

1 Title: Long-term research avoids spurious and misleading trends in sustainability attributes of  
2 no-till

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4 Running Title: Long-term data avoids false trends

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## 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<sub>2</sub>O 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, U.S. 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<sub>2</sub>O 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

yield, soil moisture, soil water availability, N<sub>2</sub>O fluxes, LTER, power analysis, moving window, profitability of no-till adoption, long-term research, sustainable intensification

## 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 U.S. 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; Spiegel et al., 2018), including crop fertility, pest protection, seed genetics, water management, soil health, and aspects of sustainability (Delonge et al., 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 et al., 1995). However, the environmental costs of regular tillage are great, including decreased soil carbon, increased potentials for soil erosion, and poor soil structure (Lal et al., 2007a). Following the 1930's dustbowl, U.S. agronomists and soil scientists became increasingly concerned about the long-term environmental sustainability of tillage-based agriculture (Derpsch et al., 2010). With the advent of modern herbicides in the 1960's, along with glyphosate resistant crops in the 1990's, 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<sub>2</sub> emissions when compared to conventional tilling practices (Karlen et al., 1994; Kladivko, 2001; Bolliger et al., 2006).

In the last few decades, the adoption of no-till continues to rise (Claassen et al., 2018). The most recent USDA survey estimates that no-till and strip till accounts for 45 % of total U.S. 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 et al., 2009). Converting a field to no-till, for example, involves both the upfront expenses of investment in novel machinery (Krause & Black, 1995) as well as 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 as well as short-term economic costs.

That many of the attributes and perhaps functional benefits of no-till management may take decades to consistently affect yields, profits, and environmental outcomes begs 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, U.S. to 1) determine the number of years required for consistent differences in crop yield, soil water availability, and N<sub>2</sub>O 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 U.S. 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 1027 mm yr<sup>-1</sup>, evenly distributed seasonally; potential evapotranspiration exceeds precipitation for about four months of the year. Loam soils are well-drained Typic Hapludalfs developed on glacial outwash with soil carbon contents around 1% C (Syswerda et al., 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 et al., 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 (*Glycine 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 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 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 h, weighed, and reported as Mg/ha at standard moisture.



We also assessed the effect of tillage on soil water availability and N<sub>2</sub>O 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 grams of fresh soil from each replicate (N=6) at 60° C for 48 hours. Samples were collected each month when soil was not frozen (typically April-November) at each of 5 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<sub>2</sub>O/g dry soil) ([www.lter.kbs.msu.edu](http://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<sub>2</sub>O) is an ozone depleting greenhouse gas (Ravishankara et al., 2009) and agricultural soil management is the largest anthropogenic source of N<sub>2</sub>O emissions globally (Paustian et al., 2016). N<sub>2</sub>O 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 et al., 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 minutes. 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<sub>2</sub>O, 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 <sup>63</sup>Ni 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<sub>2</sub>O fluxes over our 29-year period, we fit linear mixed effects models to the data using crop (corn, soybean, wheat) and block (1-6 for crop yield and soil water availability, 1-4 for N<sub>2</sub>O fluxes) as fixed variables, year as a random variable, and difference in crop yield, soil water availability, and N<sub>2</sub>O fluxes as response variables with the ‘lmer4’ package in R (Bates et al., 2015). We then executed a power analysis for our linear mixed effects models through simulation with a traditional alpha value of 0.05, 1000 simulations, and power of 0.8, using the ‘simr’ package in R (Green et al., 2016). We also executed a second power analysis at a more liberal alpha value for comparison (alpha = 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 one in five 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 U.S. monthly average price received for corn, soybean, and wheat at 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](http://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 1995-2014 (Edwards & Johanns, 2014), and 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 present value, “*FV*” is future value, “*i*” is 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 supplemental materials (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:  $\text{USD/ha} = a * \text{Year} + b * \text{Year}^2 + c * \text{Year}^3$ , where ‘a’, ‘b’, and ‘c’ are coefficients (estimates provided in Table S2).

To understand 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 three-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<sub>2</sub>O 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<sub>2</sub>O/g dry soil in 1990 to 0.05 g H<sub>2</sub>O/g dry soil in 2013 and averaged 0.02 g H<sub>2</sub>O/g dry soil (SE: 0.002). Differences in N<sub>2</sub>O gas fluxes between the two treatments across crop types (No-till –

Conventional) ranged from  $-4.3 \text{ g N}_2\text{O-N ha}^{-1} \text{ d}^{-1}$  in 2007 to  $6.9 \text{ g ha}^{-1} \text{ day}^{-1}$  in 2000 and averaged  $0.4 \text{ g ha}^{-1} \text{ d}^{-1}$  (SE: 0.2).

### **3.2 Time needed to detect effects of management change**

We found a significant positive relationship between window duration and difference in crop yield between No-till and Conventionally managed treatments (Estimate: 0.043, T: 4.96,  $P < 0.001$ ) (Figure 2a). Further, 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,  $P < 0.001$ ) (Figure 2b). Lastly, we found a non-significant relationship between differences in  $\text{N}_2\text{O}$  fluxes between No-till and Conventionally managed treatments and window duration (Estimate:  $-0.012$ , T:  $-0.39$ ,  $P: 0.70$ ) (Figure 2c).

In a conservative power analysis, we found that with a calculated effect size of 0.043 Mg/ha/year, alpha of 0.05, and power of 0.8, it would 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  $0.0003 \text{ g H}_2\text{O/g dry soil/year}$ , 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  $-0.012 \text{ N}_2\text{O-N ha}^{-1} \text{ d}^{-1} \text{ year}^{-1}$ , we would not see a significant effect of the No-till treatment on  $\text{N}_2\text{O}$  flux (Table 1a). Using a more liberal alpha 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, Table S1, Table 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  $p < 0.05$  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 21-29 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 three and 29 years for our long-term datasets (difference in yield, soil water availability, and N<sub>2</sub>O 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<sub>2</sub>O 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 U.S. 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 alpha 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. Further, 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 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 value assigned to the environmental benefits of continuous no-till (i.e. carbon sequestration, reduced nitrate leaching, etc.) the economic profits would further increase (Lal et al., 1994; Constantin et al., 2010).

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 (Martínez et al., 2016; Sindelar et al., 2015; Gaudin et al., 2015; Al-Kaisi et al., 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<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O 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 et al., 2014). Nevertheless, in our study continuous no-till does not (yet) have consistent detectable effect on N<sub>2</sub>O fluxes, as noted for earlier shorter-term analyses (Robertson et al., 2000; Grandy et al., 2006; Gelfand et al., 2016). The importance of N<sub>2</sub>O'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<sub>2</sub>O 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 et al., 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 et al., 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. Further, 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 et al., 2007b; Rathke et al., 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 U.S. 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.

## 6 ACKNOWLEDGMENTS

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## 7 DATA SHARING AND ACCESSIBILITY STATEMENT

All data are available on the KBS LTER Website (<https://lter.kbs.msu.edu/datatables>).

Supporting information is available as supplementary data.

## 8 REFERENCES

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