9-1-2020

Benefits and tradeoffs of reduced tillage and manure application methods in a Zea mays silage system

Kyle M. Dittmer
University of Vermont

Heather M. Darby
University of Vermont

Tyler R. Goeschel
University of Vermont

E. Carol Adair
University of Vermont

Benefits and tradeoffs of reduced tillage and manure application methods in a Zea mays silage system

Article *in* Journal of Environmental Quality · July 2020

DOI: 10.1002/jeq2.20125

4 authors, including:

Heather Darby
University of Vermont

Carol Adair
University of Vermont

Received: 23 March 2020 | Accepted: 25 June 2020 | Published online: 16 August 2020

DOI: 10.1002/jeq2.20125

Journal of Environmental Quality

TECHNICAL REPORTS

Atmospheric Pollutants and Trace Gases

Benefits and tradeoffs of reduced tillage and manure application methods in a *Zea mays* silage system

Kyle M. Dittmer[1] | **Heather M. Darby**[2] | **Tyler R. Goeschel**[1,3] | **E. Carol Adair**[1]

[1] Global Change Biogeochemistry Lab., Rubenstein School of Environment and Natural Resources, Univ. of Vermont, Burlington, VT 05405, USA

[2] Univ. of Vermont Extension, St. Albans, VT 05478, USA

[3] Little Blue Natural Resources District, Davenport, NE 68335, USA

Correspondence
Kyle M. Dittmer, Global Change Biogeochemistry Lab., Rubenstein School of Environment and Natural Resources, Univ. of Vermont, Burlington, VT 05405, USA.
Email: kyle.dittmer@uvm.edu

Assigned to Associate Editor Curtis Dell.

Funding information
Office of Experimental Program to Stimulate Competitive Research, Grant/Award Number: EPS-1101317; Northeast SARE, Grant/Award Number: ONE15-228; National Institute of Food and Agriculture, Grant/Award Number: 2015-67020-23180

Abstract

A critical question is whether there are agricultural management practices that can attain the multiple management goals of increasing yields, preventing nutrient losses, and suppressing greenhouse gas (GHG) emissions. No-till and manure application methods, such as manure injection, can enhance nutrient retention, but both may also enhance emissions of nitrous oxide (N_2O), a powerful GHG. We assessed differences in soil N_2O and carbon dioxide (CO_2) emissions, nitrate and ammonium retention, and crop yield and protein content under combinations of vertical-till, no-till, manure injection, and manure broadcast without incorporation in a corn (*Zea mays* L.) silage system. During the growing seasons of 2015–2017, GHG emissions and soil mineral nitrogen (N) were measured every other week or more frequently after management events. Crop yield and protein content were measured annually at harvest. No-till reduced CO_2 emissions but had no impact on N_2O emissions relative to vertical-till. Manure injection increased N_2O and CO_2 emissions, with the magnitude of this effect being greatest for 1 mo post-application. Manure injection also increased soil ammonium and nitrate but did not increase yield or crop quality relative to broadcast application. Similarly, tillage did not affect crop yield or protein content. Despite the tradeoffs between mineral N retention and elevated GHG emissions, manure injection in no-till systems benefits farmers by reducing soil carbon losses as CO_2, retaining mineral N, and maintaining crop yields and quality.

1 | INTRODUCTION

Under traditional agricultural management, pressure to feed a growing population may degrade soils, exacerbate nutrient pollution, and enhance greenhouse gas (GHG) emissions by increasing fertilizer inputs and cultivation (Foley et al., 2011). Traditional agriculture has decreased soil organic carbon (SOC) by 40–75% (Lal, 2004), ultimately increasing carbon dioxide (CO_2) fluxes to the atmosphere (Houghton et al., 1983). Furthermore, agriculture is responsible for >60% of nitrous oxide (N_2O) emissions; N_2O is a GHG 265–298 times more powerful than CO_2 at trapping heat (Myhre et al., 2013; Syakila & Kroeze, 2011). Given the potential for agricultural soils to be nutrient and GHG sources, many best management practices (BMPs) aim to retain nutrients and prevent transport into the atmosphere and surface or groundwater (Liu et al., 2017; Logan, 1993). However, because the primary goal of agricultural management is increasing crop productivity, a critical question is: Are there BMPs that can attain the multiple management goals of increasing yields, retaining nutrients, and suppressing GHG emissions?

Abbreviations: BMP, best management practice; GHG, greenhouse gas; PAS, photoacoustic spectroscopy; SOC, soil organic carbon.

Because GHG emissions and the fate of carbon (C) and nitrogen (N) within agricultural soils depend on soil and fertilizer management (Duncan, Dell, Kleinman, & Beegle, 2017; Flach, Barnwell, & Crossen, 1997; Lognoul et al., 2017; Plaza-Bonilla, Álvaro-Fuentes, Arrúe, & Cantero-Martínez, 2014; Wang & Dalal, 2015; Webb, Pain, Bittman, & Morgan, 2010), BMPs can be designed to retain added nutrients and reduce GHG emissions (Mangalassery et al., 2014; Ruidisch, Bartsch, Kettering, Huwe, & Frei, 2013). Best management practices affect nutrient retention and GHG emissions by altering their drivers. Nitrogen losses can be reduced by incorporating added N into soils to minimize gaseous and runoff losses (Daverede et al., 2004; Duncan et al., 2017; Kulesza, Maguire, Thomason, Hodges, & Pote, 2014) and maximize plant and microbial uptake, which are enhanced when water, temperature, and substrate (for microbes) are not limiting (Hart, Stark, Davidson, & Firestone, 1994; Sarker et al., 2017). Soil CO_2 flux, a combination of microbial and root respiration (Oertel, Matschullat, Zurba, Zimmermann, & Erasmi, 2016), increases with temperature (Lloyd & Taylor, 1994) and C availability (Hungate, Chapin, Zhong, Holland, & Field, 1997) as long as water is not limiting. Soil N_2O emissions are primarily from autotrophic nitrification or heterotrophic denitrification, which are controlled by C or N availability (ammonium [NH_4^+] for nitrification; SOC and nitrate [NO_3^-] for denitrification), temperature, pH, and oxygen (O_2) availability (Livesley, Kiese, & Graham, 2008; Mørkved, Dörsch, & Bakken, 2007). Thus, BMPs that alter soil microclimate, porosity, moisture or aggregation, and substrate availability (Robertson & Groffman, 2007) may affect nutrient retention and GHG emissions.

Two BMPs of interest for mitigating GHG emissions and nutrient losses while maintaining or enhancing yields are low- or no-till and manure injection. Vertical-till is a low-till method whereby only approximately 7 cm of the soil is tilled without soil profile inversion (vs. 25–33 cm for conventional-till with moldboard plow; S. Ziegler, personal communication, 2017). Another method is no-till, which can enhance soil aggregation, biological activity, and water retention (FAO, 2011; Six et al., 2002; Verhulst et al., 2010). No-till can also improve crop yields (Kassam et al., 2014), although yields may decline for 5–10 yr after converting from conventional-till (Derpsch et al., 2014; Rusinamhodzi et al., 2011). Low- and no-till can reduce SOC losses and CO_2 emissions (Alvarez, 2005; Giller et al., 2015; Paustian et al., 1997; Six et al., 2002), but recent evidence indicates C may be concurrently lost from deeper soils, resulting in no net C gain (Olson, Al-Kaisi, Lal, & Lowery, 2014; Powlson et al., 2014; Wendt & Hauser, 2013). Furthermore, no-till may increase N_2O emissions (Abdalla et al., 2013; Ball, Scott, & Parker, 1999; Burford, Dowdell, & Crees, 1981) by enhancing soil aggregation and water retention (Holland, 2003), creating the anaerobic conditions needed for denitrification.

Core Ideas

- No-till and manure injection aim to improve crop production while reducing soil N and C losses.
- Manure injection increased soil mineral N but also increased GHG emissions relative to broadcast application.
- No-till reduced CO_2 emissions relative to vertical-till without affecting crop production or N_2O emissions.

Another BMP of interest is manure injection, which may improve nutrient retention, crop uptake, and yield relative to conventional broadcast spreading without incorporation (Duncan et al., 2017; Sutton, Nelson, Hoff, & Mayrose, 1982) but may enhance GHG emissions (Adair, Barbieri, Schiavone, & Darby, 2019; Duncan et al., 2017). Because more than 50% of manure ammonium-N can be volatilized if not immediately incorporated (Maguire et al., 2011; Powell, Jokela, & Misselbrook, 2011), incorporation is a management priority, particularly in no-till. Traditionally, manure broadcasted on the soil surface is incorporated by moldboard or chisel plow. Manure injection places manure into the subsurface using coulters or chisels. In no-till systems, manure injection can reduce volatilization and runoff losses (Duncan et al., 2017; Meisinger & Jokela, 2000); it may also enhance GHG emissions, including N_2O (Chadwick, Pain, & Brookman, 2000; Dell, Meisinger, & Beegle, 2011; Lovanh, Warren, & Sistani, 2010), by concurrently increasing C and N substrates and promoting subsurface anaerobic zones (Bremner, 1997; Duncan et al., 2017; Xue et al., 2013).

Clearly, there are tradeoffs and uncertainties when considering BMPs. Few studies have investigated the interacting effects of combining BMPs. Even fewer have quantified tradeoffs among nutrient retention, GHG emissions, and crop quality and yields. Therefore, our objective was to determine the effects of combinations of BMPs (i.e., vertical-till, no-till, broadcast manure, and manure injection) on CO_2 and N_2O emissions, soil mineral N retention, and corn (*Zea mays* L.) silage yield and protein content. We hypothesized that injecting manure in a no-till system would increase C and N substrate availability for microbes under anaerobic conditions and would therefore increase N_2O emissions yet reduce CO_2 emissions by minimally disturbing the soil profile. We also hypothesized that the same treatment combination would increase crop yield and protein content by enhancing nutrient retention and availability. This study provides one of the first looks at how these BMPs combine to affect multiple management goals.

2 | MATERIALS AND METHODS

2.1 | Site description

The Manure Injection No Tillage (MINT) field trial in Alburgh, VT (45.005° N, 73.308° W), established in May of 2013, was continuous corn (*Zea mays* L.) silage with winter rye (*Secale cereal* L.) cover crop during the non-growing season. Prior to the trial, the field was conventional-till continuous corn with a winter rye cover crop and no manure application. The soil is a Benson rocky silt loam (loamy-skeletal, mixed, active, mesic Lithic Eutrudepts) formed in loamy till and is somewhat excessively to excessively drained with moderate permeability (Soil Survey Staff, 2017). Site measurements indicated that the soil was a sandy loam (hydrometer) with a bulk density of 1.2 g cm^{-3}; pH of 6.3; 4% organic matter; and average total C and N of 2.4 and 0.2%, respectively (June–July 2015; 0–10 cm).

The trial was a randomized complete block with a split-split plot arrangement (three blocks, two plot treatments, two subplot treatments). Within each block the plot (36.6 by 7.4 m) treatments were tillage treatments: no-till and vertical-till. Vertical-till was to a depth of 7.6 cm with a blade spacing of 18.4 cm (2623VT, John Deere). Each block included a 12.2-m buffer between tillage treatments. Each tillage treatment plot had two subplot (3.7 by 12.2 m) manure application treatments: injected and broadcast without incorporation. Liquid dairy manure was broadcasted or injected to a depth of 15–20 cm, but injection lines were typically filled to or just below (within 2–3 cm) the soil surface. Double-disk injection bands were approximately 10 cm wide, with 75 cm spacing between bands (NUTRI-JECTOR, Jamesway Farm Equipment Inc.). Each manure × tillage treatment combination (no-till plus injection, no-till plus broadcast, vertical-till plus injection, and vertical-till plus broadcast) was replicated three times (once in each of three blocks), for a total of 12 subplots (four per block). Manure characteristics, cropping, fertilization, and harvest details are in Table 1.

TABLE 1 Dates, manure characteristics/events, and cropping events for 2015–2017

Manure characteristics/events	2015	2016	2017
Tillage			
Date	15 May	17 May	12 May
Liquid dairy manure application			
Date	15 May	17 May	12 May
Rate, L ha^{-1}	58,929	56,123	57,994
Dry matter, %	8	3.84	4.7
Organic N, kg ha^{-1}	157.4	75.7	93.8
NH_4–N, kg ha^{-1}	74.1	53.3	56.3
Total N, kg ha^{-1}	230.8	128.9	150
Corn planting			
Date	18 May	19 May	18 May
Rate, seed ha^{-1}	83,980	83,980	83,980
Starter fertilizer (10–20–20)			
Date	18 May	19 May	18 May
Rate, kg ha^{-1}	280	224	224
Harvest			
Date	30 Sept.	21 Sept.	21 Sept.
Cover crop planting			
Date	31 Sept.	3 Oct.	6 Oct.
Rate, seed ha^{-1}	112	112	112
Cover crop termination[a]			
Date	15 May	17 May	12 May

[a]Cover crops terminated with glyphosate (7 L ha^{-1}).

2.2 | Nitrous oxide and carbon dioxide measurements

Soil N_2O and CO_2 emissions were measured every 2 wk from 6 June to 9 Nov. 2015, 11 Mar. to 18 Nov. 2016, and 19 Apr. to 26 Nov. 2017. Measurement frequency increased to every other day for a week after manure application, then once a week for a month. We measured fluxes with static chambers (one per subplot; n = 12) and an infrared photoacoustic spectroscopy (PAS) gas analyzer (Model 1412i, Innova Air Tech Instruments; calibrated as in Iqbal, Castellano, & Parkin, 2013). Polyvinyl chloride chamber collars (30 cm i.d., 15 cm height) were installed to a depth of 12 cm (Parkin & Venterea, 2010). Gas concentrations were recorded every minute for 10 min in each subplot by placing a vented polyvinyl chloride lid (30 cm i.d., 9.5 cm height) on the chamber collar with an air-tight seal connected to a closed-loop system with the PAS (e.g., as Iqbal et al., 2013). The PAS measures gas concentrations nondestructively; gases pass through the detector and returned to the chamber unaltered. Chambers were removed before management events and reinstalled randomly within subplots but were large enough to be placed to capture portions of the between- and within-corn row spaces; chambers were placed 1 m from subplot edges to avoid edge effects. Residues were allowed to remain in the chambers irrespective of tillage regime, but live vegetation was clipped at ground level and removed.

Gas fluxes were calculated by fitting a linear regression of concentration against time after chamber closure. The changes in N_2O and CO_2 were calculated as:

$$F = \frac{\Delta C}{\Delta t} * \frac{V}{A} * M * \rho\alpha$$

where F is the CO_2 (mg CO_2–C m^{-2} h^{-1}) or N_2O (mg N_2O–N m^{-2} h^{-1}) production rate, $\Delta C/\Delta t$ is the change in chamber gas concentration (10^6 mol^{-1} h^{-1}), V is chamber volume (0.00954 m^3), A is chamber surface area (0.0707 m^2), M is the molecular weight of CO_2 or N_2O (mg mol^{-1}), ρ is the density of gas at 20 °C and 0.101 MPa (1 mole per 24.04 m^3), and α is a conversion coefficient (28/44 for N_2O and 12/44 for CO_2).

2.3 | Soil sampling and analysis

Soil samples (0–15 cm) were collected during each gas sampling within one meter of the chamber. Samples were placed on ice for transportation to the laboratory. Within 24 h, we extracted 5-g field-wet soil subsamples with 2 M potassium chloride to determine availabile NO_3^- and NH_4^+ via colometric analysis (BioTek Synergy HTX, BioTek Instruments, Inc.). We also determined gravimetric soil moisture by drying a 5-g field-wet subsample at 60 °C to constant weight. At each gas sampling, soil temperature was recorded adjacent to each chamber.

2.4 | Crop analysis

To determine corn yield, the entire plot was harvested with a John Deere 3950 two-row chopper into a wagon equipped with an Avery Weigh-Tronix weighing system at a target cutting height of 15–20 cm. A 500-g sample from each subplot was collected and used to determine dry matter content (gravimetric) and crude protein concentration. A 500-g fresh whole-plant sample from each subplot was collected, weighed, dried at 60 °C for 7 d, and reweighed for dry matter. Dried samples were ground with a Wiley mill (Arthur H. Thomas Co.) to pass a 2-mm screen and with a cyclone forage mill (UDY Corporation) to pass a 1-mm screen. Ground samples were scanned on a Foss DS2500F near-infrared reflectance spectrophotometer system, and near-infrared reflectance calibrations obtained through the Dairy One Forage Laboratory were used to determine crude protein. Spectra were scanned between 400 and 2,500 nm every 2 nm using ISIScan software v.4.6.1 (Infrasoft Intl., LLC). All samples were scanned in duplicate to maximize spectral input and to minimize the impact of a poor scan.

2.5 | Statistical analysis

Daily CO_2 and N_2O emissions and soil NH_4^+ and NO_3^- were analyzed using linear mixed models that included (a) *subplot* as a random effect to account for nonindependent subplot measurements over time, (b) *date* as a factor to examine how treatment effects changed among days, (c) a constant variance function to account for heterogeneous errors among tillage (N_2O) or tillage and manure application treatments (NH_4^+ and NO_3^-; none for CO_2), and (d) two- and three-way interactions among *tillage*, *manure*, and *date*. Data were cube root (N_2O), Box-Cox (CO_2), or log (NH_4^+ and NO_3^-) transformed to meet normality assumptions. Daily CO_2 fluxes showed evidence of temporal correlation, so the model included an auto-regressive correlation structure. Cumulative growing season CO_2 and N_2O and crop yield and protein content (all untransformed) were analyzed with *subplot* as a random effect, a constant variance function for manure application and tillage treatments, and two- and three-way interactions among *tillage, manure,* and *year* (continuous).

To examine direct and indirect effects of management practices and hypothesized drivers of soil N and daily GHG emissions, we developed and compared structural equation models. Classical statistical techniques do not permit the investigation of causal relationships; however, the use of structural equation models develops causal understanding from data by testing networks of causal relationships (Figure 1) (Eisenhauer, Bowker, Grace, & Powell, 2015; Grace & Irvine, 2020; Grace et al., 2012). While relying on some correlative information, structural equation model approaches causal understanding (as in Shipley, 2002) by fitting data to models that represent alternative causal hypotheses (e.g., Supplemental Figure S1) and by testing and comparing model fit (based on model-implied vs. observed covariance matrices; Eisenhauer et al., 2015; Grace et al., 2006, 2012). Structural equation models may contain unidirectional causal relationships among variables (Figure 1; single-headed arrows) and correlations (Figure 1; double-headed arrows). Direct effects are indicated by one arrow linking two variables (e.g., direct effect of CO_2 on N_2O; Figure 1); indirect effects are where two variables are linked through one or more other variable(s) (e.g., indirect effect of Temp on N_2O via CO_2; Figure 1). Structural equation models also allow researchers to compare the strength of various pathways by using either standardized (values near 1 are strong; values near 0 are weak) or unstandardized path coefficients. Unstandardized path coefficients estimate the response of the variable of interest in the original units (e.g., g N_2O–N ha^{-1} d^{-1} for N_2O) to a one-unit increase in a driving variable (e.g., a 1 °C increase in soil

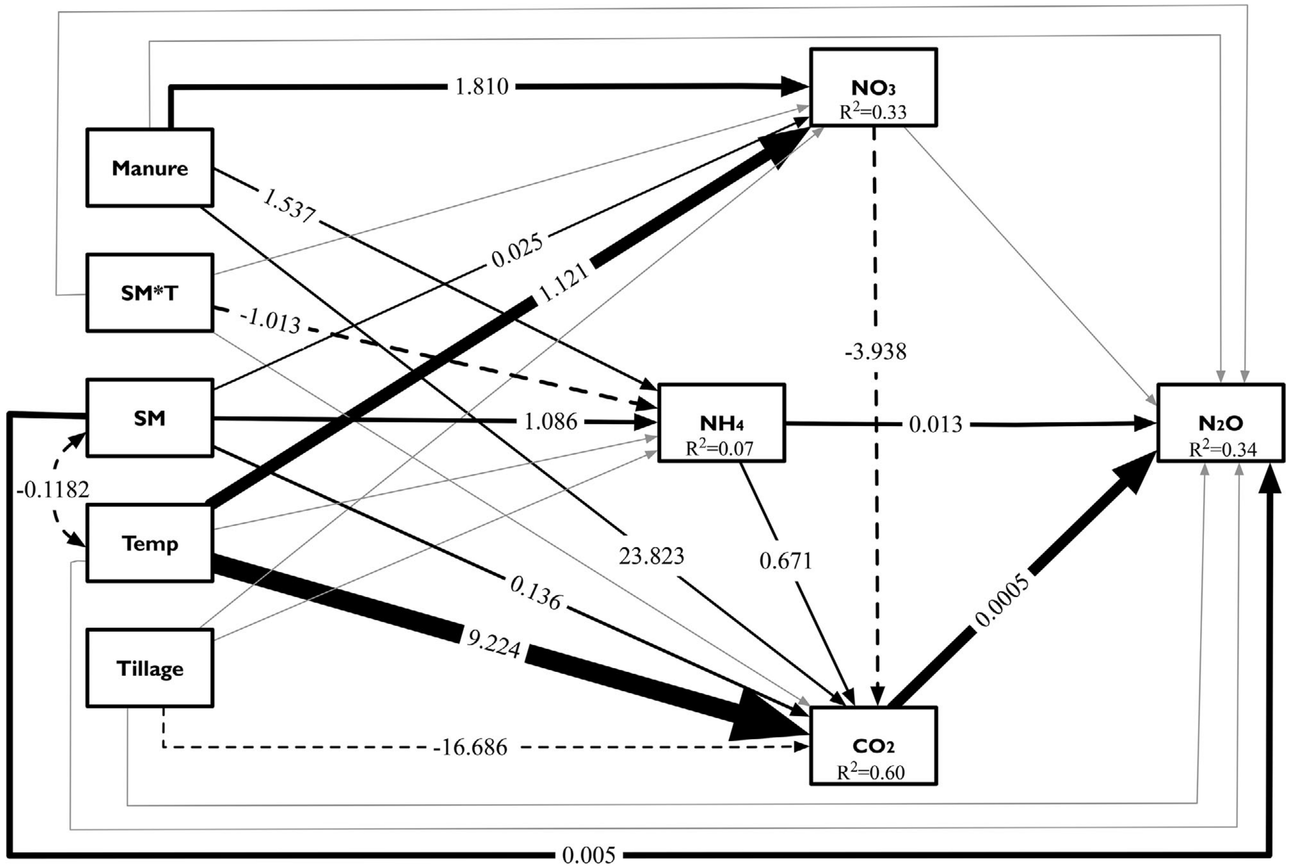

FIGURE 1 Best fit full structural equation model for daily greenhouse gas flux data and covariates. Single-headed arrows represent causal relationships; double-headed arrow denotes correlation between soil moisture (SM) and soil temperature (Temp). Arrows are scaled by standardized path coefficient values. Untransformed unstandardized path coefficients are shown. Dashed lines indicate negative and solid lines indicate positive path coefficients. Significant pathways are black arrows with path coefficients ($P < .05$). Gray arrows are nonsignificant pathways. SM*T, soil moisture × temperature interaction; Manure, manure treatment; Tillage, tillage treatment. Positive estimates for Tillage indicate that vertical-till increased the response variable relative to no-till. Positive estimates for Manure indicate that manure injection increased the response variable relative to broadcast

temperature) while holding all other variables constant at their average values.

Our three structural equation models had (a) the structure in Figure 1 or (b) the structure in Figure 1 plus an arrow from NH_4^+ to NO_3^- or (c) as (b) plus an arrow from manure and tillage treatments to soil moisture and temperature to test whether treatments altered soil microclimate (Supplemental Figure S1). In the structural equation models, data were transformed, and model structures were as in the ANOVAs. Because C availability, as it influences denitrification and N_2O fluxes, can be quantified as concurrent CO_2 fluxes (Farquharson & Baldock, 2008; Xu, Tian, & Hui, 2008), we included it as a driver of N_2O. Akaike's Information Criterion modified for small sample sizes (AIC_c) was used to select the best structural equation model. To choose the best model(s) we considered models with $dAIC_c \leq 2$ to have substantial support, where $dAIC_c$ is the difference between the model under consideration and the model with the lowest AIC_c value (Burnham & Anderson, 2002). When no single model was best, we chose the simplest model with a $dAIC_c < 2$ (i.e., the model with the fewest independent variables). Furthermore, we examined model fit using Fisher's C ($P > .05$ indicates good fit). Using the best structural equation model, we calculated total effects as the sum of statistically significant direct and indirect effects. To better understand each variable's impact on daily N_2O and CO_2 emissions, we multiplied the unstandardized total effect (transformed into original units; e.g., g N_2O–N ha^{-1} d^{-1}) by the maximum daily range of each variable. This provided an estimate of the maximum change in N_2O or CO_2 emissions (in g N_2O–N ha^{-1} d^{-1} or kg CO_2–C ha^{-1} d^{-1}) due to a model driver (e.g., temperature) within one day.

For cumulative GHG emissions, corn yield, and corn protein content, we did not have sufficient sample sizes to construct structural equation models (n = 36), so we constructed analysis of covariance (ANCOVA) models using the above-described ANOVA model structures and measured covariates: soil mineral-N, soil temperature, soil moisture, and, for N_2O, CO_2 flux. To characterize covariate availability or conditions throughout the growing season, we calculated the area under the curve (*trapz* function in *pracma* package; Borchers, 2019) during each growing season (15 May to 1 Sept.). The ANCOVAs did not include interactions among covariates or treatments and covariates, except for a soil temperature × moisture interaction.

All linear mixed effects models were fit using the *nlme* package in R Studio (Pinheiro, Bates, DebRoy, & Sarkar, 2018; R Development Core Team, 2008; RStudio Team, 2015). Treatment significance ($P < .05$) was assessed using F-tests. We fit structural equation models and calculated marginal and conditional R^2 values using *piecewiseSEM* (Lefcheck, 2016). Marginal R^2 describes the proportion of variance explained by fixed factors (e.g., manure, tillage, date). Conditional R^2 describes the proportion of variance explained by fixed and random factors (Nakagawa & Schielzeth, 2013).

3 | RESULTS AND DISCUSSION

3.1 | Manure injection increased nitrous oxide and carbon dioxide emissions

3.1.1 | Nitrous oxide emissions

Consistent with other research (Duncan et al., 2017; Flessa & Beese, 2000; Rubaek, Henriksen, Petersen, Rasmussen, & Sommer, 1996; Vallejo, García-Torres, Díez, Arce, & López-Fernández, 2005; Velthof, Kuikman, & Oenema, 2003; Wulf, Maeting, & Clemens, 2002), manure injection increased N_2O emissions but not on all days (significant ANOVA manure and manure by date effects; Supplemental Table S1). On average, daily N_2O emissions resulting from manure injection (107.9 ± 12.1 g N_2O–N ha^{-1} d^{-1}) were 2.4 times higher than those resulting from broadcast (45 ± 5.7 g N_2O–N ha^{-1} d^{-1}), but the impact of injection was greatest post-application, with N_2O emissions 4 times greater than broadcast (Figure 2b).

In the best structural equation model for the full growing season, manure application method only increased N_2O emissions indirectly by increasing NH_4^+ and CO_2 as an index of C availability (Farquharson & Baldock, 2008; Xu et al., 2008) (Figure 1). In the best structural equation model, manure and tillage treatments did not affect soil moisture and temperature (ANOVAs also indicated soil moisture and temperature were unaffected by treatments [Supplemental Tables S2–S4]). Two structural equation models had $dAIC_c$ <2. One included a nonsignificant pathway from NH_4^+ to NO_3^- ($dAIC_c = 1.9$), and the other did not ($dAIC_c = 0$; Supplemental Table S2). Of these, we selected the simpler model without a pathway from NH_4^+ to NO_3^- as the best model (Fisher's C $P = .817$; Supplemental Table S2). In this structural equation model, the total effect of injection across the growing season was small, increasing N_2O emissions by 0.03 g N_2O–N ha^{-1} d^{-1} relative to broadcast application (direct plus indirect effects; Supplemental Table S5). Soil moisture, CO_2 emissions, and available NH_4^+ had the largest impacts on N_2O emissions via direct and/or indirect effects (Figure 1). Across the maximum range of values for each variable measured within a day, increasing CO_2, soil moisture, and available NH_4^+ increased N_2O emissions by 109.2, 118.7, and 12.3 g N_2O–N ha^{-1} d^{-1}, respectively (Supplemental Table S5).

Manure injection had the greatest impact during pulse events (i.e., 1 mo after application), when manure application method had direct and indirect effects on N_2O emissions (Figure 3a; Supplemental Table S4). On average, daily N_2O emissions from injection soils were 9.4 g N_2O–N ha^{-1} d^{-1} greater than from broadcast during pulse events (Supplemental Table S4). Because manure is rich in C and N substrates for nitrification and denitrification (Table 1) (Firestone & Davidson, 1989), elevated post-injection N_2O emissions may be related to the addition of these substrates paired with a lack of soil aeration, which increases denitrification activity (Vallejo et al., 2005; Webb et al., 2010). The positive indirect impact of injection on N_2O emissions via CO_2 (Figure 3a) supports these ideas and suggests that injection may increase N_2O emissions by increasing C availability (Farquharson & Baldock, 2008; Xu et al., 2008) and by increasing microbial activity (e.g., the large post-application CO_2 fluxes; Figure 2c–d) and O_2 consumption to create anaerobic conditions (Van Groenigen et al., 2006). Furthermore, the direct positive effect of NH_4^+ (single-headed arrow from NH_4^+ to N_2O; Figure 3a) after application suggests that there may also be a role for nitrification in promoting N_2O emissions, particularly because NO_3^- had no direct effect on N_2O emissions despite NO_3^- being a precursor to N_2O via denitrification. However, nitrification is an autotrophic process, and the positive direct effect of CO_2 mineralization on N_2O (Figure 3a) suggests that denitrification, a heterotrophic process, likely also plays a role in N_2O production. Indeed, injection may promote coupled nitrification–denitrification by creating conditions favorable for nitrification on the outer edges of the manure slot, with denitrification taking place in anaerobic microsites within the manure (Comfort, Kelling, Keeney, & Converse, 1990). Apart from manure application, soil moisture and temperature interacted to directly affect N_2O (Figure 3a): At low soil moisture, increasing soil temperature had little or no effect on

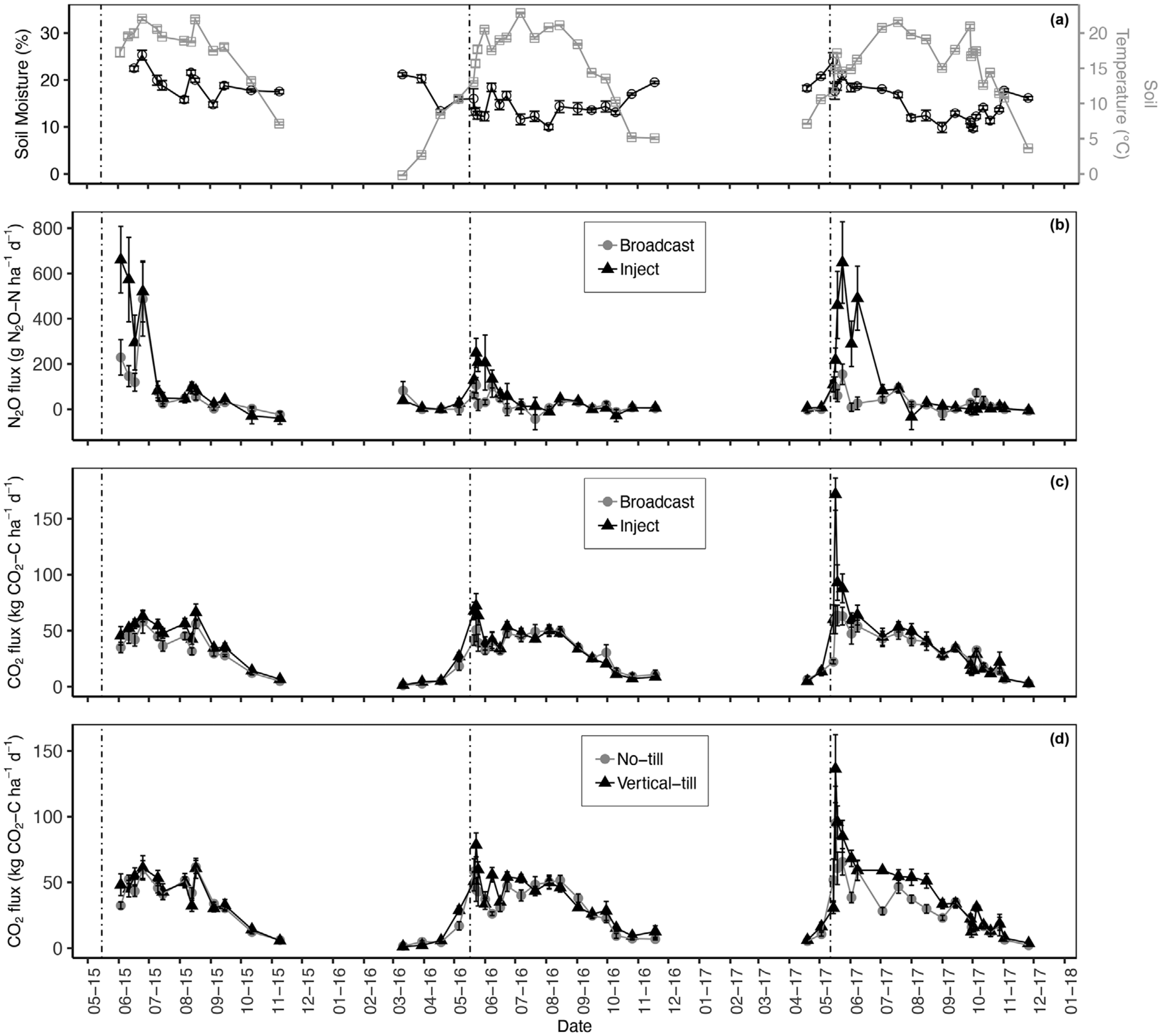

FIGURE 2 Daily (a) soil moisture (black line) and soil temperature (grey line) averaged across manure and tillage treatments, (b) N_2O fluxes and (c) CO_2 fluxes by manure application treatment, and (d) CO_2 fluxes by tillage treatment. Error bars are ±1 SE. Vertical dashed lines show manure application and tillage events

N_2O emissions, but at high soil moisture, N_2O emissions increased with temperature (Supplemental Figure S2). Carbon dioxide emissions and soil NH_4^+ also directly increased N_2O emissions by 22.5 and 8 g N_2O–N ha^{-1} d^{-1}, respectively, across the maximum daily range of values (Supplemental Table S5).

Later in the growing season, N_2O fluxes were low, and between-treatment differences became indistinguishable, as in Duncan et al. (2017). In the non-pulse structural equation model, manure application method had only small indirect effects on N_2O emissions (Figure 3b). During this time, N_2O emissions were directly increased only by soil moisture and available C (CO_2 flux), which increased N_2O emissions by 37.9 and 49.8 g N_2O–N ha^{-1} d^{-1}, respectively, across the maximum daily range (Supplemental Table S5). This suggests that these N_2O fluxes may have been associated with periods of high soil moisture and O_2 depletion that triggered small bursts of denitrification (Dobbie, McTaggart, & Smith, 1999; Robertson & Groffman, 2007; Sierra, Malghani, & Loescher, 2017; Smith et al., 2003).

On average, cumulative growing season N_2O emissions from manure injection (15,900 ± 300 g N_2O–N ha^{-1}) were two times greater than broadcast (7,350 ± 490 g N_2O–N ha^{-1}; Supplemental Figure S3) and increased with cumulative CO_2 fluxes, soil moisture, and temperature (Table 2).

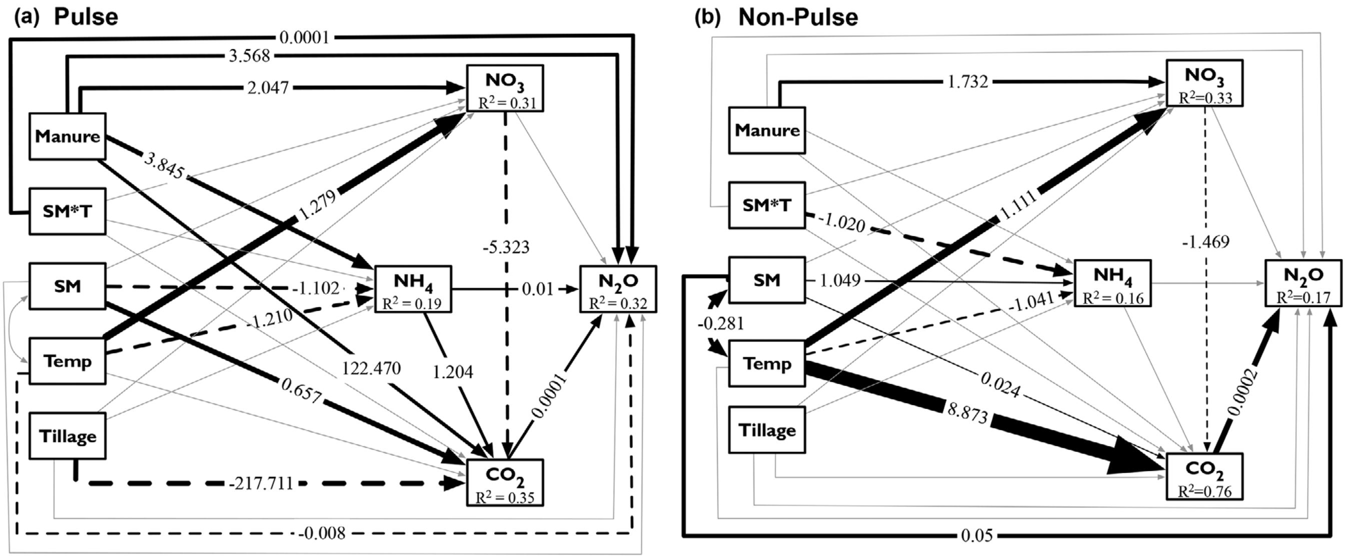

FIGURE 3 Pulse (a) and non-pulse (b) structural equation models for daily greenhouse gas flux data and covariates. Pulse relates to measurements 1 mo after manure application and tillage events; non-pulse are all other measurements. Single-headed arrows represent causal relationships; double-headed arrow denotes correlation between soil moisture (SM) and soil temperature (Temp). Arrows are scaled by standardized path coefficient values. Untransformed unstandardized path coefficients are shown. Dashed lines indicate negative and solid lines indicate positive path coefficients. Significant pathways are black arrows with path coefficients ($P < .05$). Gray arrows are nonsignificant pathways. SM*T, soil moisture × temperature interaction; Manure, manure treatment; Tillage, tillage treatment. Positive estimates for Tillage indicate that vertical-till increased the response variable relative to no-till. Positive estimates for Manure indicate that manure injection increased the response variable relative to broadcast

Cumulative N_2O flux was smaller in 2016 (~6,300 g N ha^{-1}) than in 2015 (~15,000 g N ha^{-1}) and 2017 (~13,500 g N ha^{-1}), as was peak flux (Figure 2b); however, soil mineral N concentrations were greater during 2016 than during 2015 and 2017 (Figure 4). Mean precipitation during 2016 was lower than during 2015 and 2017 (2.65 mm in 2016 vs. 3.57 and 3.20 mm in 2015 and 2017, *daymetr* package) (Hufkens, Basler, Milliman, Melaas, & Richardson, 2018), and soil moisture directly before and after application (through 2 June) averaged 14.0 and 20.1%, respectively (Figure 2a). The role of soil moisture in promoting N_2O fluxes in the cumulative flux ANOVA and structural equation models suggests that the low 2016 N_2O fluxes may be related to relatively low precipitation and post-application soil moisture impeding denitrification and resulting in an accumulation of NO_3^-. This highlights the importance of abiotic parameters, such as sufficiently high soil moisture, for N transformations and N_2O fluxes from agricultural soils via their impacts on microbial processes (Xu et al., 2012). Low soil moisture in 2016, which likely reduced denitrification and plant uptake rates and subsequently drove low N_2O emissions and high soil NO_3^- accumulation, may explain why we did not observe an impact of soil NO_3^- on daily or cumulative N_2O emissions. Denitrification may have been the primary mechanism for N_2O production, but, given the relatively high levels of NO_3^- in each year (Figure 4a), NO_3^- was likely not limiting. Rather, low soil moisture and elevated soil O_2 likely impeded denitrification and N_2O production.

3.1.2 | Carbon dioxide emissions

Emissions of CO_2 were generally highest from manure injection plots, consistent with Dosch and Gutser (1996) and Phan et al. (2012). Cumulative CO_2 emissions from manure injection (7,200 ± 70 kg CO_2–C ha^{-1}) was, on average, slightly greater than from broadcast (6,300 ± 80 kg CO_2–C ha^{-1}) (Table 2; Supplemental Figure S3). However, for daily emissions, the size of the difference varied by day (significant ANOVA manure and manure by date effects) and was relatively small on average (Figure 2c; injection averaged 39 ± 4.7 kg CO_2–C ha^{-1} d^{-1}; broadcast averaged 31.7 ± 4.1 kg CO_2–C ha^{-1} d^{-1}).

In the full structural equation model, manure injection increased CO_2 emissions via direct and indirect effects by 13.8 kg CO_2–C ha^{-1} d^{-1}; the positive direct impact of manure injection was reduced by the negative impact of increased NO_3^- availability in manure-injected soils on CO_2 emissions (Figure 1). Soil temperature had the greatest total effect on CO_2 emissions: across the maximum daily range of values, increasing soil temperature increased CO_2 emissions by 408.4 kg CO_2–C ha^{-1} d^{-1} via direct and indirect effects. Soil moisture, soil NH_4^+, and soil NO_3^-

TABLE 2 Analysis of variance (ANOVA) and analysis of covariance (ANCOVA) results for cumulative N_2O, cumulative CO_2, corn yield, and protein content

	Cumulative N_2O				Cumulative CO_2				Yield				Protein			
	ANOVA		ANCOVA		ANOVA		ANCOVA		ANOVA		ANCOVA		ANOVA		ANCOVA	
Treatment	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Manure	14.16	.006*	29.39	.001*	5.76	.04*	2.78	.1	0.34	.57	0.25	.63	0.01	.94	0.04	.85
Till	0.05	.83	0.12	.74	8.13	.02*	8.86	.04*	0.73	.42	0.93	.36	0.12	.73	0.26	.62
Year (Yr)	2.71	.12	2.91	.11	13.88	.001*	52.18	.003*	0.16	.69	0.02	.88	39.64	<.0001*	176	<.0001*
Manure/Till	0.01	.91	0.09	.77	0.07	.8	0.27	.62	1.59	.24	1.15	.32	0.5	.5	0.78	.4
Manure/Yr	0.95	.34	3.26	.09	0.0003	.99	0.16	.7	1.01	.33	0.68	.42	0.15	.7	0.54	.48
Till/Yr	0.1	.76	0.65	.43	4.79	.04*	1.65	.22	0.23	.64	0.75	.40	0	.96	0.23	.64
Manure/Till/Yr	0.76	.39	1.61	.22	0.02	.89	0	.99	0.91	.35	0.70	.42	0.12	.74	0.08	.78
NO_3^-, mg-N kg^{-1}	–	–	0.32	.57	–	–	0.25	.62	–	–	0.48	.50	–	–	0.06	.81
NH_4^+, mg-N kg^{-1}	–	–	0.02	.9	–	–	2.76	.12	–	–	1.49	.24	–	–	2.13	.17
SM, %	–	–	12.52	.003*	–	–	0.07	.8	–	–	0.07	.78	–	–	38.24	<.0001*
ST	–	–	8.47	.01*	–	–	3.6	. 08	–	–	0.00	.97	–	–	33.61	.0001*
SM/ST	–	–	8.18	.55	–	–	0.88	.36	–	–	0.06	.82	–	–	3.88	.07
Cum. CO_2 flux	–	–	16.29	.001*	–	–	–	–	–	–	–	–	–	–	–	–
Marginal R^2	.16		.57		.48		.36		.35		.26		.43		.83	
Conditional R^2	.16		.57		.48		.36		.35		.38		.43		.83	
$n_{observations}$	36		36		36		36		36		36		34		34	
n_{groups}	12		12		12		12		12		12		12		12	

Note. SM, soil moisture (%); ST, soil temperature (°C); SM, ST, NO_3^-, and NH_4^+ values for the ANCOVA were calculated as the area under the curve during each year.
*Significant at the .05 probability level.

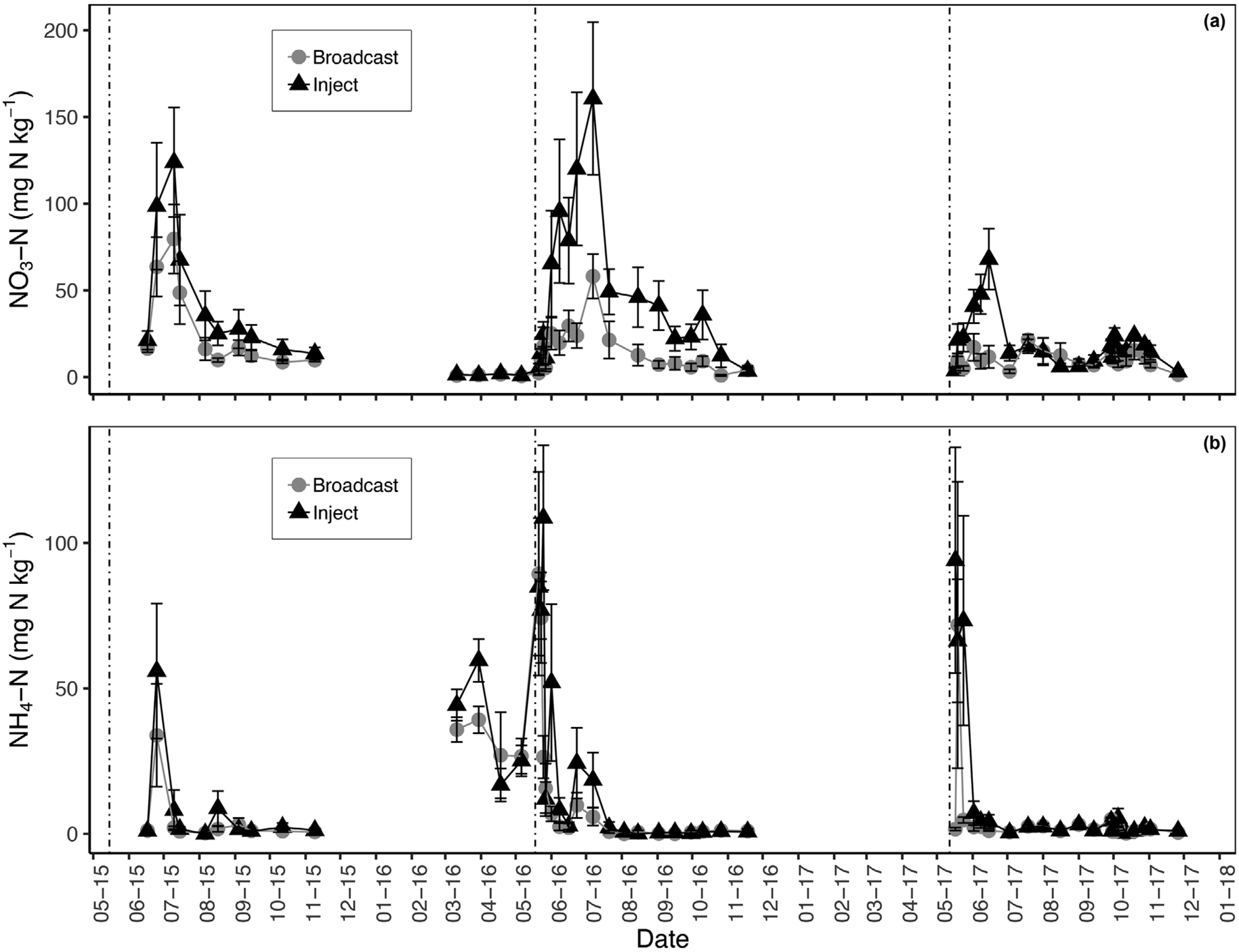

FIGURE 4 Soil (a) NO_3^- and (b) NH_4^+ concentrations by manure application method for 2015 to 2017. Error bars are ±1 SE. Vertical dashed lines show manure application and tillage events

had somewhat smaller total effects on CO_2 emissions: Across the maximum daily range of values, increasing soil moisture and soil NH_4^+ enhanced CO_2 emissions by 87.2 and 133.8 kg CO_2–C ha^{-1} d^{-1}, respectively; increasing soil NO_3^- decreased CO_2 emissions by 332.8 kg CO_2–C ha^{-1} d^{-1} (Figure 1; Supplemental Table S5).

Despite the minimal impact of manure application in these results, we observed large pulses of CO_2 post-injection, indicating that injection had a relatively large, but short-lived, effect on emissions (Figure 2c). Post-application, manure injection emissions were 1.5 times broadcast emissions. Unlike N_2O emissions, CO_2 emissions peaked quickly at about 74 h after manure application and tillage and were likely related to the addition of readily oxidizable manure C entering the soil (Comfort, Kelling, Keeney, & Converse, 1988, 1990; Farquharson & Baldock, 2008; Xu et al., 2008). In the post-application pulse structural equation model, manure application method had direct and indirect effects on CO_2 emissions (Figure 3a; Supplemental Table S4). Compared with broadcast, manure injection increased emissions by 126.8 kg CO_2–C ha^{-1} d^{-1} via direct and indirect effects (Supplemental Table S5). Soil moisture had the largest total effect on CO_2 emissions, increasing emissions by 1,706.3 kg CO_2–C ha^{-1} d^{-1} across the maximum daily range (Supplemental Table S5). Soil NO_3^- and NH_4^+ also had large impacts on CO_2 emissions: soil NO_3^- decreased CO_2 emissions by 449.8 kg CO_2–C ha^{-1} d^{-1}, whereas soil NH_4^+ increased emissions by 240 kg CO_2–C ha^{-1} d^{-1} across the maximum daily range (Supplemental Table S5).

In the non-pulse structural equation model, manure application had no direct impact on CO_2 flux. The largest impacts were from soil temperature and moisture (Figure 3b). Across the maximum daily range of values, soil temperature increased CO_2 emissions by 422.7 g CO_2–C ha^{-1} d^{-1}, whereas soil moisture decreased emissions by 87.2 g CO_2–C ha^{-1} d^{-1}, likely due to the negative correlation with soil temperature (Figure 3b). Soil NO_3^-

also decreased CO_2 emissions by 124 kg CO_2–C ha^{-1} d^{-1} across the maximum daily range of values (Supplemental Table S5). In all three structural equation models, manure injection increased soil NO_3^- concentrations, which led to a decrease in daily CO_2 emissions (Figures 1 and 3). The relationship between soil NO_3^- and CO_2 emissions has only recently been re-evaluated as previous modeling studies (e.g., Li & Harriss, 1994), generally predicted higher soil CO_2 emissions with N fertilization. However, Gagnon et al. (2016) found that N-fertilization reduced heterotrophic respiration, particularly when NO_3^- was added. Combined with our results, this suggests that NO_3^- may reduce microbial oxidation of SOC. Alternatively, the co-occurrence of high NO_3^- and low soil moisture (which reduced CO_2 emissions) in 2016 could be driving this negative relationship.

3.2 | No-till reduced carbon dioxide emissions without enhancing nitrous oxide emissions

Overall, no-till reduced CO_2 emissions without affecting N_2O emissions. This demonstrates that even reduced-tillage practices, such as vertical-till, have the potential to increase SOC losses relative to no-till. Although there was a significant tillage × date interaction for N_2O emissions, the effect of tillage was small and inconsistent ($P < .05$ in ANOVA) (Supplemental Figure S4; Supplemental Table S1). In the full structural equation model, no-till had only a small negative indirect impact on N_2O emissions by decreasing CO_2, which decreased N_2O emissions 0.01 g N_2O–N ha^{-1} d^{-1} relative to vertical-till (Figure 1). In the post-application pulse structural equation model, no-till slightly decreased N_2O emissions by <1 g N_2O–N ha^{-1} d^{-1}, again via a negative indirect impact through CO_2 emissions (Figure 3a). In the non-pulse SEM, tillage method had no direct or indirect effects on any variable. Our results are consistent with Chen, Kolb, Cavigelli, Well, and Hooks (2018), who found no-till emissions to be less than reduced- and conventional-till emissions in coarse-textured soils. The soil at our site is well-drained, and soil moisture was not affected by tillage or manure application treatments, further suggesting that no-till practices on well-drained soils may not promote N_2O losses.

Tillage did affect CO_2 emissions, with the greatest emissions from vertical-till plots, although the size of the difference varied by date (significant tillage by date effect in ANOVA), with the largest fluxes occurring post-application and tillage (Figure 2d). This temporal pattern was also evident in the structural equation models, where no-till had a small negative impact on CO_2 emissions in the full structural equation model, a much larger impact in the post-application/tillage pulse structural equation model (decreasing emissions by 217.7 kg CO_2–C ha^{-1} d^{-1} via direct and indirect effects), and no impact in the non-pulse structural equation model (Figures 1 and 3). Although soil temperature and moisture at times increased CO_2 fluxes, the largest CO_2 fluxes occurred directly after manure application and tillage events and did not coincide with the highest soil temperatures. Thus, our results suggest that nutrient addition and soil disturbance can, at times, overwhelm abiotic drivers of CO_2 emissions.

Annually, vertical-till (7,230 ± 90 kg CO_2–C ha^{-1}) slightly increased emissions relative to no-till (6,270 ± 50 kg CO_2–C ha^{-1}), but the size of this difference increased over time, with very little between-treatment difference in 2015 and average differences of 720 and 2,020 kg CO_2–C ha^{-1} in 2016 and 2017, respectively (Table 2; Supplemental Figure S3). Cumulative CO_2 emissions were not significantly affected by covariates (Table 2). Our results suggest that the benefits of no-till for reducing CO_2 emissions may increase over time.

3.3 | Soil mineral nitrogen

Manure injection roughly doubled soil NO_3^- and NH_4^+ on average, suggesting that it enhances soil N retention. However, manure application only enhanced soil NH_4^+ during the post-application pulse, whereas soil NO_3^- was elevated throughout the sampling period, likely as a result of post-application nitrification (Figures 3 and 4). Manure injection increased average soil NH_4^+ concentrations by 1.7 times versus broadcast application, but this difference varied with date (in ANOVA; Supplemental Table S6) and was largest post-application and negligible later in the growing season (Figure 4b). In the structural equation models, soil moisture increased NH_4^+ during non-pulse times but decreased soil NH_4^+ immediately after manure application (Figure 3). Soil temperature in the structural equation models consistently decreased NH_4^+ (Figure 3). On average, soil NO_3^- was 2.2 times higher in manure injection than in broadcast soils but also varied by date (in ANOVA) (Supplemental Table S6; Figure 4a). Soil NO_3^- increased with soil moisture and temperature in the full structural equation model but only with temperature in the pulse and non-pulse structural equation models (Figures 1 and 3).

3.4 | Corn yield and protein content

In contrast to our expectations and despite higher soil mineral N, manure injection did not enhance corn yield or protein content. Yield was relatively consistent across years with no treatment effects (Table 2) but was most variable in no-till broadcast plots: Average yield was 43,500 ± 4,400 kg ha^{-1} in no-till broadcast; 51,000 ± 2,900 kg ha^{-1} in no-till injection; 51,000 ± 2,200 kg ha^{-1} in vertical-till broadcast; and 50,800 ± 1,900 kg ha^{-1} in vertical-till injection (Supplemental Figure S5). Yield did not change significantly with any covariates (Table 2). Similarly, corn protein content was not affected by treatments but did increase with soil moisture and temperature (Supplemental Figures S5b and S6). Overall, our results indicate that no-till did not reduce crop yields or quality, as in other studies (Derpsch et al., 2014; Rusinamhodzi et al., 2011), although using no-till with broadcast application resulted in more variable yields. Thus, no-till with manure injection may be viable BMPs for reducing CO_2 fluxes without risking crop production or quality.

4 | CONCLUSIONS

Our findings highlight the tradeoff between mineral N retention and elevated N_2O emissions with manure injection. Manure injection more than doubled N_2O emissions and mineral N concentrations relative to broadcast, but average growing season N_2O losses were only equivalent to 9.5% of the annual N applied. Yet, there is still concern with choosing management practices that exacerbate N_2O losses due to its potent global warming potential. Alternatively, practices that do not immediately incorporate manure, such as broadcast application in no-till systems, pose a concern for N loss via ammonia volatilization (Duncan et al., 2017; Gordon, Jamieson, Rodd, Patterson, & Harz, 2001) or surface runoff (Diaz, Sawyer, Barker, & Mallarino, 2010; Kleinman & Sharpley, 2003). For these reasons, manure injection stands as a BMP for reducing nutrient losses (Webb et al., 2010).

We also found that no-till mitigated SOC losses via CO_2 emissions without enhancing N_2O emissions relative to vertical-till. Because no-till and manure injection did not reduce crop yields or quality, our results suggest that these BMPs are viable options to reduce SOC losses and nutrient pollution while providing stable crop production. Efforts to mitigate N_2O production from manure injection may focus on applying manure when climatic conditions suppress denitrification or on co-management strategies, such as reducing N inputs to match crop requirements (Kim & Giltrap, 2017).

ACKNOWLEDGMENTS

This work was supported by a Northeast Sustainable Agriculture Research & Education Partnership Grant ONE15-228 and an award for transdisciplinary research from the UVM Food Systems Initiative. A portion of this material is also based on work supported by the National Institute of Food and Agriculture, USDA, under award number 2015-67020-23180. Support for E.C. Adair was provided by Vermont EPSCoR with funds from the National Science Foundation Grants EPS-1101317 and OIA # 1556770. The authors thank S. Ziegler and R. Rainville of the University of Vermont Extension and Borderview Farm, respectively, for the upkeeping of the field trial and for providing insightful information on cropping and management characteristics.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Kyle M. Dittmer https://orcid.org/0000-0002-1086-5978
E. Carol Adair https://orcid.org/0000-0002-8567-9045

REFERENCES

Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P., & Jones, M. B. (2013). Conservation tillage systems: A review of its consequences for greenhouse gas emissions. *Soil Use Management*, *29*, 199–209.

Adair, E. C., Barbieri, L., Schiavone, K., & Darby, H. M. (2019). Manure application decisions impact nitrous oxide and carbon dioxide emissions during non-growing season thaws. *Soil Science Society of America Journal*, *83*, 163–172. https://doi.org/10.2136/sssaj2018.07.0248

Alvarez, R. (2005). A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use Management*, *21*, 38–52. https://doi.org/10.1079/SUM2005291

Ball, B. C., Scott, A., & Parker, J. P. (1999). Field N_2O, CO_2, and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. *Soil and Tillage Research*, *53*, 29–39.

Borchers, H. W. (2019). pracma: Practical numerical math functions. R package version 2.2.5. Retrieved from https://CRAN.R-project.org/package=pracma

Bremner, J. M. (1997). Sources of nitrous oxide in soils. *Nutrient Cycling in Agroecosystems*, *49*, 7–16.

Burford, J. R., Dowdell, R. J., & Crees, R. (1981). Emission of nitrous-oxide to the atmosphere from direct-drilled and ploughed clay soil. *Journal of the Science of Food and Agriculture*, *32*, 219–223.

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd ed.). New York: Springer.

Chadwick, D. R., Pain, B. F., & Brookman, S. K. E. (2000). Nitrous oxide and methane emissions following application of animal manures to grassland. *Journal of Environmental Quality*, *29*, 277–287. https://doi.org/10.2134/jeq2000.00472425002900010035.

Chen, G., Kolb, L., Cavigelli, M. A., Well, R. R., & Hooks, C. R. R. (2018). Can conservation tillage reduce N_2O emissions on cropland transitioning to organic vegetable production? *Science of the Total Environment*, *15*(618), 927–940. https://doi.org/10.1016/j.scitotenv.2017.08.296

Comfort, S. D., Kelling, K. A., Keeney, D. R., & Converse, J. C. (1988). The fate of nitrogen from injected liquid manure in a silt loam soil.

Journal of Environmental Quality, *17*, 317–322. https://doi.org/10.2134/jeq1988.00472425001700020027x

Comfort, S. D., Kelling, K. A., Keeney, D. R., & Converse, J. C. (1990). Nitrous oxide production from injected liquid dairy manure. *Soil Science Society of America Journal*, *54*, 421–427.

Daverede, I. C., Kravchenko, A. N., Hoeft, R. G., Nafziger, E. D., Bullock, D. G., Warren, J. J., & Gonzini, L. C. (2004). Phosphorus runoff from incorporated and surface-applied liquid swine manure and phosphorus fertilizer. *Journal of Environmental Quality*, *33*, 1535–1544. https://doi.org/10.2134/jeq2004.1535

Dell, C. J., Meisinger, J. J., & Beegle, D. B. (2011). Subsurface application of manures slurries for conservation tillage and pasture soils and their impact on the nitrogen balance. *Journal of Environmental Quality*, *40*, 352–361. https://doi.org/10.2134/jeq2010.0069

Derpsch, R., Franzluebbers, A. J., Duiker, S. W., Reicosky, D. C., Koeller, K., & Friedrich, T. (2014). Why do we need to standardize no-till research? *Soil and Tillage Research*, *137*, 16–22. https://doi.org/10.1016/j.still.2013.10.002

Diaz, D. A. R., Sawyer, J. E., Barker, D. W., & Mallarino, A. P. (2010). Runoff nitrogen loss with simulated rainfall immediately following poultry manure application for corn production. *Soil Science Society of America Journal*, *74*(1), 221–230. https://doi.org/10.2136/sssaj2009.0134

Dobbie, K. E., McTaggart, I. P., & Smith, K. A. (1999). Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors. *Journal of Geophysical Research [Atmospheres]*, *104*, 26891–26899.

Dosch, P., & Gutser, R. (1996). Reducing N losses (NH_3, N_2O, N_2) and immobilization from slurry through optimized application techniques. *Fertilizer Research*, *43*, 165–171.

Duncan, E. W., Dell, C. J., Kleinman, P. J., & Beegle, D. B. (2017). Nitrous oxide and ammonia emissions from injected and broadcast-applied dairy slurry. *Journal of Environmental Quality*, *44*, 36–44. https://doi.org/10.2134/jeq2016.05.0171

Eisenhauer, N., Bowker, M. A., Grace, J. B., & Powell, J. R. (2015). From patterns to causal understanding: Structural Equation Modeling (SEM) in soil ecology. *Pedobiologia*, *58*, 65–72. https://doi.org/10.1016/j.pedobi.2015.03.002

Farquharson, R., & Baldock, J. (2008). Concepts in modelling N_2O emissions from land use. *Plant and Soil*, *309*, 147–167. https://doi.org/10.1007/s11104-007-9485-0

Firestone, M. K., & Davidson, E. A. (1989). Microbiological basis of NO and N_2O production and consumption in soil. *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*, *47*, 7–21.

Flach, K. W., Barnwell, T. O. J., & Crossen, P. (1997). Impacts of agriculture on atmospheric carbon dioxide. In E. A. Paul et al. (Eds.), *Soil organic matter in temperate agroecosystems: Long-term experiments in North America* (pp. 3–13). Boca Raton, FL: CRC Press.

Flessa, H., & Beese, F. (2000). Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. *Journal of Environmental Quality*, *29*, 262–268. https://doi.org/10.2134/jeq2000.00472425002900010033x

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*, 337–342. https://doi.org/10.1038/nature10452

Food and Agriculture Organization of the United Nations (FAO). (2011). *Save and grow: A policymaker's guide to the sustainable intensification of smallholder crop production*. Rome: FAO.

Gagnon, B., Ziadi, N., Rochette, P., Chantigny, M. H., Angers, D. A., Bertrand, N., & Smith, W. N. (2016). Soil-surface carbon dioxide emission following nitrogen fertilization in corn. *Canadian Journal of Soil Science*, *96*, 219–232. https://doi.org/10.1139/cjss-2015-0053

Giller, K. E., Andersson, J. A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., & Vanlauwe, B. (2015). Beyond conservation agriculture. *Frontiers in Plant Science*, *6*, 870. https://doi.org/10.3389/fpls.2015.00870

Gordon, R., Jamieson, R., Rodd, V., Patterson, G., & Harz, T. (2001). Effects of surface manure application timing on ammonia volatilization. *Canadian Journal of Soil Science*, *81*(4), 525–533.

Grace, J. B. (2006). *Structural equation modeling and natural systems*. Cambridge, U.K.: Cambridge University Press. https://doi.org/10.1017/CBO9780511617799

Grace, J. B., Schoolmaster, D. R. Jr., Guntenspergen, G. R., Little, A. M., Mitchell, B. R., Miller, K. M., & Schweiger, E. W. (2012). Guidelines for a graph-theoretic implementation of structural equation modeling. *Ecosphere*, *3*(8), 1–44. https://doi.org/10.1890/ES12-00048.1

Grace, J. B., & Irvine, K. M. (2020). Scientist's guide to developing explanatory statistical models using causal analysis principles. *Ecology*, *101*(4), e02962. https://doi.org/10.1002/ecy.2962

Hart, S. C., Stark, J. M., Davidson, E. A., & Firestone, M. K. (1994). Nitrogen mineralization, immobilization, and nitrification. In R. W. Weaver et al. (Eds.), *Methods of soil analysis. Part 2. Microbiological and biochemical properties* (pp. 985–1018). Madison, WI: SSSA.

Holland, J. M. (2003). The environmental consequences of adopting conservation tillage in Europe: Reviewing the evidence. *Agriculture, Ecosystems and Environment*, *103*, 1–25.

Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R., & Woodwell, G. M. (1983). Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO2 to the atmosphere. *Ecological Monographs*, *53*, 235–262.

Hufkens, K., Basler, D., Milliman, T., Melaas, E. K., & Richardson, A. D. (2018). An integrated phenology modelling framework in R. *Methods in Ecology and Evolution*, *9*, 1276–1285. https://doi.org/10.1111/2041-210X.12970

Hungate, B. A., Chapin, F. S. III, Zhong, H., Holland, E. A., & Field, C. B. (1997). Stimulation of grassland nitrogen cycling under carbon dioxide enrichment. *Oecologia*, *109*, 149–153.

Iqbal, J., Castellano, M. J., & Parkin, T. B. (2013). Evaluation of photoacoustic infrared spectroscopy for simultaneous measurement of N_2O and CO_2 gas concentrations and fluxes at the soil surface. *Global Change Biology*, *19*, 327–336. https://doi.org/10.1111/gcb.12021

Kassam, A., Friedrich, T., Shaxson, F., Bartz, H., Mello, I., & Kienzle, J. (2014). The spread of conservation agriculture: Policy and institutional support for adoption and uptake. *Field Actions Science Reports*, *7*, 1–12.

Kim, D. G., & Giltrap, D. (2017). Determining optimum nitrogen input rate and optimum yield-scaled nitrous oxide emissions: Theory, field observations, usage, and limitations. *Agriculture, Ecosystems and Environment*, *274*, 371–378. https://doi.org/10.1016/j.agee.2017.07.003

Kleinman, P. J. A., & Sharpley, A. N. (2003). Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. *Journal of Environmental Quality*, *32*(3), 1072–1081.

Kulesza, S. B., Maguire, R. O., Thomason, W. E., Hodges, S. C., & Pote, D. H. (2014). Effects of poultry litter injection on ammonia volatilization, nitrogen availability, and nutrient losses in runoff. *Soil Science*, *179*(4), 190–196.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623–1627.

Lefcheck, J. S. (2016). piecewiseSEM: Piecewise structural equation modeling in R for ecology, evolution, and systematics. *Methods in Ecology and Evolution*, *7*(5), 573–579. https://doi.org/10.1111/2041-210X.12512

Li, C., Frolking, S., & Harriss, R. (1994). Modeling carbon biogeochemistry in agricultural soils. *Global Biogeochemical Cycles*, *8*, 237–254. https://doi.org/10.1029/94GB00767.

Liu, Y., Engel, B. A., Flanagan, D. C., Gitau, M. W., McMillan, S. K., & Chaubey, I. (2017). A review on effectiveness of best management practices in improving hydrology and water quality: Needs and opportunities. *Science of The Total Environment*, *601–602*, 580–593. https://doi.org/10.1016/j.scitotenv.2017.05.212

Livesley, S., Kiese, R., & Graham, J. (2008). Trace gas flux and the influence of short-term soil water and temperature dynamics in Australian sheep grazed pastures of differing productivity. *Plant and Soil*, *309*, 89–103. https://doi.org/10.1007/s11104-008-9647-8

Lloyd, J., & Taylor, J. A. (1994). On the temperature dependence of soil respiration. *Functional Ecology*, *8*, 315–323.

Logan, T. J. (1993). Agricultural best management practices for water pollution control: Current issues. *Agriculture, ecosystems, and Environment*, *46*, 223–231.

Lognoul, M., Theodorakopoulos, N. M., Hiel, D., Regaert, F., Broux, B., Heinesch, B., … Aubinet, M. (2017). Impact of tillage on greenhouse gas emissions by an agricultural crop and dynamics of N_2O fluxes: Insights from automated closed chamber measurements. *Soil and Tillage Research*, *167*, 80–89. https://doi.org/10.1016/j.still.2016.11.008

Lovanh, N., Warren, J., & Sistani, K. (2010). Determination of ammonia and greenhouse gas emissions from land application of swine slurry: A comparison of three application methods. *Bioresource Technology*, *101*(6), 1662–1667. https://doi.org/10.1016/j.biortech.2009.09.078

Maguire, R. O., Kleinman, P. J. A., Dell, C. J., Beegle, D. B., Brandt, R. C., & McGrath, J. M. (2011). Manure application technology in reduced tillage and forage systems: A review. *Journal of Environmental Quality*, *40*, 292–301. https://doi.org/10.2134/jeq2009.0228

Mangalassery, S., Sjoegersten, S., Sparkes, D. L., Sturrock, C. J., Craigon, J., & Mooney, S. J. (2014). To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? *Scientific Reports*, *4*, 4586. https://doi.org/10.1038/srep04586

Meisinger, J. J., & Jokela, D. (2000). Ammonia volatilization from dairy and poultry manure. Retrieved from https://pdfs.semanticscholar.org/664d/9986bf116cfb7cb6f5309b2467bfc1168692.pdf

Mørkved, P. T., Dörsch, P., & Bakken, L. R. (2007). The N_2O product ratio of nitrification and its dependence on long-term changes in soil pH. *Soil Biology & Biochemistry*, *39*, 2048–2057. https://doi.org/10.1016/j.soilbio.2007.03.006

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., … Zhang, H. (2013). Anthropogenic and natural radiative forcing. In T. F. Stocker et al. (Eds.), *Climate change 2013: The physical science basis* (pp. 659–740). Cambridge, U.K.: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.018

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R^2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*, *4*(2), 133–142. https://doi.org/10.1111/J.2041-210x.2012.00261.X

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmi, S. (2016). Greenhouse gas emissions from soils: A review. *Geochemistry*, *76*, 327–352. https://doi.org/10.1016/j.chemer.2016.04.002

Olson, K. R., Al-Kaisi, M. M., Lal, R., & Lowery, B. (2014). Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. *Soil Science Society of America Journal*, *78*, 348–360. https://doi.org/10.2136/sssaj2013.09.0412

Parkin, T. B., & Venterea, R. T. (2010). Chamber-based trace gas flux measurements. In R. F. Follett (Ed.), *Sampling protocols* (pp. 3-1–3-39). Retrieved from www.ars.usda.gov/research/GRACEnet

Paustian, K., Andrén, O., Janzen, H. H., Lal, R., Smith, P., Tian, G., … Woomer, P. L. (1997). Agricultural soils as sink to mitigate CO_2 emissions. *Soil Use and Management*, *13*, 230–244.

Phan, N-T., Kim, K-H., Parker, D., Jeon, E-C., Sa, J. H., & Cho, C-S. (2012). Effect of beef cattle manure application rate on CH_4 and CO_2 emissions. *Atmospheric Environment*, *63*, 327–336. https://doi.org/10.1016/j.atmosenv.2012.09.028

Pinheiro, J., Bates, D., DebRoy, S., & Sarkar, D., R Core Team. (2018). nlme: Linear and nonlinear mixed effects models. R package version 3. Retrieved from https://CRAN.R-project.org/package=nlme

Plaza-Bonilla, D., Álvaro-Fuentes, J., Arrúe, J. L., & Cantero-Martínez, C. (2014). Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. *Agriculture Ecosystems and Environment*, *189*, 43–52.

Powell, J. M., Jokela, W. E., & Misselbrook, T. H. (2011). Dairy slurry application method impacts ammonia emission and nitrate leaching in no-till corn silage. *Journal of Environmental Quality*, *40*, 383–392. https://doi.org/10.2134/jeq2010.0082

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., & Sanchez, P. A. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, *4*, 678–683. https://doi.org/10.1038/nclimate2292

R Development Core Team. (2008). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing.

Robertson, G. P., & Groffman, P. M. (2007). Nitrogen transformations. In E. A. Paul (Ed.), *Soil microbiology, ecology, and biochemistry* (pp. 341–364). New York: Academic Press.

RStudio Team. (2015). RStudio: Integrated development for R. Retrieved from http://www.rstudio.com/

Rubaek, G. H., Henriksen, K., Petersen, J., Rasmussen, B., & Sommer, S. G. (1996). Effects of application technique and anaerobic digestion on gaseous nitrogen loss from animal slurry applied to

ryegrass (*Lolium perenne*). *Journal of Agricultural Science 126*, 481–492.
Ruidisch, M., Bartsch, S., Kettering, J., Huwe, B., & Frei, S. (2013). The effect of fertilizer best management practices on nitrate leaching in a plastic mulched ridge cultivation system. *Agriculture Ecosystems and Environment*, *169*, 21–32.
Rusinamhodzi, L., Corbeels, M., van Wijk, M., Rufino, M. C., Nyamangara, J., & Giller, K. E. (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rainfed conditions. *Agronomy for Sustainable Development*, *31*, 657–763. https://doi.org/10.1007/s13593-011-0040-2
Sarker, J. R., Singh, B. P., He, X., Fang, Y., Li, G. D., Collins, D., & Cowie, A. L. (2017). Tillage and nitrogen fertilization enhanced belowground carbon allocation and plant nitrogen uptake in a semi-arid canola crop–soil system. *Scientific Reports*, *7*, 10726. https://doi.org/10.1038/s41598-017-11190-4
Shipley, B. (2002). *Cause and correlation in biology: A user's guide to path analysis, structural equations and causal inference*. Cambridge, U.K.: Cambridge University Press.
Sierra, C. A., Malghani, S., & Loescher, H. W. (2017). Interactions among temperature, moisture, and oxygen concentrations in controlling decomposition rates in a boreal forest soil. *Biogeosciences*, *14*, 703–710. https://doi.org/10.5194/bg-14-703-2017
Six, J., Feller, C., Denef, K., Ogle, S. M., Moraes, J. C., & Albrech, A. (2002). Soil organic matter, biota and aggregation in temperate and tropical soils: Effects of no-till. *Agronomie*, *22*, 755–775.
Smith, K. A., Ball, T., Conen, F., Dobbie, K. E., Massheder, J., & Rey, A. (2003). Exchange of greenhouse gases between soil and atmosphere: Interactions of soil physical factors and biological processes. *European Journal of Soil Science*, *54*, 779–791.
Soil Survey Staff, N.R.C.S., United States Department of Agriculture. (2017). *Web soil survey*. Washington, DC: USDA-NRCS.
Sutton, A. L., Nelson, D. W., Hoff, J. D., & Mayrose, V. B. (1982). Effects of injection and surface applications of liquid swine manure on corn yield and soil composition. *Journal of Environmental Quality*, *11*, 468–472.
Syakila, A., & Kroeze, C. (2011). The global nitrous oxide budget revisited. *Greenhouse Gas Measurement and Management*, *1*(1), 17–26.
Vallejo, A., García-Torres, L., Díez, J. A., Arce, A., & López-Fernández, S. (2005). Comparison of N losses (NO_3, N_2O, NO) from surface applied, injected or amended (DCD) pig slurry of an irrigated soil in a Mediterranean climate. *Plant Soil*, *272*, 313–325.
Van Groenigen, K-J., Six, J., Hungate, B. A., de Graaff, M-A., van Breemen, N., & van Kessel, C. (2006). Element interactions limit soil carbon storage. *Proceedings of the National Academy of Sciences of the USA*, *103*(17), 6571–6574. https://doi.org/10.1073/pnas.0509038103
Velthof, G. L., Kuikman, P. K., & Oenema, O. (2003). Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biology and Fertility of Soils*, *37*, 221–230.
Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P., … Sayre, K. D. (2010). Conservation agriculture, improving soil quality for sustainable production systems? In R. Lal & B. A. Stewart (Eds.), *Advances in soil science: Food security and soil quality* (pp. 137–208). Boca Raton, FL: CRC Press.
Wang, W., & Dalal, R. C. (2015). Nitrogen management is the key for low-emission wheat production in Australia: A life cycle perspective. *European Journal of Agronomy*, *66*, 74–82.
Webb, J., Pain, B., Bittman, S., & Morgan, J. (2010). Impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response: A review. *Agriculture Ecosystems and Environment*, *137*, 39–46. https://doi.org/10.1016/j.agee.2010.01.001
Wendt, J. W., & Hauser, S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *European Journal of Soil Science*, *64*, 58–65. https://doi.org/10.1111/ejss.12002
Wulf, S., Maeting, M., & Clemens, J. (2002). Application technique and slurry co-fermentation effects on ammonia, nitrous oxide, and methane emissions after spreading: I. Ammonia volatilization. *Journal of Environmental Quality*, *31*, 1789–1794. https://doi.org/10.2134/jeq2002.1789
Xu, X., Tian, H., & Hui, D. (2008). Convergence in the relationship of CO_2 and N_2O exchanges between soil and atmosphere within terrestrial ecosystems. *Global Change Biology*, *14*, 1651–1660. https://doi.org/10.1111/j.1365-2486.2008.01595.x
Xu, X. F., Tian, H. Q., Chen, G. S., Liu, M. L., Ren, W., Lu, C. Q., & Zhang, C. (2012). Multiple factor controls on terrestrial N_2O flux over North America from 1979 through 2010. *Biogeosciences*, *9*, 1351–1366. https://doi.org/10.5194/bg-9-1351-2012
Xue, Y., van Es, H. M., Schindelbeck, R. R., Moebius-Clune, B. N., Melkonian, J. J., Graham, C., & Yang, P. (2013). Effects of N placement, carbon distribution and temperature on N_2O emissions in clay loam and loamy sand soils. *Soil Use Management*, *29*, 240–249. https://doi.org/10.1111/sum.12037

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Dittmer KM, Darby HM, Goeschel TR, Adair EC. Benefits and tradeoffs of reduced tillage and manure application methods in a *Zea mays* silage system. *J. Environ. Qual.* 2020;49:1236–1250.
https://doi.org/10.1002/jeq2.20125