Received: 9 October 2019 | Revised: 13 February 2020 | Accepted: 8 March 2020

DOI: 10.1111/gcb.15080

PRIMARY RESEARCH ARTICLE

Global Change Biology WILEY

Long-term research avoids spurious and misleading trends in sustainability attributes of no-till

Sarah Cusser[1,2] | Christie Bahlai[1,3] | Scott M. Swinton[4] | G. Philip Robertson[1,5] | Nick M. Haddad[1,2]

[1]W.K. Kellogg Biological Station, Department of Integrative Biology, Michigan State University, Hickory Corners, MI, USA

[2]Department of Integrative Biology, Michigan State University, East Lansing, MI, USA

[3]Department of Biological Science, Kent State University, Kent, OH, USA

[4]Department of Agricultural, Food, and Resource Economics, Michigan State University, East Lansing, MI, USA

[5]Department of Plant, Soil, and Microbial Sciences, Michigan State University, East Lansing, MI, USA

Correspondence
Sarah Cusser, W.K. Kellogg Biological Station, Department of Integrative Biology, Michigan State University, 3700 East Gull Lake Dr., Hickory Corners, MI 49060, USA.
Email: sarah.cusser@gmail.com

Funding information
AgBioResearch, Michigan State University; National Science Foundation, Grant/Award Number: DEB 1832042 and OAC 1838807; National Institute of Food and Agriculture

Abstract

Agricultural management recommendations based on short-term studies can produce findings inconsistent with long-term reality. Here, we test the long-term environmental sustainability and profitability of continuous no-till agriculture on yield, soil water availability, and N_2O fluxes. Using a moving window approach, we investigate the development and stability of several attributes of continuous no-till as compared to conventional till agriculture over a 29-year period at a site in the upper Midwest, US. Over a decade is needed to detect the consistent effects of no-till. Both crop yield and soil water availability required 15 years or longer to generate patterns consistent with 29-year trends. Only marginal trends for N_2O fluxes appeared in this period. Relative profitability analysis suggests that after initial implementation, 86% of periods between 10 and 29 years recuperated the initial expense of no-till implementation, with the probability of higher relative profit increasing with longevity. Importantly, statistically significant but misleading short-term trends appeared in more than 20% of the periods examined. Results underscore the importance of decadal and longer studies for revealing consistent dynamics and emergent outcomes of no-till agriculture, shown to be beneficial in the long term.

KEYWORDS

long-term research, LTER, moving window, N_2O fluxes, power analysis, profitability of no-till adoption, soil moisture, soil water availability, sustainable intensification, yield

1 | INTRODUCTION

Agricultural decisions must promote sustainable benefits in the long term. Considerable investment in agricultural research and development informs these important land management decisions. The United States alone invested $2.9 billion in 2020 for public and private agricultural research (USDA, 2020) to promote innovative advances for many aspects of cropping system management (NRC, 2003; Robertson et al., 2008; Spiegal et al., 2018), including crop fertility, pest protection, seed genetics, water management, soil health, and aspects of sustainability (Delonge, Miles, & Carlisle, 2016), among others. However, the outcomes of many management changes can be slow to develop and detect, especially those that depend on slow-to-change attributes of cropping systems such as soil structure and organic matter. This adds to uncertainty regarding the long-term sustainability of management decisions (Robertson et al., 2008), raising the potential for misinterpretation of short-term studies.

Tillage is a well-researched management strategy that is a case in point. Tillage mechanically incorporates crop residues and/or amendments into soils, controls weeds, promotes soil warming and drying, and thereby prepares soil for planting, creating optimal conditions for crop seed germination and emergence (Reicosky, Kemper, Langdale, Douglas, & Rasmussen, 1995). However, the environmental costs of regular tillage are great, including decreased soil carbon, increased potentials for soil erosion, and poor soil structure (Lal, Reicosky, & Hanson, 2007). Following the 1930's Dust Bowl, US agronomists and soil scientists became increasingly concerned about the long-term environmental sustainability of tillage-based agriculture (Derpsch, Friedrich, Kassam, & Li, 2010). With the advent of modern herbicides in the 1960s, along with glyphosate-resistant crops in the 1990s, no-till, whereby crop residues are left on the surface following harvest, has become gradually more popular. No-till can often increase soil carbon, quality, and function, and reduce CO_2 emissions when compared to conventional tilling practices (Bolliger et al., 2006; Karlen et al., 1994; Kladivko, 2001).

In the last few decades, the adoption of no-till continues to rise (Claassen, Bowman, McFadden, Smith, & Wallander, 2018). The most recent USDA survey estimates that no-till and strip till account for 45% of total US acreage in wheat (2017), 40% in soybeans (2012), 18% in cotton (2015), and 27% in corn (2016; Claassen et al., 2018). A global meta-analysis of no-till productivity across a range of climates, soils, and crop types found that no-till management consistently out-performed conventional tillage for rainfed crops in dry climates (Pittelkow et al., 2015). However, in more mesic climates, or under irrigated conditions, differences were more variable. Some of the variation uncovered by this meta-analysis is likely due to the short duration of many of the studies—only 60 of the 520 studies lasted 10 years or longer.

Short-term research experiments are important for identifying ecosystem-related changes to land management in a timely and cost-efficient manner. In fact, for a variety of reasons, including the short duration of most research funding, human or business constraints, and a need for actionable solutions, agricultural research is often performed on short time scales. Yet, research conducted at these constrained time scales has the potential to be misleading. Short-term research can be insufficient especially for evaluating ecosystem properties and phenomena that change slowly, such as soil structure and soil carbon, or require proper evaluation over an appropriately variable climate and management history (Paustian et al., 1997; Rasmussen et al., 1998; Robertson et al., 2008).

Beyond the variable findings that confound the relative environmental benefits of no-till, economic concerns have also slowed the adoption of more sustainable practices (Wade & Claassen, 2017). Surveys note that when asked, farmers responded that compared to other factors (e.g., lack of education and/or information, resistance to change, social considerations, infrastructure, or landlessness), economic concerns are the largest barrier to adopting sustainable agricultural practices such as no-till management (Rodriguez, Molnar, Fazio, Sydnor, & Lowe, 2009). Converting a field to no-till, for example, involves both the upfront expenses of investment in novel machinery (Krause & Black, 1995) and the increased herbicide cost of controlling weeds, which can exceed the short-term savings associated with reduced tillage. Thus, farmers may choose to avoid no-till as a result of both the uncertainty surrounding benefits and short-term economic costs.

Many of the attributes and perhaps functional benefits of no-till management may take decades to consistently affect yields, profits, and environmental outcomes beg three questions: (1) How long does continuous no-till need to be implemented (or studied) until economic and ecological impacts are consistently detectable? (2) How many years of continuous no-till management are needed to recoup the upfront expenses of converting conventionally tilled fields to continuous no-till management? (3) How consistent are changes in economic and environmental attributes over long periods? We apply power analysis to a 29-year experimental dataset for a long-term research site in the upper Midwest, US to (1) determine the number of years required for consistent differences in crop yield, soil water availability, and N_2O fluxes to be detectable, (2) determine the number of years before continuous no-till consistently recovers initial management costs, and (3) investigate the consistency of trends over time. To address questions 2 and 3, we use a moving window approach. To further address question 2, we also use a partial budgeting analysis of relative profitability.

2 | METHODS

2.1 | Study site and treatments

We explicitly test the economic and ecological effects of no-till in the Main Cropping System Experiment (MCSE) of the Kellogg Biological Station Long-Term Ecological Research site (LTER) located in southwest Michigan (42°24′N, 85°24′W) in the northeastern portion of the US Corn Belt. The mean annual air temperature at KBS is 10.1°C, ranging from a monthly mean of −9.4°C in January to 28.9°C in July. Rainfall averages 1,027 mm/year, evenly distributed seasonally; potential evapotranspiration exceeds precipitation for about 4 months of the year. Loam soils are well-drained Typic Hapludalfs developed on glacial outwash with soil carbon contents around 1% C (Syswerda, Corbin, Mokma, Kravchenko, & Robertson, 2011). More site-specific details are available in Robertson and Hamilton (2015).

Within our experiment, we compare conventional tillage and continuous no-till management systems. These are two of seven treatments that are part of the MCSE that was established in 1989 and includes four annual and three perennial cropping systems. Each cropping system is replicated as 1 ha plots in six blocks and is intended to represent a model ecosystem relevant to agricultural landscapes of the region (Gage, Doll, & Safir, 2015). The four annual cropping systems are arranged along a gradient of decreasing chemical and management inputs in such a way that differences along the management intensity gradient can be understood, predicted, simulated (Basso & Ritchie, 2015), and extended to row-crop ecosystems in general. The two annual cropping systems are managed as corn (*Zea mays* L.), soybean (*Gylcine max* L.), and wheat (*Triticum aestivum* L.) rotations such that a single crop is grown each year. Conventional tillage represents a management system practiced by many farmers in the region: standard varieties planted with conventional tillage and with chemical inputs at rates recommended by university and industry consultants. Conventional tillage consisted of moldboard plowing in the spring from 1989 to 1998, and chisel plowing in the spring from 1999 to present. Additional tillage consisted of disking before winter wheat planting. No-till management is identical to the conventional system except for tillage and herbicide applications. A no-till planter was used to drill seed directly into untilled soil through existing crop residue without primary or secondary tillage. When prescribed, additional herbicide is used to control weeds that would otherwise be suppressed by tillage. The system has been managed without tillage since its establishment in 1989 (Figure 1). Other than tillage and herbicide inputs, both treatments are managed identically as described in Robertson and Hamilton (2015).

Site history prior to 1989 consisted of mixed agricultural and horticultural cropping for 100+ years, with the most recent years prior to experiment establishment dominated by conventionally managed continuous corn production. In 2009, soybean varieties were changed from conventional to transgenic (glyphosate resistant) and in 2011 corn varieties were changed from conventional to transgenic (glyphosate, European corn borer, and root worm resistant), consequently reducing the expense of post-planting agrichemical management. Detailed descriptions of the other treatments not used in this study, management protocols, and site history are provided in Robertson and Hamilton (2015).

2.2 | Time needed to detect effects of management change

To test the time required to detect the effects of conversion from conventional tillage to continuous no-till (Question 1), we examined

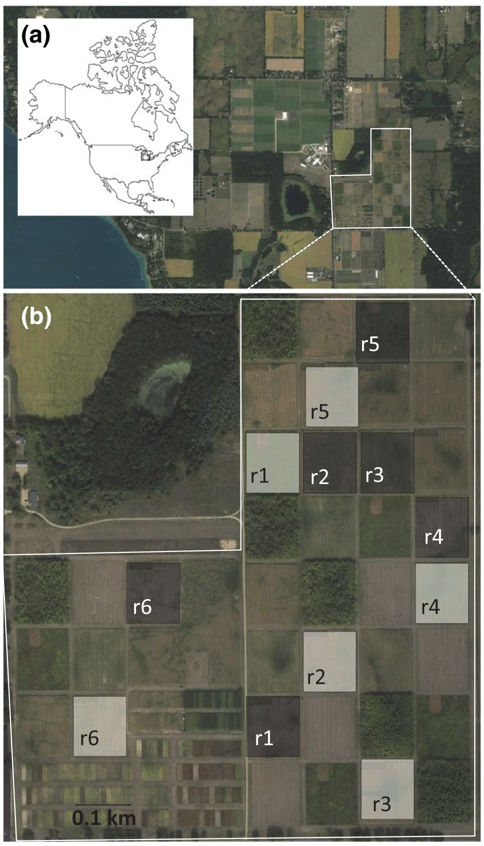

FIGURE 1 Location of study site. (a) Inset of North America with outline of study region. Satellite image of the Kellogg Biological Station Long-Term Ecological Research in Hickory Corners, Michigan, U.S.; (b) enlarged image of Main Cropping System Experiment (MSCE). White squares show conventionally managed 1-ha blocks (*N* = 6) and black squares show no-till managed 1-ha blocks (*N* = 6). Blocks were established in 1988

both environmental responses and relative profitability in conventional and no-till treatments over a 29-year period from 1989 to 2017. Wheat, soybean, and corn were typically harvested in June, October, and November, respectively, although some deviations occurred due to weather and crop maturity. Grain from each block replicate (*N* = 6) was dried at 60°C for at least 48 hr, weighed, and reported as Mg/ha at standard moisture.

We also assessed the effect of tillage on soil water availability and N_2O gas fluxes, our environmental response variables. Soil water availability affects microbial activity, carbon and nutrient availability and movement, and plant growth (Lal, 2004). Soil water availability was determined gravimetrically by drying 40 g of fresh soil from each replicate (*N* = 6) at 60°C for 48 hr. Samples were collected each month when soil was not frozen (typically April–November) at each of five sampling stations per block using sampling (push) probes (2 cm dia., 25 cm depth) or by bucket auger (5 cm dia., 25 cm depth) when the soil is too dry to use push probes. After drying, samples were reweighed, and gravimetric soil water availability was calculated as the difference between fresh and dry weight, expressed as dry weight (g H_2O/g dry soil; www.lter.kbs.msu.edu). Soil water availability was then averaged across subsamples to produce a single value, per block, per year, per treatment to use in analysis.

Nitrous oxide (N_2O) is an ozone-depleting greenhouse gas (Ravishankara, Daniel, & Portmann, 2009) and agricultural soil management is the largest anthropogenic source of N_2O emissions globally (Paustian et al., 2016). N_2O gas measurements were made using static chambers (Livingston & Hutchinson, 1995) at weekly to monthly intervals when soils were not frozen between 1991 and 2017 (Gelfand, Shcherbak, Millar, Kravchenko, & Robertson, 2016). In situ static (closed-cover) flux chambers were 28 cm dia. × 26 cm high and consisted of a cylindrical metal base and an airtight plastic lid. Single chambers were located in four of the six blocks of each tillage treatment; thus, models are formed from the average of weekly to monthly measurements in four replicates per year, rather than six, as in the cases of yield and soil water availability. Chamber lids were placed on semi-permanent aluminum bases removed only for cropping activities and accumulated headspace was sampled four times over 120 min. All chambers were sampled on the same dates, although no data are available for 1995. Samples were stored in 3 ml crimp-top vials and analyzed in the laboratory for N_2O, with the flux for each chamber calculated as the linear portion of the gas accumulation curve for that chamber. Nitrous oxide was analyzed by gas chromatography using a 63Ni electron capture detector. More details appear in Gelfand et al. (2016).

To test for tillage-related changes in crop yield, soil water availability, and N_2O fluxes over our 29-year period, we fit linear mixed effects models to the data using crop (corn, soybean, and wheat) and block (1–6 for crop yield and soil water availability, 1–4 for N_2O fluxes) as fixed variables, year as a random variable, and difference in crop yield, soil water availability, and N_2O fluxes as response variables with the "lmer4" package in R (Bates, Maechler, Bolker, & Walker, 2015). We then executed a power analysis for our linear mixed effects models through simulation with a traditional α value of 0.05, 1,000 simulations, and power of 0.8, using the "simr" package in R (Green & MacLeod, 2016). We also executed a second power analysis at a more liberal α value for comparison (α = 0.2, a lower, less confident level of significance). This value may better represent realistic expectations of farmers, who may accept losses as frequently as 1 in 5 years, or 20% of the time.

2.3 | Recuperating implementation and maintenance expenses

To answer our second question, comparing the expenses of implementation and management of the two tillage systems, we used a partial budgeting relative profitability analysis combined with a moving window approach. We determined the relative profitability impacts of no-till management as the difference in annual gross margins between conventional till and no-till treatments (Cimmyt & Cimmyt, 1988). Gross margins were calculated as annual crop grain yield multiplied by current year crop price ($/kg) minus costs that varied between the two treatments. We subdivided the gross margins by tracking differences in crop revenues and expenses between the treatments. For revenues, we determined differences in yield as described in Section 2.1 and crop prices as the US monthly average price received for corn, soybean, and wheat at the time of harvest (December, November, and June, respectively; FarmDoc, 2019; Table S1).

We determined the relative expenses of no-till management as the combined difference in expense of input and custom work rates between the two treatments. We determined input expenses only for those chemical inputs that differed in application between the two treatments as described in the KBS "Expanded Agronomic Log" (www.lter.kbs.msu.edu). All differences were first converted to fluid oz/ha or kg/ha and then, using historic prices (USDA, 2019), into differences in expense and revenue, expressed in USD$/ha each year. We determined differences in custom work rates between treatments using information from the Michigan State University Department of Agricultural Food and Resource Economics (Michigan State University, 2019) between 1994 and 2018. Years prior to 1994 and years with missing values were extrapolated and interpolated, respectively, from an estimated linear relationship.

Conventional tillage expenses included the custom rates for tillage (moldboard or chisel plow), soil finishing, and planting. No-till expenses included custom rates for planting, spraying, and mowing. Custom work estimates included the expense of labor, fuel, and equipment rental. Custom rates in Michigan were compared to those calculated for Iowa between 1995 and 2014 (Edwards & Johanns, 2014), and they were found to follow similar trajectories over time. Finally, differences in revenue ($/ha) and expense ($/ha) were converted from different time periods to present values (base year 2017) using the present value formula: $PV = FV(1 + i)^n$, where "PV" is the present value, "FV" is the future value, "i" is the interest rate (we used 5%), and "n" is the number of years. Derivation of value estimates of expenses and revenue by year are given in Table S1. We determined accumulated expenses, revenue, and difference between treatments (no-till–conventional) to determine when no-till blocks recuperated initial implementation and ongoing maintenance expenses. To fit the plotted data, we estimated model curves using third-order polynomials: USD/ha = $a * \text{Year} + b * \text{Year}^2 + c * \text{Year}^3$, where "$a$", "$b$", and "$c$" are coefficients (estimates provided in Table S2).

To understand the relative profitability over time intervals, we applied a moving window algorithm developed in R (Bahlai, 2019) to measure the overall trajectory and consistency of our response variables throughout our 29-year dataset. First, we fit linear mixed effects models to defined subsets of data and produced summary statistics of interest (e.g., slope of the relationship between the response variable and time, standard error of this relationship, and p value). The moving window then iterated through the entire dataset at set intervals. We used moving windows of 3-year periods or longer, fed each interval through the algorithm described above, and compiled resulting summary statistics. The direction and magnitude of statistically significant slopes are plotted against corresponding window length (number of years) to investigate the relationship between trend consistency, direction, and magnitude with study duration. No adjustments were made for multiple statistical comparisons in our analysis as each linear regression was considered in isolation, as a hypothetical observation period from which an observer would use to reach conclusions regarding system behavior, from non-independent but still separate experimental durations. Conceptually, we were interested in the trajectory of the relationship between accumulated relative profitability between no-till and conventional agriculture with time, and how linear mixed effects model outputs vary with the starting point of sample period and sample period duration. The direction and magnitude of statistically significant slopes were plotted against corresponding window length (number of years) to investigate the relationships among relative profitability trend consistency, direction, and magnitude with study duration.

2.4 | Trend consistency

To investigate our third question, concerning the variability of trends in our long-term dataset, we used the same response variables described in Section 2.2 (yield, soil water availability, and N_2O fluxes) and a moving window approach, described in Section 2.3. Conceptually, this provides a trajectory of the relationship of each response variable with time, and describes how the fit of linear mixed effects model results vary with different sample periods, start years, and durations. The direction and magnitude of statistically significant slopes are plotted against corresponding window length (number of years) to investigate the relationship between trend consistency, direction, and magnitude with study duration.

3 | RESULTS

3.1 | Summary of study site and treatments

Between 1989 and 2017, differences in corn yield between treatments (no-till–conventional) ranged from −3.57 Mg/ha in 1999 to 2.91 Mg/ha in 2008 and averaged 0.68 Mg/ha (*SE*: 0.017). Differences in soybean yield (no-till–conventional) ranged from −2.68 Mg/ha in 1994 to

1.07 Mg/ha in 2006 and averaged 0.306 Mg/ha (*SE*: 0.007). Differences in wheat yield (no-till–conventional) ranged from −4.14 Mg/ha in 2001 to 1.62 Mg/ha in 2010 and averaged 0.042 Mg/ha (*SE*: 0.001). Over the same time period, differences in soil water availability between the two treatments across crop types (no-till–conventional) ranged from −0.026 g H_2O/g dry soil in 1990 to 0.05 g H_2O/g dry soil in 2013 and averaged 0.02 g H_2O/g dry soil (*SE*: 0.002). Differences in N_2O gas fluxes between the two treatments across crop types (no-till–conventional) ranged from −4.3 g N_2O-N ha^{-1} day^{-1} in 2007 to 6.9 g ha^{-1} day^{-1} in 2000 and averaged 0.4 g ha^{-1} day^{-1} (*SE*: 0.2).

3.2 | Time needed to detect effects of management change

We found a significant positive relationship between duration and difference in crop yield between no-till and conventionally managed treatments (estimate: 0.043, *T*: 4.96, $p < .001$; Figure 2a). Furthermore, we found a significant positive relationship between differences in soil water availability between no-till and conventionally managed treatments and duration (estimate: 0.0003, *T*: 4.005, $p < .001$; Figure 2b). Lastly, we found a non-significant relationship between differences in N_2O fluxes between no-till and conventionally managed treatments and duration (estimate: −0.012, *T*: −0.39, *p*: 0.70; Figure 2c).

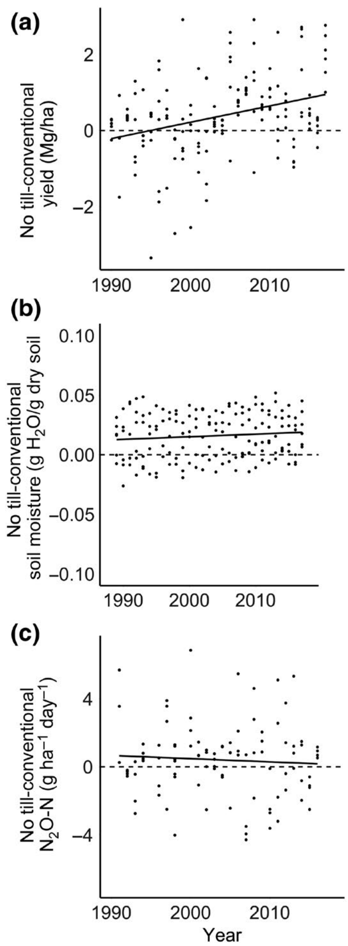

FIGURE 2 Scatterplots showing (a) the difference in crop yield (Mg/ha) between no-till and conventional treatments within each block and year, (b) the difference in gravimetric soil water availability (g H_2O/g dry soil) between no-till and conventional treatments within each block and year, and (c) the difference in N_2O-N (g ha^{-1} day^{-1}) between no-till and conventional treatments within each block and year

In a conservative power analysis, we found that with a calculated effect size of 0.043 Mg ha^{-1} $year^{-1}$, α of 0.05, and power of 0.8, it would

TABLE 1 Summary of (a) power analysis predicting the number of years needed to detect effects of no-till treatment on crop yield (Mg/ha), soil moisture (g H_2O/g dry soil), and N_2O-N (g ha^{-1} day^{-1}) in linear mixed effects models given a conservative α value of 0.05 and power of 0.8, and (b) for a more liberal α value of 0.2 and power of 0.8

	Effect size	α	Power	Predicted years
(a)				
Yield (Mg/ha)	0.043	0.05	0.8	19
Soil moisture (g H_2O/g dry soil)	0.0003	0.05	0.8	25
N_2O-N (g ha^{-1} day^{-1})	−0.012	0.05	0.8	NA
(b)				
Yield (Mg/ha)	0.043	0.20	0.8	16
Soil moisture (g H_2O/g dry soil)	0.0003	0.20	0.8	19
N_2O-N (g ha^{-1} day^{-1})	−0.012	0.20	0.8	NA

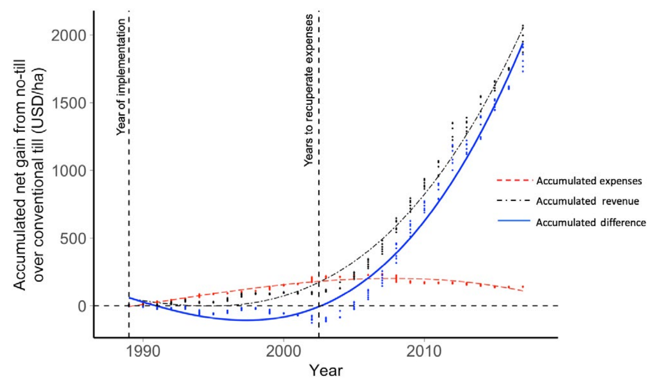

FIGURE 3 Partial budgeting analysis of relative profitability plot comparing the expense of implementation and management of the two tillage systems. Dots represent values for each block each year. Accumulated expenses, shown as red dots and the dashed red line, include differences in custom hire ($/ha) and input expenses ($/ha) between the two treatments (no-till – conventional). Accumulated revenue, shown as black dots and the dashed black line, include the difference in yield between the treatments (no-till – conventional; Mg/ha) each year and historic crop prices at time of harvest ($/kg). The blue dots and blue line describe accumulated net gain from no-till over conventionally tilled management. Values were converted from different time periods to present values using the present value formula: $PV = FV(1 + i)^n$, where "PV" is present value, "FV" is future value, "*i*" is interest rate (we used 5%), and "*n*" is the number of years. The vertical, black dotted line estimates the time at which accumulated expenses equal accumulated revenue

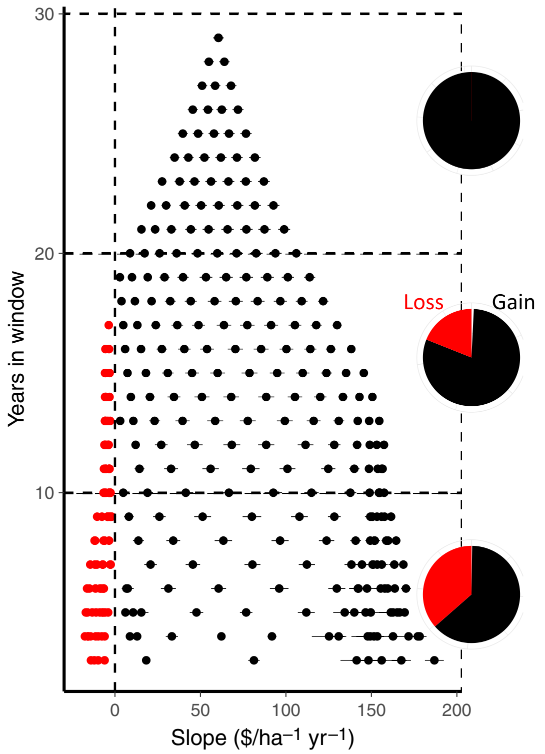

FIGURE 4 Scatterplot showing the relationship between slope ($/ha/year) and the number of years in a given window in terms of accumulated difference between no-till and conventional management ($/ha). Slopes were determined using linear mixed effects models using crop (corn, soybean, wheat) and block (1–6) as fixed variables, year as a random variable, and accumulated gain in no-till over conventional till for each window of time 3 years in length or longer, between 1989 and 2017. Only models with statistically significant slopes at the $\alpha < 0.05$ level are shown. Dots represent slope and solid lines represent standard error. Positive slopes, shown in black, indicate accruing gain in relative profitability of continuous no-till management when compared directly to conventionally managed blocks. Negative slopes, shown in red, indicate accruing loss of no-till management over time when compared directly to conventionally managed blocks. Pie charts show the percent of trends that are significantly negative (shown in red) and significantly positive (black) for early windows (0–10 years long, bottom), middle windows (11–20 years, middle), and long windows (21–29 years, top)

take at least 19 years to detect a significant effect of the no-till treatment on crop yield using a linear mixed effects model. Likewise, with a calculated effect size of 0.0003 g H_2O g^{-1} dry soil $year^{-1}$, it would take 25 years to detect a significant effect of the no-till treatment on soil water availability. Lastly, even with a calculated effect size of −0.012 N_2O-N ha^{-1} day^{-1} $year^{-1}$, we would not see a significant effect of the no-till treatment on N_2O flux (Table 1a). Using a more liberal α value that better represents the expectations of farmers ($\alpha = 0.2$), we found that long-term datasets on differences in yield and soil would take 16 and 19 years to detect significant effects of no-till management on crop yield and soil water availability, respectively (Table 1b).

3.3 | Recuperating implementation and maintenance expenses

Because the relative cost of no-till flattened out over time while crop yields under no-till increasingly gained over conventional tillage, the accumulated expenses ($/ha) of no-till compared to conventional did not grow as fast as the accumulated revenue. Hence, gross margin differences reveal that while no-till was a money loser in early years, by the end of 2002 (13 years after implementation), no-till recuperated initial losses at our site. By 2017, over the 29-year period, no-till had accumulated nearly $2,000/ha in differences in relative profitability as measured by partial budgets (Figure 3; Tables S1 and S2). Using the moving window algorithm on the partial budgeting analysis of relative profitability, we see that of the 379 windows formed, 338 were significant at the $p < .05$ level. While most trends were positive, of windows between 3 and 10 years long, 37% (57/156) were negatively trending, 19% (26/137) of windows between 11 and 20 years long were negatively trending, and of the windows between 21 and 29 years long none (0/46) were negatively trending (Figure 4; Table 2).

3.4 | Trend consistency

The moving window algorithm formed 379, 379, and 142 windows of lengths between 3 and 29 years for our long-term datasets

	Total trends	Total significant trends	Positive trends	Positive Significant trends	Negative trends	Negative Significant trends
Early (3–10 years)	188	156	115	99	73	57
Mid (11–20 years)	145	136	115	26	30	110
Long (21–29 years)	46	46	46	46	0	0
Full (3–29 years)	379	338	276	255	103	83

TABLE 2 Trend summaries for partial budgeting analysis of relative profitability comparing the expense of implementation and management of the two tillage systems from moving window analysis applied to a linear mixed effects model using crop (corn, soybean, and wheat) and block (1–6) as fixed variables, and year as a random variable

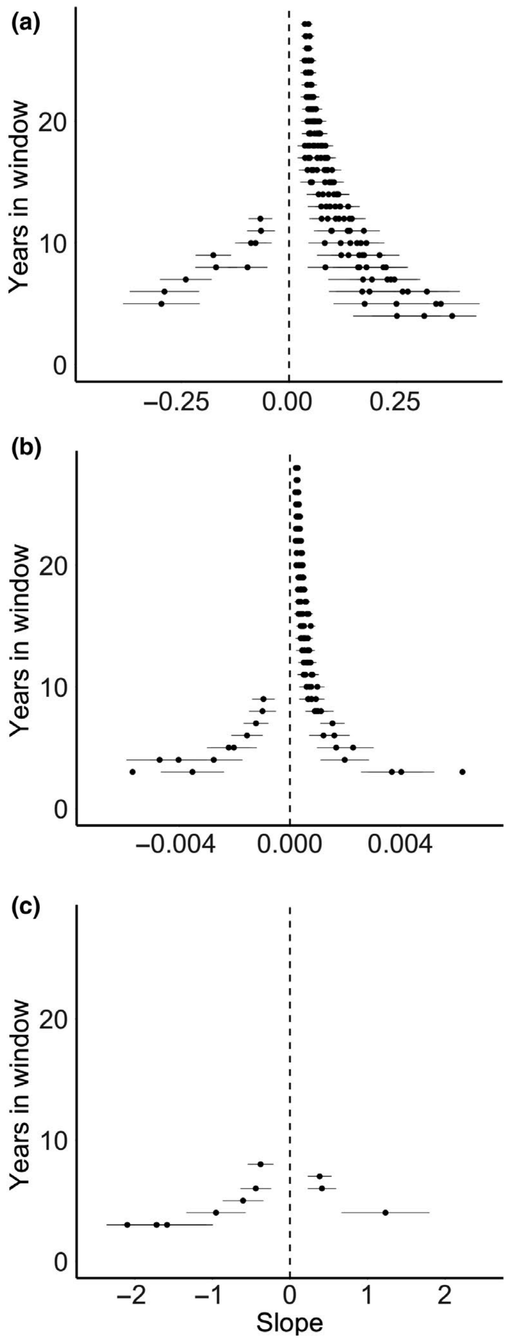

FIGURE 5 Results from the moving window analysis. Scatterplots showing the relationship between slope and the number of years in a given window for (a) crop yield (Mg/ha), (b) gravimetric soil water availability (g H_2O/g dry soil), and (c) N_2O-N (g ha^{-1} day^{-1}). Slopes were determined using linear mixed effects models using crop (corn, soybean, wheat) and block (1–6) as fixed variables, and year as a random variable for each window of time 3 years in length or longer, between 1988 and 2017. Only models with statistically significant slopes at the $\alpha < 0.05$ level are shown. Dots represent slope and solid lines represent standard error. Positive slopes indicate an accruing benefit of no-till management over time when compared directly to conventionally managed blocks. The vertical black dotted line indicates a slope of zero, where the benefits of no-till management have saturated

(difference in yield, soil water availability, and N_2O fluxes, respectively). Addressing our last question concerning the consistency of trends, we found that for differences in yield, 250 windows had a positive slope (66%) and 129 windows had a negative slope (34%). Of the positive trending windows, 170 were significant at the $\alpha < 0.05$ level; of the negative trending windows, 12 were significant (Figure 5a; Table 3). For soil water availability, we found that 299 windows had a positive slope (79%) and 80 windows had a negative slope (21%). Of the positive trending windows, 128 were significant; of the negative trending windows, 11 were significant (Figure 5b; Table 3). Lastly, for N_2O fluxes, of the 142 windows, we found 65 windows were positively trending (46%), 77 were negatively trending (54%), and three of the positive windows and seven of the negative windows were found to be significant (Figure 5c; Table 3).

4 | DISCUSSION

Using a long-term experimental dataset spanning nearly 30 years, we used power analysis and a moving window approach to show that both yield and soil water availability require periods 15 years or longer to generate consistent results in this rainfed corn–soybean–wheat system in the upper Midwest US. In fact, given our effect sizes, it would take 16 and 19 years to detect significant effects of continuous no-till management on crop yield and soil water availability, respectively, even with a liberal α value ($\alpha = 0.2$). Analyses performed on periods shorter than 15 years suggest misleading trends, even though these findings were sometimes statistically significant.

Through relative profitability analysis, we found that 13 years were needed to fully recover the initial expenses of continuous no-till management in our system, and that the longer the implementation of no-till, the greater likelihood of relative profitability, regardless of stochastic effects. Here, we show that more than a decade is needed to detect the consistent benefits of continuous no-till on these economic and environmentally important attributes, suggesting that a shorter-term experiment could have led to contradictory and misleading results. While it is possible that increased replication could have reduced the number of misleading results we detected, increased replication would not have captured the emergent properties that took time to accumulate, as we see in our long-term data set. Furthermore, when considering the degree of environmental variation that defines modern and future agriculture, especially in the face of global climate change, we argue that long datasets are essential.

We also show that longer periods of implementation increase the likelihood that continuous no-till management becomes more profitable than tillage. Immediately following implementation of no-till management (periods between 3 and 10 years), more than one-third of periods resulted in the loss of net revenue (37%). However, as periods became longer, the likelihood of greater relative

	Total trends	Total significant trends	Positive trends	Positive significant trends	Negative trends	Negative significant trends
Yield (Mg/ha)	379	182	250	170	129	12
Soil moisture (g H_2O/g dry soil)	379	139	299	128	80	11
N_2O-N (g ha^{-1} day^{-1})	142	10	65	3	77	7

TABLE 3 Trend summaries for crop yield (Mg/ha), gravimetric soil moisture (g H_2O/g dry soil), and N_2O-N (g ha^{-1} day^{-1}) for each block from moving window analysis applied to linear mixed effects models

profitability increased. In fact, for periods between 11 and 20 years, fewer than 20% of periods lost revenue, and for periods between 21 and 29 years, all periods were profitable. Overall, 86% of periods greater than 10 years were profitable. Were values assigned to the environmental benefits of continuous no-till (i.e. carbon sequestration, reduced nitrate leaching, etc.), the economic profits would further increase (Constantin et al., 2010; Lal, Logan, Eckert, Dick, & Shipitalo, 1994).

On investigating trend consistency, we found that nine out of 45 significant results for periods shorter than 10 years support a negative relationship between continuous no-till and the difference in yield over time (20%), in direct contradiction to the positive pattern we observed. Only analyses performed on periods 10 years or longer resemble more closely the broader positive pattern. The positive pattern between yield and management regime at longer time scales is echoed throughout other studies (Al-Kaisi, Archontoulis, Kwaw-Mensah, & Miguez, 2015; Gaudin, Janovicek, Deen, & Hooker, 2015; Martínez et al., 2016; Sindelar, Schmer, Jin, Wienhold, & Varvel, 2015; among others). Further, 31% (11/35) of the analyses on periods shorter than 10 years indicate a statistically significant negative relationship for soil water availability over time, in direct contradiction to the relationship suggested by longer periods. Among the periods tested for N_2O fluxes, 10 of 142 were found to contain a statistically significant trend (seven negative and three positive). This low detection of significant trends is consistent with recent N_2O flux meta-analyses (e.g., van Kessel et al., 2013), where only for studies greater than 10 years duration, particularly in drier climates, were trends of lower fluxes in no-till than conventional management significant. Results from our study suggest that such a trend may take substantially longer (perhaps scores of decades) to detect, likely in part due to relative increases in N_2O fluxes for the rotation's corn and soybean years' offsetting decreases in wheat years (Gelfand et al., 2016). In fact, consistent trends may not emerge until the rotation or some other important aspect of agricultural management changes, such as fertilizer rate (Shcherbak, Millar, & Robertson, 2014). Nevertheless, in our study, continuous no-till does not (yet) have consistent detectable effect on N_2O fluxes, as noted for earlier shorter-term analyses (Gelfand et al., 2016; Grandy, Loecke, Parr, & Robertson, 2006; Robertson, Paul, & Harwood, 2000). The importance of N_2O's contribution to the global warming impact of intensive cropping systems underscores the importance of better understanding time-dependent trends (Six et al., 2004).

Our results show that even in the absence of an overarching trend, spurious relationships in temporal processes or short-term trends associated with stochastic processes are common in tillage systems. Thus, the conflicting trends and predictions noted in previous studies concerning the impact of tillage on crop yield, soil water availability, and N_2O fluxes may be explained, at least in part, by their durations: strong, statistically significant relationships between parameters and duration may have been the result of high variation in the system over shorter time periods. This phenomenon of confident though misleading results highlights the importance of long-term studies for detecting trends and informing robust, accurate management recommendations.

To maximize the impact of research at any time scale, it is essential to understand how patterns emerge as studies become longer, enabling us to more effectively extrapolate results to long-term patterns. As our results show, variation can be highly idiosyncratic and dependent on study duration. Predicting the future effects of continuous no-till depends on understanding both the short- and long-term dynamics of crops following significant changes in management. This is likely to be especially important for detecting the consequences of slow to change properties like soil organic matter accretion following no-till initiation.

Our results highlight the importance of not only study duration but also of the selection of study starting and ending points. If a study period captures an outlying data point in a system's natural variability near the beginning or end of the study, those years are likely to be disproportionately influential on statistical outcomes and thus on conclusions, and presumed management implications (Swinton & King, 1991; White, 2019). Periods that reveal contrary results may be the response of high variation, possibly caused by extreme weather events, changes in crops, or other system-level idiosyncrasies.

In the case of no-till implementation, transient dynamics leading to short-term risks associated with continuous no-till management can, in fact, be accurately captured by short-term studies that focus on the establishment of no-till at new locales. These risks include increased pest and disease danger, altered nitrogen cycling, and increased nutrient requirements due to nutrient immobilization under cooler soil temperatures (Baker, Saxton, & Ritchie, 1996). Also, due to the potential slower soil warm-up in the spring, no-till management may result in stunted growth in initial years. Lastly, increased pressure by herbicide resistant weeds may cause future problems (Van Deynze, Swinton, & Hennessy, 2018).

Notwithstanding, as revealed by our results, benefits accrue over time. And as Choudhary and Baker (1994) predicted, despite potential negative results in the first few years of no-till, benefits of the reduced fertilizer requirements and pest protection, as well as an increased stable crop yield, are only realized with long-term management. Furthermore, because continuous no-till can be economically attractive for other reasons in the long term (e.g., reduced machinery fuel, energy, and maintenance costs, as well as reduced soil loss and degradation; Lal, Follett, Stewart, & Kimble, 2007; Rathke, Wienhold, Wilhelm, & Diepenbrock, 2007), our results are consistent with recommendations to support the long-term adoption of continuous no-till management despite initial losses.

5 | CONCLUSIONS

We used 29 years of no-till crop management data to reveal the temporal processes and long-term impacts of a change in agricultural management at a site in the US Corn Belt. We illustrate that management recommendations based on short-term studies can be contradictory because spurious, misleading trends can appear in time series at rates between 20% and 50% of the time, even independent of stochastic elements associated with external disturbances. Furthermore, the initiation of a new experiment almost certainly represents a strong disturbance to an ecosystem; thus, the early years in a study involving temporal processes may produce data that is not representative of the system's equilibrium behavior.

ACKNOWLEDGEMENTS

This work was performed on traditional Anishinaabe land where Hickory Corners, Michigan is currently located. Authors have no conflict of interest to declare. Support for this work was provided by the National Science Foundation Long-term Ecological Research Program (DEB 1832042) at the Kellogg Biological Station, the National Science Foundation Directorate for Computer and Information Science and Engineering (OAC 1838807), USDA National Institute on Food and Agriculture, and by Michigan State University AgBioResearch. Thanks to KBS colleagues for providing data and maintaining experimental infrastructure, especially Sven Bohm for database curation. The scaling algorithm was developed with feedback and perspective from Elise Zipkin, Ilya Gelfand, Kaitlin Stack Whitney, Easton White, and Julia Perrone.

DATA AVAILABILITY STATEMENT

All data are available on the KBS LTER website (https://lter.kbs.msu.edu/datatables). Supporting information is available as supplementary data (Michigan State University, Kellogg Biological Station, 2019).

ORCID

Sarah Cusser https://orcid.org/0000-0002-0100-026X
Nick M. Haddad https://orcid.org/0000-0002-1591-9322

REFERENCES

Al-Kaisi, M. M., Archontoulis, S. V., Kwaw-Mensah, D., & Miguez, F. (2015). Tillage and crop rotation effects on corn agronomic response and economic return at seven Iowa locations. *Agronomy Journal*, *107*, 1411–1424. https://doi.org/10.2134/agronj14.0470

Bahlai, C. (2019). *GitHub, bad_breakup*. Retrieved from https://github.com/cbahlai/bad_breakup

Baker, C. J., Saxton, K. E., & Ritchie, W. R. (1996). *No-tillage seeding: Science and practice*. Cambridge, UK: Cambridge University Press.

Basso, B., & Ritchie, J. T. (2015). Simulating crop growth and biogeochemical fluxes in response to land management using the SALUS model. In S. K. Hamilton & G. P. Robertson (Eds.), *The ecology of agricultural landscapes: Long-term research on the path to sustainability* (pp. 252–274). New York, NY: Oxford University Press.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48. https://doi.org/10.18637/jss.v067.i01

Bolliger, A., Magid, J., Amado, J. C., Neto, F. S., dos Santos Ribeiro, M. D., Calegari, A., … de Neergaard, A. (2006). Taking stock of the Brazilian "Zero-Till Revolution": A review of landmark research and farmers' practice. *Advances in Agronomy*, *91*, 47–110. https://doi.org/10.1016/S0065-2113(06)91002-5

Choudhary, M. A., & Baker, C. J. (1994). Overcoming constraints to conservation tillage in New Zealand. In M. R. Carter (Ed.), *Conservation tillage in temperate agro-ecosystems* (pp. 183–207). Boca Raton, FL: Lewis Publishers.

Cimmyt, M., & Cimmyt, M. (1988). *From agronomic data to farmer recommendations: An economics training manual*. Completely Revised ed. Mexico City: Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT).

Claassen, R., Bowman, M., McFadden, J., Smith, D., & Wallander, S. (2018). Tillage intensity and conservation cropping in the United States. Economic Research Service, U.S.: Department of Agriculture. Retrieved from https://www.ers.usda.gov/webdocs/publications/90201/eib-197.pdf?v=1783.8

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., & Beaudoin, N. (2010). Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture, Ecosystems & Environment*, *135*, 268–278. https://doi.org/10.1016/j.agee.2009.10.005

DeLonge, M. S., Miles, A., & Carlisle, L. (2016). Investing in the transition to sustainable agriculture. *Environmental Science & Policy*, *55*, 266–273. https://doi.org/10.1016/j.envsci.2015.09.013

Derpsch, R., Friedrich, T., Kassam, A., & Li, H. (2010). Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering*, *3*, 1–25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.0-0

Edwards, W., & Johanns, A. (2014). Iowa farm custom rate survey. Iowa State University Extension and Outreach, Ag Decision Maker file C2–21/FM-1698. Retrieved from www.extension.iastate.edu/agdm/

FarmDoc. (2019). *US average farm price received database*. Retrieved from http://www.farmdoc.illinois.edu/manage/uspricehistory/us_price_history.html

Gage, S. H., Doll, J. E., & Safir, G. R. (2015). A crop stress index to predict climatic effects on row-crop agriculture in the US North Central Region. In S. K. Hamilton, J. E. Doll, & G. P. Robertson (Eds.), *The ecology of agricultural landscapes: Long-term research on the path to sustainability* (pp. 77–103). New York, NY: Oxford University Press.

Gaudin, A. C., Janovicek, K., Deen, B., & Hooker, D. C. (2015). Wheat improves nitrogen use efficiency of maize and soybean-based cropping systems. *Agriculture, Ecosystems & Environment*, *210*, 1–10. https://doi.org/10.1016/j.agee.2015.04.034

Gelfand, I., Shcherbak, I., Millar, N., Kravchenko, A. N., & Robertson, G. P. (2016). Long-term nitrous oxide fluxes in annual and perennial agricultural and unmanaged ecosystems in the upper Midwest USA.

Global Change Biology, *22*, 3594–3607. https://doi.org/10.1111/gcb.13426

Grandy, A. S., Loecke, T. D., Parr, S., & Robertson, G. P. (2006). Long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. *Journal of Environmental Quality*, *35*, 1487–1495. https://doi.org/10.2134/jeq2005.0166

Green, P., & MacLeod, C. J. (2016). SIMR: A R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution*, *7*, 493–498. https://doi.org/10.1111/2041-210X.12504

Karlen, D. L., Wollenhaupt, N. C., Erbach, D. C., Berry, E. C., Swan, J. B., Eash, N. S., & Jordahl, J. L. (1994). Long-term tillage effects on soil quality. *Soil and Tillage Research*, *32*, 313–327. https://doi.org/10.1016/0167-1987(94)00427-G

Kladivko, E. J. (2001). Tillage systems and soil ecology. *Soil and Tillage Research*, *61*, 61–76. https://doi.org/10.1016/S0167-1987(01)00179-9

Krause, M. A., & Black, J. R. (1995). Optimal adoption strategies for no-till technology in Michigan. *Review of Agricultural Economics*, *17*, 299–310. https://doi.org/10.2307/1349575

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*, 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lal, R., Follett, R. F., Stewart, B. A., & Kimble, J. M. (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*, *172*, 943–956. https://doi.org/10.1097/ss.0b013e31815cc498

Lal, R., Logan, T. J., Eckert, D. J., Dick, W. A., & Shipitalo, M. J. (1994). Conservation tillage in the corn belt of the United States. In M. R. Carter (Ed.), *Conservation tillage in temperate agroecosystems* (pp. 73–114). Boca Raton, FL: Lewis Publishers.

Lal, R., Reicosky, D. L., & Hanson, J. D. (2007). Evolution of the plow over 10,000 years and the rationale for no-till farming. *Soil and Tillage Research*, *93*, 1–12. https://doi.org/10.1016/j.still.2006.11.004

Livingston, G. P., & Hutchinson, G. L. (1995). Enclosure-based measurement of trace gas exchange: Applications and sources of error. In P. A. Matson & R. C. Harriss (Eds.), *Biogenic trace gases: Measuring emissions from soil and water* (Vol. 51, pp. 14–51). Oxford, UK: Blackwell Publishing.

Martínez, I., Chervet, A., Weisskopf, P., Sturny, W. G., Etana, A., Stettler, M., … Keller, T. (2016). Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile. *Soil and Tillage Research*, *163*, 141–151. https://doi.org/10.1016/j.still.2016.05.021

Michigan State University, Department of Agricultural Food and Resource, Economics. (2019). Machinery costs, prices of crops and variable inputs, consumer and producer price indexes. Retrieved from https://www.canr.msu.edu/afre/centers_services/economic_analysis_of_sustainable_ag._food_systems/useful_data_sources

Michigan State University, Kellogg Biological Station. (2019). KBS LTER data catalog. Retrieved from https://lter.kbs.msu.edu/datatables

NRC (National Research Council). (2003). *Frontiers in agricultural research. Food, health, environment, and communities*. Washington, DC: National Academy Press.

Paustian, K., Andrén, O., Janzen, H. H., Lal, R., Smith, P., Tian, G., … Woomer, P. L. (1997). Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management*, *13*, 230–244. https://doi.org/10.1111/j.1475-2743.1997.tb00594.x

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*, 49–57. https://doi.org/10.1038/nature17174

Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., van Groenigen, K. J., Lee, J., … van Kessel, C. (2015). When does no-till yield more? A global meta-analysis. *Field Crops Research*, *183*, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020

Rasmussen, P. E., Goulding, K. W. T., Brown, J. R., Grace, P. R., Janzen, H. H., & Korschens, M. (1998). Long-term agroecosystem experiments: Assessing agricultural sustainability and global change. *Science*, *282*, 893–896. https://doi.org/10.1126/science.282.5390.893

Rathke, G. W., Wienhold, B. J., Wilhelm, W. W., & Diepenbrock, W. (2007). Tillage and rotation effect on corn–soybean energy balances in eastern Nebraska. *Soil and Tillage Research*, *97*, 60–70. https://doi.org/10.1016/j.still.2007.08.008

Ravishankara, A. R., Daniel, J. S., & Portmann, R. W. (2009). Nitrous oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st century. *Science*, *326*, 123–125. https://doi.org/10.1126/science.1176985

Reicosky, D. C., Kemper, W. D., Langdale, G., Douglas, C. L., & Rasmussen, P. E. (1995). Soil organic matter changes resulting from tillage and biomass production. *Journal of Soil and Water Conservation*, *50*, 253–261.

Robertson, G. P., Allen, V. G., Boody, G., Boose, E. R., Creamer, N. G., Drinkwater, L. E., … Wall, D. H. (2008). Long-term agricultural research: A research, education, and extension imperative. *BioScience*, *58*, 640–645. https://doi.org/10.1641/B580711

Robertson, G. P., & Hamilton, S. K. (2015). Long-term ecological research at the Kellogg Biological Station LTER site Conceptual and experimental framework. In G. P. Robertson & S. K. Hamilton (Eds.), *The ecology of agricultural landscapes: Long-term research on the path to sustainability* (pp. 1–32). New York, NY: Oxford University Press.

Robertson, G. P., Paul, E. A., & Harwood, R. R. (2000). Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science*, *289*, 1922–1925. https://doi.org/10.1126/science.289.5486.1922

Rodriguez, J. M., Molnar, J. J., Fazio, R. A., Sydnor, E., & Lowe, M. J. (2009). Barriers to adoption of sustainable agriculture practices: Change agent perspectives. *Renewable Agriculture and Food Systems*, *24*, 60–71. https://doi.org/10.1017/S1742170508002421

Shcherbak, I., Millar, N., & Robertson, G. P. (2014). Global meta-analysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 9199–9204. https://doi.org/10.1073/pnas.1322434111

Sindelar, A. J., Schmer, M. R., Jin, V. L., Wienhold, B. J., & Varvel, G. E. (2015). Long-term corn and soybean response to crop rotation and tillage. *Agronomy Journal*, *107*, 2241–2252. https://doi.org/10.2134/agronj15.0085

Six, J., Ogle, S. M., Jay Breidt, F., Conant, R. T., Mosier, A. R., & Paustian, K. (2004). The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Global Change Biology*, *10*, 155–160. https://doi.org/10.1111/j.1529-8817.2003.00730.x

Spiegal, S., Bestelmeyer, B. T., Archer, D. W., Augustine, D. J., Boughton, E. H., Boughton, R. K., … Walthall, C. L. (2018). Evaluating strategies for sustainable intensification of US agriculture through the long-term agroecosystem research network. *Environmental Research Letters*, *13*, 034031. https://doi.org/10.1088/1748-9326/aaa779

Swinton, S. M., & King, R. P. (1991). Evaluating robust regression techniques for detrending crop yield data with non-normal errors. *American Journal of Agricultural Economics*, *73*, 446–545. https://doi.org/10.2307/1242729

Syswerda, S. P., Corbin, A. T., Mokma, D. L., Kravchenko, A. N., & Robertson, G. P. (2011). Agricultural management and soil carbon storage in surface vs. deep layers. *Soil Science Society of America*, *75*, 92–101. https://doi.org/10.2136/sssaj2009.0414

USDA. (2019). National Agricultural Statistics Service. Retrieved from https://quickstats.nass.usda.gov/

USDA. (2020). Fiscal year 2020 budget summary. Retrieved from https://www.obpa.usda.gov/budsum/fy2020budsum.pdf

Van Deynze, B., Swinton, S. M., & Hennessy, D. A. (2018). Are glyphosate-resistant weeds a threat to conservation agriculture? Evidence from tillage practices in soybean. Paper presented at Agricultural and Applied Economics Association. Washington, DC, August 5–7, 2018.

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M. A., Linquist, B., & van Groenigen, K. J. (2013). Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: A meta-analysis. *Global Change Biology*, *19*, 33–44. https://doi.org/10.1111/j.1365-2486.2012.02779.x

Wade, T., & Claassen, R. (2017). Modeling no-till adoption by corn and soybean producers: Insights into sustained adoption. *Journal of Agricultural and Applied Economics*, *49*, 186–210. https://doi.org/10.1017/aae.2016.48

White, E. R. (2019). Minimum time required to detect population trends: The need for long-term monitoring programs. *BioScience*, *69*, 40–46. https://doi.org/10.1093/biosci/biy144

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Cusser S, Bahlai C, Swinton SM, Robertson GP, Haddad NM. Long-term research avoids spurious and misleading trends in sustainability attributes of no-till. *Glob Change Biol*. 2020;00:1–11. https://doi.org/10.1111/gcb.15080