Attachment No. 2

Received: 19 May 2022 | Accepted: 16 November 2022 | Published online: 9 February 2023

DOI: 10.1002/saj2.20506

Soil Science Society of America Journal

ORIGINAL ARTICLE

Soil & Water Management & Conservation

Soil degradation and crop yield declines persist 5 years after pipeline installations

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Assigned to Associate Editor Shannon Osborne.

Abstract

Degradation of natural resources, including increased soil compaction, soil horizon mixing, and decreased crop yields have been common outcomes of underground pipeline installation. However, most of the research documenting the impacts of pipeline installation on soil and crops was conducted before contemporary best management practices were developed and implemented. The objective of this study was to evaluate the impact of pipeline installation on soils and field crops after a 4- to 5-year remediation period, coinciding with the end of landowner compensation and when sites are considered fully remediated by pipeline companies. We report soil properties and corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yields from three independently operated pipelines at 29 sites across 8 Ohio counties. We observed significant degradation in soil physical properties, such as surface penetration resistance (15.3% increase) and mean weight diameter of soil aggregates (13.6% decrease) in right-of-way (ROW) areas compared with adjacent (ADJ) areas, respectively. Soils in ROW showed evidence of soil horizon mixing, with 25.0 g kg^{-1} higher clay compared with ADJ areas. Soil degradation resulted in decreases of 23.8% and 19.5% in corn yields and 7.4% and 12.5% in soybean yields during 2020 and 2021, respectively. Widespread disturbance persisted 5 years following pipeline installation in soil physical, chemical, and biological properties. Current best management practices of pipeline installation and remediation employed by three companies were insufficient to combat widespread soil degradation and crop yield loss.

1 | INTRODUCTION

The installation of underground pipelines for natural gas and other petroleum sources has historically resulted in lasting soil degradation, primarily driven by soil horizon mixing and soil compaction (Batey, 2015; Culley & Dow, 1988; de Jong & Button, 1973; Tekeste et al., 2020). For example, in a comprehensive literature review of underground pipeline studies, Brehm and Culman (2022) found 24 of the 28 studies documented significant changes in soil texture and clay content, and an average increase in soil compaction via penetration resistance or bulk density in 17 of the 26 studies. Increased compaction and soil mixing with pipeline installation has resulted in declines of other soil properties, including soil carbon (Culley & Dow, 1988; Naeth et al., 1987; Shi et al., 2014),

Abbreviations: ADJ, adjacent; CEC, cation exchange capacity; MBC, microbial biomass carbon; MWD, mean weight diameter; POXC, permanganate oxidizable carbon; PR, penetration resistance; ROW, right-of-way; SOC, soil organic carbon; TC, total carbon; TSN, total soil nitrogen.

soil nitrogen (Cully et al., 1981; Shi et al., 2015; Soon et al., 2000), aggregate stability (Duncan & Dejoia, 2011; Ivey & McBride, 1999; Shi et al., 2014), and soil moisture (Halmova et al., 2017; Olson & Doherty, 2012). Soil degradation following pipeline installations typically has led to decreased crop yields and plant productivity, with average decreases of field crops from 34 reported studies between 10.6% and 40.3% (Brehm & Culman, 2022; Culley & Dow, 1988; Culley et al., 1982).

Historically, single lift excavations were common in pipeline installation, where topsoil and subsoil were extracted together, then stored as a single pile and backfilled into the trench (de Jong & Button, 1973; Harper & Kershaw, 1997; Landsburg & Cannon, 1995; Zellmer et al., 1985). Current best practices of double lift excavation attempt to ensure topsoil and subsoil are lifted separately from the trench area, stored in separate piles and then backfilled into the trench as two separate horizons (Neilsen et al., 1990; Soon et al., 2000; Soon, Rice, et al., 2000, Tekeste et al., 2019). Efforts to separate soil horizons via double lifts aim to decrease rates of soil mixing between horizon layers, which often differ in texture, porosity, organic matter content, soil chemistry, and overall soil function (Desserud et al., 2010; Landsburg & Cannon, 1995; Olson & Dougherty, 2012; Shi et al., 2014). While double lift installation techniques are suggested to mitigate soil horizon mixing and subsequent detrimental impacts to soil and vegetation, only 13 of 34 previous studies have examined these differences (either double lift or a combination of single and double lift), particularly as best management practices continue to evolve and improve (Brehm & Culman, 2022; Desserud et al., 2010; Soon et al., 2000; Tekeste et al., 2020).

Landowner compensation for signing easement contracts with pipeline installation companies is routine, but details of compensation plans are often not publicly available, as many contracts contain non-disclosure agreements. In Ohio, it has become common practice for many natural gas and oil companies to compensate farmers for crop losses for 3 to 4 years after pipeline installation is completed (Nexus Staff, 2016; Federal Energy Regulatory Commission, 2016). Typically, in Year 1, farmers and landowners are compensated 100% of crop losses, while Years 2, 3, and 4 following pipeline installation are often compensated 75%, 50%, and 25%, respectively. The basis or rationale of this 4- to 5-year compensation timeframe not well understood, nor is it aligned with previous studies which have documented lasting deleterious effects on soils and crops from years to decades.

Underground pipeline mileage has expanded globally in recent decades, but field-based research projects studying the impacts of the installation process on soil and vegetation resources have not kept pace, particularly as best management practices have improved over time. The United States has had an 8.5% increase in pipeline mileage between 2010 and 2020, paired with only seven studies on pipeline effects on soil and vegetation in the same time (U.S. PHMSA Staff, 2020; e.g., Olson & Doherty, 2012; Schindelbeck & van Es, 2012; Tekeste et al., 2019). Current best management practices have improved from single lift to double lift techniques in recent decades, and site remediation practices are now commonly implemented following installation. Because construction, installation, and remediation practices often vary between pipeline parent companies, construction crews, soil types, climatic events, and landowners, attempting to generalize the impacts of pipeline installation using current best management practices requires evaluating multiple pipelines over diverse soils and environments.

Core Ideas

- Three underground pipelines were evaluated within 5 years of installation in Ohio at 29 farms.
- Soil degradation persisted after the remediation period, particularly with soil physical properties.
- Corn yields were 23.8% and 19.5% lower over pipeline right-of-way (ROW) areas in 2020 and 2021, respectively.
- Soybean yields were 7.4% and 12.6% lower over pipeline ROW areas in 2020 and 2021, respectively.
- Pipeline installation and remediation best management practices were insufficient to prevent soil degradation.

The objective of this study was to evaluate the impact of pipeline installation on Ohio soils and field crops after a 4- to 5-year remediation period. This period coincides with when landowner payments for easements end and when the sites are considered fully remediated by the pipeline companies. Here, we examined three independently operated pipelines constructed and remediated using current best management practices. We report a suite of soil properties and crop yields from 29 fields across 8 Ohio counties to assess if impacts persisted after site remediation was complete.

2 | MATERIALS AND METHODS

2.1 | Site description

The study took place in Ohio during the 2020 and 2021 growing seasons. Field sites of interested landowners and farmers were identified following communication with Ohio State University Extension educators, Soil and Water Conservation District specialists, Ohio Farm Bureau, landowners, and

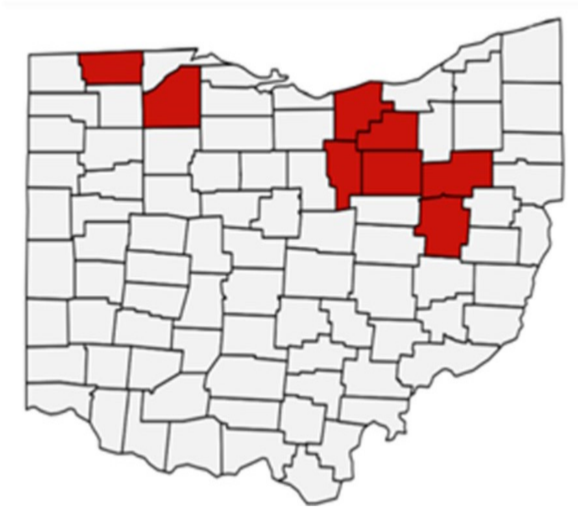

FIGURE 1 A map of Ohio with counties highlighted in red where sampling occurred for this study in 2020 and 2021

local farmers along the Rover, Utopia, and Nexus pipelines. A general "call for participation" announcement was published in the Wooster Daily Record and to a statewide online agronomic crop newsletter, the Crop Observation and Recommendation Network newsletter, to create broader awareness of the research project and develop engagement opportunities.

Final field sites were selected to represent diverse geographic locations, soil types, and topographies. Mean annual temperature for this region is ~10˚C, with a mean annual precipitation of ~900–1000 mm (NOAA Staff, 2021a). Soils in this region commonly developed over glacial limestone or lake sediments, depending on proximity to Lake Erie, which borders much of the northern portion of Ohio (Barker et al., 2017).

Selected fields were planted to corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] in 2020 and planned to be in grain crops for the 2021 growing season. Twenty-three field sites were sampled during 2020, and 20 field sites were sampled during 2021, for a total of 29 unique field sites with 14 sites sampled during both years. These 29 sites were located in 8 counties in Ohio (Figure 1) including 20 different USDA soil series (Table 1) and were divided between Rover ($n = 15$), Utopia ($n = 7$), and Nexus ($n = 6$) pipelines.

2.2 | Pipeline Description

We selected three pipelines to study in northern Ohio, the Rover, Utopia, and Nexus pipelines. Construction began in 2016 or 2017 and ended in 2018 for all three natural gas pipelines (Table 2).

The Rover and Nexus pipelines were federally funded utilities projects, subject to eminent domain laws, while the Utopia pipeline was a privately funded project which was not federally regulated. These pipelines follow routes around the northern part of Ohio, crossing over 20 counties throughout the state.

All three pipelines were constructed within a right-of-way (ROW) roughly 50 m wide using double lift installation techniques, with trench depth varying at each site depending on classification of the land (i.e., prime farmland, rivers). Within agricultural areas, Environmental Impact Statements (EIS) and Agricultural Impact Mitigation Plans from Rover and Nexus pipelines state these pipelines were installed at a depth of roughly 1 m, and crop yields over impacted areas would be monitored for 5 years following start of construction, though compensation to landowners was only required for 3 years for the Rover pipeline (Nexus Staff, 2016; Federal Energy Regulatory Commission, 2016). Permanent ROW width for the Rover pipeline was 18.2 m, while Utopia and Nexus pipelines had permanent ROWs of 15.2 m each. Decompaction efforts by individual pipeline companies following pipeline installation occurred via deep ripping at a depth of 45 cm, with some sites having multiple occurrences of deep ripping. Re-establishment of herbaceous vegetation on the ROW followed within all pipeline-disturbed areas for Rover and Nexus. Landowners often completed additional remediation efforts such as additional applications of lime and fertilizers, planting deep-rooting cover crops like clovers and alfalfa, and additional tillage. EIS were not made publicly available for the Utopia pipeline.

2.3 | Field soil and crop sampling

At each site, a pseudo-replicated complete block design was implemented for direct comparison between the pipeline ROW transect and an adjacent (ADJ), unaffected area within the same field for each site. Given the nature of pipeline installation, true randomization of blocks was not possible, but pseudo-replication provided greater confidence of measured effects relative to a single-point measurement. The pipeline trench was located through a combination of visual identification from roadside pipeline markers, printed pipeline installation schematics, and online aerial photos from the year of pipeline installation. After delineation of pipeline location within a field, three sampling points, each 30 to 60 m apart and roughly 3 m away from trench centerline, were identified as ROW sampling locations and GPS coordinates were recorded. For this study, the trench, road area, and piling areas were all determined to be a part of the pipeline ROW. From each of the ROW sampling points, an ADJ sampling point was identified directly off and 30 to 60 m from the ROW, making a total of three ADJ sampling points to serve as a control. Therefore, each field was made up of six sampling areas, three ROW paired with three ADJ. Within a field, all six sampling points were selected by visually finding areas in the field that

TABLE 1 Description of all pipeline sites sampled including crops harvested per year and soil classifications

			Crop			Soil classification	
Site ID	County	Pipeline	Year 1	Year 2	Soil series	Soil series subgroup	Soil sampled
Site 1	Wayne	Rover	Corn silage	Soybeans	Wooster Riddles	Ultic Hapludalfs	Yes
Site 2	Wayne	Utopia	Corn	Soybeans	Wooster Riddles	Ultic Hapludalfs	Yes
Site 3	Wayne	Rover	Corn	Soybeans	Chili	Typic Hapludalfs	Yes
Site 4	Wayne	Rover	Corn	Soybeans	Canfield	Aquic Fragiudalfs	Yes
Site 5	Medina	Nexus	Corn silage	Not sampled	Oshtemo	Typic Hapludalfs	Yes
Site 6	Wayne	Utopia	Corn	Soybeans	Canfield	Aquic Fragiudalfs	Yes
Site 7	Wood	Nexus	Soybeans	Not sampled	Hoytville	Mollic Epiaqualfs	Yes
Site 8	Wayne	Rover	Soybeans	Corn	Wooster Riddles	Typic Hapludalfs	Yes
Site 9	Wayne	Utopia	Corn	Not sampled	Canfield	Aquic Fragiudalfs	Yes
Site 10	Lorain	Nexus	Corn	Not sampled	Chili	Typic Hapludalfs	Yes
Site 11	Lorain	Nexus	Not sampled	Soybeans	Mahoning	Aeric Epiaqualfs	Yes
Site 12	Lorain	Nexus	Soybeans	Corn	Mahoning	Aeric Epiaqualfs	Yes
Site 13	Lorain	Nexus	Soybeans	Not sampled	Mahoning	Aeric Epiaqualfs	Yes
Site 14	Wayne	Rover	Corn	Corn	Luray	Typic Argiaquolls	Yes
Site 15	Wayne	Utopia	Corn	Soybeans	Fitchville	Aeric Endoaqualfs	Yes
Site 16	Stark	Rover	Soybeans	Not sampled	Seabring	Typic Endoaqualfs	Yes
Site 17	Stark	Utopia	Corn	Not sampled	Sparta	Entic Hapludolls	Yes
Site 18	Tuscarawas	Rover	Not sampled	Not sampled	Chili	Typic Hapludalfs	Yes
Site 19	Tuscarawas	Rover	Not sampled	Not sampled	Elkinsville	Ultic Hapludalfs	Yes
Site 20	Tuscarawas	Utopia	Corn	Not sampled	Elkinsville	Ultic Hapludalfs	Yes
Site 21	Ashland	Rover	Corn	Soybeans	Jimtown	Aeric Ochraqualfs	Yes
Site 22	Ashland	Rover	Corn	Soybeans	Bogart	Aquic Hapludalfs	Yes
Site 23	Wayne	Utopia	Corn	Soybeans	Ravenna	Aeric Fragiaqualfs	Yes
Site 24	Fulton	Rover	Not sampled	Corn	Colwood	Typic Haplaquolls	No
Site 25	Fulton	Rover	Not sampled	Soybeans	Kibbie	Aquollic Hapludalfs	No
Site 26	Fulton	Rover	Not sampled	Corn	Millgrove	Typic Argiaquolls	No
Site 27	Fulton	Rover	Not sampled	Corn	Gilford	Typic Haplaquolls	No
Site 28	Fulton	Rover	Not sampled	Soybeans	Granby	Typic Haplaquolls	No
Site 29	Fulton	Rover	Not sampled	Corn	Sloan	Fluvaquentic Haplaquolls	No

were typical regarding crop stand (density of plants) and crop vigor (height, productivity). Areas with poor stands and poor crop vigor relative to the rest of the field were avoided when possible.

All soil and crop sampling took place after reproductive maturity (R6 for corn, R8 for soybean), between mid-September and early November in 2020 and 2021. A 12 m^2 sampling area surrounding each of the six sampling points was demarcated. Within this sampling area, 10 soil cores (2.5 cm diameter) were collected from 0 to 20 cm using a push probe and combined into a composite sample for further laboratory analysis. Cone penetrometer readings were taken with a Spot On digital penetrometer (Innoquest, Inc.) within each sampling area. Twelve independent penetrometer readings were taken at 0–10 and 10–20 cm, and an average reading for each sampling area was calculated for each depth. Soil sampling and penetrometer readings occurred during the first year of data collection (2020) at a total of 23 sites across 7 counties.

Crop yields were taken in both years at a total of 18 sites across 6 counties, and 20 sites across 4 counties in 2020 and 2021, respectively (Table 1). In addition to corn and soybean grain, corn silage biomass were also collected for 2020 (sites 1 and 5), but rodent damage during the drying process compromised these yield data and therefore are not reported here. Field corn ears were collected by hand from 12 m^2 (3 linear m of four rows with 0.76 m spacing) the first year and 6 m^2 (1.5 linear m of four rows with 0.76 m spacing) the second year of sampling. All corn ears from the sampling area were counted, whole cobs were dried for 7 days at 49°C, and corn ears were hand shelled. Soybean plant biomass was

TABLE 2 Description of Rover, Utopia, and Nexus pipelines included in this study

Pipeline name	Parent company	Number of lines	Diameter (cm)	Length in Ohio (km)	Capacity million cubic meters (MCuM) per day	Ohio counties crossed	Year construction began	Year construction completed
Rover	Energy Transfer Partners	Dual	107	338	92.03	18	2016	2018
Utopia	Kinder Morgan	Single	30	425	5.95	13	2016	2018
Nexus	DTE Energy and Enbridge, Inc.	Single	91	336	42.48	13	2017	2018

collected from 5.4 m^2 (1.8 linear m of three rows, spaced at 0.19 and 0.38 m). Whole plants were counted, clipped at ground level, then dried for 7 days at 49˚C and hand shelled. Oven-dry weights of field crops were adjusted to standard moisture at harvest (15.5% and 13% for corn and soybean, respectively) to determine yield.

2.4 | Laboratory analyses

Collected soils were weighed to determine total mass at field moisture. Soils were then hand sieved to 8 mm. Rock fragments which did not pass through the 8 mm sieve were collected and counted to identify coarse rocks within each soil sample (1013 cm^3). Gravimetric soil moisture was quantified on a 50 g sample and bulk density was estimated by calculating total dry soil mass from the fixed volume of 10 soil cores. The remaining <8 mm soil sample was oven-dried at 40˚C for 72 h.

Aggregate stability was measured via wet sieving by Yoder (1936). Four aggregate size classes were measured: >2000, 250–2000, 53–250, and 53 µm. Fifty grams of soil (<8 mm and dried) was placed on nested sieves and lowered into deionized water until fully submerged. Samples were immediately subjected to vertical oscillations for 10 min with a stroke of 4 cm at a speed of 30 oscillations per minute. After the 10-min cycle, nested sieves were raised out of the water and allowed to freely drain. Aggregates from each sieve were washed into an aluminum tin, oven-dried at 40˚C, and weighed. Aggregates from each size class were calculated as a percentage of the total sample, with the 53 µm sample being determined by difference. The mean weight diameter (MWD, µm) was calculated as the sum of products of the mean diameter of each size class and the relative proportion of aggregates in that size class (Kemper & Rosenau, 1986).

For all other analyses, soils were flail ground to <2 mm using a Dynacrush DC-5 hammer flail grinder. Infrared spectroscopy via diffuse reflectance infrared Fourier transform spectroscopy in the mid-infrared region (DRIFTS) was used to predict soil texture, following methods described by Deiss et al. (2020). Briefly, mid-IR spectra were collected on finely ground soil using an X,Y Autosampler (PIKE Technologies, Inc.) equipped with a deuterated triglycine sulfate (DTGS) detector, coupled with a Nicolet iS50 spectrometer with a diffuse reflectance accessory (Thermo Fisher Scientific Inc.). Potassium bromide (KBr) was used for the background spectrum, collected at the beginning of each plate reading (i.e., every 23 samples). All measurements were conducted from 4000 to 400 cm^{-1}, 4 cm^{-1} wavenumber resolution, and with 24 co-added scans in absorbance mode (Deiss et al., 2020). Four spectral readings were done on each soil sample (24 co-added scans each) and averaged prior to peak area analysis and predictions.

Routine soil nutrient analysis was measured following recommended procedures (NCERA-13, 2015). Mehlich-3 extractable nutrients (P, K, Ca, Mg, and S), soil pH (1:1 water:soil basis), organic matter (via loss-on-ignition at 360˚C for 2 h), and cation exchange capacity was estimated from the sum of cations, using Mehlich-3 extraction. Soils were analyzed for total soil C and soil N via a CHNS elemental analyzer.

Autoclaved-citrate extractable soil protein was quantified following Hurisso et al. (2018). In a centrifuge tube, 24 ml of 0.02 M sodium citrate (pH 7) was added to 3 g of soil, then shaken for 5 min at 180 oscillations per minute. After shaking, samples were autoclaved at 121˚C for 30 min. Samples were allowed to cool to room temperature before being resuspended by being shaken again for 3 min at 180 oscillations per minute. A 1.5 ml subsample was collected, transferred to a 2 ml centrifuge tube, and subsequently centrifuged at 10,000 × *g* for 3 min. Ten microliters of the supernatant was combined with 200 µl of bicinchoninic acid working reagent (Pierce, Thermo Scientific), then incubated on a block heater at 60˚C for 60 min. Soil protein was quantified using colorimetric bicinchoninic acid assay (Thermo Scientific) in a 96-well spectrophotometric plate reader at 562 nm.

Soil respiration via CO_2 evolution over a 24-h aerobic incubation period was determined using the Franzluebbers et al. (2000) method. Ten grams of air-dried soil were weighed into a 50 ml polypropylene centrifuge tube, and 3 ml of deionized water were added to each sample in a circular motion to prevent excess disturbance of the soil. Tubes were capped and wrapped in parafilm to create an airtight seal, then incubated at 25˚C for exactly 24 h. Following the incubation period, a 1 ml air sample from each tube was collected with a syringe and injected into an LI-820 infrared gas analyzer (LICOR, Biosciences) to determine the CO_2 concentration within each sample.

Permanganate oxidizable carbon following Weil et al. (2003), adapted by Culman et al. (2012), was measured starting with 2.5 g of dry soil added to 50 ml centrifuge tubes. Then, 18 ml of deionized water and 2 ml of $KMnO_4$ were added to each sample tube. Tubes were shaken at 240 oscillations per minute for 2 min, then left to settle for 10 min. A 0.5 ml subsample of the supernatant was then diluted with 49.5 ml of deionized water, and samples were read on a 96-well spectrophotometer plate reader at 550 nm.

2.5 | Statistical analysis

Statistical analysis was conducted using SAS v. 9.4 and R version 4.1.1 (R Foundation for Statistical Computing) with the tidyverse package. Raw data were subjected to analysis of variance (ANOVA) using the PROC MIXED model in SAS to determine the significance ($p < 0.05$). Data were analyzed on an individual site basis for each variable ($n = 6$ observations per site), as well as across sites as a two-way factorial design with pipeline treatment and site as fixed main effects and replication as a random effect. A percent difference calculation between the ROW and control (ADJ) was also used to normalize site-to-site differences and facilitate a site-wide comparison for selected variables of interest. The percent difference was calculated using Equation (1):

$$\%\mathrm{Difference} = \frac{(\mathrm{ROW} - \mathrm{ADJ})}{\mathrm{ADJ}} \times 100 \quad (1)$$

Percent differences were calculated for each site-replication combination and means and standard errors were calculated from the three treatment replicate observations for each site. There were no coarse fragments counted in subsamples from 11 sites, so 0.001 was added to all coarse rock fragment values to enable percent difference calculations (eliminate dividing by zero). All figures were generated using the "ggplot2" package in R.

3 | RESULTS AND DISCUSSION

3.1 | Soil physical characteristics

Penetration resistance (PR) was significantly higher in pipeline ROW relative to the ADJ soils in the 0–10 cm depth but was not statistically different at the 10–20 cm depth (Table 3; Table S1). Within the ROW, PR increased an average of 15.3% (ranged −39.3% to 77.0%) between 0 and 10 cm and 13.6% (ranged −37.5% to 76.7%) between 10 and 20 cm relative to ADJ (Figure 2).

In many sampling areas, PR measurements were unable to be taken as the penetrometer reached the upper detection limits (6.9 MPa) due to the severity of compaction. Of the total 1656 PR observations per depth across all sites, there were significantly more observations that exceeded upper detection limits from 0 to 10 cm in the ROW ($n = 75$) relative to the ADJ ($n = 47$, $p = 0.009$). Similarly, there were significantly more observations that exceeded upper detection limits from the 10–20 cm depth in the ROW ($n = 227$) compared with the ADJ ($n = 99$, $p < 0.001$). Despite a multi-year remediation effort, significant compaction persisted within the ROW relative to the ADJ, unaffected areas of the same field.

This finding is consistent with similar studies over the last 40 years. Over the course of 2 years following installation of a pipeline in central Iowa, Tekeste et al. (2020) found that PR on ROW soils increased an average of 38.7% and 51.3% in conventional tillage and no-tillage systems, respectively, when compared with a control. Additionally, Culley et al. (1982) reported a 55.7% increase in cone index PR within ROW soils compared with undisturbed areas between 0 and 30 cm in

TABLE 3 Mean (standard error) and F-statistics of soil physical characteristics in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites

	Mean (standard error)		F-statistic		
Variable	**ROW**	**ADJ**	**Trt**	**Site**	**Site × Trt**
Penetration resistance (MPa)					
0–10 cm	2.6 (0.1)	2.3 (0.1)	12.0***	23.0****	3.5****
10–20 cm	3.2 (0.1)	2.9 (0.1)	1.0	10.7****	1.3
Bulk density (g cm^{-3})	1.19 (0.0)	1.18 (0.0)	11.7****	22.4****	1.5
Texture (g kg^{-1})					
Clay	201.6 (8.6)	176.6 (6.9)	20.9****	31.6****	1.7
Sand	263.2 (16.9)	269.4 (18.2)	0.0	18.2****	1.4
Silt	578.9 (10.8)	591.0 (11.0)	12.0***	33.9****	2.4**
Rocks per sampled soil	12.0 (1.5)	6.3 (0.9)	9.4**	40.4****	2.7***
Aggregate stability (%)					
>2000 µm	35.2 (1.8)	43.7 (1.6)	34.0****	11.3****	1.5
250–2000 µm	35.0 (1.0)	37.0 (1.1)	6.2*	12.9****	3.9****
53–250 µm	22.9 (1.0)	16.2 (0.9)	67.4****	9.7****	2.0*
<53 µm	6.9 (0.5)	4.0 (0.3)	32.8****	3.5****	1.2
Mean weight diameter (µm)	1136.1 (27.7)	1317.1 (23.7)	57.7****	9.2****	1.1
Soil moisture (g kg^{-1})	191.5 (4.2)	203.0 (3.9)	25.8****	30.1****	1.6

*Significance reported as 0.05.
**Significance reported as 0.01.
***Significance reported as 0.001.
****Significance reported as 0.0001.

conventional tillage systems after a 5-year recovery period. In severely compacted soils, complete site remediation may take up to decades to occur and is largely dependent on the severity of initial compaction at each site (Batey, 2009; Spoor, 2006).

Significant changes in soil texture were found with average clay content increasing 25.0 g kg^{-1} (ranging from −17.4 to 167.0 g kg^{-1}) in ROW soils compared with ADJ areas (Table 3). As clay content increased in six sites, there was a paired decrease in silt content in four sites (Table S2), with an average silt decrease of 12.1 g kg^{-1} across all 23 sites sampled (Table 3). Overall, sand content was not significantly affected by pipeline installation (Table 3).

Increases in surface soil clay concentration, decreases in soil carbon stocks, and visible changes in soil color among horizons have been reported (Batey, 2015; Ivey & McBride, 1999; Neilsen et al., 1990; Wester et al., 2019). Notably, Naeth et al. (1987) reported 102.6% increase in mean clay percentage in a pipelined Solonetzic mixed prairie in southern Alberta. The authors noted that, as surface clay content increased, silt content similarly decreased, and the converse occurred at deeper soil depths, which is consistent with our findings regarding textural changes in ROW soils. Soil mixing also occurred in a 2012 wetland study, where the percentage of sand in ROW soils declined by 19.8% compared with an ADJ area, indicating that either clay or silt percentage had a similar but opposite shift (Olson & Dougherty, 2012). ROW soil mixing was evident 10 years following pipeline installation in Ontario, Canada, where clay percentage by weight increased 25.9% compared with undisturbed sampling areas (Culley & Dow, 1988).

Remediation practices varied at each site and can at least partially explain site-by-site differences. Overall, it was evident that soil mixing between topsoil (A horizon) and subsoil (B horizon) occurred at most sites, indicating that best management practices of double lift excavation used by pipeline companies were insufficient to eliminate degradation of soil.

A significant increase in the number of coarse fragments (>8 mm) was observed, with an average of almost double the number of rock fragments found in ROW soils (12.0) compared with ADJ soils (6.3) (Table 3). During the pipeline installation process, rocks in the subsoil may rise to the surface through excavation and soil moving. Additionally, mechanical pressure and explosives are often used to break up bedrock layers if a pipeline must be installed deeper than the natural soil horizon depths, with stone pulverizers used to break down larger rocks to use as backfill within the pipeline trench (Batey, 2015). The combination of these two practices can create a much larger prevalence of coarse rock fragments within agricultural soils than would occur naturally.

Aggregate stability was significantly decreased under ROW sites relative to ADJ in both macroaggregate size classes (>2000, 250–2000 µm) and significantly increased in

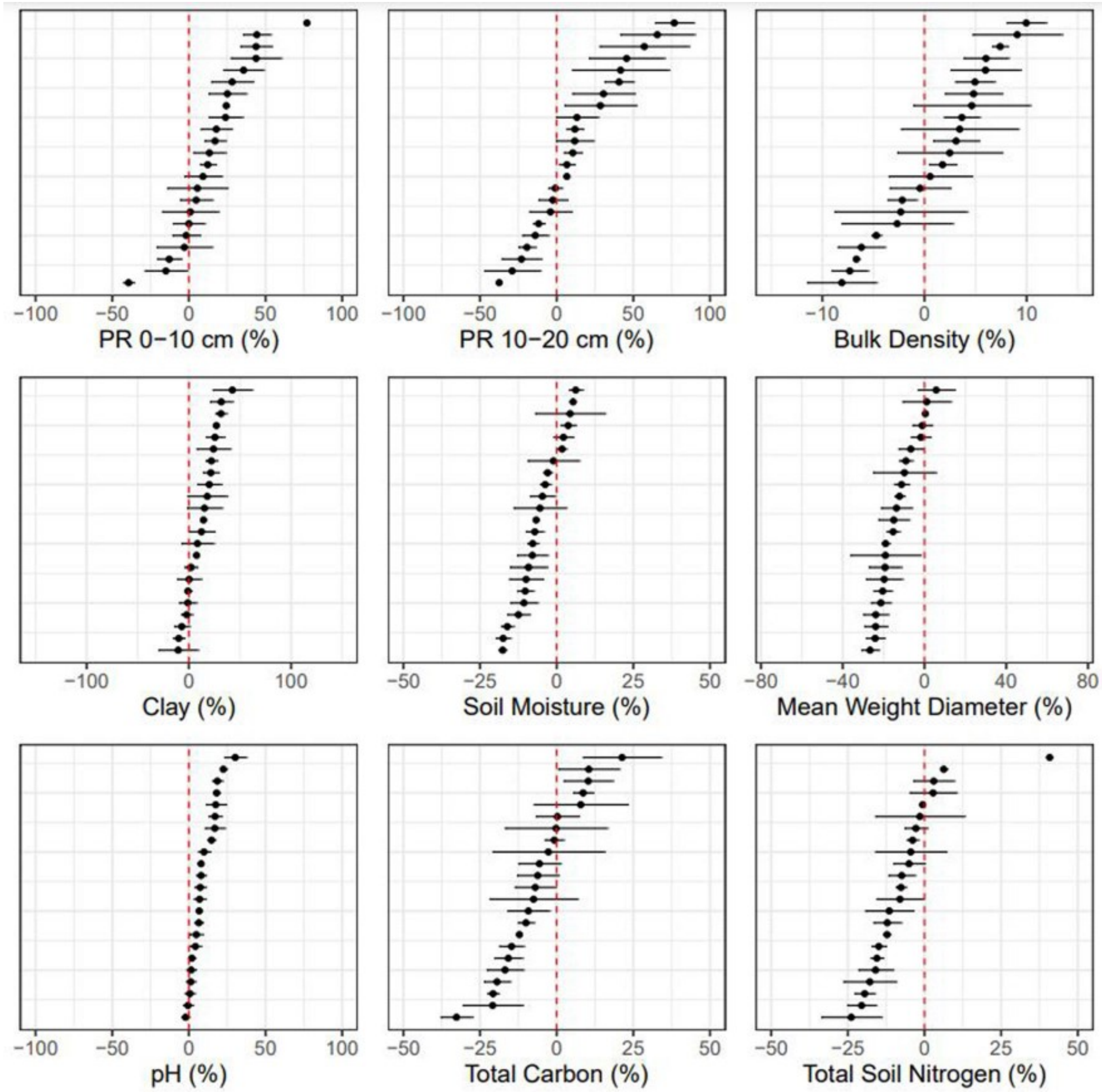

FIGURE 2 Average percent difference values for select soil properties between right-of-way (ROW) versus adjacent, unaffected areas (control, ADJ) across 23 sites. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing the standard error among replicates. Observations are arranged by site from greatest increase to greatest decrease. Values on the left side of the dotted line indicate a decrease in soil characteristic values when compared with adjacent values, while values on the right side indicate an increase in soil characteristic values. PR, cone penetration resistance at depths of 0–10 and 10–20 cm

microaggregates (53–250 μm) and the silt and clay fraction (<53 μm) (Table 3). Macroaggregate prevalence significantly decreased overall within ROW soils, with average MWD decreasing by 13.6% (ranging from −24.1% to 5.7%) across all sites when comparing ROW versus ADJ areas (Figure 2; Table S3). Indicatively, microaggregate prevalence increased in almost half of the sampling sites (Table S3). The size class distribution of soil aggregates illuminates the level of physical disturbance and stress soils were put under during the pipeline installation process.

Our findings are consistent with a 2012 study in New York by Schindelbeck and van Es, which found a significant reduction in aggregate stability in all land types studied (agricultural areas, wetlands, and fallow lands) following pipeline installation, resulting in an average reduction of 32% in aggregate stability following construction activities. Fallow lands showed the most intensive decrease in aggregate stability (60%), while agricultural lands decreased an average of 27% (Schindelbeck & van Es, 2012). This indicates that, in pipelined areas where revegetation is delayed or more difficult to establish following disturbance, aggregate stability and, thus erodibility potential, could be subject to high rates of change when compared with undisturbed soils of the same fields.

The increase in microaggregate sites and subsequent decrease in macroaggregate sites create a more hostile germinating and growing environment for vegetation, alter nutrient cycling and bioavailability, and change hydrologic functions within the soil (Braunack & Dexter, 1988; Guber et al., 2003; Jastrow et al., 1996). Compacted soils with altered pore distributions, particularly when paired with landscape disturbances as seen following pipeline installation, have a higher potential of wind and water erosion which could persist or intensify for years following disturbance (Antille et al., 2016; Vacher et al., 2014; Vacher et al., 2016).

Gravimetric soil moisture at sampling time in ROW areas decreased an average of 11.5 g kg^{-1} across all 23 sites measured, compared with ADJ areas (Table 3), with an average percent difference of −6.3% across all sites including values ranging from −17.8% to 6.2% (Figure 2). A possible driving factor in soil moisture differences is the maintenance and repair of tile drainage following pipeline installation at each site. Other factors such as soil temperature, aggregate stability and size, porosity, and soil texture can also influence soil moisture in pipelined areas. For example, studies within the Slovak Republic and western China both reported increased soil temperatures in ROW soils relative to ADJ soils (Halmova et al., 2017; Shi et al., 2015). Halmova et al. (2017) explicitly attribute decreases in gravimetric soil moisture to increases in ROW soil temperatures from pipeline heating. Culley et al. (1982) found that hydraulic conductivity on ROWs decreased by an average of 38.0% compared to undisturbed fields, noting that while total porosity decreased, drainable porosity and volumetric water content were similar between ROW and undisturbed fields. Reports of decreased soil moisture in other studies following pipeline installation closely relate to our findings here.

3.2 | Soil chemical characteristics

Soil pH significantly increased in ROW soils in 8 of the 23 sites measured when compared with ADJ areas (Figure 2), with an average increase of 0.6 across all sites (Table 4). Given the largely acidic subsoils within the counties sampled, the increase in pH is likely due to agricultural lime applied as a remediation tactic. De Jong and Button (1973) reported pH increases between 0.5 and 1.0 in Chernozemic soils of Alberta, Canada, while Culley and Dow (1988) observed a pH increase of only 0.1 in soils remediated over the course of 10 years. However, the vast majority of the literature disclose no significant change in pH among the ROW versus ADJ areas (Harper & Kershaw, 1997; Ivey & McBride, 1999; Kowaljow & Rostagno, 2008; Shi et al., 2015; Zellmer et al., 1985).

There was an average increase in CEC of 0.8 cmol$_c$ kg^{-1} in ROW soils compared with ADJ soils across all sites (Table 4), which likely resulted from increasing clay content in ROW areas. Additionally, this increase could also be attributed to farmer application of agricultural lime as a remediation measure on pipelined areas, which may have overestimated CEC due to undissolved lime. Nonetheless, this finding of increased CEC follows a similar trend seen in pipelined soils in Ontario, Canada, where Culley and Dow (1988) reported a 42.5% increase in CEC between ROW and ADJ soils following 10 years of remediation activities.

Soil organic carbon (SOC) within the ROW decreased an average of 1.0 g kg^{-1} when compared with ADJ, unaffected areas (Table 4). This equated to an average SOC decrease of 6.5%, ranging from −32.7% to 21.3% across all sites (Figure 2; Table S4). Total soil N (TSN) decreased an average of 0.1 g kg^{-1} in ROW soils compared with ADJ areas (Table 4). These decreases were significant within 7 of the 23 sites measured, while 2 sites documented significant increases (Table S4). Culley and Dow (1988) saw similar declines in total carbon (TC) under pipelines, with a 28.4% decrease in TC in ROW versus ADJ soils. Similarly, Ivey and McBride (1999), Naeth et al. (1990), Harper and Kershaw (1997), and Kowaljow and Rostagno (2008) reported 27.2%, 45.1%, 14.2%, and 49.7% decreases in SOC, respectively. TSN trends in our study are consistent with much of the literature showing decreases after pipeline disturbances (Culley et al., 1982; Culley & Dow, 1988; Kowaljow & Rostagno, 2008; Landsburg & Cannon, 1995; Shi et al., 2014, 2015; Soon et al., 2000).

Mean Mehlich-3 extractable P values decreased an average of 4.9 mg kg^{-1} over the ROW, while K, Ca, Mg, and S increased an average of 10.5, 560.4, 59.6, and 3.8 mg kg^{-1}, respectively (Table 4; Table S5). Increases in calcium and magnesium values were likely elevated as a response to widespread agricultural liming practices by farmers at most sampling sites as a remediation tactic, but could also be caused by soil horizon mixing, where subsoil and bedrock materials naturally elevated in Ca and Mg were brought to the surface (Barker et al., 2017).

These findings are consistent with previous studies that documented decreases in P ranging from 25.2% to 71.3% in ROW soils compared with ADJ areas (Culley et al., 1982; de Jong & Button, 1973; Kowaljow & Rostagno, 2008; Putwain et al., 1982). However, there are many individual reports of no significant changes to either K, Ca, Mg, or S, with significant changes occurring in one or more of the other extractable nutrients (Duncan & Dejoia, 2011; Schindelbeck & van Es, 2012; Shi et al., 2014; Soon, Rice, et al., 2000; Wester et al., 2019; Zellmer et al., 1985). When considered with CEC, Mehlich-3 extractable nutrient concentrations may also be a reflection of changes in CEC and pH, as these factors influence nutrient transport and bioavailability within a soil (Ram, 1980).

TABLE 4 Mean (standard error) and F-statistics of soil chemical characteristics in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites

	Mean (standard error)		F-statistic		
Variable	ROW	ADJ	Trt	Site	Site × Trt
Soil pH	6.7 (0.1)	6.1 (0.1)	110.0****	15.8****	3.3****
OM (g kg^{-1})	19.6 (0.7)	20.2 (0.7)	1.4	14.1****	1.6
CEC ($cmol_c$ kg^{-1})	11.5 (0.5)	10.7 (0.5)	5.6*	18.3****	3.8****
Total C (g kg^{-1})	12.3 (0.5)	13.2 (0.5)	7.8**	22.2****	1.0
Total soil N (g kg^{-1})	1.3 (0.0)	1.4 (0.0)	15.1***	21.3****	1.7*
Mehlich-3 extractable nutrients (mg kg^{-1})					
P	35.6 (2.1)	40.5 (2.9)	5.2*	11.5****	1.6
K	127.9 (4.6)	117.4 (5.0)	10.3**	20.7****	1.9*
Ca	2148.9 (133.0)	1588.5 (85.0)	48.8****	16.7****	3.0***
Mg	309.4 14.7)	249.8 (14.63)	43.2****	25.9****	2.2**
S	17.3 (1.1)	13.5 (0.5)	18.5****	4.8****	2.8***

*Significance reported as 0.05.
**Significance reported as 0.01.
***Significance reported as 0.001.
****Significance reported as 0.0001.

TABLE 5 Mean (standard error) and F-statistics of soil biological characteristics in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites

	Mean (standard error)		F-statistic		
Variable	ROW	ADJ	Trt	Site	Site × Trt
POXC (mg kg^{-1})	413.0 (14.0)	424.7 (11.5)	1.1	9.5****	2.0*
Protein (g kg^{-1})	3.7 (0.1)	4.2 (0.1)	25.5****	5.6****	1.4
Respiration (mg kg^{-1})	37.9 (2.7)	46.3 (4.1)	10.6**	15.7****	2.3**

Abbreviation: POXC, permanganate oxidizable carbon.
*Significance reported as 0.05.
**Significance reported as 0.01.
***Significance reported as 0.001.
****Significance reported as 0.0001.

3.3 | Soil biological and biochemical characteristics

Soil biological factors of autoclaved-extractable soil protein and soil respiration were significantly decreased in ROW areas when compared with ADJ (Table 5). Pipeline installations did not affect POXC values across all sites (Table 5), although three individual sites were significantly decreased over the ROW, with percent differences ranging from −28.1% to 44.5% between all 23 sites (Table S6). Conversely, soil protein decreased over pipeline ROWs, indicating that the organic N pool within the ROW was significantly reduced relative to ADJ areas. Similarly, soil respiration was reduced by pipeline installation, with percent difference ranging from −61.2% to 97.9% between ROW and ADJ areas (Table S6).

Few studies have analyzed soil biological or biochemical properties following underground pipeline installation. In a 2000 study by Soon, Rice, et al., microbial biomass carbon (MBC) varied from year to year, leading researchers to conclude that the average level of MBC was not adversely affected by pipeline disturbances. Conversely, a 73% decrease in POXC in ROW areas was reported in New York, which researchers attributed to soil mixing, increasing biological activity at depth, and decreasing biological activity in surface soils, all as a result of pipeline activity (Schindelbeck & van Es, 2012). It is likely that microbial populations face the most severe decrease in abundance and activity within the first few years following installation, particularly as soil aggregates are dramatically altered, and that microbial activity within ROW soils will likely equilibrate over time as populations adapt to changing soil conditions (Vermeire et al., 2018). Decreased soil protein and respiration values indicate a suppression of labile N and microbial activity in ROW soils relative to undisturbed soils. It is also possible that ROW soil mixing could be

TABLE 6 Mean (standard error) and F-statistics of yields for corn and soybean in 2020 and 2021 across Ohio field sites

		Mean (standard error)		F-statistic		
Crop (Mg ha^{-1})	Year	ROW	ADJ	Trt	Site	Site × Trt
Corn	2020	8.69 (0.71)	11.96 (0.55)	132.3****	35.1****	6.3****
	2021	6.52 (0.52)	7.86 (0.34)	28.6****	18.6****	3.6*
Soybean	2020	4.30 (0.29)	4.36 (0.22)	2.7	19.9****	0.3
	2021	4.39 (0.32)	5.00 (0.28)	19.0****	44.8****	5.1****

*Significance reported as 0.05.
**Significance reported as 0.01.
***Significance reported as 0.001.
****Significance reported as 0.0001.

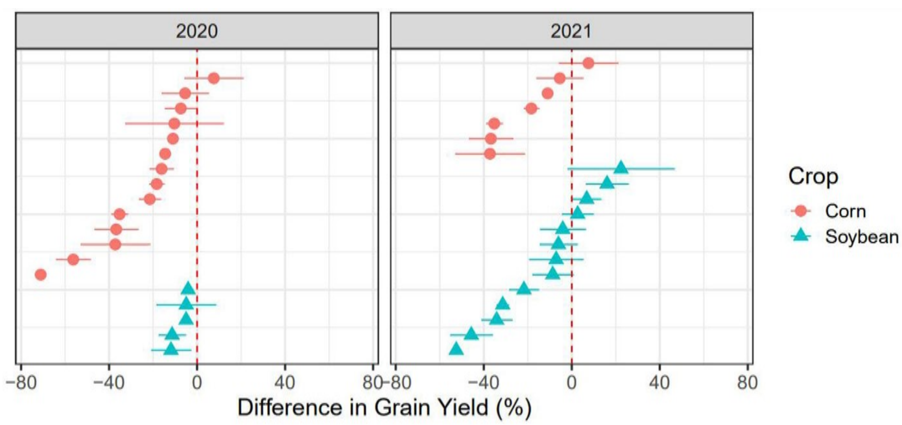

FIGURE 3 Average percent difference in crop yields in 2020 and 2021 between right-of-way (ROW) and adjacent (control, ADJ) sampling areas. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing the standard error among replicates. Observations are arranged by site from greatest increase to greatest decrease. Values on the left side of the dotted line indicate a decrease in yield when compared with adjacent values, while values on the right side indicate an increase in yield

disrupting microbial "hotspots" of activity near root channels and incorporated soil organic matter (Wang et al., 2020; Zegeye et al., 2019), so microbes may be physically disconnected from their carbon source, which reduces microbial activity and thus respiration, while leaving POXC unchanged.

3.4 | Crop yield

Corn yield decreases were documented during both years of sampling, with an average decrease of 3.27 Mg ha^{-1} in 2020 (ranging from −5.43 to 0.30 Mg ha^{-1}) and 1.34 Mg ha^{-1} (ranging from −2.17 to 0.28 Mg ha^{-1}) in 2021 (Table 6; Table S7). This translates to an average yield decrease of 23.8% in 2020 and 19.5% in 2021 in ROW areas compared with ADJ (Figure 3). Comparatively, soybean yields were not significantly different during 2020, with a 7.4% decrease (mean = −0.42 Mg ha^{-1}, ranging from −0.92 to −0.18 Mg ha^{-1}) in ROW yields compared with ADJ. However, during 2021, soybean yield decreased by an average of 0.61 Mg ha^{-1}, ranging from −2.25 to 0.88 Mg ha^{-1} (Table 6; Table S7). This decline equates to a 12.6% decrease in ROW soybean yields compared with ADJ areas (Figure 3). Overall, corn was more impacted by pipeline installation than soybean. Significant decreases in corn yield occurred at over 70% of fields sampled during both years, compared with decreases of 0% and 31% in soybean fields during 2020 and 2021, respectively.

More extreme decreases in our reported yields during 2020 may be a factor of rainfall, as precipitation in Ohio from June–August of 2020 was extremely low (29th driest year since 1895) while the same period in 2021 ranked the 113th wettest out of 128 years (NOAA Staff, 2021b). Corn can be extremely susceptible to drought, with 2.1%–8.0% yield reductions per day of stress experienced between pollination and dent (Lauer, 2018). Comparatively, drought-stressed soybean plants can flower again and initiate pod setting, even into the mid seed filling stage, so increased rainfall at the end of August 2020 may have been a factor in increased soybean yields in this crop-year combination (Licht & Clemens, 2020).

Decreases in yields following pipeline installation have been commonly reported, though the longevity of these impacts often varies on a site, crop, and climatic basis (de Jong & Button, 1973; Nielsen et al., 1990; Olson & Dougherty, 2012; Tekeste et al., 2020). Culley et al. (1982) reported up to 50% yield reductions in corn grain within 2 years of pipeline installation, while still maintaining a 23.7% yield decrease 10 years following pipeline installation (Culley & Dow, 1988). While yield decreases are common following installation, Shi et al. (2015) reported no significant difference between ROW and ADJ corn grain yields when directly comparing three pipelines installed 2, 6, and 8 years prior to sampling. Our data confirm that, even after a 4- to 5-year remediation period, corn and soybean grain yields at our sites were still negatively impacted relative to ADJ, unaffected areas within the same field, showing that yield declines persist for years following installation.

4 | CONCLUSIONS

Across a diverse set of farms and soil types in eight counties across northern Ohio, soil properties and crop yields were detrimentally impacted following a 4- to 5-year recovery period on three recently installed pipelines. These pipelines were all installed and remediated with best management practices including double lift installation techniques and deep ripping to repair any compacted areas. Soil physical characteristics, such as penetration resistance and aggregate stability indicated that large-scale compaction prevailed at almost all sites evaluated in this study. Future degradation via wind and water erosion may exacerbate degradation in ROW areas if the degradation legacy is not addressed and soil fully remediated. Likely, a combination of physical compaction and soil mixing resulted in degradation of other measured soil chemical and biological properties reported here. Finally, paired comparisons of fields demonstrated reduced crop yields across most field sites.

Site-to-site variability remains high throughout most metrics in this study, which is likely derived from differing initial site conditions like moisture and heavy machinery disturbance during the installation process, inconsistent contract negotiations between pipeline companies and landowners, and variable rates and intensities of remediation activities. Thus, trends are not always consistent between sites. Difficulty also arises from pipeline crews periodically re-visiting sites over the course of pipeline installation and remediation activities, making it difficult to fully track the magnitude of both degradation and remediation, as the two processes often temporally and spatially overlap.

All pipelines involved in this study were constructed using double lift practices, as opposed with many studies in the literature which were conducted on single lift installation practices (n = 7) or did not specify type of installation practice used (n = 14). However, the sustained detrimental impacts to both soil characteristics and agricultural crop yields following pipeline installation reported here, suggests that these double lift practices either: (1) are not being carried out properly by pipeline installation and remediation crews or (2) even if handled properly, are insufficient preventative measures to mitigate soil degradation and crop yield losses. Likely, a combination of these factors has driven our findings.

Collectively our data suggest contemporary pipeline installation still results in sustained soil degradation and crop yield losses and that current easement compensations plans are not appropriately compensating farmers for these losses. Additional monitoring of crop yields is needed, as is research to better predict crop losses over time as soil remediation continues. Future research needs to address identifying effective remediation techniques that can rapidly restore soil to the pre-installation state. Finally, and most importantly, improving installation practices and strict adherence to these practices by pipeline installation crews are needed to minimize the severity of initial soil degradation via compaction and soil mixing that are still commonly observed with current industry best management practices.

AUTHOR CONTRIBUTIONS

Theresa Brehm: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing–original draft; writing–review & editing. **Steve Culman**: Conceptualization; data curation; formal analysis; funding acquisition; methodology; project administration; resources; software; supervision; validation; visualization; writing–review & editing.

ACKNOWLEDGMENTS

Partial financial support for this project was provided by Kinder Morgan, the parent company for the Utopia pipeline project. However, Kinder Morgan had no involvement in the project's study design, collection, analysis, interpretation of data, or manuscript preparation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Antille, D. L., Huth, N. I., Eberhard, J., Marinoni, O., Cocks, B., Poulton, P. L., Macdonald, B. C. T., & Schmidt, E. J. (2016). The effects of coal seam gas infrastructure development on arable land in southern Queensland, Australia: Field investigations and modeling. *Transactions of the ASABE*, *59*(4), 879–901. https://doi.org/10.13031/trans.59.11547

Barker, D., Culman, S., Dorrance, A., Fulton, J., Haden, R., Lentz, E., Lindsey, A., Loux, M., McCoy, E., Michel, A., Noel, J., Paul, P., Sulc, R. M., Thomison, P., Tilmon, K.,

& Witter, J. (2017). *Ohio agronomy guide*. The Ohio State University Extension. https://stepupsoy.osu.edu/sites/hcs-soy/files/472%20Ohio%20Agronomy%20Guide%2015%20Ed%20red_0.pdf

Batey, T. (2009). Soil compaction and soil management—A review. *Soil Use and Management*, *25*(4), 335–345. https://doi.org/10.1111/j.1475-2743.2009.00236.x

Batey, T. (2015). The installation of underground pipelines: Effects on soil properties. *Soil Use and Management*, *31*(1), 60–66. https://doi.org/10.1111/sum.12163

Braunack, M. V., & Dexter, A. R. (1988). The effect of aggregate size in the seedbed on surface crusting and growth and yield of wheat (*Triticum aestivum* L., cv. halberd) under dryland conditions. *Soil and Tillage Research*, *11*(2), 133–145. https://doi.org/10.1016/0167-1987(88)90021-9

Brehm, T., & Culman, S. (2022). Pipeline installation effects on soils and plants: A review and quantitative synthesis. *Agrosystems, Geosciences & Environment*, *5*(4), 1–15. https://doi.org/10.1002/agg2.20312

CIA World Factbook Staff. (2021a). *Pipelines - The world factbook*. https://www.cia.gov/the-world-factbook/field/pipelines/

Culley, J. L., & Dow, B. K. (1988). Long-term effects of an oil pipeline installation on soil productivity. *Canadian Journal of Soil Science*, *68*(1), 177–181. https://doi.org/10.4141/cjss88-018

Culley, J. L., Dow, B. K., Presant, E. W., & Maclean, A. J. (1981). *Impacts of installation of an oil pipeline on the productivity of Ontario cropland*. Research Branch, Agriculture Canada.

Culley, J. L., Dow, B. K., Presant, E. W., & MacLean, A. J. (1982). Recovery of productivity of Ontario soils disturbed by an oil pipeline installation. *Canadian Journal of Soil Science*, *62*(2), 267–279. https://doi.org/10.4141/cjss82-031

Culman, S. W., Snapp, S. S., Freeman, M. A., Schipanski, M. E., Beniston, J., Lal, R., Drinkwater, L. E., Franzluebbers, A. J., Glover, J. D., Grandy, A. S., Lee, J., Six, J., Maul, J. E., Mirksy, S. B., Spargo, J. T., & Wander, M. M. (2012). Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. *Soil Science Society of America Journal*, *76*(2), 494–504. https://doi.org/10.2136/sssaj2011.0286

Deiss, L., Culman, S. W., & Demyan, M. S. (2020). Grinding and spectra replication often improves mid-DRIFTS predictions of soil properties. *Soil Science Society of America Journal*, *84*, 914–929. https://doi.org/10.1002/saj2.20021

de Jong, E., & Button, R. G. (1973). Effects of pipeline installation on soil properties and productivity. *Canadian Journal of Soil Science*, *53*(1), 37–47. https://doi.org/10.4141/cjss73-005

Desserud, P., Gates, C. C., Adams, B., & Revel, R. D. (2010). Restoration of foothills rough fescue grassland following pipeline disturbance in southwestern Alberta. *Journal of Environmental Management*, *91*(12), 2763–2770. https://doi.org/10.1016/j.jenvman.2010.08.006

Duncan, M. M., & Dejoia, A. (2011). Topsoil loss: Evaluating agronomic characteristics of surface soils on a pipeline right-of-way. *Journal of the American Society of Mining and Reclamation*, *2011*(1), 185–201. https://doi.org/10.21000/jasmr11010185

Federal Energy Regulatory Commission. (2016). *Rover pipeline, panhandle backhaul, and trunkline backhaul projects: Final environmental impact statement*. Federal Energy Regulatory Commission. https://cms.ferc.gov/sites/default/files/2020-05/impact-statement.pdf

Franzluebbers, A. J., Haney, R. L., Honeycutt, C. W., Schomberg, H. H., & Hons, F. M. (2000). Flush of carbon dioxide following rewetting of dried soil relates to active organic pools. *Soil Science Society of America Journal*, *64*(2), 613–623. https://doi.org/10.2136/sssaj2000.642613x

Gasch, C. K., Huzurbazar, S. V., & Stahl, P. D. (2016). Description of vegetation and soil properties in sagebrush steppe following pipeline burial, reclamation, and recovery time. *Geoderma*, *265*, 19–26. https://doi.org/10.1016/j.geoderma.2015.11.013

Guber, A. K., Rawls, W. J., Shein, E. V., & Pachepsky, Y. A. (2003). Effect of soil aggregate size distribution on water retention. *Soil Science*, *168*(4), 223–233. https://doi.org/10.1097/01.ss.0000064887.94869.d3

Halmova, D., Polánkova, Z., Končekova, L., & Fehér, A. (2017). Impact of operating temperature of gas transit pipeline on soil quality and production potential of crops. *Agriculture (Pol'nohospodárstvo)*, *63*(3), 120–127. https://doi.org/10.1515/agri-2017-0012

Harper, K. A., & Kershaw, G. P. (1997). Soil characteristics of 48-year-old borrow pits and vehicle tracks in shrub tundra along the CANOL No. 1 pipeline corridor, Northwest Territories, Canada. *Arctic and Alpine Research*, *29*(1), 105–111. https://doi.org/10.2307/1551840

Hurisso, T. T., Moebius-Clune, D. J., Culman, S. W., Moebius-Clune, B. N., Thies, J. E., & van Es, H. M. (2018). Soil protein as a rapid soil health indicator of potentially available organic nitrogen. *Agricultural & Environmental Letters*, *3*(1), 180006. https://doi.org/10.2134/ael2018.02.0006

Ivey, J. L., & McBride, R. A. (1999). Delineating the zone of topsoil disturbance around buried utilities on agricultural land. *Land Degradation & Development*, *10*(6), 531–544. https://doi.org/10.1002/(sici)1099-145x(199911/12)10:6⟨531::aid-ldr353⟩3.0.co;2-7

Jastrow, J. D., Miller, R. M., & Boutton, T. W. (1996). Carbon dynamics of aggregate-associated organic matter estimated by carbon-13 natural abundance. *Soil Science Society of America Journal*, *60*(3), 801–807. https://doi.org/10.2136/sssaj1996.03615995006000030017x

Kemper, W. D., & Rosenau, R. C. (2018). Aggregate stability and size distribution. In A. Klute (Ed.), *Methods of soil analysis: Part 1, physical and mineralogical methods* (2nd ed., pp. 425–442). SSSA. https://doi.org/10.2136/sssabookser5.1.2ed.c17

Kowaljow, E., & Rostagno, C. M. (2008). *Efectos de la instalacio'n de un gasoducto sobre algunas propiedades del suelo superficial y la cobertura vegetal en el ne de Chebut*.

Landsburg, S. (1989). Effects of pipeline construction on Cheronzemic and Solonetzic A and B horizons in central Alberta. *Canadian Journal of Soil Science*, *69*(2), 327–336. https://doi.org/10.4141/cjss89-033

Landsburg, S., & Cannon, K. R. (1995). *Impacts of overstripping topsoil on native rangelands in Southeastern Alberta: A literature review* (NGTL Environmental Research Monographs, 1995-1). NOVA Gas Transmission Ltd.

Lauer, J. (2018). *What happens within the corn plant when drought occurs?* Extension Dunn County. https://dunn.extension.wisc.edu/files/2018/09/CV-Ag-News-Fall-2018-Page-2-Corn-plant-during-drought.pdf

Licht, M., & Clemens, Z. (2020). *Drought effect on corn and soybean and alternative management considerations*. https://crops.extension.iastate.edu/blog/mark-licht-zachary-clemens/drought-effectcorn-and-soybean-and-alternative-management

Low, C. H. (2016). *Impacts of a six-year-old pipeline right of way on Halimolobos Virgata (Nutt.) O.E. Schulz (slender mouse ear cress), native dry mixedgrass prairie uplands, and wetlands*. University of Alberta.

Naeth, M. A., Bailey, A. W., & McGill, W. B. (1987). Persistence of changes in selected soil chemical and physical properties after pipeline installation in Solonetzic native rangeland. *Canadian*

Journal of Soil Science, *67*(4), 747–763. https://doi.org/10.4141/cjss87-073

Naeth, M. A., Chanasyk, D. S., McGill, W. B., & Bailey, A. W. (1993). Soil temperature regime in mixed prairie rangeland after pipeline construction and operation. *Canadian Agricultural Engineering*, *35*(2), 89–95.

Nielsen, D., Mackenzie, A. F., & Stewart, A. (1990). The effects of buried pipeline installation and fertilizer treatments on corn productivity on three eastern Canadian soils. *Canadian Journal of Soil Science*, *70*(2), 169–179. https://doi.org/10.4141/cjss90-019

NEXUS Staff. (2016). *Final environmental impact statement: NEXUS gas transmission project and Texas Eastern Appalachian lease project*. NEXUS Gas Transmission, LLC. https://cms.ferc.gov/sites/default/files/2020-05/FEIS.pdf

NOAA Staff. (2021a). *Cleveland normals*. National Weather Service. https://www.weather.gov/cle/CLENormals

NOAA Staff. (2021b). *National temperature and precipitation maps*. NOAA. https://www.ncei.noaa.gov/access/monitoring/us-maps/

Olson, E., & Doherty, J. (2012). The legacy of pipeline installation on the soil and vegetation of southeast Wisconsin wetlands. *Ecological Engineering*, *39*, 53–62. https://doi.org/10.1016/j.ecoleng.2011.11.005

Putwain, P. D., Gillham, D. A., & Holliday, R. J. (1982). Restoration of heather moorland and lowland heathland, with special reference to pipelines. *Environmental Conservation*, *9*(3), 225–235. https://doi.org/10.1017/s0376892900020439

Ram, L. C. (1980). Cation exchange capacity of plant roots in relation to nutrients uptake by shoot and grain as influenced by age. *Plant and Soil*, *55*(2), 215–224. https://doi.org/10.1007/bf02181801

Schindelbeck, R. R., & van Es, H. M. (2012). Using soil health indicators to follow carbon dynamics in disturbed Urban environments—A case study of gas pipeline right-of-way construction. In R. Lal & B. Augustin (Eds.), *Carbon sequestration in urban ecosystems*. Springer. https://doi.org/10.1007/978-94-007-2366-5

Shi, P., Huang, Y., Chen, H., Wang, Y., Xiao, J., & Chen, L. (2015). Quantifying the effects of pipeline installation on agricultural productivity in west China. *Agronomy Journal*, *107*(2), 524–531. https://doi.org/10.2134/agronj14.0023

Shi, P., Xiao, J., Wang, Y.-F., & Chen, L. D. (2014). The effects of pipeline construction disturbance on soil properties and restoration cycle. *Environmental Monitoring and Assessment*, *186*(3), 1825–1835. https://doi.org/10.1007/s10661-013-3496-5

Soon, Y. K., Arshad, M. A., Rice, W. A., & Mills, P. (2000). Recovery of chemical and physical properties of boreal plain soils impacted by pipeline burial. *Canadian Journal of Soil Science*, *80*(3), 489–497. https://doi.org/10.4141/s99-097

Soon, Y. K., Rice, W. A., Arshad, M. A., & Mills, P. (2000). Effect of pipeline installation on crop yield and some biological properties of boreal soils. *Canadian Journal of Soil Science*, *80*(3), 483–488. https://doi.org/10.4141/s99-096

Spoor, G. (2006). Alleviation of soil compaction: Requirements, equipment and techniques. *Soil Use and Management*, *22*(2), 113–122. https://doi.org/10.1111/j.1475-2743.2006.00015.x

Tekeste, M. Z., Ebrahimi, E., Hanna, M. H., Neideigh, E. R., & Horton, R. (2020). Effect of subsoil tillage during pipeline construction activities on near-term soil physical properties and crop yields in the right-of-way. *Soil Use and Management*, *37*, 545–555. https://doi.org/10.1111/sum.12623

Tekeste, M. Z., Hanna, H. M., Neideigh, E. R., & Guillemette, A. (2019). Pipeline right-of-way construction activities impact on deep soil compaction. *Soil Use and Management*, *35*(2), 293–302. https://doi.org/10.1111/sum.12489

Turner, T. (2016). *Edaphic and crop production changes resulting from pipeline installation in semiarid agricultural ecosystems*. University of Northern British Columbia. https://core.ac.uk/download/pdf/84874737.pdf

U.S. Bureau of Transportation Statistics Staff. (2021). *U.S.* oil *and* gas *pipeline* mileage. U.S. Bureau of Transportation Statistics. https://www.bts.gov/content/us-oil-and-gas-pipeline-mileage

U.S. PHMSA Staff. (2018). *General pipeline FAQs*. https://www.phmsa.dot.gov/faqs/general-pipeline-faqs

U.S. PHMSA Staff. (2020). *By-decade inventory*. https://www.phmsa.dot.gov/data-and-statistics/pipeline-replacement/decade-inventory

USDA-NASS Staff. (2021). *2021 State agriculture overview*. USDA/NASS 2021 State Agriculture Overview for Ohio. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=OHIO

Vacher, C., Antille, D., Huth, N., & Raine, S. (2016). Assessing erosion processes associated with establishment of coal seam gas pipeline infrastructure in Queensland, Australia. *2016 ASABE International Meeting*, 1–13. https://doi.org/10.13031/aim.20162461210

Vacher, C. A., White, S., Eberhard, J., Schmidt, E., Huth, N. I., & Antille, D. L. (2014). Quantifying the impacts of coal seam gas (CSG) activities on the soil resource of agricultural lands in Queensland, Australia. *2014 ASABE Annual International Meeting*, 1–11. https://doi.org/10.13031/aim.20141898868

Vermeire, M.-L., Cornélis, J.-T., Van Ranst, E., Bonneville, S., Doetterl, S., & Delvaux, B. (2018). Soil microbial populations shift as processes protecting organic matter change during podzolization. *Frontiers in Environmental Science*, *6*, 70. https://doi.org/10.3389/fenvs.2018.00070

Wang, H., Liu, S., Kuzyakov, Y., Zhan, P., Wang, Q., Hettenhausen, C., Xiao, D., Qi, J., & Zhang, Z. (2020). Differentiating microbial taxonomic and functional responses to physical disturbance in bulk and rhizosphere soils. *Land Degradation & Development*, *31*(18), 2858–2871. https://doi.org/10.1002/ldr.3679

Warncke, D., & Brown, J. R (1998). Potassium and other basic cations. In J. R. Brown (Ed.), *Recommended chemical soil test procedures for the north central region (Revised) (North central region publication 221, pp. 31–34)*. University of Missouri, Missouri Agricultural Experiment Station.

Weil, R. R., Islam, K. R., Stine, M. A., Gruver, J. B., & Samson-Liebig, S. E. (2003). Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture*, *18*(1), 3–17. http://www.jstor.org/stable/44503242

Wester, D. B., Hoffman, J. B., Rideout-Hanzak, S., Ruppert, D. E., Acosta-Martinéz, V., Smith, F. S., & Stumberg, P. M. (2019). Restoration of mixed soils along pipelines in the western Rio Grande Plains, Texas, USA. *Journal of Arid Environments*, *161*, 25–34. https://doi.org/10.1016/j.jaridenv.2018.10.002

Winning, H. K., & Hann, M. J. (2014). Modelling soil erosion risk for pipelines using remote sensed data. *Biosystems Engineering*, *127*, 135–143. https://doi.org/10.1016/j.biosystemseng.2014.08.020

Xiao, J., Shi, P., Wang, Y.-F., Yu, Y., & Yang, L. (2017). A framework for quantifying the extent of impact to plants from linear construction. *Scientific Reports*, *7*(1), 2488. https://doi.org/10.1038/s41598-017-02443-3

Xiao, J., Wang, Y.-F., Shi, P., Yang, L., & Chen, L.-D. (2014). Potential effects of large linear pipeline construction on soil and vegetation in ecologically fragile regions. *Environmental Monitoring and Assessment*, *186*(11), 8037–8048. https://doi.org/10.1007/s10661-014-3986-0

Yoder, R. E. (1936). A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. *Agronomy Journal*, *28*(5), 337–351. https://doi.org/10.2134/agronj1936.00021962002800050001x

Zegeye, E. K., Brislawn, C. J., Farris, Y., Fansler, S. J., Hofmockel, K. S., Jansson, J. K., Wright, A. T., Graham, E. B., Naylor, D., McClure, R. S., & Bernstein, H. C. (2019). Selection, succession, and stabilization of soil microbial consortia. *mSystems*, *4*(4), 1–13. https://doi.org/10.1128/msystems.00055-19

Zellmer, S. D., Taylor, J. D., & Carter, R. P. (1985). Edaphic and crop production changes resulting from pipeline installation in semiarid agricultural ecosystems. *Journal of the American Society of Mining and Reclamation*, *1985*(1), 181–189. https://doi.org/10.21000/JASMR85010181

SUPPORTING INFORMATION

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How to cite this article: Brehm, T., & Culman, S. (2023). Soil degradation and crop yield declines persist 5 years after pipeline installations. *Soil Science Society of America Journal*, *87,* 350–364. https://doi.org/10.1002/saj2.20506