.1497	(3.1566)
N	1155		1324	
LL	-822172.99		-742533.97	

Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01

Table A2. Summary statistics corn fields by region (standard deviations in parentheses)

Corn	Heartland	Northern Crescent	Northern Great Plains	Prairie Gateway	Eastern Uplands	Southern Seaboard	Fruitful Rim
NCCPI	66.0 (16.9)	45.6 (18.2)	27.38 (7.94)	45.1 (13.3)	39.5 (20.3)	55.5 (23.5)	30.5 (10.5)
Highly Erodible Land	0.127 (0.333)	0.064 (0.246)	0.037 (0.189)	0.156 (0.364)	0.006 (0.077)	0.056 (0.231)	0
Well-Drained Soil	0.530 (0.500)	0.723 (0.449)	0.820 (0.386)	0.930 (0.256)	0.709 (0.462)	0.625 (0.488)	0.889 (0.324)
Irrigated Field	0.032 (0.176)	0.00006 (0.00767)	0.139 (0.347)	0.364 (0.483)	0.0012 (0.0359)	0.057 (0.233)	0.213 (0.422)
Log of Cropland	6.57 (1.06)	6.17 (1.03)	7.372 (0.999)	6.96 (1.05)	5.72 (1.08)	5.45 (1.20)	7.06 (1.31)
Intermediate Farm	0.150 (0.357)	0.234 (0.425)	0.175 (0.382)	0.225 (0.419)	0.327 (0.477)	0.328 (0.473)	0.148 (0.366)
Commercial Farm	0.749 (0.434)	0.657 (0.476)	0.808 (0.396)	0.715 (0.453)	0.580 (0.502)	0.320 (0.470)	0.789 (0.421)
Average Temperature	17.55 (1.40)	15.770 (1.035)	14.988 (0.704)	19.72 (2.65)	16.95 (1.83)	21.96 (1.20)	26.156 (0.941)
Temperature Variability	26.83 (2.89)	27.17 (2.55)	33.795 (0.692)	26.51 (6.20)	22.22 (2.02)	16.05 (2.07)	8.67 (1.69)
Average Precipitation	94.43 (7.56)	90.49 (6.58)	63.91 (7.40)	80.1 (16.8)	101.6 (12.0)	114.1 (13.4)	86.19 (16.03)
Precipitation Variability	2684 (590)	2128 (503)	1634 (253)	2871 (1090)	2514 (1246)	4736 (1741)	4851 (1078)
Age	55.0 (11. 3)	56.0 (10.6)	52.4 (11.8)	55.1 (13.0)	54.31 (7.86)	60.2 (10.1)	63.1 (12.2)
Tenure	0.482 (0.500)	0.644 (0.480)	0.473 (0.502)	0.418 (0.495)	0.896 (0.310)	0.592 (0.495)	0.662 (0.488)
College Graduate	0.204 (0.403)	0.176 (0.382)	0.243 (0.431)	0.327 (0.471)	0.138 (0.351)	0.140 (0.350)	0.450 (0.513)

Table A3. Summary statistics for soybean fields by region (standard deviations in parenthesis)

Soybeans	Heartland	Northern Crescent	Northern Great Plains	Prairie Gateway	Eastern Uplands	Southern Seaboard	Mississippi Portal
NCCPI	61.9 (17.7)	0.523 (0.142)	28.2 (10.9)	0.541 (0.139)	45.7 (21.4)	56.1 (26.3)	68.4 (15.6)
Highly Erodible Land	0.177 (0.382)	0.084 (0.278)	0.014 (0.116)	0.232 (0.424)	0.127 (0.339)	0.237 (0.431)	0.029 (0.169)
Well-Drained Soil	0.579 (0.494)	0.489 (0.501)	0.649 (0.480)	0.901 (0.300)	0.980 (0.142)	0.796 (0.408)	0.321 (0.468)
Irrigated Field	0.041 (0.199)	0.016 (0.124)	0.044 (0.206)	0.138 (0.347)	0	0.043 (0.205)	0.379 (0.486)
Log of Cropland	6.49 (1.07)	5.95 (1.39)	7.374 (0.919)	6.829 (0.919)	5.94 (1.25)	6.50 (1.06)	7.20 (1.29)
Intermediate Farm	0.233 (0.423)	0.250 (0.434)	0.152 (0.361)	0.289 (0.455)	0.390 (0.496)	0.138 (0.349)	0.122 (0.328)
Commercial Farm	0.645 (0.479)	0.573 (0.496)	0.785 (0.413)	0.631 (0.484)	0.392 (0.496)	0.703 (0.463)	0.838 (0.369)
Average Temperature	19.05 (1.34)	17.240 (0.737)	15.966 (0.858)	20.610 (0.984)	20.48 (1.10)	21.45 (1.05)	23.625 (0.981)
Temperature Variability	19.48 (2.21)	19.14 (1.79)	25.532 (0.661)	21.40 (1.41)	15.62 (1.22)	15.11 (1.18)	13.65 (2.21)
Average Precipitation	94.92 (7.35)	91.59 (6.20)	69.30 (5.92)	96.4 (13.5)	102.03 (6.32)	102.73 (7.01)	101.3 (10.7)
Precipitation Variability	2783 (627)	2065 (515)	1629 (184)	3435 (890	2731 (688)	3444 (797)	3994 (9958)
Age	57.2 (11.2)	57.4 (10.9)	52.4 (10.3)	56.4 (11.3)	59.9 (12.8)	57.6 (11.3)	57.7 (10.2)
Tenure	0.481 (0.500)	0.442 (0.498)	0.363 (0.483)	0.477 (0.502)	0.754 (0.438)	0.393 (0.495)	0.423 (0.495)
College Graduate	0.249 (0.433)	0.161 (0.369)	0.223 (0.419)	0.216 (0.414)	0.181 (0.392)	0.134 (0.345)	0.335 (0.473)