

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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6 Authors: Sarah Cusser ^{1,2}, Christie Bahlai ^{1,3}, Scott M. Swinton ⁴, G. Philip Robertson ^{1,5}, Nick
7 M. Haddad ^{1,2}

8

9 Institutional Affiliations:

10 1 W.K. Kellogg Biological Station, Department of Integrative Biology, Michigan State
11 University, 3700 East Gull Lake Dr., Hickory Corners, MI 49060, U.S.

12

13 2 Department of Integrative Biology, Michigan State University, East Lansing, MI 48824, U.S.

14

15 3 Department of Biological Science, Kent State University, 249 Cunningham Hall, Kent, OH
16 44240, U.S.

17

18 4 Department of Agricultural, Food, and Resource Economics, Michigan State University, East
19 Lansing, MI 48824, U.S.

20

21 5 Department of Plant, Soil, and Microbial Sciences, Michigan State University, East Lansing,
22 MI 48824, U.S.

23

24 Corresponding Author Information: sarah.cusser@gmail.com

25

26 **ABSTRACT**

27 Agricultural management recommendations based on short-term studies can produce findings
28 inconsistent with long-term reality. Here, we test the long-term environmental sustainability and
29 profitability of continuous no-till agriculture on yield, soil water availability, and N₂O fluxes.
30 Using a moving window approach, we investigate the development and stability of several
31 attributes of continuous no-till as compared to conventional till agriculture over a 29-year period
32 at a site in the upper Midwest, U.S. Over a decade is needed to detect the consistent effects of
33 no-till. Both crop yield and soil water availability required 15 years or longer to generate patterns
34 consistent with 29-year trends. Only marginal trends for N₂O fluxes appeared in this period.
35 Relative profitability analysis suggests that after initial implementation, 86% of periods between
36 10 and 29 years recuperated the initial expense of no-till implementation, with the probability of
37 higher relative profit increasing with longevity. Importantly, statistically significant but
38 misleading short-term trends appeared in more than 20% of the periods examined. Results
39 underscore the importance of decadal and longer studies for revealing consistent dynamics and
40 emergent outcomes of no-till agriculture, shown to be beneficial in the long term.

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42 **KEYWORDS**

43 yield, soil moisture, soil water availability, N₂O fluxes, LTER, power analysis, moving window,
44 profitability of no-till adoption, long-term research, sustainable intensification

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49 **1 INTRODUCTION**

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

61 Tillage is a well-researched management strategy that is a case in point. Tillage
62 mechanically incorporates crop residues and/or amendments into soils, controls weeds, promotes
63 soil warming and drying, and thereby prepares soil for planting, creating optimal conditions for
64 crop seed germination and emergence (Reicosky et al., 1995). However, the environmental costs
65 of regular tillage are great, including decreased soil carbon, increased potentials for soil erosion,
66 and poor soil structure (Lal et al., 2007a). Following the 1930's dustbowl, U.S. agronomists and
67 soil scientists became increasingly concerned about the long-term environmental sustainability of
68 tillage-based agriculture (Derpsch et al., 2010). With the advent of modern herbicides in the
69 1960's, along with glyphosate resistant crops in the 1990's, no-till, whereby crop residues are
70 left on the surface following harvest, has become gradually more popular. No-till can often

71 increase soil carbon, quality, and function, and reduce CO₂ emissions when compared to
72 conventional tilling practices (Karlen et al., 1994; Kladivko, 2001; Bolliger et al., 2006).

73 In the last few decades, the adoption of no-till continues to rise (Claassen et al., 2018).

74 The most recent USDA survey estimates that no-till and strip till accounts for 45 % of total U.S.
75 acreage in wheat (2017), 40 % in soybeans (2012), 18 % in cotton (2015), and 27 % in corn
76 (2016) (Claassen et al., 2018). A global meta-analysis of no-till productivity across a range of
77 climates, soils, and crop types found that no-till management consistently out-performed
78 conventional tillage for rainfed crops in dry climates (Pittelkow et al., 2015). However, in more
79 mesic climates, or under irrigated conditions, differences were more variable. Some of the
80 variation uncovered by this meta-analysis is likely due to the short duration of many of the
81 studies – only 60 of the 520 studies lasted 10 years or longer.

82 Short-term research experiments are important for identifying ecosystem-related changes
83 to land management in a timely and cost-efficient manner. In fact, for a variety of reasons,
84 including the short duration of most research funding, human or business constraints, and a need
85 for actionable solutions, agricultural research is often performed on short time scales. Yet,
86 research conducted at these constrained time scales has the potential to be misleading. Short-term
87 research can be insufficient especially for evaluating ecosystem properties and phenomena that
88 change slowly, such as soil structure and soil carbon, or require proper evaluation over an
89 appropriately variable climate and management history (Paustian et al., 1997; Rasmussen et al.,
90 1998; Robertson et al., 2008).

91 Beyond the variable findings that confound the relative environmental benefits of no-till,
92 economic concerns have also slowed the adoption of more sustainable practices (Wade &
93 Claassen, 2017). Surveys note that when asked, farmers responded that compared to other factors

94 (e.g. lack of education and/or information, resistance to change, social considerations,
95 infrastructure, or landlessness), economic concerns are the largest barrier to adopting sustainable
96 agricultural practices such as no-till management (Rodriguez et al., 2009). Converting a field to
97 no-till, for example, involves both the upfront expenses of investment in novel machinery
98 (Krause & Black, 1995) as well as the increased herbicide cost of controlling weeds, which can
99 exceed the short-term savings associated with reduced tillage. Thus, farmers may choose to
100 avoid no-till as a result of both the uncertainty surrounding benefits as well as short-term
101 economic costs.

102 That many of the attributes and perhaps functional benefits of no-till management may
103 take decades to consistently affect yields, profits, and environmental outcomes begs three
104 questions: 1) How long does continuous no-till need to be implemented (or studied) until
105 economic and ecological impacts are consistently detectable? 2) How many years of continuous
106 no-till management are needed to recoup the upfront expenses of converting conventionally tilled
107 fields to continuous no-till management? 3) How consistent are changes in economic and
108 environmental attributes over long periods? We apply power analysis to a 29-year experimental
109 dataset for a long-term research site in the upper Midwest, U.S. to 1) determine the number of
110 years required for consistent differences in crop yield, soil water availability, and N₂O fluxes to
111 be detectable, 2) determine the number of years before continuous no-till consistently recovers
112 initial management costs, and 3) investigate the consistency of trends over time. To address
113 questions 2 and 3, we use a moving window approach. To further address question 2, we also use
114 a partial budgeting analysis of relative profitability.

115 **2 METHODS**

116 **2.1 Study site and treatments**

117 We explicitly test the economic and ecological effects of no-till in the Main Cropping System
118 Experiment (MCSE) of the Kellogg Biological Station Long-Term Ecological Research site
119 (LTER) located in southwest Michigan (42°24' N, 85°24' W) in the northeastern portion of the
120 U.S. Corn Belt. The mean annual air temperature at KBS is 10.1 °C, ranging from a monthly
121 mean of -9.4 °C in January to 28.9 °C in July. Rainfall averages 1027 mm yr⁻¹, evenly
122 distributed seasonally; potential evapotranspiration exceeds precipitation for about four months
123 of the year. Loam soils are well-drained Typic Hapludalfs developed on glacial outwash with
124 soil carbon contents around 1% C (Syswerda et al., 2011). More site-specific details are available
125 in Robertson and Hamilton (2015).

126 Within our experiment, we compare Conventional tillage and Continuous no-till management
127 systems. These are two of seven treatments that are part of the MCSE that was established in
128 1989 and includes four annual and three perennial cropping systems. Each cropping system is
129 replicated as 1 ha plots in six blocks and is intended to represent a model ecosystem relevant to
130 agricultural landscapes of the region (Gage et al., 2015). The four annual cropping systems are
131 arranged along a gradient of decreasing chemical and management inputs in such a way that
132 differences along the management intensity gradient can be understood, predicted, simulated
133 (Basso & Ritchie, 2015), and extended to row-crop ecosystems in general. The two annual
134 cropping systems are managed as corn (*Zea mays* L.), soybean (*Glycine max* L.), and wheat
135 (*Triticum aestivum* L.) rotations such that a single crop is grown each year. Conventional tillage
136 represents a management system practiced by many farmers in the region: standard varieties
137 planted with conventional tillage and with chemical inputs at rates recommended by university
138 and industry consultants. Conventional tillage consisted of moldboard plowing in the spring from
139 1989 to 1998, and chisel plowing in the spring from 1999 to present. Additional tillage consisted

140 of disking before winter wheat planting. No-till management is identical to the Conventional
141 system except for tillage and herbicide applications. A no-till planter was used to drill seed
142 directly into untilled soil through existing crop residue without primary or secondary tillage.
143 When prescribed, additional herbicide is used to control weeds that would otherwise be
144 suppressed by tillage. The system has been managed without tillage since its establishment in
145 1989 (Figure 1). Other than tillage and herbicide inputs, both treatments are managed identically
146 as described in Robertson and Hamilton (2015).

147 Site history prior to 1989 consisted of mixed agricultural and horticultural cropping for
148 100+ years, with the most recent years prior to experiment establishment dominated by
149 conventionally managed continuous corn production. In 2009, soybean varieties were changed
150 from conventional to transgenic (glyphosate resistant) and in 2011 corn varieties changed from
151 conventional to transgenic (glyphosate, European corn borer, and root worm resistant),
152 consequently reducing the expense of post planting agrichemical management. Detailed
153 descriptions of the other treatments not used in this study, management protocols, and site
154 history are provided in Robertson and Hamilton (2015).

155 **2.2 Time needed to detect effects of management change**

156 To test the time required to detect the effects of conversion from conventional tillage to
157 continuous no-till (Question 1), we examined both environmental responses and relative
158 profitability in Conventional and No-till treatments over a 29-year period from 1989 to 2017.
159 Wheat, soybean, and corn were typically harvested in June, October, and November,
160 respectively, although some deviations occurred due to weather and crop maturity. Grain from
161 each block replicate (N=6) was dried at 60 °C for at least 48 h, weighed, and reported as Mg/ha
162 at standard moisture.

163 We also assessed the effect of tillage on soil water availability and N₂O gas fluxes, our
164 environmental response variables. Soil water availability affects microbial activity, carbon and
165 nutrient availability and movement, and plant growth (Lal, 2004). Soil water availability was
166 determined gravimetrically by drying 40 grams of fresh soil from each replicate (N=6) at 60° C
167 for 48 hours. Samples were collected each month when soil was not frozen (typically April-
168 November) at each of 5 sampling stations per block using sampling (push) probes (2 cm dia., 25
169 cm depth) or by bucket auger (5 cm dia., 25 cm depth) when the soil is too dry to use push
170 probes. After drying, samples were reweighed, and gravimetric soil water availability was
171 calculated as the difference between fresh and dry weight, expressed as dry weight (g H₂O/g dry
172 soil) (www.lter.kbs.msu.edu). Soil water availability was then averaged across subsamples to
173 produce a single value, per block, per year, per treatment to use in analysis.

174 Nitrous oxide (N₂O) is an ozone depleting greenhouse gas (Ravishankara et al., 2009)
175 and agricultural soil management is the largest anthropogenic source of N₂O emissions globally
176 (Paustian et al., 2016). N₂O gas measurements were made using static chambers (Livingston &
177 Hutchinson, 1995) at weekly to monthly intervals when soils were not frozen between 1991 and
178 2017 (Gelfand et al., 2016). In situ static (closed-cover) flux chambers were 28 cm dia. × 26 cm
179 high and consisted of a cylindrical metal base and an airtight plastic lid. Single chambers were
180 located in four of the six blocks of each tillage treatment, thus models are formed from the
181 average of weekly to monthly measurements in four replicates per year, rather than six, as in the
182 cases of yield and soil water availability. Chamber lids were placed on semi-permanent
183 aluminum bases removed only for cropping activities and accumulated headspace was sampled
184 four times over 120 minutes. All chambers were sampled on the same dates, although no data are
185 available for 1995. Samples were stored in 3-mL crimp-top vials and analyzed in the laboratory

186 for N₂O, with the flux for each chamber calculated as the linear portion of the gas accumulation
187 curve for that chamber. Nitrous oxide was analyzed by gas chromatography using a 63Ni
188 electron capture detector. More details appear in Gelfand et al., 2016.

189 To test for tillage related changes in crop yield, soil water availability, and N₂O fluxes
190 over our 29-year period, we fit linear mixed effects models to the data using crop (corn, soybean,
191 wheat) and block (1-6 for crop yield and soil water availability, 1-4 for N₂O fluxes) as fixed
192 variables, year as a random variable, and difference in crop yield, soil water availability, and
193 N₂O fluxes as response variables with the ‘lmer4’ package in R (Bates et al., 2015). We then
194 executed a power analysis for our linear mixed effects models through simulation with a
195 traditional alpha value of 0.05, 1000 simulations, and power of 0.8, using the ‘simr’ package in R
196 (Green et al., 2016). We also executed a second power analysis at a more liberal alpha value for
197 comparison (alpha = 0.2, a lower, less confident level of significance). This value may better
198 represent realistic expectations of farmers, who may accept losses as frequently as one in five
199 years, or 20% of the time.

200 **2.3 Recuperating implementation and maintenance expenses**

201 To answer our second question, comparing the expenses of implementation and
202 management of the two tillage systems, we used a partial budgeting relative profitability analysis
203 combined with a moving window approach. We determined the relative profitability impacts of
204 no-till management as the difference in annual gross margins between Conventional till and No-
205 till treatments (Cimmyt & Cimmyt, 1988). Gross margins were calculated as annual crop grain
206 yield multiplied by current year crop price (\$/kg) minus costs that varied between the two
207 treatments. We subdivided the gross margins by tracking differences in crop revenues and
208 expenses between the treatments. For revenues, we determined differences in yield as described

209 in Section 2.1 and crop prices as the U.S. monthly average price received for corn, soybean, and
210 wheat at time of harvest (December, November, and June, respectively) (FarmDoc, 2019) (Table
211 S1).

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

222 Conventional tillage expenses included the custom rates for tillage (moldboard or chisel
223 plow), soil finishing, and planting. No-till expenses included custom rates for planting, spraying,
224 and mowing. Custom work estimates included the expense of labor, fuel, and equipment rental.
225 Custom rates in Michigan were compared to those calculated for Iowa between 1995-2014
226 (Edwards & Johanns, 2014), and were found to follow similar trajectories over time. Finally,
227 differences in revenue (\$/ha) and expense (\$/ha) were converted from different time periods to
228 present values (base year 2017) using the present value formula: $PV=FV(1+i)^n$, where “ PV ” is
229 present value, “ FV ” is future value, “ i ” is interest rate (we used 5%), and “ n ” is the number of
230 years. Derivation of value estimates of expenses and revenue by year are given in supplemental
231 materials (Table S1). We determined accumulated expenses, revenue, and difference between

232 treatments (No-till – Conventional) to determine when No-till blocks recuperated initial
233 implementation and ongoing maintenance expenses. To fit the plotted data, we estimated model
234 curves using third order polynomials: $USD/ha = a*Year + b* Year^2 + c* Year^3$, where 'a', 'b',
235 and 'c' are coefficients (estimates provided in Table S2).

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

254 investigate the relationships among relative profitability trend consistency, direction, and
255 magnitude with study duration.

256 **2.4 Trend consistency**

257 To investigate our third question, concerning the variability of trends in our long-term
258 dataset, we used the same response variables described in Section 2.2 (yield, soil water
259 availability, and N₂O fluxes) and a moving window approach, described in Section 2.3.
260 Conceptually, this provides a trajectory of the relationship of each response variable with time,
261 and describes how the fit of linear mixed effects model results vary with different sample
262 periods, start years, and durations. The direction and magnitude of statistically significant slopes
263 are plotted against corresponding window length (number of years) to investigate the relationship
264 between trend consistency, direction, and magnitude with study duration.

265 **3 RESULTS**

266 **3.1 Summary of study site and treatments**

267 Between 1989 and 2017, differences in corn yield between treatments (No-till –
268 Conventional) ranged from -3.57 Mg/ha in 1999 to 2.91 Mg/ha in 2008 and averaged 0.68 Mg/ha
269 (SE: 0.017). Differences in soybean yield (No-till – Conventional) ranged from -2.68 Mg/ha in
270 1994 to 1.07 Mg/ha in 2006 and averaged 0.306 Mg/ha (SE: 0.007). Differences in wheat yield
271 (No-till – Conventional) ranged from -4.14 Mg/ha in 2001 to 1.62 Mg/ha in 2010 and averaged
272 0.042 Mg/ha (SE: 0.001). Over the same time period, differences in soil water availability
273 between the two treatments across crop types (No-till – Conventional) ranged from -0.026 g
274 H₂O/g dry soil in 1990 to 0.05 g H₂O/g dry soil in 2013 and averaged 0.02 g H₂O/g dry soil (SE:
275 0.002). Differences in N₂O gas fluxes between the two treatments across crop types (No-till –

276 Conventional) ranged from -4.3 g N₂O-N ha⁻¹ d⁻¹ in 2007 to 6.9 g ha⁻¹ day⁻¹ in 2000 and averaged
277 0.4 g ha⁻¹ d⁻¹ (SE: 0.2).

278 **3.2 Time needed to detect effects of management change**

279 We found a significant positive relationship between window duration and difference in
280 crop yield between No-till and Conventionally managed treatments (Estimate: 0.043, T: 4.96, P
281 < 0.001) (Figure 2a). Further, we found a significant positive relationship between differences in
282 soil water availability between No-till and Conventionally managed treatments and duration
283 (Estimate 0.0003, T: 4.005, P < 0.001) (Figure 2b). Lastly, we found a non-significant
284 relationship between differences in N₂O fluxes between No-till and Conventionally managed
285 treatments and window duration (Estimate: -0.012, T: -0.39, P: 0.70) (Figure 2c).

286 In a conservative power analysis, we found that with a calculated effect size of 0.043
287 Mg/ha/year, alpha of 0.05, and power of 0.8, it would take at least 19 years to detect a significant
288 effect of the No-till treatment on crop yield using a linear mixed effects model. Likewise, with a
289 calculated effect size of 0.0003 g H₂O/g dry soil/year, it would take 25 years to detect a
290 significant effect of the No-till treatment on soil water availability. Lastly, even with a calculated
291 effect size of -0.012 N₂O-N ha⁻¹ d⁻¹ year⁻¹, we would not see a significant effect of the No-till
292 treatment on N₂O flux (Table 1a). Using a more liberal alpha value that better represents the
293 expectations of farmers (alpha = 0.2), we found that long-term datasets on differences in yield
294 and soil would take 16 and 19 years to detect significant effects of No-till management on crop
295 yield and soil water availability, respectively (Table 1b).

296 **3.3 Recuperating implementation and maintenance expenses**

297 Because the relative cost of no-till flattened out over time while crop yields under no-till
298 increasingly gained over conventional tillage, the accumulated expenses (\$/ha) of No-till

299 compared to Conventional did not grow as fast as the accumulated revenue. Hence, gross
300 margin differences reveal that while No-till was a money loser in early years, by the end of 2002
301 (13 years after implementation), No-till recuperated initial losses at our site. By 2017, over the
302 29-year period, No-till had accumulated nearly \$2,000/ha in differences in relative profitability
303 as measured by partial budgets (Figure 3, Table S1, Table S2). Using the moving window
304 algorithm on the partial budgeting analysis of relative profitability, we see that of the 379
305 windows formed, 338 were significant at the $p < 0.05$ level. While most trends were positive, of
306 windows between 3 and 10 years long, 37% (57/156) were negatively trending, 19% (26/137) of
307 windows between 11 and 20 years long were negatively trending, and of the windows between
308 21-29 years long none (0/46) were negatively trending (Figure 4, Table 2).

309 **3.4 Trend consistency**

310 The moving window algorithm formed 379, 379, and 142 windows of lengths between
311 three and 29 years for our long-term datasets (difference in yield, soil water availability, and N₂O
312 fluxes, respectively). Addressing our last question concerning the consistency of trends, we
313 found that for differences in yield, 250 windows had a positive slope (66%) and 129 windows
314 had a negative slope (34%). Of the positive trending windows, 170 were significant at the alpha
315 <0.05 level; of the negative trending windows, 12 were significant. (Figure 5a, Table 3). For soil
316 water availability, we found that 299 windows had a positive slope (79%) and 80 windows had a
317 negative slope (21%). Of the positive trending windows, 128 were significant; of the negative
318 trending windows, 11 were significant (Figure 5b, Table 3). Lastly, for N₂O fluxes, of the 142
319 windows, we found 65 windows were positively trending (46%), 77 were negatively trending
320 (54%), and three of the positive windows and seven of the negative windows were found to be
321 significant (Figure 5c, Table 3).

322 **4 DISCUSSION**

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

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

342 We also show that longer periods of implementation increase the likelihood that continuous
343 no-till management becomes more profitable than tillage. Immediately following
344 implementation of no-till management (periods between 3 and 10 years) more than one third of

345 periods resulted in the loss of net revenue (37%). However, as periods became longer, the
346 likelihood of greater relative profitability increased. In fact, for periods between 11 and 20 years,
347 fewer than 20% of periods lost revenue, and for periods between 21 and 29 years, all periods
348 were profitable. Overall, 86% of periods greater than 10 years were profitable. Were value
349 assigned to the environmental benefits of continuous no-till (i.e. carbon sequestration, reduced
350 nitrate leaching, etc.) the economic profits would further increase (Lal et al., 1994; Constantin et
351 al., 2010).

352 Investigating trend consistency, we found that nine out of 45 significant results for
353 periods shorter than 10 years support a negative relationship between continuous no-till and the
354 difference in yield over time (20%), in direct contradiction to the positive pattern we observed.
355 Only analyses performed on periods 10 years or longer resemble more closely the broader
356 positive pattern. The positive pattern between yield and management regime at longer time
357 scales is echoed throughout other studies (Martínez et al., 2016; Sindelar et al., 2015; Gaudin et
358 al., 2015; Al-Kaisi et al., 2015; among others). Further, 31% (11/35) of the analyses on periods
359 shorter than 10 years indicate a statistically significant negative relationship for soil water
360 availability over time, in direct contradiction to the relationship suggested by longer periods.
361 Among the periods tested for N₂O fluxes, 10 of 142 were found to contain a statistically
362 significant trend (seven negative and three positive). This low detection of significant trends is
363 consistent with recent N₂O flux meta-analyses (e.g., van Kessel et al., 2013), where only for
364 studies greater than 10 years duration, particularly in drier climates, were trends of lower fluxes
365 in no-till than conventional management significant. Results from our study suggest that such a
366 trend may take substantially longer (perhaps scores of decades) to detect, likely in part due to
367 relative increases in N₂O fluxes for the rotation's corn and soybean years' offsetting decreases in

368 wheat years (Gelfand et al., 2016). In fact, consistent trends may not emerge until the rotation or
369 some other important aspect of agricultural management changes, such as fertilizer rate
370 (Shcherbak et al., 2014). Nevertheless, in our study continuous no-till does not (yet) have
371 consistent detectable effect on N₂O fluxes, as noted for earlier shorter-term analyses (Robertson
372 et al., 2000; Grandy et al., 2006; Gelfand et al., 2016). The importance of N₂O's contribution to
373 the global warming impact of intensive cropping systems underscores the importance of better
374 understanding time-dependent trends (Six et al., 2004).

375 Our results show that even in the absence of an overarching trend, spurious relationships in
376 temporal processes or short-term trends associated with stochastic processes are common in
377 tillage systems. Thus, the conflicting trends and predictions noted in previous studies concerning
378 the impact of tillage on crop yield, soil water availability, and N₂O fluxes may be explained, at
379 least in part, by their durations: strong, statistically significant relationships between parameters
380 and duration may have been the result of high variation in the system over shorter time periods.
381 This phenomenon of confident though misleading results highlights the importance of long-term
382 studies for detecting trends and informing robust, accurate management recommendations.

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

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

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

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

413 **5 CONCLUSIONS**

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

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432

433 **7 DATA SHARING AND ACCESSIBILITY STATEMENT**

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

435 Supporting information is available as supplementary data.

436

437 **8 REFERENCES**

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

441

442 Bahlai, C. (2019). GitHub, bad_breakup. https://github.com/cbahlai/bad_breakup (accessed 20
443 March 2019)

444

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

447

448 Basso, B., & Ritchie, J.T. (2015). Simulating crop growth and biogeochemical fluxes in response
449 to land management using the SALUS model. *The ecology of agricultural landscapes: long-term research on the path to sustainability*. *Oxford University Press*, New York, NY
450 USA, 252-274.

452

453 Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models
454 Using lme4. *Journal of Statistical Software*, **67**, 1-48. DOI:10.18637/jss.v067.i01

455

456 Bolliger, A., Magid, J., Amado, J.C., Neto, F.S., dos Santos Ribeiro, M.D., Calegari, A., Ralisch,
457 R., & de Neergaard, A. (2006). Taking stock of the Brazilian “Zero-Till Revolution”: A
458 Review of Landmark Research and Farmers' Practice. *Advances in Agronomy*, **91**, 47-
459 110. DOI: 10.1016/S0065-2113(06)91002-5

460

461 Choudhary, M.A., & Baker, C.J. (1994). Overcoming constraints to conservation tillage in New
462 Zealand. Conservation Tillage in Temperate Agro-ecosystems. *Lewis Publisher*, Boca
463 Raton, USA.

464

465 Claassen, R., M., Bowman, J., McFadden, D., & Wallander S. (2018). Tillage Intensity and
466 Conservation Cropping in the United States. Economic Research Service, U.S.
467 Department of Agriculture. <https://www.ers.usda.gov/webdocs/publications/90201/eib-197.pdf?v=1783.8>

468

469

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

473

474 Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., & Beaudoin, N.
475 (2010). Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen
476 leaching and balance in three long-term experiments. *Agriculture, ecosystems &*
477 *environment*, **135**, 268-278. DOI: 10.1016/j.agee.2009.10.005

478

479 DeLonge, M. S., Miles, A., & Carlisle, L. (2016). Investing in the transition to sustainable
480 agriculture. *Environmental Science & Policy*, **55**, 266-273. DOI:
481 10.1016/j.envsci.2015.09.013

482

483

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

487

488 Edwards, W., & Johanns, A. (2014). Iowa Farm Custom Rate Survey. Iowa State University
489 Extension and Outreach, Ag Decision Maker file C2-21/FM-1698.
490 www.extension.iastate.edu/agdm/ (Accessed 20 March 2019)

491

492 FarmDoc (2019). US Average Farm Price Received Database.
493 http://www.farmdoc.illinois.edu/manage/uspricehistory/us_price_history.html (accessed
494 20 March 2019)

495

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

499

500 Gage, S.H., Doll, J.E., & Safir, G.R. (2015). A crop stress index to predict climatic effects on
501 row-crop agriculture in the US North Central Region. *The ecology of agricultural*
502 *landscapes: Long-term research on the path to sustainability*, 77-103.

503

504 Gelfand, I., Shcherbak, I., Millar, N., Kravchenko, A.N., & Robertson, G.P. (2016). Long-term
505 nitrous oxide fluxes in annual and perennial agricultural and unmanaged ecosystems in
506 the upper Midwest USA. *Global Change Biology*, **22**, 3594-3607. DOI
507 10.1111/gcb.13426

508

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

512

513 Green, P., & MacLeod, C.J. (2016). SIMR: A R package for power analysis of generalized linear
514 mixed models by simulation. *Methods in Ecology and Evolution*, **7**, 493-498. DOI:
515 10.1111/2041-210X.12504

516

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

520

521 Kladivko, E.J. (2001). Tillage systems and soil ecology. *Soil and Tillage Research*, **61**, 61-76.
522 DOI: 10.1016/S0167-1987(01)00179-9

523

524 Krause, M.A., & Black J.R. (1995). Optimal Adoption Strategies for No-Till Technology in
525 Michigan. *Review of Agricultural Economics*, **17**, 299-310. DOI: 10.2307/1349575

526

527 Lal, R., Logan, T.J., Eckert, D.J., Dick, W.A., Shipitalo, M.J., (1994). Conservation tillage in the
528 corn belt of the United States. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate
529 Agroecosystems. *Lewis Publishers*, Boca Raton, FL, 73–114.

530

531 Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, **123**, 1-22. DOI
532 10.1016/j.geoderma.2004.01.032

533

534 Lal, R., Reicosky, D. L., & Hanson, J.D. (2007a). Evolution of the plow over 10,000 years and
535 the rationale for no-till farming. *Soil and Tillage Research*, **93**, 1-12. DOI:
536 10.1016/j.still.2006.11.004

537

538 Lal, R., Follett, R.F., Stewart, B.A., & Kimble, J.M. (2007b). Soil carbon sequestration to
539 mitigate climate change and advance food security. *Soil Science*, **172**, 943-56. DOI:
540 10.1097/ss.0b013e31815cc498

541

542 Livingston, G.P., & Hutchinson, G.L. (1995). Enclosure-based measurement of trace gas
543 exchange: applications and sources of error. *Biogenic trace gases: measuring emissions*
544 *from soil and water*, **51**: 14-51.

545

546 Martínez, I., Chervet, A., Weisskopf, P., Sturny, W. G., Etana, A., Stettler, M., & Keller, T.

547 (2016). Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop

548 yield, soil organic carbon and nutrient distribution in the soil profile. *Soil and Tillage*

549 *Research*, **163**, 141-151. DOI: 10.1016/j.still.2016.05.021

550

551 Michigan State University, Department of Agricultural Food and Resource, Economics (2019).

552 https://www.canr.msu.edu/afre/centers_services/economic_analysis_of_sustainable_ag_food_systems/useful_data_sources (accessed 20 March 2019)

554

555 Michigan State University, Kellogg Biological Station (2019). KBS LTER Data Catalog.

556 <https://lter.kbs.msu.edu/datatables> (accessed 20 March 2019)

557

558 Noordzij, M., Tripepi, G., Dekker, F.W., Zoccali, C., Tanck, M. W., & Jager, K.J. (2010).

559 Sample size calculations: basic principles and common pitfalls. *Nephrology*

560 *Dialysis Transplant*, **25**, 1388-1393. DOI: 10.1093/ndt/gfp732

561

562 NRC (National Research Council (2003). Frontiers in agricultural research. Food, health,

563 environment, and communities. National Academy Press, Washington DC, USA.

564

565 Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van

566 Noordwijk, M., & Woomer, P.L. (1997). Agricultural soils as a sink to mitigate CO₂

567 emissions. *Soil Use and Management*, **13**, 230-244. DOI: 10.1111/j.1475-

568 2743.1997.tb00594.x

569

570 Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., & Smith, P. (2016). Climate-
571 smart soils. *Nature*, **532**, 49. DOI: 10.1038/nature17174

572

573 Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van
574 Gestel, N., Six, J., Venterea, R.T., & van Kessel, C. (2015). When does no-till yield
575 more? A global meta-analysis. *Field Crop Research*, **183**, 156-68. DOI:
576 10.1016/j.fcr.2015.07.020

577

578 Rasmussen, P.E., Goulding, K.W.T., Brown, J.R., Grace, P.R., Janzen, H.H., & Korschens M.
579 (1998). Long-term agroecosystem experiments: assessing agricultural sustainability and
580 global change. *Science*, **282**, 893-896. DOI: 10.1126/science.282.5390.893

581

582 Rathke, G.W., Wienhold, B.J., Wilhelm, W.W., & Diepenbrock, W. (2007). Tillage and rotation
583 effect on corn–soybean energy balances in eastern Nebraska. *Soil and Tillage Research*,
584 **97**, 60-70. DOI: 10.1016/j.still.2007.08.008

585

586 Ravishankara, A.R., Daniel, J.S., & Portmann, R.W. (2009). Nitrous oxide (N₂O): the dominant
587 ozone-depleting substance emitted in the 21st century. *Science*, **326**, 123-125. DOI:
588 10.1126/science.1176985

589

590 Reicosky, D.C., Kemper, W.D., Langdale, G., Douglas, C.L., & Rasmussen, P.E. (1995). Soil
591 organic matter changes resulting from tillage and biomass production. *Journal of Soil and*
592 *Water Conservation*, **50**, 253-61.

593

594 Robertson, G.P., Allen, V.G., Boody, G., Boose, E.R., Creamer, N.G., Drinkwater, L.E., Gosz,
595 J.R., Lynch, L., Havlin, J.L., Jackson, L.E., & Pickett, S.T. (2008). Long-term
596 agricultural research: a research, education, and extension imperative. *BioScience*, **58**,
597 640-645. DOI:10.1641/B580711

598

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

603

604 Robertson, G. P., Paul E. A., & Harwood R. R. (2000). Greenhouse gases in intensive
605 agriculture: contributions of individual gases to the radiative forcing of the atmosphere.
606 *Science*, **289**, 1922-1925. DOI: 10.1126/science.289.5486.1922

607

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

611

612 Shcherbak, I., Millar, N., & Robertson, G. P. (2014). Global meta-analysis of the nonlinear
613 response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. *Proceedings of the*
614 *National Academy of Sciences*, **111**, 9199-9204. DOI: 10.1073/pnas.1322434111

615

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

619

620 Six, J., Ogle, S.M., Jay Breidt, F., Conant, R.T., Mosier, A.R., & Paustian, K. (2004). The
621 potential to mitigate global warming with no-tillage management is only realized when
622 practised in the long term. *Global Change Biology*, **10**, 155-160. DOI: 10.1111/j.1529-
623 8817.2003.00730.x

624

625 Spiegel, S., Bestelmeyer, B.T., Archer, D.W., Augustine, D.J., Boughton, E.H., Boughton, R.K.,
626 Cavigelli, M.A., Clark, P.E., Derner, J.D., Duncan, E.W., Hapeman, C., Harmel, D.H.,
627 Heilman, P., Holly, M.A. , Huggins, D.R., King, K., Kleinman, P.J.A., Liebig, M.A.,
628 Locke, M.A., McCarty, G.W. , Millar, N., Mirsky, S.B., Moorman, T.B., Pierson, F.B.,
629 Rigby, J.R., Robertson, G.P., Steiner, J.L., Strickland, T.C., Swain, H.M., Wienhold, B.J.,
630 Wulfhorst, J.D., Yost, M.A., & Walthall, C.L. (2018). Evaluating strategies for
631 sustainable intensification of US agriculture through the Long-Term Agroecosystem
632 Research network. *Environmental Research Letters*, **13**, 034031. DOI: 10.1088/1748-
633 9326/aaa779

634

635 Swinton, S.M., & King R.P. (1991). Evaluating Robust Regression Techniques for Detrending
636 Crop Yield Data with Non-normal Errors. *American Journal of Agricultural Economics*,
637 73, 446-45. DOI: 10.2307/1242729

638

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

642

643 USDA (2019). National Agricultural Statistics Service. <https://quickstats.nass.usda.gov/>
644 (accessed 20 March 2019)

645

646 USDA (2020). Fiscal Year 2020 Budget Summary.
647 <https://www.obpa.usda.gov/budsum/fy2020budsum.pdf> (accessed 14 Jan 2020)

648

649 Van Deynze, B., Swinton S.M., & Hennessy D.A. (2018). Are Glyphosate-Resistant Weeds a
650 Threat to Conservation Agriculture? Evidence from Tillage Practices in Soybean. Paper
651 presented at Agricultural and Applied Economics Association. Washington, DC, August
652 5-7, 2018.

653

654 van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., & van Groenigen, K.J.
655 (2013). Climate, duration, and N placement determine N₂O emissions in reduced tillage
656 systems: a meta-analysis. *Global Change Biology*, 19, 33-44. DOI: 10.1111/j.1365-
657 2486.2012.02779.x

658

659 Wade, T., & Claassen, R. (2017). Modeling no-till adoption by corn and soybean producers:

660 Insights into sustained adoption. *Journal of Agricultural and Applied Economics*, **49**,

661 186-210. DOI:10.1017/aae.2016.48

662

663 White, E.R. (2019). Minimum time required to detect population trends: the need for long-term

664 monitoring programs. *BioScience*, **69**, 40-46. DOI: 10.1093/biosci/biy144









