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Long-term economic impacts of no-till adoption

Yuyuan Che[a], Roderick M. Rejesus[b,*], Michel A. Cavigelli[c], Kathryn E. White[c], Serkan Aglasan[d], Lynn G. Knight[e], Curt Dell[f], David Hollinger[g], Erin D. Lane[g]

[a] Department of Agricultural and Applied Economics, Texas Tech University, Lubbock, TX, United States
[b] Department of Agricultural and Resource Economics, North Carolina State University, Raleigh, NC, United States
[c] Agricultural Research Service (ARS), U.S. Department of Agriculture, Beltsville, MD, United States
[d] Department of Agricultural and Resource Economics, University of Arizona, Tucson, AZ, United States
[e] Natural Resources Conservation Service (NRCS), U.S. Department of Agriculture, Milton, VT, United States
[f] Agricultural Research Service (ARS), U.S. Department of Agriculture, University Park, PA, United States
[g] Northeast Climate Hub and US Forest Service, U.S. Department of Agriculture, Durham, NH, United States

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ABSTRACT

No-till has long been considered a sustainable agricultural practice because of its potential to provide on-farm productivity benefits as well as off-site environmental benefits. However, “economic concerns” have been identified as one of the largest barriers to adopting no-till (i.e., costs associated with adoption possibly being greater than the returns in the short term). This study evaluates the long-term economic impact of no-till adoption using rich plot-level data from a long-term field experiment over the period 1996–2019. Linear fixed-effect models and partial budgeting techniques are used in the empirical analysis. Estimation results reveal that there are generally no statistically significant differences between long-term yields from no-till relative to the conventional tillage practice when considering corn, soybean, and wheat. Nonetheless, the partial budgeting analysis using the long-term data suggests that net returns (or profits) per acre tend to be greater for no-till compared to conventional tillage for all three crops. This is primarily due to the statistically lower farm operation costs associated with no-till. Moreover, our analysis also suggests that relative profitability of no-till increases as the practice is used longer over time. This insight supports suggestions from previous studies that long-term adoption of continuous no-till is important to best realize the benefits from the practice.

1. Introduction

Long-term resource conservation through the use of environmentally-friendly agricultural practices has been recognized as an important goal to achieve sustainable growth in the agricultural sector. For example, many soil health conservation practices, including no-till, have been shown to provide on-farm economic benefits and off-farm environmental benefits. However, some of the beneficial outcomes of these practices take time to realize, especially those that depend on slowly changing attributes of cropping systems such as soil structure and organic matter, and those that need large initial investments or additional recurring costs over time (Robertson et al., 2008; Cusser et al., 2020). Moreover, continuous yearly adoption of these soil health practices is often critical for sustained accumulation of environmental benefits from the practice. For example, Sawadgo and Plastina (2022) suggest that discontinuing adoption of no-till for just one year (i.e., using conventional till in one year, after years of using no-till) can rapidly erase the carbon sequestration benefits accumulated from the continued no-till adoption in previous years. However, the literature is mixed on this matter with some studies indicating that non-continuous no-till does not reduce carbon sequestration benefits from the practice (Blanco-Canqui and Wortmann 2020).

No-till is a practice where the land is not tilled and crop residues are left on the land surface (Wade and Claassen 2017). It is primarily for the purpose of minimizing soil disturbance that is associated with conventional tillage. Previous literature has shown that no-till can provide large-scale environmental benefits by reducing soil erosion, preventing sediment runoff to water bodies, and conserving water and organic matter (Kladivko 2001; Bolliger et al., 2006; Busari et al., 2015). No-till can also contribute to soil carbon sequestration and help mitigate the adverse impacts of climate-change-induced weather events (Manley et al., 2005). To be specific, the use of no-till has been shown to mitigate

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* Corresponding author.
E-mail address: rmrejesu@ncsu.edu (R.M. Rejesus).

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the impact of drought on crop development and yields (Ding et al., 2009; Wallander et al., 2013; Chen et al., 2021).

Likely due to the perceived benefits from no-till, the adoption rate for this practice has continuously been rising in the United States (US) (Claassen et al., 2018). The most recent US Department of Agriculture (DA) survey estimates that no-till accounts for about 24.8% of the total cropland acres in 2012 and 26.4% in 2017. However, there was a decline in no-till adoption in soybean acres over the 2006–2012 period, while the growth of no-till uptake in corn acres was only relatively modest (Sawadgo and Plastina 2022). Although there are many possible reasons for the slower recent growth in no-till adoption for some crops, previous studies have indicated that "economic concerns" are one of the largest barriers to adopting sustainable agricultural practices like no-till (Kurkalova et al., 2006; Rodriguez et al., 2009; Wade and Claassen 2017). For example, past literature suggests that the effects of no-till on crop yields tend to be mixed (e.g., Pittelkow et al., 2015; Sindelar et al., 2015; Daigh et al., 2018; Deines et al., 2019). Even if no-till can generate positive yield effects in some cases, these benefits are typically not fully realized upon initial adoption of no-till (Deines et al., 2019). In addition, converting from conventional tillage to no-till involves both upfront investments in machinery (Krause and Black 1995), and usually increases in herbicide costs for controlling weeds (Cusser et al., 2020). Therefore, when only considering the economic impact of no-till in the first few years after initial adoption, it is likely that the no-till practice does not immediately result in positive net economic returns (i.e., private costs of adoption may outweigh the private benefits in the short-term) (Kurkalova et al., 2006; Rodriguez et al., 2009; Cusser et al., 2020).

Given the perceived ambiguity in the profitability of no-till (especially in the short-term), this paper considers the long-term scenario and addresses the question of whether and how mean net economic returns from continuous long-term adoption of no-till (in $/acre/year) compare to long-term net economic returns from conventional tillage. To achieve this objective, we utilize plot-level data from a long-term agronomic field experiment in Maryland (MD) with information on no-till use, crop yields, and different categories of input costs (i.e., seeds, farm operations, fertilizers, and chemicals). The data covers the period from 1996 to 2019. The plot-level data set allows us to estimate linear fixed-effect (FE) models to more precisely identify whether and how continuous no-till adoption affects crop yields and input costs. After identifying whether no-till influences yields or particular input cost categories, we utilize partial budgeting techniques to quantify the average change in the long-term profitability of continuous no-till adoption compared to conventional tillage.

Our study contributes to the literature on the economics of no-till since we are among the few who focus specifically on analyzing the long-term *economic* performance of no-till. The previous empirical literature on no-till has largely been limited to yield analysis, based on field experiments (Sindelar et al., 2015; Daigh et al., 2018), remotely-sensed data (Deines et al., 2019; Chen et al., 2021), or meta-analysis of data from previous studies (DeFelice et al., 2006; Rusinamhodzi et al., 2011; Ogle et al., 2012; Toliver et al., 2012; Pittelkow et al., 2015). The other set of literature on no-till economics is mostly on econometric analyses of factors affecting farmers' tillage decisions, including government payments, land tenure, farmer and farm characteristics (Rahm and Huffman 1984; Helms et al., 1987; Soule et al., 2000; Wu et al., 2004; Schoengold et al., 2015; Perry et al., 2016; Wade et al., 2016; Wade and Claassen 2017; Ogieriakhi and Woodward 2022). However, very few studies have focused on the economic assessment of long-term adoption of conservation practices (i.e., mainly due to lack of long-term economic data) (Prokopy et al., 2008). Only a few other observational studies have evaluated the long-term profitability of no-till. One such study is that of Cusser et al. (2020). Based on long-term agronomic experiments in Michigan, Cusser et al. (2020) find that the probability of having no-till profits greater than conventional till profits goes up, the longer one uses no-till (i.e., 20 to 30 plus years). Hence, although our analysis focuses on one field site in Maryland, we make a contribution by providing new insights as to the long-term economic impacts of no-till in the US Mid-Atlantic region (i.e., a location where most past analyses have not focused on).

In addition, we also contribute to the literature given that our data and methods allow us to exactly identify which input categories are statistically affected by no-till adoption, rather than only providing evidence on whether the overall net economic returns from long-term no-till adoption are greater than conventional tillage. In turn, inferences from these input-specific results provide more nuanced information about the sources of the relative profit differential between long-term no-till use and conventional tillage. Lastly, the panel (or longitudinal) nature of our data allows us to better account for time-invariant confounding factors that can lead to misleading estimates from the statistical analysis of the impact of no-till on cash crop yields and input costs. For example, having data for the same plots over time gives us the opportunity to control for unobserved plot-specific characteristics that are time-invariant (i.e., unobserved plot-specific soil quality) that can confound the estimated impacts of no-till.

The main findings from our empirical analysis are summarized as follows. First, there is no statistically significant yield increasing effect of no-till compared to conventional tillage when considering corn, soybean, and wheat together within experimental fields on silt loam soils in Maryland. The effect of no-till on wheat yield is statistically positive, though the effect is weak. Numerous studies have examined the yield effects of conservation tillage or no-till. Some literature finds that no-till reduces yield in aggregate (though the estimated magnitude of the negative yield effects varies across different crops) (Pittelkow et al., 2015). In contrast, other studies have found no-till produces no or positive yield impacts for corn and soybean (DeFelice et al., 2006; Rusinamhodzi et al., 2011; Toliver et al., 2012; Pittelkow et al., 2015; Sindelar et al., 2015; Daigh et al., 2018; Deines et al., 2019). Specifically, Deines et al. (2019) find long-term conservation tillage has a small positive yield effect for corn and soybean, and this effect is even smaller on fields that recently switched from conventional to conservation tillage. They also suggest that the yield effects are small and thus would be difficult to detect using field experiments with limited number of field replicates conducted in small research plots in level fields without field-scale equipment. But note that our study uses data from a field experiment with large plots, non-level fields (e.g., sloping), and use of field-scale equipment.

Second, we find that, for corn, soybean and wheat, continuous no-till adoption strongly decreases farm operation costs but increases chemical costs. Third, the overall net returns per acre are greater when implementing no-till in the long-term compared to conventional tillage (i.e., primarily due to the magnitudes of lower operating costs). In addition, when considering two separate periods of identical length over the 1996–2019 period, we find that the positive net change in income per acre is greater in the latter half period. This is consistent with the insights from Cusser et al. (2020) who argue that the probability of higher relative profit of no-till is greater when no-till is continuously adopted for a longer period.

The remainder of this paper proceeds as follows. First, we discuss the experimental field data that we analyze and present summary statistics. This is followed by a description of the empirical methods used in the study, which includes the linear FE model, a partial budgeting method, and sensitivity analysis. These procedures allow us to identify the potential effects of no-till on crop yields and input cost categories, and then evaluate the long-run economic impact of no-till. The results are discussed in the third section. Finally, we conclude with a brief summary and suggested future research directions.

2. Materials and methods

2.1. Data description

Our economic analysis was conducted using a dataset from a long-term field experiment conducted over the 1996–2019 period, the Farming Systems Project (FSP) at the Beltsville Agricultural Research Center in Beltsville, MD (39.0°N, 76.9°W). The main soil types at the site are Christiana (fine, kaolinitic, mesic Typic Hapludults), Matapeake (fine-silty, mixed, semiactive, mesic Typic Hapludults), Keyport (fine, mixed, semiactive, mesic Aquic Hapludults), and Mattapex (fine-silty, mixed, active, mesic Aquic Hapludults) silt loams. The thirty-year average annual precipitation is 1110 mm distributed evenly throughout the year. The annual average temperature is 12.8 °C (White et al., 2019).

The FSP was designed to evaluate sustainability of five cropping systems typical for the US Mid-Atlantic region. The FSP dataset used here contains two of these cropping systems — no-till and conventional tillage. The systems were designed in consultation with regional grain farmers, extension agents, specialists, research center farm managers, and researchers from the University of Maryland, University of Delaware, and Delaware State College, and a representative of the National Center of Appropriate Technology's Appropriate Transfer for Rural Areas agency (White et al., 2019). Management is guided by university recommendations and input from farmers and other agricultural professionals. The no-till and conventional tillage cropping systems are replicated four times in a randomized split-plot experimental design. Cropping systems are assigned to two main plots (e.g., the no-till main plot and the conventional till main plot). Each main plot is then split into three sub-plots (or split-plots) that coincide with the three crop rotation phases considered in the study. The crop rotation used in both the no-till and conventional till systems is essentially a corn/soybean/wheat rotation, with each crop in the rotation coinciding with each split-plot within the main plot.[1] All crops are grown every year. For further details, including discussion about some minor changes in crop rotations in 2000 (mainly due to weather), please see the studies of Cavigelli et al. (2008), Teasdale and Cavigelli (2017), and White et al. (2019).

Enterprise budgets for each crop (corn, soybean, and wheat) within a given tillage system were prepared for each year using data from field records of farm operations at the site, seeding rates, field operations, fertilizer application rates, chemical uses, and grain yield data. Actual purchase costs for input materials were used when records were available or were obtained from local agricultural suppliers. Field operation costs were tabulated using the Pennsylvania custom work charges published by the National Agricultural Statistics Service (NASS 2017), which is the basis for the costs of labor and machinery operation (fuel, lubrication, and repairs), as well as a portion of machinery ownership fixed costs. Other costs were calculated using crop farm input prices available from the NASS QuickStats database (NASS 2022). The costs of management and fixed costs associated with land and building ownership were assumed to be the same for all the systems and were not included in the analysis (White et al., 2019).

Table 1 presents the summary statistics for the crop yield and input cost categories, by tillage management system. On average, mean crop yields are very similar for both no-till and conventional till. However, mean corn and soybean yields are slightly higher under no-till. In addition, no-till management is associated with lower mean field operation costs and higher mean chemical costs for all three crops. Mean seed costs and fertilizer costs tend to be very similar in both tillage systems. Overall, total input costs (i.e., sum of the mean costs for all input categories) under no-till are much less than under conventional tillage.

2.2. Empirical methods

2.2.1. Linear fixed-effect model

To rigorously examine the effects of no-till adoption on crop yield and each of the four input cost categories in the data (i.e., seed costs, farm operation costs, fertilizer costs, and chemical costs), we utilize the following empirical specification:

$$y_{ijt} = \beta_0 + \beta_1 NT_{ijt} + \lambda t + \varphi_i + \eta_j + \varepsilon_{ijt} \tag{1}$$

where y_{ijt} denotes crop yields (bu/acre) or input costs ($/acre) in plot i for crop j at time t, NT_{ijt} is a dummy variable representing whether no-till is applied in plot i for crop j at time t, t is a linear time trend, φ_i are the plot fixed effects, η_j are the crop fixed effects, and ε_{ijt} is the idiosyncratic error term. The following are parameters to be estimated: β_0, β_1, and λ. In this study, β_1 is the main parameter of interest.[2]

Considering the panel nature of our dataset, we utilize a traditional linear panel fixed-effect (FE) model to estimate Eq. (1). The FE model allows us to address the time-invariant unobservables (i.e., the so-called unobservable heterogeneity across plots or crops). For example, the overall soil quality of each plot is considered roughly time-invariant in our plot-level context, and it may influence crop yields or input costs. This kind of time-invariant unobservable is absorbed by the plot-fixed-effects (φ_i) included in the specification and allows for better identification of the no-till impacts even though the no-till treatment is already explicitly randomized in the experimental design (i.e., further lowering potential endogeneity in the model). In addition, the crop-specific characteristics are also regarded as time-invariant, and these variables may also influence crop yield or input costs. These kinds of unobservables are absorbed by the crop-fixed-effects (η_j) included in the specification. In addition, the time trend helps control for unobserved time-varying factors affecting crop yields and input costs in all plots in the same way.

2.2.2. Partial budgeting method

After identifying the farm budget components that statistically significantly change revenue or cost as one applies no-till (i.e., increase or decrease revenue or costs), we then employ a long-term partial budgeting method to calculate the long-term expected changes in net returns per acre ($/acre) due to adoption of no-till (rather than conventional tillage). Partial budgets capture the net annual economic return associated with the use of no-till by identifying and monetizing the differences in crop yields and input costs between no-till and conventional till practices (Kay et al., 2016).

For each field plot, revenues and costs of production are compared between no-till and conventional tillage. The potential sources of profit-increasing values due to no-till use are increased revenue (or increased production) and decreased input costs. The potential sources of profit-

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[1] A simplified schematic of the main plot and split-plot design (for one replication) can be seen in Appendix Fig. A1. More specifically, the rotation used is a three-year corn/rye cover crop-soybean/wheat/soybean system. In particular, a rye cover crop is planted immediately after corn harvest before the full season soybean. In addition, the winter wheat plot is also double cropped with soybeans. Hence, there is a full season soybean and double cropped soybean each year. Due to a relatively small sample size, we analyze data from the full season soybeans and the double cropped soybeans together.

[2] The expression in equation (1) is our baseline specification. As suggested by a reviewer, we also conduct a robustness check by including weather variables in the specification (i.e., growing degree days (GDD), heat degree days (HDD), precipitation, precipitation squared), instead of using a linear time trend. Although a time trend likely accounts for the effects of weather on all plots (e.g., since all plots experience the same weather in our context, given that we are only studying one location), it would still be interesting to see how yields differ between no-till and conventional till systems when weather variables are explicitly accounted for. Note that the results from the "weather-variable-augmented" specification are still consistent with the results from our baseline model specification that uses a linear time trend. See Tables A19-21.

Table 1
Summary statistics of crop yields and input costs by tillage management.

		No-till					Conventional tillage				
Crop	Variable	Obs	Mean	Std. Dev.	Min	Max	Obs	Mean	Std. Dev.	Min	Max
Corn	Yield (bu/ac)	90	117.458	54.498	12.033	209.853	89	115.774	51.950	11.581	206.657
	Seed costs ($/ac)	90	64.730	27.080	29.170	115.500	89	66.127	26.074	29.170	115.500
	Field operation costs ($/ac)	90	155.443	46.281	70.903	244.547	89	212.263	59.767	102.738	329.350
	Fertilizer costs ($/ac)	90	102.741	42.239	16.699	209.700	89	103.524	40.979	48.389	209.700
	Chemical costs ($/ac)	90	83.411	33.159	13.318	133.560	89	58.125	29.878	5.900	106.058
Soybean	Yield (bu/ac)	102	47.060	17.670	4.309	73.071	102	43.410	15.911	8.500	74.571
	Seed costs ($/ac)	102	73.777	27.425	33.210	166.176	102	114.222	179.936	33.210	985.808
	Field operation costs ($/ac)	102	113.566	36.182	56.828	258.863	102	175.037	46.151	99.553	274.499
	Fertilizer costs ($/ac)	102	53.790	45.135	0.000	134.320	102	53.402	42.633	0.000	134.320
	Chemical costs ($/ac)	102	33.559	14.299	6.292	62.752	102	26.373	27.366	6.292	152.340
Wheat	Yield (bu/ac)	66	63.210	15.230	26.174	103.691	66	64.582	16.738	23.413	96.050
	Seed costs ($/ac)	66	81.293	36.562	13.771	172.750	66	76.298	27.728	10.951	118.750
	Field operation costs ($/ac)	66	210.123	40.551	85.966	286.275	66	232.980	55.385	114.108	386.145
	Fertilizer costs ($/ac)	66	59.498	54.549	0.000	227.000	66	58.192	53.635	0.000	227.000
	Chemical costs ($/ac)	66	35.750	10.833	16.025	66.957	66	31.541	11.543	7.335	50.707

decreasing values due to no-till use are decreased revenue (or decreased production) and increased input costs. Among four categories of input costs, seed costs depend on the planting density of the cash crops and seed prices. Farm operation costs mainly depend on the labor and machinery costs associated with the following operations: chisel plow, disk, planter, fertilizer application, and grain hauling. Fertilizer costs depend on applied fertilizer amounts for nitrogen (N), phosphorus (P), potassium (K), and the corresponding prices. Chemical costs depend on the amount of crop chemicals used, such as for herbicides and pesticides, and their prices.

2.2.3. Sensitivity analysis

To conduct sensitivity analysis, we first examine the potential change in crop yields and input costs due to no-till adoption, and then compute the partial budgets separately for corn, soybean, and wheat. In the main analysis we consider all crops together in the analysis. Separately constructing partial budgets for each crop allows us to identify whether there are differences in the economic impacts of no-till due specifically to different crop characteristics. Second, we divide the twenty-four-year period into two identical time intervals and compute the partial budget for both intervals.[3] This allows us to examine whether the economic impacts of no-till are different in earlier vis-à-vis the latter adoption period. Third, we compute the partial budget for each year and explore the yearly variations in the economic impacts of using no-till over time.

3. Results

3.1. Effects of no-till use on crop yield

Parameter estimates from the linear panel fixed effect regressions with all samples (and for all three crops) are presented in Table 2. Our results suggest that there are no statistically significant crop yield increasing effects of no-till compared to conventional tillage when including all three crops in the analysis (i.e., corn, soybean, and wheat). We also estimate the yield effects of no-till when considering corn, soybean, and wheat separately. The corresponding estimation results can be found in Appendix Tables A1–A9, respectively. Based on results from these Appendix Tables, there are also no statistically significant yield increasing effects due to no-till for corn and soybean in particular. This is consistent with an earlier analysis of corn and soybean yields at FSP from 1996 to 2014 (see Teasdale and Cavigelli, 2017), which showed no difference in grain yields between no-till and conventional tillage systems. That analysis also showed that year to year variation in corn and soybean yields were partly driven by annual weather variation, particularly precipitation and heat stress during late vegetative and early reproductive phases of crop growth (Teasdale and Cavigelli, 2017). This earlier study further justifies the robustness check below where we use weather variables as controls instead of using linear time trends (see discussion in the next paragraph). In addition, weather conditions a few weeks before and after planting only had a secondary impact on crop yields in that earlier study. On the other hand, based on our analysis, we find that no-till has a statistically significant increasing effect on wheat yields over the whole period and the latter half period, but the increasing effect is relatively weak (see Tables A7 and A9).

Table 2
The effects of no-till on yields and input costs: Linear FE (Corn, Soybeans, Wheat, 1996–2019).

Independent variables	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−6.357	7.303	−40.923***	−2.136	17.190**
	(10.277)	(23.960)	(0.396)	(12.826)	(6.714)
Trend	0.560**	4.470***	4.529***	3.090***	1.437***
	(0.237)	(0.553)	(0.137)	(0.304)	(0.155)
Plot FE	Yes	Yes	Yes	Yes	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes
Observations	515	515	515	459	515
R-squared	0.474	0.165	0.631	0.323	0.509

Notes: (i) Standard errors in parentheses; (ii) *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

As a robustness check, so as to account for the effects of weather on crop yields, we obtain data on four weather variables (i.e., growing degree days (GDD), heat degree days (HDD), precipitation, precipitation squared)[4] in Prince George's County, Maryland, where our experiment sites are located. The weather data are from the "Parameter-Elevation Regression on Independent Slopes Model" (PRISM). We then include the four aforementioned weather variables as additional controls in our specification to serve as a robustness check. In this specification with weather controls, we get similar results as our baseline model with just a time trend variable as control (see Appendix Tables A19–A21). To be

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[3] Note that the year 1999 is not included in our analysis. We have no data in 1999, since that year was such a dry year that no crops were harvested for grain.

[4] Roughly speaking, GDD refers to exposure to "good" growing temperatures between 10°C and 29°C, while HDD refers to exposure to damaging "extreme heat" temperatures above 29°C. All the weather variables are aggregated to coincide with the typical May to September growing season. These weather variables are typically used in the climate change econometrics literature that examine the effect of weather variables on crop yields. See Schlenker and Roberts (2009) and Ortiz-Bobea (2021) for more details.

specific, we again find that there is no statistically significant difference in crop yields between conventional tillage and no-till systems. In addition, the effects of weather on crop yields are very intuitive. In Tables A19-A21, moderate temperatures (i.e., higher GDD) increase crop yields and exposure to extreme heat (i.e., higher HDD) decreases crop yields. The parameters associated with the precipitation variables indicate a "U-shaped" behavior, i.e., crop yields increase as precipitation increases from zero, and after a threshold, higher levels of precipitation decrease crop yields.

3.2. *Effects of no-till use on input costs*

Fig. 1 visually shows that field operation costs with no-till are lower than those with conventional tillage, while chemical costs with no-till are slightly greater than conventional tillage in most years. For the first half of the study period (1996–2007), the average field operation costs are about \$165 per acre for conventional tillage, and about \$122 per acre for no-till. Compared to the 1996–2007 interval, the mean field operation costs are larger for the latter half of the study period (2008–2019) for both conventional tillage (\$231/acre) and no-till (\$175/acre). In contrast, the average chemical costs are about \$24 per acre for conventional tillage and about \$42 per acre for no-till in the 1996–2007 period. While in the 2008–2019 period, chemical costs are larger for both tillage types, i.e., chemical costs are about \$48/acre for conventional tillage and \$59/acre for no-till. Similar cost patterns are observed when considering each crop (e.g., corn, soybeans, and wheat) separately (see Fig. A2).

We also examine whether no-till adoption statistically significantly affects different categories of input costs (i.e., seeds, field operations, fertilizers, and chemicals) through linear FE models (Table 2). Looking across the parameter estimates in Table 2, we find that no-till adoption significantly decreases farm operation costs and increases chemical costs, while no-till does not have significant effects on seed costs and fertilizer costs. The results are similar when considering different time intervals (Tables 3 and 4) or different crops (Tables A1-A9) as well as including weather controls (Tables A19-A21). Note that no-till adoption has a statistically significant positive effect on seed costs for corn over the whole period and the latter half period of the data (Tables A1 and A3).

The effects of no-till on farm operation costs and chemical costs are very intuitive. To be specific, with no-till, farm operation costs for labor and custom hiring are typically less than conventional tillage (i.e., since no-till does not require operations to till land prior to planting) (Hobbs et al., 2008; Triplett and Dick, 2008; Al-Kaisi et al., 2015). Consequently, there is less wear and tear on equipment under no-till and also less depreciation. On the other hand, a common reason for increased chemical costs due to no-till is weed management. In no-till, weeds cannot be eradicated mechanically prior to planting (as is done in conventional till). Thus, the use of no-till can potentially increase weeds and changes weed composition, which in turn requires more herbicides for weed control (Deines et al., 2019; Cusser et al., 2020).

Table 3
The effects of no-till on yield and input costs: Linear FE (Corn, Soybeans, Wheat, 1996–2007).

Independent variables	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−15.734	4.296	−38.618***	0.043	21.554***
	(17.170)	(4.397)	(0.617)	(7.808)	(7.206)
Trend	−1.765**	2.676***	3.346***	4.187***	2.173***
	(0.831)	(0.213)	(0.503)	(0.377)	(0.349)
Plot FE	Yes	Yes	Yes	Yes	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes
Observations	227	227	227	179	227
R-squared	0.351	0.586	0.634	0.750	0.473

Notes: (i) Standard errors in parentheses; (ii) *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 4
The effects of no-till on yield and input costs: Linear FE (Corn, Soybeans, Wheat, 2008–2019).

Independent variables	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	3.334	8.278	−40.697***	1.210	16.212*
	(12.169)	(43.743)	(0.000)	(18.237)	(9.258)
Trend	0.890*	3.245*	3.162***	−3.159***	−0.706*
	(0.509)	(1.830)	(0.634)	(0.758)	(0.387)
Plot FE	Yes	Yes	Yes	Yes	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes
Observations	288	288	288	280	288
R-squared	0.626	0.106	0.549	0.266	0.622

Notes: (i) Standard errors in parentheses; (ii) *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

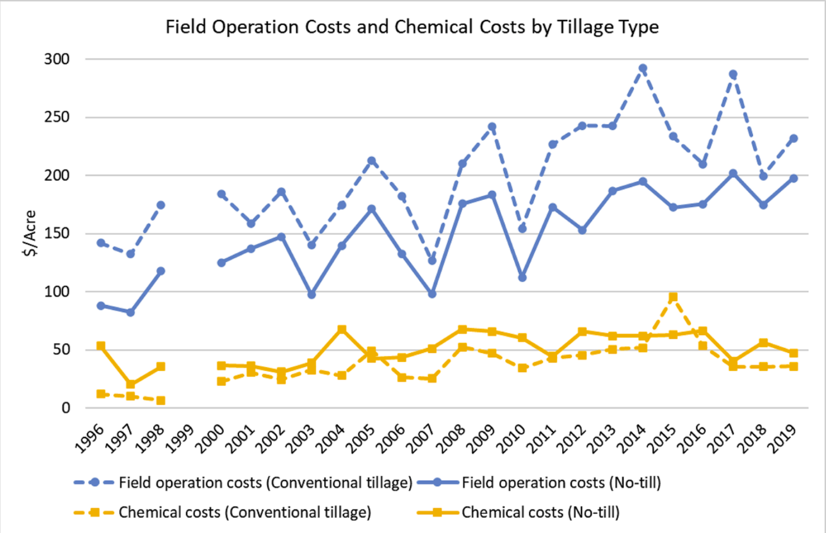

Fig. 1. Yearly field operation costs and chemical costs by tillage type for all three crops in the study (corn, soybeans, wheat).

3.3. No-till increases overall net returns in the long run

After estimating the effects of no-till on crop yields and input costs, we then use partial budgeting techniques to compute the change in net returns when considering no-till instead of conventional tillage. The partial budgeting calculations considering all three crops over the 1996–2019 period are presented in Table 5. We find that the overall net returns per acre are greater when implementing no-till compared to conventional tillage. To be specific, the main source of the positive profit-increasing change is the cost-decreasing effect due to reduced field operation costs of no-till, which we identified in the previous section. The profit-decreasing change is from the cost-increasing effect due to increased chemical costs associated with adopting no-till. Finally, the net change in income is calculated by taking the difference between the total profit increasing change and total profit decreasing change. The positive value of net change in income suggests that, on average, no-till adoption increased long-term net returns by $37.12 per acre (relative to conventional till).

In addition, when considering two identical separate periods over the study period (i.e., 1996–2007 and 2008–2019), we find that the positive net change in income per acre is greater in the latter period ($45.76/acre) than in the earlier period ($25.78/acre). See Tables 6 and 7. This is consistent with the insights from Cusser et al. (2020) that the probability of higher relative profits from no-till increases with longevity of use. We also calculate the yearly net return per acre for no-till compared to conventional tillage (for all crops) and present it in Fig. 2. Although there are great variations in the net returns year by year, we find a slightly increasing trend over the period spanned by the experiment. These findings suggest that the economic benefits tend to be larger when no-till is used continuously for an extended period of time.[5]

4. Summary and conclusions

Although there have been numerous previous studies that explored the effect of no-till on crop yields (DeFelice et al., 2006; Rusinamhodzi et al., 2011; Ogle et al., 2012; Toliver et al., 2012; Pittelkow et al., 2015; Sindelar et al., 2015; Daigh et al., 2018; Deines et al., 2019; Chen et al., 2021), only a handful of them have examined the *long-term* economic impacts of continuous no-till adoption (Cusser et al., 2020). Investigating how the net return from no-till use changes in the long term is important since no-till is considered one of the most promising soil health conservation practices that can provide on-field benefits as well as off-site environmental benefits. In this paper, we identify yield and input cost components of farm budgets that are strongly statistically influenced by long-term no-till adoption, and then quantify the long-term net return change from adopting no-till rather than conventional tillage management based on these statistically significant effects. Linear fixed-effect models and partial budgeting methods are used in the empirical analysis. Moreover, data from a long-term field experiment, spanning more than twenty years, are used to conduct the empirical analysis.

Table 5
Partial budget analysis (Corn, Soybeans, Wheat, 1996–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	49.93	Increased chemical cost ($/ac)	12.81
E. Total Profit Increasing ($/ac)	49.93	F. Total Profit Decreasing ($/ac)	12.81
		Net Change in Income in $/ac (E-F)	37.12

Table 6
Partial budget analysis (Corn, Soybeans, Wheat, 1996–2007).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	42.03	Increased chemical cost ($/ac)	16.25
E. Total Profit Increasing ($/ac)	42.03	F. Total Profit Decreasing ($/ac)	16.25
		Net Change in Income in $/ac (E-F)	25.78

Table 7
Partial budget analysis (Corn, Soybeans, Wheat, 2008–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	55.94	Increased chemical cost ($/ac)	10.18
E. Total Profit Increasing ($/ac)	55.94	F. Total Profit Decreasing ($/ac)	10.18
		Net Change in Income in $/ac (E-F)	45.76

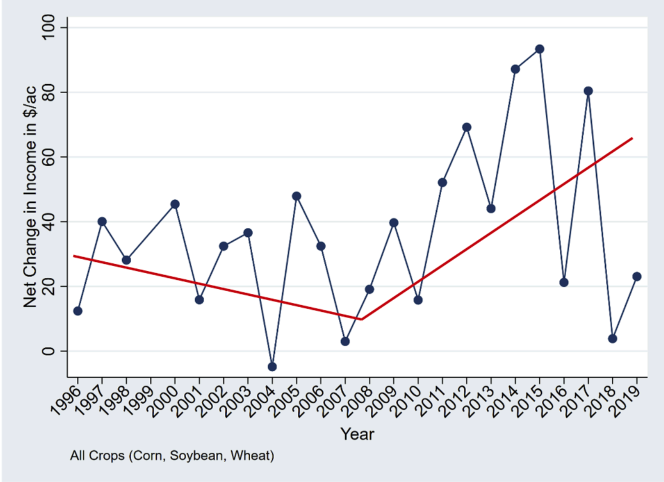

Fig. 2. Yearly net change in income per acre of no-till compared to conventional tillage for all three crops in the study (corn, soybeans, wheat).

Our results reveal that continuous no-till adoption generates positive economic benefits by reducing overall input costs. Moreover, the profitability of no-till increases as one continuously uses this practice over an extended period of time. Furthermore, because continuous no-till can be both economically and environmentally attractive, our results are consistent with recommendations to support long-term adoption of continuous no-till management despite the possibility that no-till will not have a statistically significant or will have a weak positive yield effect (especially in the short-term). This research provides insights that can help encourage no-till adoption (especially in the Mid-Atlantic States) by providing data-driven evidence of the positive long-term economic benefit of the practice for farmers and agricultural stakeholders. The study also has relevance to other agricultural practices where benefits are slowly and gradually realized over a longer period of time, but the adoption requires upfront (and recurring) costs to

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[5] We also conduct the same partial budgeting analysis for corn, soybean and wheat separately. The results also suggest that in general no-till use has a greater net return in income per acre compared to conventional tillage for each of the three crops. The detailed partial budgeting results are presented in the Appendix (see Tables A10 to A18 and Appendix Fig. A3).

implement.

While our research represents a step forward in understanding the long-term economic impacts of no-till adoption, it is important to acknowledge study limitations and issues that deserve future attention. First, even though our data set covers a longer time period than many studies, it is for only one location. Since the FSP is on-going, future economic analyses can reveal whether patterns identified here are still consistent as more data are added moving forward. Our analysis relies on randomized field trials that allow for direct assessment of the economic impacts of no-till, but in some cases, it may still have limited implications for real-world practices. For example, the economic impacts of no-till likely vary based on many factors; our results based on observations at one certain location may not generalize to areas with dissimilar soil types and agro-climatic conditions. The data set used is also from carefully designed research trials that are arguably managed differently as compared to actual on-farm conditions. To have better external validity, it is important to assess the economic impacts of continuous no-till adoption using data from a wider variety of locations and a longer time period; and perhaps using actual farmer data. This will allow for a better evaluation of whether there is regional heterogeneity in the economic impacts of no-till use, and whether there are any changes in the most recent years due to climate change. Second, the partial budgeting calculations in our study only compare the difference in net economic returns between conventional tillage and no-till. It will be more insightful if one can conduct in-depth studies that show whether continuous no-till adoption also translates to greater benefits for water quality or carbon sequestration (not just economic dollar outcomes). We leave all these suggested research directions for future work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

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Appendix

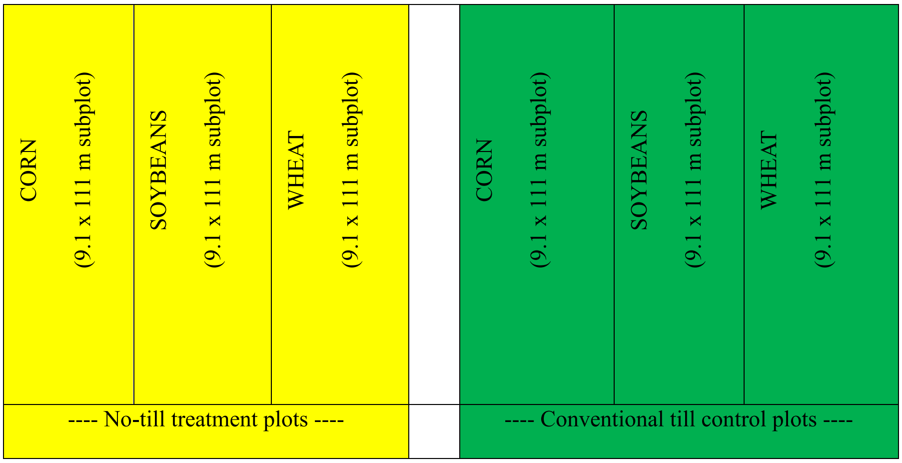
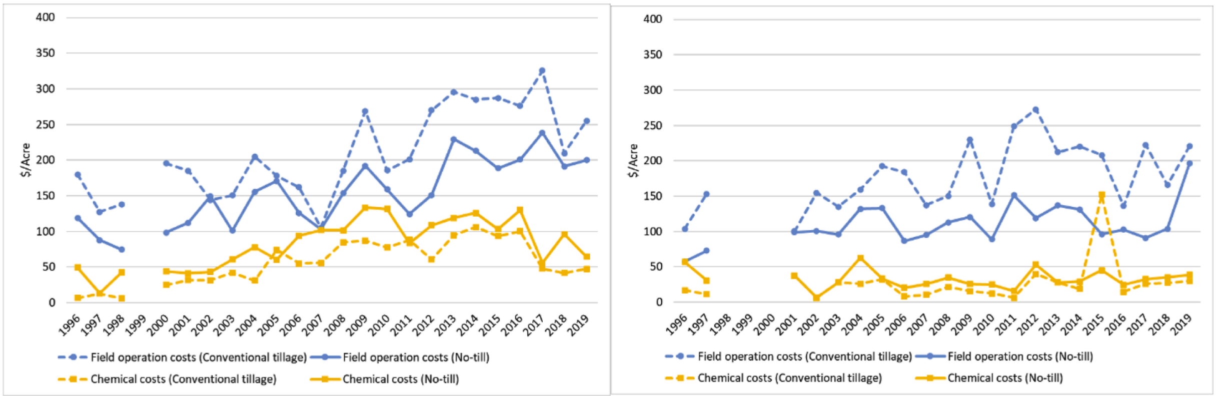
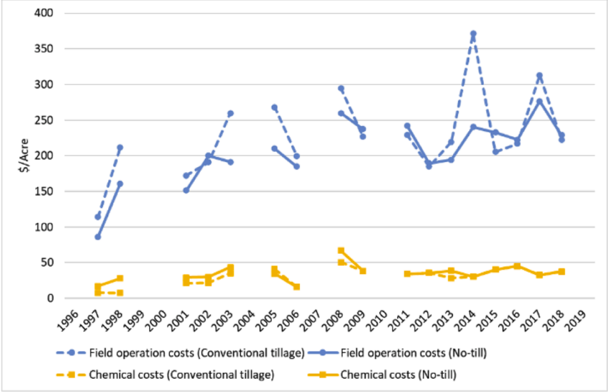


Fig. A1. Simplified Schematic of the Experimental Design.
Note: The design above is randomly replicated four times in the field trial.



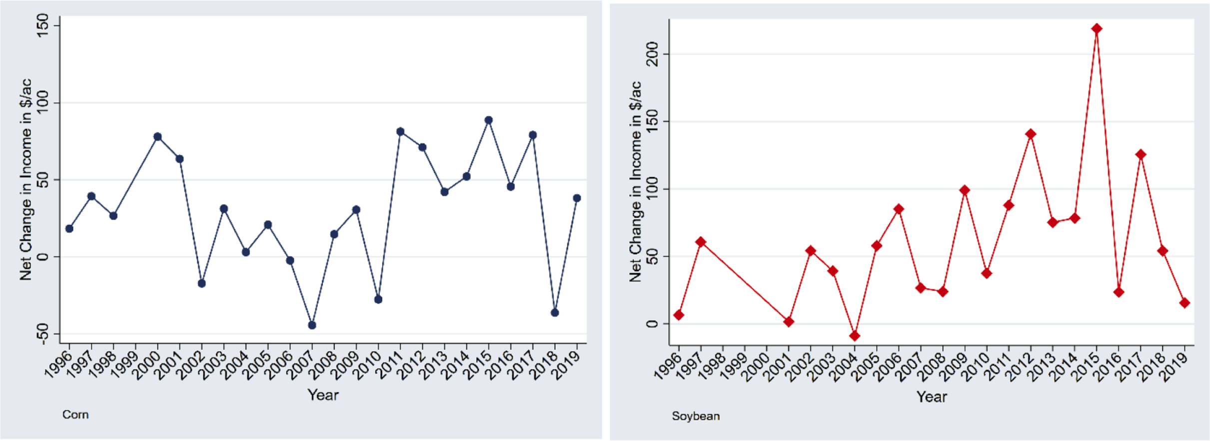
(a) Corn

(b) Soybean

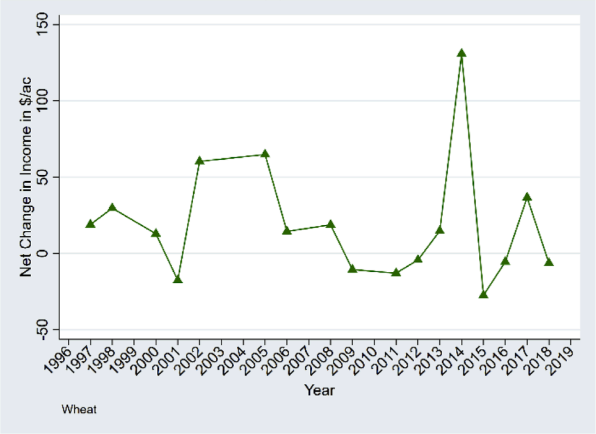


(c) Wheat

Fig. A2. Field operation costs and chemical costs by crop.



(a) Corn (b) Soybean



(c) Wheat

Fig. A3. Net change in income per acre of no-till compared to conventional tillage by crop.

Table A1
The effects of no-till on yield and input costs (Corn, 1996–2019).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−17.249	14.958*	−61.392***	−6.692	29.693**
	(27.501)	(8.132)	(18.749)	(19.563)	(12.797)
Trend	1.769***	3.264***	5.954***	2.960***	2.936***
	(0.626)	(0.185)	(0.427)	(0.445)	(0.291)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	179	179	179	179	179
R-squared	0.093	0.682	0.674	0.248	0.519

Notes: (i) Standard errors in parentheses;.
*** (ii) $p<0.01$,.
** $p<0.05$,.
* $p<0.1$.

Table A2
The effects of no-till on yield and input costs (Corn, 1996–2007).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−46.225	−0.127	−64.283***	8.257	38.416***
	(49.078)	(6.997)	(22.092)	(10.998)	(8.020)
Trend	−4.053*	1.541***	0.127	5.510***	5.832***
	(2.350)	(0.335)	(1.058)	(0.527)	(0.384)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	83	83	83	83	83
R-squared	0.083	0.343	0.535	0.672	0.868

Notes: (i) Standard errors in parentheses; (ii) ***$p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A3
The effects of no-till on yield and input costs (Corn, 2008–2019).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−4.182	22.919**	−74.678***	−18.798	27.125*
	(33.318)	(11.093)	(28.179)	(25.406)	(14.764)
Trend	4.724***	1.109**	5.593***	−6.915***	−3.801***
	(1.432)	(0.477)	(1.212)	(1.092)	(0.635)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	96	96	96	96	96
R-squared	0.193	0.356	0.567	0.379	0.552

Notes: (i) Standard errors in parentheses;.
*** (ii) $p<0.01$,.
** $p<0.05$,.
* $p<0.1$.

Table A4
The effects of no-till on yield and input costs (Soybean, 1996–2019).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−4.449	−7.116	−70.004***	−16.735	16.910
	(7.986)	(62.439)	(17.927)	(20.922)	(11.248)
Trend	0.231	5.789***	3.597***	2.754***	0.295
	(0.184)	(1.438)	(0.413)	(0.519)	(0.259)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	204	204	204	156	204
R-squared	0.210	0.187	0.574	0.302	0.085

Notes: (i) Standard errors in parentheses; (ii) *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A5
The effects of no-till on yield and input costs (Soybean, 1996–2007).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−6.394	11.475	−45.200**	4.882	20.864*
	(14.256)	(7.236)	(18.632)	(21.164)	(10.984)
Trend	−2.094***	3.353***	4.179***	7.669***	−1.224**
	(0.745)	(0.378)	(0.974)	(1.115)	(0.574)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	92	92	92	52	92
R-squared	0.187	0.657	0.580	0.662	0.312

Notes: (i) Standard errors in parentheses;.
*** (ii) $p<0.01$,.
** $p<0.05$,.
* $p<0.1$.

Table A6
The effects of no-till on yield and input costs (Soybean, 2008–2019).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−1.559	−18.380	−95.007***	3.539	11.950
	(8.526)	(119.706)	(30.673)	(25.215)	(19.107)
Trend	0.630*	3.039	3.479***	−1.937**	1.367*
	(0.320)	(4.488)	(1.150)	(0.945)	(0.716)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	112	112	112	104	112
R-squared	0.473	0.223	0.542	0.304	0.154

Notes: (i) Standard errors in parentheses;.
*** (ii) $p<0.01$,.
** $p<0.05$,.
* $p<0.1$.

Table A7
The effects of no-till on yield and input costs (Wheat, 1996–2019).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	14.884*	8.670	30.293	12.819	11.374*
	(7.956)	(11.155)	(19.157)	(30.692)	(5.786)
Trend	−0.732***	3.965***	3.861***	3.484***	0.769***
	(0.193)	(0.271)	(0.465)	(0.736)	(0.141)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	132	132	132	124	132
R-squared	0.344	0.688	0.608	0.228	0.315

Notes: (i) Standard errors in parentheses; (ii)*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A8
The effects of no-till on yield and input costs (Wheat, 1996–2007).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	2.624	−7.720	−8.234	−2.873	22.761**
	(12.154)	(7.346)	(32.964)	(6.989)	(9.221)
Trend	1.646**	3.479***	6.944***	0.448	0.686
	(0.641)	(0.387)	(1.738)	(0.297)	(0.486)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	52	52	52	44	52
R-squared	0.414	0.799	0.626	0.594	0.554

Notes: (i) Standard errors in parentheses; (ii) *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A9
The effects of no-till on yield and input costs (Wheat, 2008–2019).

VARIABLES	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	16.475*	19.735	48.575**	13.846	1.920
	(9.219)	(18.061)	(22.503)	(47.903)	(6.360)
Trend	−2.730***	4.410***	2.344**	0.371	−1.104***
	(0.474)	(0.928)	(1.156)	(2.461)	(0.327)
Plot FE	Yes	Yes	Yes	Yes	Yes
Observations	80	80	80	80	80
R-squared	0.614	0.395	0.648	0.052	0.211

Notes: (i) Standard errors in parentheses;.
[***] (ii) $p<0.01$,.
[**] $p<0.05$,.
[*] $p<0.1$.

Table A10
Partial budget analysis (Corn, 1996–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	56.82	Increased chemical cost ($/ac)	25.29
		Increased seed cost ($/ac)	−1.40
E. Total Profit Increasing ($/ac)	56.82	F. Total Profit Decreasing ($/ac)	23.89
		Net Change in Income in $/ac (E-F)	27.87

Table A11
Partial budget analysis (Corn, 1996–2007).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	44.07	Increased chemical cost ($/ac)	23.88
E. Total Profit Increasing ($/ac)	44.07	F. Total Profit Decreasing ($/ac)	23.88
		Net Change in Income in $/ac (E-F)	20.19

Table A12
Partial budget analysis (Corn, 2008–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	66.96	Increased chemical cost ($/ac)	26.99
		Increased seed cost ($/ac)	0.47
E. Total Profit Increasing ($/ac)	66.96	F. Total Profit Decreasing ($/ac)	27.46
		Net Change in Income in $/ac (E-F)	39.50

Table A13
Partial budget analysis (Soybean, 1996–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	61.47		
E. Total Profit Increasing ($/ac)	61.47	F. Total Profit Decreasing ($/ac)	0.00
		Net Change in Income in $/ac (E-F)	61.47

Table A14
Partial budget analysis (Soybean, 1996–2007).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	45.00	Increased chemical cost ($/ac)	14.54
E. Total Profit Increasing ($/ac)	45.00	F. Total Profit Decreasing ($/ac)	14.54
		Net Change in Income in $/ac (E-F)	30.46

Table A15
Partial budget analysis (Soybean, 2008–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	75.00		
E. Total Profit Increasing ($/ac)	75.00	F. Total Profit Decreasing ($/ac)	0.00
		Net Change in Income in $/ac (E-F)	75.00

Table A16
Partial budget analysis (Wheat, 1996–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
Increased revenue due to yield increase ($/ac)	39.54		
B. Cost Decreasing		D. Cost Increasing	
		Increased chemical cost ($/ac)	4.21
E. Total Profit Increasing ($/ac)	39.54	F. Total Profit Decreasing ($/ac)	4.21
		Net Change in Income in $/ac (E-F)	35.33

Table A17
Partial budget analysis (Wheat, 1996–2007).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
B. Cost Decreasing		D. Cost Increasing	
		Increased chemical cost ($/ac)	6.60
E. Total Profit Increasing ($/ac)	0.00	F. Total Profit Decreasing ($/ac)	6.60
		Net Change in Income in $/ac (E-F)	−6.60

Table A18
Partial budget analysis (Wheat, 2008–2019).

Profit Increasing		Profit Decreasing	
A. Revenue Increasing		C. Revenue Decreasing	
Increased revenue due to yield increase ($/ac)	68.19		
B. Cost Decreasing		D. Cost Increasing	
Reduced field operation cost ($/ac)	16.03		
E. Total Profit Increasing ($/ac)	85.22	F. Total Profit Decreasing ($/ac)	0.00
		Net Change in Income in $/ac (E-F)	85.22

Table A19
The effects of no-till on yields and input costs: Linear FE (Corn, Soybeans, Wheat, 1996–2019).

Independent variables	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−5.867	7.082	−39.939***	−0.744	17.590**
	(8.556)	(25.069)	(0.559)	(13.711)	(6.937)
GDD	0.057***	0.157***	0.278***	0.116***	0.078***
	(0.016)	(0.047)	(0.012)	(0.025)	(0.013)
HDD	−0.862***	−0.180	−1.363***	−0.071	−0.230***
	(0.106)	(0.311)	(0.144)	(0.165)	(0.086)
Precipitation	544.107***	435.482*	236.784*	510.851***	207.574***
	(79.468)	(232.826)	(129.506)	(128.179)	(64.423)
Precipitation^2	−448.456***	−369.786**	−245.406**	−420.976***	−159.985***
	(60.823)	(178.199)	(93.447)	(100.459)	(49.308)
Plot FE	Yes	Yes	Yes	Yes	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes
Observations	515	515	515	459	515
R-squared	0.637	0.092	0.563	0.233	0.479

Notes: (i) Standard errors in parentheses;.
*** (ii) $p<0.01$,.
** $p<0.05$,.
* $p<0.1$.

Table A20
The effects of no-till on yield and input costs: Linear FE (Corn, Soybeans, Wheat, 1996–2007).

Independent variables	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	−12.231	3.453	−35.973***	−7.807	22.219***
	(14.113)	(5.377)	(0.830)	(10.219)	(7.540)
GDD	0.059*	0.031***	0.159***	0.012	0.062***
	(0.030)	(0.011)	(0.024)	(0.020)	(0.016)
HDD	−0.561***	0.165**	0.249**	0.178	−0.145
	(0.204)	(0.078)	(0.102)	(0.137)	(0.109)
Precipitation	637.640***	22.798	525.261***	−153.579	15.385
	(143.748)	(54.770)	(80.078)	(107.842)	(76.802)
Precipitation^2	−477.539***	−16.862	−364.070***	125.677	0.896
	(108.329)	(41.275)	(60.343)	(86.883)	(57.878)
Plot FE	Yes	Yes	Yes	Yes	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes
Observations	227	227	227	179	227
R-squared	0.569	0.392	0.707	0.582	0.433

Notes: (i) Standard errors in parentheses;.
*** (ii) $p<0.01$,.
** $p<0.05$,.
* $p<0.1$.

Table A21
The effects of no-till on yield and input costs: Linear FE (Corn, Soybeans, Wheat, 2008–2019).

Independent variables	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
NT	3.334	8.278	−40.697***	−0.445	16.212*
	(9.733)	(43.901)	(0.000)	(18.167)	(9.226)
GDD	−0.017	−0.172	0.115***	−0.085	−0.010
	(0.028)	(0.128)	(0.018)	(0.052)	(0.027)
HDD	−0.754***	0.655	−1.601***	0.343	−0.014

(*continued on next page*)

Table A21 (*continued*)

Independent variables	(1) Yield	(2) Seed costs	(3) Field operation costs	(4) Fertilizer costs	(5) Chemical costs
	(0.135)	(0.610)	(0.151)	(0.250)	(0.128)
Precipitation	319.129***	−3.046	−158.471	477.237**	186.369*
	(101.205)	(456.491)	(171.421)	(185.875)	(95.930)
Precipitation^2	−290.342***	−39.313	30.432	−400.054***	−148.325**
	(78.559)	(354.345)	(117.766)	(144.518)	(74.464)
Plot FE	Yes	Yes	Yes	Yes	Yes
Crop FE	Yes	Yes	Yes	Yes	Yes
Observations	288	288	288	280	288
R-squared	0.763	0.110	0.632	0.280	0.629

Notes: (i) Standard errors in parentheses;.

*** (ii) $p<0.01$,.

** $p<0.05$,.

* $p<0.1$.

Table 18,Table 19,Table 20,Table 21

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