September 4, 2023

TO: LUP-Comments@multco.us

RE: Case File No. T3-2022-16220 [Portland Water Bureau]

Please accept this letter in rebuttal of the applicant's *Agricultural Soil Restoration Study by Jacobs Consultants*, labeled as Exhibit A.35. In the Executive Summary, the report states *"This Agricultural Soils Restoration Plan describes the methods that will be used to reduce, minimize, or mitigate for impacts on agricultural resources associated with construction of the Facility…."* The report further states "*The Water Bureau is committed to using state-of-art practices to return the land to pre-construction productivity…"*

Response:

Below you will see scientific evidence that what the PWB says they can and will do is impossible. [Please see additional scientific evidence to substantiate this impossibility in *Exhibit I.11, Ekstrom Rebuttal; Exhibit I.11.a, Pipeline Installation Effects; Exhibit I.11.c, Pipeline Study*; and *Exhibit I.11.d, Pipelines keep robbing the land*.]

You will see that a "condition for approval" cannot mitigate the impact on disturbed productive soil that cannot be restored to pre-construction condition. The result for affected farmers will be a loss of land production and a loss of income.

The soil restoration process proposed in A.35 is often referred to as the 2-Lift system. Steve Culman*, Endowed Chair of Soil Health, Washington State University, was personally contacted via phone call on August 31, 2023 about his research into the 2-Lift system. Some of this research, including *"Soil degradation and crop yield declines persist 5 years after pipeline installations"* is attached and can also be viewed in this link http://go.osu.edu/pipeline-study.

The 2-Lift system has been used for a long time. It is important to note that most of the research on the 2-Lift system has been about restoring or improving contaminated soils. Of course these types of contaminated soils are going to benefit somewhat with the newer soil mixture. But we are not talking about contaminated soils here. We are talking about prime farmland.

Professor Culman explained that the protocols stated by Jacobs and used in the 2-Lift process are usually not followed, in his research, because the process is labor intensive, and the road crews would hurry through the process and make many errors. They were "careless" and even "reckless," he said. So, the process was not thoroughly or strictly followed. Culman continued that many times the road crews would continue with the soil replacement procedures even when the soils were wet which completely undermined the process. These errors were routinely made, Culman stated.

Culman pointed out that in an Ohio Study, the restoration process did not return the farmland to normal productivity, i.e., the soils stayed degraded after 5 years.

Culman summarizes it best ….. "Current best management practices of pipeline installation and remediation employed by three companies were insufficient to combat widespread soil degradation and crop yield loss." (see Attachment).

MCC 39.7515 (C) The use will not: (1) Force a significant change in accepted farm or forest practices on surrounding lands devoted to farm or forest use; nor (2) Significantly increase the cost of accepted farm or forest practices on surrounding lands devoted to farm or forest use **has not been met.**

<u>The loss to affected farmers cannot be mitigated and cannot be mitigated through "conditions for approval".</u>

Respectfully,
Cottrell Community Planning Organization [Cottrell CPO]
cottrellcpo@gmail.com

- Steve Culman. Associate Professor, Washington State University; Ph.D., Agronomy, Cornell University; M.S. Soil Science, Cornell University; B.A. Biology, Thomas More College; Endowed Chair of Soil Health, Washington State University.

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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.

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.

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.

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

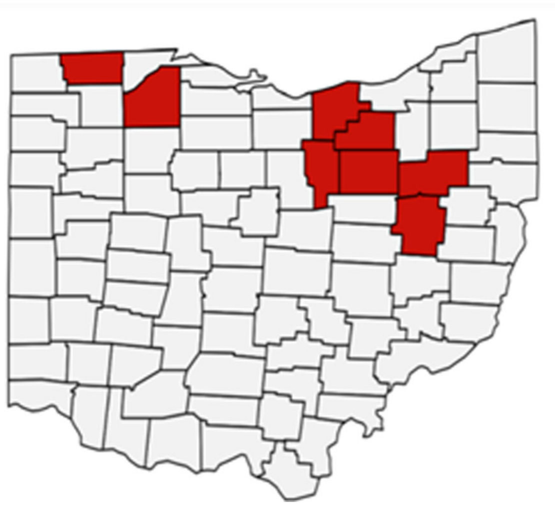

FIGURE 1 A map of Ohio with counties highlighted in red where sampling occurred for this study in 2020 and 2021

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 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.

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

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

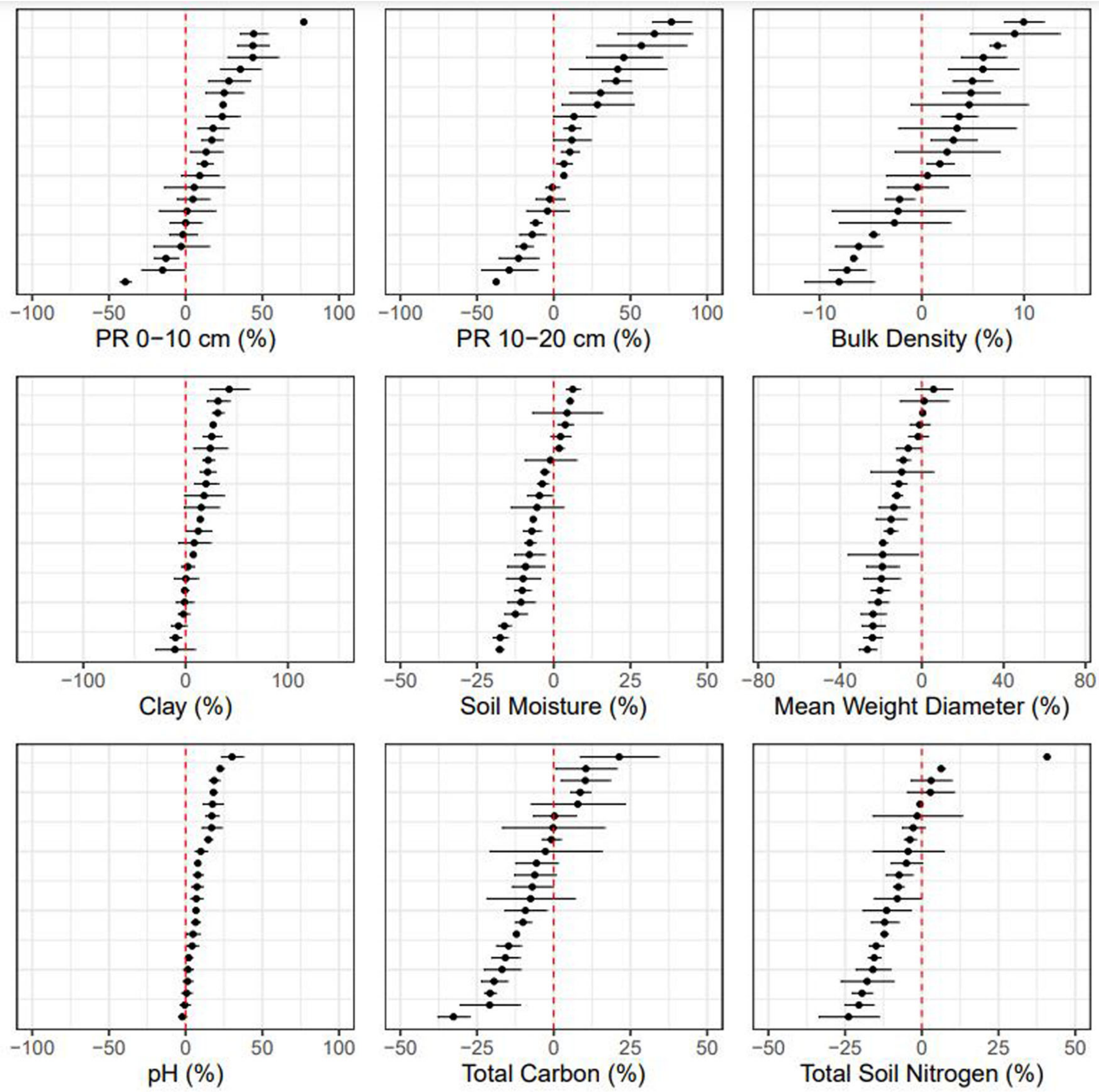

FIGURE 2 Average percent difference values for select soil properties between right-of-way (ROW) versus adjacent, unaffected areas (control, ADJ) across 23 sites. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing 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.

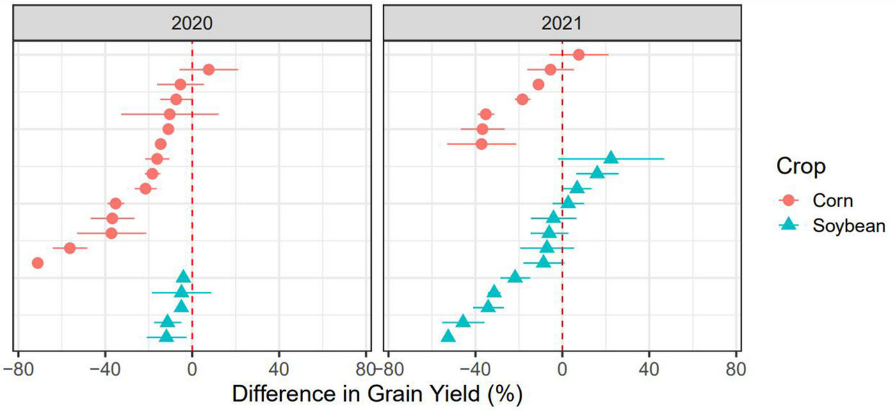

FIGURE 3 Average percent difference in crop yields in 2020 and 2021 between right-of-way (ROW) and adjacent (control, ADJ) sampling areas. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing the standard error among 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.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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

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Evaluation of Pipeline Installation

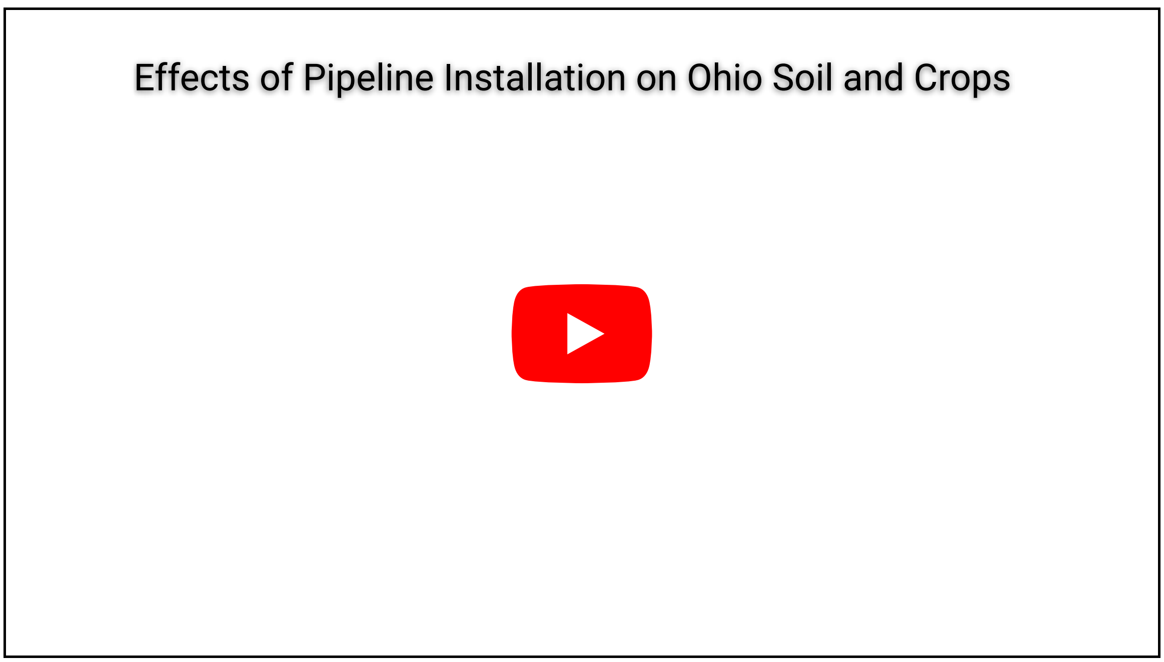
on Crop Productivity in Ohio

PROJECT OVERVIEW

We conducted a multi-faceteted study to i) summarize published literature of pipeline impacts, ii) document impacts of three recently installed pipelines in Ohio, and iii) survey landowners on their experiences with having pipelines installed on their property. Our findings are published in the pdf links below.

- Literature Review of Pipeline Impacts on Soil and Crop Properties
- Assessment of Impacts of Rover, Utopia and Nexus Pipelines in Ohio
- Ohio Landowner Experiences with Pipeline Installations

Video where Theresa summarizes the findings of her work:



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REVIEW

Pipeline installation effects on soils and plants: A review and quantitative synthesis

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Abstract

Oil and natural gas pipelines are essential to the transport of energy materials, but construction of these pipelines commonly causes disturbance to ecosystems. Due to variability in pipeline installation practices and environments, drawing consensus about how pipeline installations typically impact ecosystems is challenging. Here, we performed a systematic literature review to compile studies that have evaluated impacts of pipeline installation on soil and plant properties. We found 34 studies reporting pipeline impacts on agricultural and natural ecosystems from eight countries. We quantified and synthesized the magnitude of responses and found that the majority of studies found pipeline installation resulted in soil degradation via increased compaction and soil mixing, paired with decreased aggregate stability and soil carbon (C) relative to adjacent, undisturbed areas. Averaged across all studies, aggregate stability decreased 44.8%, water infiltration was reduced 85.6%, and compaction via penetration resistance increased 40.9% over pipeline areas relative to nondisturbed adjacent areas. This soil degradation led to general declines in plant productivity, with 15 out of 25 studies documenting declines in crop yields (6.2–45.6%) and six out of nine studies reporting decreased biomass from natural ecosystems (1.7–56.8%). We conclude from our quantitative synthesis that pipeline installation typically results in degraded soil and vegetation resources, and this can persist for many years following installation.

1 | INTRODUCTION

Underground pipelines are a safe and effective method for transporting oil and natural gas, with pipeline infrastructure systems now in 130 countries and on every continent (Central Intelligence Agency World Factbook Staff, 2021). Spanning over 4 million kilometers, the United States has the most extensive oil and natural gas pipeline system in the world, with roughly 486,400 km of natural gas transmission pipelines and 3,641,260 km of natural gas distribution pipelines (U.S. Bureau of Transportation Statistics Staff, 2021; U.S. PHMSA Staff, 2018).

Pipeline installation occurs within a right-of-way (ROW) or easement area, containing three major components: a trench where the pipe is laid, a work area where pipe-laying machinery traffic occurs, and a pile area where topsoil and subsoil are staged while the pipe is laid which is often adjacent to the trench. The total area of each pipeline's ROW can

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; MBC, microbial biomass carbon; ROW, right-of-way; SIC, soil inorganic carbon; SOC, soil organic carbon; SOM, soil organic matter; TSN, total soil nitrogen.

differ per pipeline installation, pipe size, and installation depth. Historically, pipeline trenches were excavated with little to no attention paid to separating topsoil from subsoil, a practice known as a "single lift" (de Jong & Button, 1973; Harper & Kershaw, 1997; Landsburg & Cannon, 1995; Zellmer et al., 1985). Current best practices now ensure topsoil and subsoil are lifted from the trench area individually, known as a "double lift," to maintain proper separation during the installation process (Neilsen et al., 1990; Soon, Arshad, et al., 2000; Soon, Rice, et al., 2000; Tekeste et al., 2019). Double lifts are thought to decrease the 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 & Doherty, 2012; Shi et al., 2014). Additionally, current best management practices suggest surface and deep subsoil ripping near impacted areas after pipelines have been laid to decrease long-term effects of compaction on agricultural or natural landscapes (Nexus Staff, 2022; Rover Staff, 2022).

Despite the extensive infrastructure already in place in many countries, thousands of kilometers of pipelines are still being installed globally each year (CIA World Factbook Staff, 2021). In the United States alone, pipeline mileage has increased 8.5% in the last decade (U.S. PHMSA Staff, 2020). These installations have cut through numerous ecosystems such as pastures, wetlands, forests, and agricultural fields to connect the global energy infrastructure (i.e., Jones et al., 2014; Langlois et al., 2017; McClung & Moran, 2018). The pipeline installation process causes major disturbances to these ecosystems and has the potential to fundamentally change natural soil characteristics and functioning, as well as altering the growing environment for vegetation in ROW areas compared with adjacent, undisturbed land. Through heavy machinery traffic, ineffective soil lifting via single or double lift techniques, errors in soil storage and reapplication, and inadequate site remediation after pipeline installation, areas where pipelines have been installed face potentially long-lasting deleterious effects on soil and vegetation resources (Batey, 2015; de Jong & Button, 1973; Tekeste et al., 2020).

Given the site-specific nature of pipeline installations, there is a lack of understanding and consensus on the long-term impacts on soil and vegetation resources, particularly regarding the magnitude and scope of ecosystem degradation when considering various construction, installation, and remediation practices (U.S. PHMSA Staff, 2020). To address this knowledge gap, here we present the first comprehensive, global literature review of studies documenting the effects of pipeline installations on ecosystems. The specific objectives of this study were to (a) comprehensively compile research studies reporting impacts of pipeline installation on soil and plant properties and (b) synthesize and quantify the collective mean percentage change that pipeline installations had on reported soil and plant properties in these studies.

Core Ideas

- A literature review uncovered 34 studies reporting on pipeline installation impacts to soils and plants.
- Pipelines cause sustained soil degradation for years or decades following installation.
- Soil compaction and soil horizon mixing detrimentally impact soil function.
- The 21 of 34 studies reported decreased plant biomass following installation.

2 | MATERIALS AND METHODS

Two search engines, Google Scholar and EBSCOHost, were used to find past peer-reviewed or scholarly papers about pipeline installation and effects on soil and plant yields, including journal articles, theses, dissertations, and governmental publications published prior to 15 Dec. 2020. Abstracts were required to be written in English for inclusion in this analysis. Search terms included "pipeline OR linear construction" AND "soil (characteristics OR properties OR impacts OR effects)"; "pipeline installation" AND "compaction OR erosion OR temperature"; and "pipeline installation" AND "yield OR crop yield OR producti*".

Papers were excluded if the main focus of the research was on pipeline engineering or improving installation techniques from a non-natural sciences perspective. Additionally, papers were omitted if there were no mentions of installation effects on soils or plants within the title or abstract. After an original search was conducted, these papers were also back- and front-searched to identify related studies missing from our original search, and the same exclusion processes were repeated for all back- and front-searched papers.

After examining the reported studies, our ability to conduct a meta-analysis was compromised by a (a) limited number of total studies, (b) lack of key information regarding pipeline installation processes (e.g., single vs. double lift), (c) lack of reported estimates of variability, and (d) inconsistencies across studies regarding soil and plant properties reported. As such, we opted for a quantitative synthesis which standardized responses across studies for comparative purposes. Data were compiled from all relevant papers regarding soil physical, chemical, and biological properties as well as vegetative response to pipeline installation. First, all soil and plant variables reported from each study were classified into one of three categories: increase, no significant change, or decrease. These classifications reflected what authors reported in the respective studies of how areas over pipeline ROW were impacted relative to nondisturbed adjacent areas, with statistical significance used from the original studies at $p < .05$ or

$p < .1$ levels. From each study, a percentage difference was calculated to assess the impact of pipeline installation on the reported variable. For studies that reported multiple areas over the ROW (e.g., over the trench, from work areas, etc.), all values were combined into one average "ROW" value for the study, while all measurements reported from adjacent areas were combined into one average "ADJ" value, used as a control to understand implications of pipeline installation on a study-by-study basis. Then a percentage difference for each variable within each study was calculated using Equation 1:

$$\%\ \text{difference} = \left(\frac{\text{ROW} - \text{ADJ}}{\text{ADJ}}\right) 100 \qquad (1)$$

Percentage difference was used to standardize values across soil types, ecosystems, and management styles, as well as to assess the directionality and magnitude of response throughout all studies. Finally, a mean and range of percentage difference values across all studies was calculated for each soil and plant variable.

3 | RESULTS AND DISCUSSION

3.1 | Characteristics of pipelines studied

In total, 34 peer-reviewed or scholarly papers were found from eight countries (Table 1). The first pivotal study of the effects of pipeline system installation on agricultural areas was written in 1973 by de Jong and Button. However, of the 34 total studies, the majority ($n = 19$) were published within the last decade, revealing an increase in research interest in this field. Studies have reported on many ecosystems, including agricultural land, wetlands, forests, native prairies, drylands, and grasslands. Agricultural crops studied include corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], alfalfa (*Medicago sativa* L.), cereal grains such as sorghum [*Sorghum bicolor* (L.) Moench], wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.), potato (*Solanum tuberosum* L.), raspberry (*Rubus idaeus* L.), and sunflower (*Helianthus annuus* L.).

The age of pipelines studied ranged from during the installation process to 53 yr post-installation but averaged 8.7 yr after installation. Most pipelines were studied within 10 yr of installation (25 out of 34 studies). Both single ($n = 7$) and double lift ($n = 10$) excavations were reported in the construction processes, though some studies ($n = 3$) included multiple pipelines which used different lift techniques and others ($n = 14$) did not specify the type of lift used. Studies with installations via double lifts have become more commonplace, particularly within the United States since the mid-1970s as U.S. federal regulations have attempted to standardize recommendations around separation of topsoil and subsoil in the pipeline construction process.

With research spanning five continents, differences in landscape properties have led to localized construction practices to best fit each installation site. Additionally, conditions when pipelines were installed (i.e., soil moisture conditions and time of year) also differ temporally and spatially. Studies analyzed a range of properties such as soil compaction, nutrient content, chemical data, crop yield, and plant growth, each of which will be discussed in detail below. For nearly all studies, it was typical for adjacent, undisturbed fields to be used as a control for comparative purposes. Some studies reported aggregate values from ROW areas, while others sampled separate ROW areas, differentiating between the trench, work areas, and piling areas.

3.2 | Soil physical properties

3.2.1 | Compaction

Compaction was measured via bulk density or penetration resistance. Bulk density measures the dry mass of soil including pore spaces between soil aggregates divided by a specified volume of soil collected. Higher bulk density (decreased pore space) is indicative of compacted soils. Conversely, penetration resistance is a measurement of the pressure required to reach a certain depth within a soil profile using a cone index penetrometer. Higher rates of penetration resistance are correlated with increased soil compaction.

Of the 26 studies reporting compaction via bulk density or penetration resistance, there was a mean increase of 12.6% in bulk density (ranging from −8.6 to 63.7%) and a 40.9% mean increase in penetration resistance (ranging from 1.4 to 133.3%) (Table 2, Figure 1). Culley et al. (1981) found that compaction and penetration resistance were more prevalent on fine- or medium- textured soils compared with coarse-textured soils. Additionally, bulk density and penetration resistance were consistently higher, up to a 10% increase, on pipeline ROWs compared with undisturbed fields, with work area > trench > undisturbed field (Culley et al., 1981). Naeth et al. (1987) reported 51–82% increases in bulk density in disturbed ROW, with greater subsurface compaction in the work area relative to the trench area where deeper soils had been removed and replaced.

Soon, Arshad, et al. (2000) measured bulk density in Alberta, Canada, and found that bulk density was significantly higher in the trench zone than in undisturbed fields. Additionally, penetration resistance in these fields was found to increase with disturbance, with trench = pile area > work area > undisturbed field. In a wetland study in Wisconsin, ROW soil had bulk densities 63% higher than adjacent areas

TABLE 1 Published scientific and governmental studies found evaluating the impacts of pipeline installation on soil and plant properties

Study reference no.	Country	State/province	Citation	No. of pipelines studied	Years since pipeline installed	Soil properties reported	Plant properties reported
1	Canada	Saskatoon	de Jong and Button (1973)	13	1−13	physical, chemical	grain yield
2		Ontario	Culley et al. (1981)	1	3	physical, chemical	grain yield, midsummer plant height, nutrient content
3		Ontario	Culley et al. (1982)	1	5	physical, chemical	grain yield, biomass production, plant height, cob length
4		Alberta	Naeth et al. (1987)	5	6, 15, 19, 24, 30	physical, chemical	not reported
5		Ontario	Culley and Dow (1988)	1	10	physical, chemical	grain yield, crop height
6		Alberta	Landsburg and Cannon (1989)	1	1	physical, chemical	not reported
7		Not specified	Neilsen et al. (1990)	1	2–3	physical	grain yield, emergence, seedling survival rate, plant height, silking
8		Alberta	Naeth et al. (1993)	2	12, 36	physical	not reported
9		Northwest Territories	Harper and Kershaw (1997)	1	53	physical, chemical	not reported
10		Ontario	Ivey and McBride (1999)	1	30+	physical, chemical	not reported
11		Alberta	Soon, Arshad, et al. (2000)	1	3	chemical, biological	above and belowground biomass, grain macronutrients
12		Alberta	Soon, Rice, et al. (2000)	1	3	physical, chemical	Not reported
13		Alberta	Desserud et al. (2010)	14	7−40	Physical	mean percentage cover, plant species frequency
14		Alberta	Low (2016)	1	6	not reported	species diversity, species abundance, species richness
15		British Columbia	Turner (2016)	1	2	physical, chemical	species diversity, species abundance, species richness
16	USA	Oklahoma	Zellmer et al. (1985)	1	2	physical, chemical	aboveground biomass and yield estimations
17		Kansas and Missouri	Duncan and DeJoia (2011)	1	1	physical, chemical	not reported
18		Wisconsin	Olson and Dougherty (2012)	1	8	physical	Mean percentage cover, species presence, coverage, diversity, quality, proportional species abundance

(Continues)

TABLE 1 (Continued)

Study reference no.	Country	State/province	Citation	No. of pipelines studied	Years since pipeline installed	Soil properties reported	Plant properties reported
19		New York	Schindelback and van Es (2012)	1	1	physical, chemical, biological	not reported
20		Wyoming	Gasch et al. (2016)	4	1, 5, 36, 55	physical, chemical, biological	total percentage plant coverage, plant abundance
21		Texas	Wester et al. (2019)	1	2	physical, chemical	grain yield, seedling emergence
22		Iowa	Tekeste et al. (2019)	1	0 (during installation)	physical	not reported
23		Iowa	Tekeste et al. (2020)	1	1	physical	grain yield
24	China	Xinjiang Province and Ningxia Hui Autonomous Region	Shi et al. (2014)	3	2, 6, 8	physical, chemical	not reported
25		Xinjiang Province and Ningxia Hui Autonomous Region	Xiao et al. (2014)	3	2, 6, 8	chemical	species coverage, species classification, diversity, evenness, richness, and similarity
26		Gansu and Shaanxi Provinces	Shi et al. (2015)	3	2, 6, 8	physical, chemical	plant height, stem size, corncob length and size
27		Northwest China	Xiao et al. (2017)	3	not reported		plant species classification using comparative analysis and TWINSPAN
28	Australia	Queensland	Vacher et al. (2014)	1	not reported	physical, chemical	not reported
29		Queensland	Antille et al. (2015)	1	3	physical, chemical	crop modeling using APSIM
30		Queensland	Vacher et al. (2016)	1	5+	physical	not reported
31	Argentina	Chebut	Kowaljow and Rostagno (2008)	1	3	physical, chemical	total percentage plant coverage
32	Azerbaijan	Various	Winning and Hann (2014)	1	not reported	physical	not reported
33	United Kingdom	Various	Batey (2015)	60+	studied over 40+ career years	physical, chemical	grain and harvestable yield, claims made for yield loss
34	Slovak Republic	Nitra	Halmova et al. (2017)	1	not reported	Physical	grain yield, aboveground biomass

TABLE 2 Mean and (range) of percentage change of various soil physical properties on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas

Property	No. of studies: Total	Increase	No change	Decrease	Mean percentage change (range)	Citations
Bulk density	16	10	5	1	12.6 (−8.6 to 63.7)	1, 2, 3, 4, 5, 6, 7, 11, 15, 16, 18, 20, 22, 23, 29, 33
Penetration resistance	10	7	3	0	40.9 (1.4 to 133.3)	1, 2, 3, 11, 18, 19, 22, 23, 29, 31
Soil mixing[a]	28	24	4	0	17.1 (−3.2 to 102.6)	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 24, 25, 26, 28, 29, 30, 33
Aggregate stability	12	0	0	12	−44.8 (−84.5 to −22.2)	2, 3, 10, 13, 18, 19, 21, 28, 32, 29, 15, 30
Soil temperature	5	5	0	0	38.9 (10.5 to 62.9)	8, 9, 15, 26, 34
Soil moisture	8	1	3	4	−3.9 (−25.4 to 40.4)	1, 6, 9, 11, 18, 20, 22, 34
Hydraulic conductivity	6	1	3	2	−11.2 (−38.0 to 7.1)	2, 5, 16, 17, 19, 24
Water infiltration	3	0	0	3	−85.6 (−92.7 to −78.4)	28, 29, 31
Coarse fragments/rocks	7	6	1	0	[b]	2, 4, 9, 17, 19, 24, 25

Note. Studies were classified as reporting an increase, no significant change, or decrease in the soil property in ROW relative to undisturbed areas. Positive and negative percentage changes indicate a respective increase or decrease in value over the ROW relative to the undisturbed areas. Citations refer to the study reference number listed in Table 1.

[a]Soil mixing calculated via alterations in particle size distribution and soil textural analysis.

[b]Quantitative data values rarely reported, typically observations qualitatively described in text.

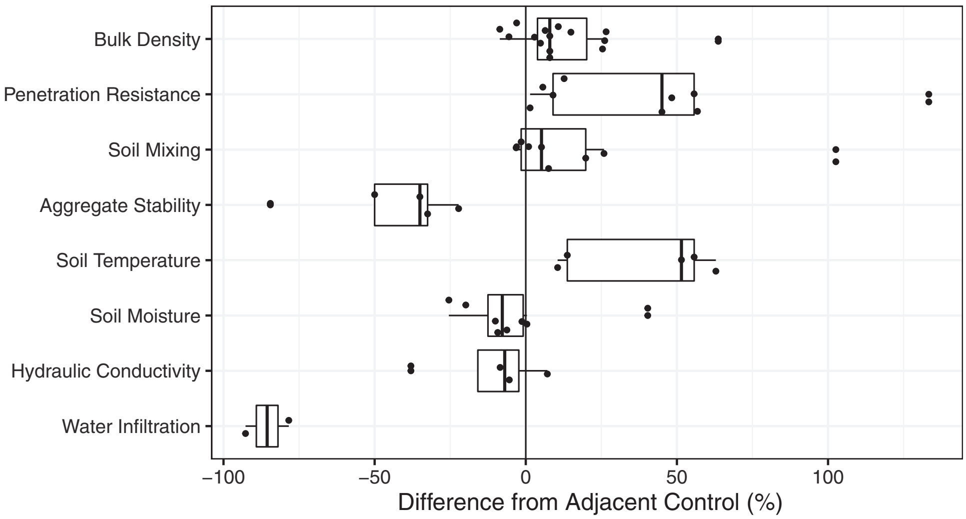

FIGURE 1 Percentage difference values for select soil physical properties between right-of-way vs. adjacent, unaffected areas. Points represent mean percentage difference of each study with boxplots representing the distribution of values. Positive and negative values indicate a respective increase or in the soil property values over the pipeline area relative to adjacent areas

(Olson & Doherty, 2012). Antille et al. (2015) found that soil compaction within lease areas increased by approximately 10% compared with undisturbed fields ($p < .05$). Additionally, surface compaction from 0 to 40 cm and subsurface compaction were significantly higher in all lease areas as well. In the United Kingdom, Batey (2015) observed that severe subsoil compaction was a factor in poor crop growth and drainage, particularly in work areas around the country. However, surface compaction in these soils was rarely detected. A similar conclusion was found by Vacher et al. (2016), where subsurface compaction increased by 15–20% in disturbed areas.

Tekeste et al. (2019) conducted compaction studies during the installation of the Dakota Access Pipeline (DAPL) in Iowa and found that ROW zones had significantly higher compaction than adjacent, undisturbed corn fields. Additionally, evidence of deep subsoil compaction, or a hardpan, was much more prevalent than surface compaction in ROW soils, with an "abrupt increase" in penetration resistance evident when instruments entered the subsoil layer.

While a majority of studies showed increases in compaction, some studies differ, including Solonetzic soils in northern Canada, where the deep ripping remediation conducted after pipeline construction increased permeability at depth and mixed soil horizons compared with adjacent areas (de Jong & Button, 1973). This ripping created an overall more favorable growing environment for vegetation by increasing porosity and hydrology of the soils, as well as elevated levels of organic matter at depth, which provided increased nutrient availability to deeper plant roots. However, within the same study, Chernozemic (mollisol) soils were also evaluated, and the opposite trends were found; soil compaction increased with depth and significant differences in wheat yields were not found.

One study by Zellmer et al. (1985) found that bulk density was significantly lower on the trench than in a control area or work area, though only by 3.0%. Schindelbeck and van Es (2012) found that decompaction efforts after pipeline installation decreased surface and subsurface hardness measured via penetration resistance by −3.0 and −11.0%, respectively, within agricultural soils, as evaluated using the Cornell Soil Health Assessment. Turner (2016) reported variable bulk densities when comparing forested and ROW soils in British Columbia, Canada, noting that high bulk density readings were found in both areas, though wetland blocks studied showed consistently higher bulk densities than forested blocks in pipeline-impacted soils.

3.2.2 | Soil mixing

Soil mixing via changes in soil texture and particle size distribution within ROW areas increased by an average of 17.1% in 28 studies, with a range of −3.2 to 102.6% (Table 2). Evidence of soil mixing can often be seen through higher clay content in surface horizons, decreased soil carbon (C), and visible changes in soil color as a result of soil churning or mixing. These effects are typically long-lasting. For example, de Jong and Button (1973) documented that soil mixed from pipeline installation 10 yr prior still had visible effects of subsoil clays on the surface. These enduring effects can fundamentally alter other soil characteristics such as water holding capacity, pH, organic matter, cation exchange capacity, and available nutrients, each of which will be discussed in greater detail in subsequent sections. Evidence of anthropogenically altered soil horizons date back to the early days of agricultural development, with Mayan and Roman agriculture and construction activities still observable on landscape scales (Dror et al., 2021; Hartshorn et al., 2006; Sandor & Homburg, 2017). However, remediation measures such as erosion control blankets, chemical amendments like humic acids, and biological amendments such as cover cropping can alleviate some detrimental effects of soil mixing in some ecological stands given proper rates of amendments (Wester et al., 2019).

3.2.3 | Aggregate stability and erodibility potential

All 12 studies that measured pipeline installation impacts on aggregate stability found significant decreases, with an average reduction of 44.8% and ranging from 22.2 to 84.5% (Table 2, Figure 1). Evidence of subsidence, or the gradual settling or sinking of soil, in ROW areas has been documented by Vacher et al. (2016), which states that depressions in disturbed fields after pipeline installation measured between 10 and 20 cm below the average slope of the adjacent study area. Introduced depressions like this can create instances of new hydric soils or vernal pools. In this study, aerial imagery was used to demonstrate alterations in elevation within the ROW, and erosion potential in these subsided areas was three to four times higher than unaffected areas. This study was conducted on vertic (vertisol) soils, which have a high shrink-swell capacity due to high clay content, paired with high water infiltration capacity, making them generally difficult to erode under normal circumstances. Ivey and McBride (1999) documented eroded areas with ROWs as well, noting that these areas contained lower percentage organic C than uneroded areas of the ROW, and similar findings were reported by Shi et al. (2014) in soils from western China and by Duncan and DeJoia (2011) in the midwestern United States. Landsburg and Cannon (1995) stated that wind erosion potential increased on pipeline areas if revegetation was not successful, particularly in soils with clayey surfaces. Additionally, Winning and Hann (2014) note that erosion potential also increased near rivers and in areas of high seismic activity. Schindelbeck and van Es (2012) found evidence of significant reduction in aggregate stability in all land types studied (agricultural areas, wetlands, and fallow lands) following pipeline installation, resulting in an average of 32% reduction 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%.

3.2.4 | Soil temperature

Increased soil temperature was documented by five studies, with an average increase in temperature of 38.9% along ROW compared with adjacent areas, ranging from 10.5 to 62.9% higher in ROW areas compared with ADJ (Table 2). Pipelines are often internally heated to ensure proper fluidity of materials being transported, and great effort is made to reduce heat loss from pipelines into the surrounding environment. Yet, some heat can escape from pipelined areas, resulting in elevated soil temperature, decreased soil moisture, and potential alteration to soil microbial communities (Naeth et al., 1993). Halmova et al. (2017) in the Slovak Republic reported the temperature of a transported gas pipeline increased soil temperature above the pipeline 2.1–3.4 ˚C higher than soils farther away from the pipeline. Comparatively, Shi et al. (2015) reported a 1.0–2.0 ˚C increase in temperature along ROW areas in western China. However, it is essential to note that changes in albedo due to surface color change from bare soil or introduction of a new type of vegetation can also impact soil temperatures. Nonetheless, pipeline-impacted areas which do experience alterations in vegetation as well as potential pipeline-derived temperature leakages may be subject to increased soil temperatures near the pipeline trench.

3.2.5 | Soil moisture, hydraulic conductivity, and water infiltration capacity

Decreases in soil moisture were reported in half of studies (four of eight), with a mean decrease of 3.9%, ranging from −25.4 to 40.4% (Table 2). Notably, Halmova et al. (2017) attributed this decrease in gravimetric soil moisture to increases in soil temperature along the ROW but could also be due to soil mixing and subsequent changes to soil texture nearer to the surface. Natural wetland areas can be particularly disturbed by this decrease in soil moisture, where much of the native vegetation is moisture-dependent for proper growth (Olson & Doherty, 2012). Introduced, non-naturally forming vernal pools can be seen in ROW areas alongside areas of decreased moisture, which could be a result of uneven rates of soil mixing across the ROW.

Hydraulic conductivity of soils over the ROW was decreased on average of 11.2% across six studies. This is largely connected to compaction and permeability alterations in the soil, which some studies connect to remediation measures implemented at sites post-installation (Culley et al., 1982; Culley & Dow, 1988; Soon, Rice, et al., 2000). Culley et al. (1982) found that hydraulic conductivity on ROWs decreased by an average of 38% compared with undisturbed fields. In this study, total porosity decreased, but drainable porosity remained the same, and volumetric water content was similar between ROW and undisturbed fields. Soon, Rice, et al. (2000) found that hydraulic conductivity rates decreased at least 10-fold in ROW soils compared with adjacent, undisturbed areas, and water retention and release capacities were reduced by at least 40% from 0 to 12 cm in depth. Alternatively, Zellmer et al. (1985) found evidence of increased water holding capacity, which they attribute to be likely due to soil mixing and remediation measures which decreased bulk density compared with pre-installation.

Between the studies which analyzed water infiltration capacity, there was an average decrease of 85.6% across all three studies (Table 2, Figure 1). Antille et al. (2015) reported significant decreases in infiltration rates in every paired comparison. Overall, in poorly remediated soils and soil with high clay content, alterations in soil hydrology have been apparent through decreased water infiltration rates, decreased total porosity, decreased water holding capacity, and decreased total soil moisture (Antille et al., 2015; Culley et al., 1982; Culley & Dow, 1988; Landsburg & Cannon, 1989; Olson & Doherty, 2012).

3.2.6 | Exposed coarse rock fragments

Increased amounts of coarse fragments were found in six of the seven studies conducted, while one study reported no significant change between the ROW and adjacent areas (Table 2). In most studies, coarse rock fragments were not directly quantified, rather often qualitatively described. During the pipeline installation process, rocks in the subsoil can be excavated and brought to the surface, or when soils are not deep enough to allow pipelines to maintain their required depth, bedrock is often broken up via mechanical pressure and explosives to create the necessary space for placement. This commonly results in an increase in rocks in installation areas, ranging from the size of small pebbles to boulders (Batey, 2015). In the review by Landsburg and Cannon (1995), evidence of increasing stoniness was reported in 8 of 48 soils studied.

TABLE 3 Mean (range) percentage change of various soil chemical properties on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas (ADJ)

Property	No. of studies Total	Increase	No change	Decrease	Mean percentage change (range)	Citations
pH	19	9	10	0	6.81 (0.57 to 41.0)	1, 2, 3, 4, 5, 6, 9, 10, 11, 15, 16, 17, 19, 20, 21, 25, 26, 29, 31
Soil organic carbon (C)[a]	21	0	4	17	−20.8 (−49.7 to 2.4)	2, 3, 4, 5, 6, 7, 9, 10, 12, 15, 16, 17, 19, 20, 24, 25, 26, 28, 29, 31, 33
Total soil nitrogen (N)	11	2	0	9	97.3 (−49.5 to 1,166.7)	2, 3, 5, 7, 12, 15, 20, 21, 24, 26, 31
Cation exchange capacity	7	1	4	2	−1.0 (−26.8 to 42.5)	1, 3, 5, 15, 16, 17, 29
Electrical conductivity	9	7	2	0	109.4 (5.2 to 267.0)	1, 4, 6, 11, 16, 20, 21, 29, 31
Nitrate-nitrogen (NO_3–N)[b]	2	0	0	2	−56.2 (−76.7 to −35.6)	1, 19
Phosphorus (P)[c]	12	1	8	3	−13.7 (−71.3 to 39.7)	1, 2, 3, 10, 15, 16, 17, 19, 21, 24, 26, 31
Potassium (K)[c]	13	3	8	2	5.8 (−19.1 to 41.4)	1, 2, 3, 4, 5, 10, 16, 17, 19, 21, 24, 26, 29
Calcium (Ca)[c]	9	6	3	0	64.7 (−6.7 to 244.6)	4, 5, 6, 10, 11, 16, 17, 21, 29
Magnesium (Mg)[c]	9	3	4	2	88.6 (−23.5 to 410.0)	5, 6, 10, 11, 16, 17, 29, 21, 29
Sodium (Na)[c]	7	5	1	1	226.4 (−16.5 to 591.7)	4, 6, 10, 11, 16, 21, 29
Sulfur (S)[c]	5	4	0	1	479.2 (−54.2 to 1,516.7)	4, 6, 11, 15, 21

Note. Studies were classified as reporting an increase, no significant change, or decrease in the soil property in ROW relative to ADJ areas. Positive and negative percentage changes indicate a respective increase or decrease in value over the ROW relative to the undisturbed areas. Citations refer to the study reference number listed in Table 1.
[a]Soil organic carbon is calculated from both soil organic matter and soil C.
[b]NO_3–N extractants used by de Jong and Button (1973) and Schindelbeck and van Es (2012) were $CuSO_4$ and KCl, respectively.
[c]Extractable P, K, Ca, Mg, Na, S.

3.3 | Soil chemical properties

3.3.1 | pH

No significant change in soil pH following pipeline installation were found in 10 out of 19 studies (Table 3). However, nine studies, including studies conducted as early as Zellmer et al. (1985) and Naeth et al. (1987) when revegetation and soil management of ROW areas were not required by law, observed relatively uniform soil pH levels throughout the entire soil profile as a result of extreme soil mixing (Figure 2). This was commonly found in studies though rates of increase were largely determined by inherent soil pH, with an average increase in pH of 6.8% (Table 3). De Jong and Button reported surface pH generally increased 0.5 for Solonetzic soils but increased up to 1.0 in Chernozemic soils. Additionally, Landsburg and Cannon (1995) reported a general increase in surface soil pH of 0.5 to 2.0, often occurring within the top 30 cm. However, Soon, Rice, et al. (2000) found that pH was highest in the year after installation, and continuously decreased in years following; the authors did not describe instances of liming on sampled areas, which may have otherwise explained decreased pH over time within the study.

3.3.2 | Soil organic C

An average decrease of 20.8% in soil organic C, measured by a combination of soil organic matter (SOM) and soil organic carbon (SOC), occurred in ROW areas compared with ADJ, throughout 21 studies (Table 3). Increases in either organic

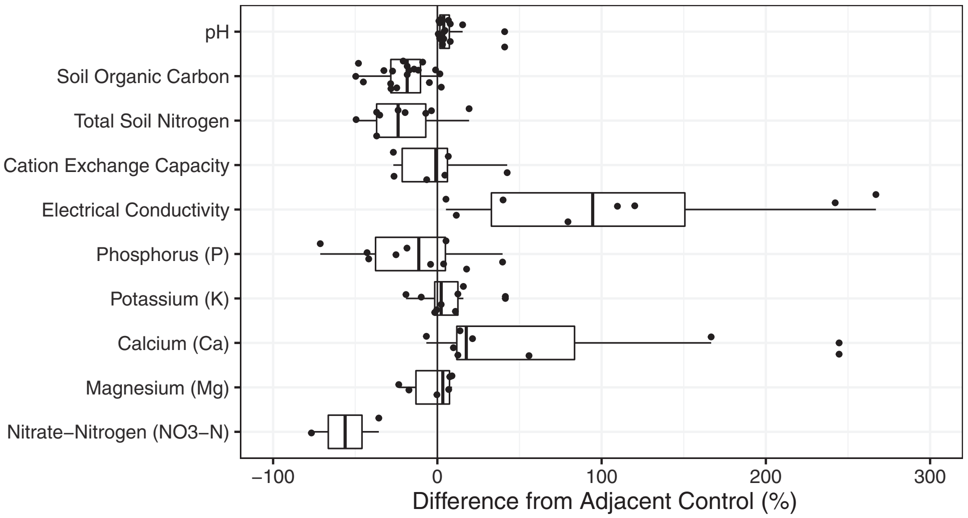

FIGURE 2 Percentage difference values for select soil chemical properties between right-of-way vs. adjacent, unaffected areas. Points represent mean percent difference of each study with boxplots representing the distribution of values. Positive and negative values indicate a respective increase or in the soil property values over the pipeline area relative to adjacent areas. Figure was truncated to improve visualization and clarity, resulting in three data points not shown for total soil N and Mg, collectively

matter or soil C were not found in any study (Figure 2). In general, most studies found the SOC levels decreased in proximity to the trench, with highest SOC levels found in undisturbed fields > work areas > trenches.

Culley et al. (1982) estimated that soil mixing and resulting topsoil dilution resulted in a 20–50% decrease in SOC from 0 to 15 cm, paired with an increase in SOC from 15 to 30 cm, compared with no changes in undisturbed fields. Likewise, Schindelbeck and van Es (2012) found a decrease of SOC by 44%, measured from 0 to 15 cm. When comparing pipelines' impacts on native grassland, Naeth et al. (1987) found that SOC concentration was between 2.5 and 6.5 times higher in undisturbed areas than ROWs and work areas had 1.1–2 times higher SOC compared with trenches. Additionally, Soon, Rice, et al. (2000) reported a SOC decrease of 12% in a work area 3 yr following pipeline installation. In a continuous study for 10 yr after a pipeline installation in Ontario, Canada, Culley and Dow (1988) reported that there were still lower SOM levels on the ROW compared with undisturbed fields. When studying a pipeline almost 50 yr after installation in the Northwest Territories of Canada, Harper and Kershaw (1997) found similarly lower SOM levels, and the authors concluded that soil development over ROW areas was slowed following pipeline installation.

However, it is not only the total SOM and SOC which is altered by pipeline installation. Ivey and McBride (1999) found that soil inorganic carbon (SIC) content increased by 1.0–3.0% while SOC decreased by 0.5–1.0% over the trench compared with a control area, with no reporting of limestone as an amendment used on this site. While disturbance in general impacts SOM and SOC levels, installation processes also create potential for more loss, particularly through period of increased precipitation accumulation and melting; however, instances of increased SOM can be found in areas with higher moisture rates, such as newly emerged vernal pools following pipeline installation. Neilsen et al. (1990) found the largest decreases in SOM occurred in soils where pipelines were installed in winter months where soil mixing was the most extreme.

3.3.3 | Nitrogen

Similar to SOC, total soil nitrogen (TSN) often decreases with disturbance. Across 11 total studies reporting TSN, there was a mean increase of 97.3%, but a median decrease of 23.9% (Table 3). Culley et al. (1981) found that TSN decreased within the 0-to-15-cm range but increased from 15 to 30 cm, and the authors estimated that organic N production was decreased by roughly 40% as a result of pipeline construction disturbance (Culley et al., 1982). After 10 yr of analysis, Culley and Dow (1988) reported ROW soils still contained 23.9% less TSN than undisturbed fields. Landsburg and Cannon (1995), Soon, Rice, et al. (2000), Kowaljow and Rostagno (2008), Shi et al. (2014), and Shi et al. (2015) reported similar decreases in TSN with pipeline installation. Schindelbeck and van Es (2012) reported a decrease of 76% in potentially mineralizable N in one soil studied following installation. Only two accounts of increases in TSN were reported, including Wester et al. (2019) which documented an increase of 1,166.7% in TSN, which the authors concluded was a result of the erosion control measures applied to the ROW compared with adjacent areas, rather than an inherent increase in TSN derived from pipeline installation.

3.3.4 | Cation exchange capacity

Cation exchange capacity (CEC) was inconsistently impacted with pipeline installations, with a mean decrease of 1.0% across seven studies (Table 3, Figure 2). Culley et al. (1982) reported a decrease in CEC within ROW agricultural soils compared with undisturbed fields following pipeline installation in Alberta, Canada. This finding is, interestingly, contradicted in a later study by Culley and Dow (1988), which found that CEC was greater in ROW relative to the undisturbed area 10 yr after pipeline installation.

3.3.5 | Electrical conductivity

In total, seven out of nine studies reported a significant increase in electrical conductivity (EC), with an average increase of 109.4% along ROW areas compared with adjacent areas across all studies, ranging from 5.2 to 267.0% (Table 3). Zellmer et al. (1985) found increasing sodium (Na) levels within the trench compared with off-ROW soils, suggesting sodium increases were due to soil horizon mixing. Similarly, Naeth et al. (1987) reported sodium adsorption rates up to five times higher in the trench compared with a control area. However, Landsburg and Cannon (1995) reported that EC levels returned to pre-disturbance levels within 5 yr of pipeline installation, beginning first at surface levels, then moving deeper as a result of leaching. De Jong and Button (1973) found that EC increased with depth, particularly in Solonetzic soils with newly installed pipelines. Similarly, Soon, Rice, et al. (2000) reported that EC levels were appreciably higher at deeper levels, from 50 to 100 cm, but the decrease after installation time Landsburg and Cannon (1995) reported was not confirmed through this study.

3.3.6 | Available nutrients

Compared with C and nitrogen (N) levels, available nutrients did not inherently decrease with proximity to pipeline and increasing rates of disturbance; rather, nutrient availability were largely dependent on soil type (Table 3). On average, alterations to phosphorus (P), potassium (K), and magnesium (Mg) nutrient levels were not significantly different from adjacent areas (Figure 2). De Jong and Button (1973) reported a decrease in P and K with depth, indicating mixing of topsoil horizons, where available nutrients are generally elevated, with subsoil, where nutrients are limited. Soon, Rice, et al. (2000) also noted that K decreased with depth in their study in Alberta, Canada.

In comparison, increases in calcium (Ca) level occurred in 67% of studies, likely derived from bedrock introduction to upper soil horizons, up to 15 cm from the soil surface, as a result of soil mixing bringing Ca-rich subsoil closer to the surface as well as remediation efforts via agricultural liming (Culley et al., 1981; Landsburg, 1989; Soon, Rice, et al., 2000; Zellmer et al., 1985). In a 10-yr study performed by Culley and Dow (1988), these findings were confirmed, stating that surface soils were increasingly calcareous compared with undisturbed fields. Additionally, Mg, Na, and S were found to increase in surface soils and with depth following pipeline installation, with mean increases of 88.6, 226.4, and 479.2%, respectively (Table 3, Landsburg, 1989; Soon, Rice, et al., 2000).

3.4 | Soil biological and biochemical properties

Little research has been conducted regarding impacts of pipelines on biological or biochemical soil properties. Soon, Arshad, et al. (2000) measured microbial biomass carbon (MBC) before and after pipeline installation, and found varying results on MBC, with no consistent effect from year to year. Overall, researchers concluded the average level of MBC was not adversely affected by pipeline installation. Gasch et al. (2016) also reported variable microbial abundance in ROW areas crossing a native sagebrush steppe in Wyoming. Conversely, Schindelbeck and van Es (2012) found significant decreases of 73% in biologically active C (permanganate oxidizable C) in pipeline areas relative to adjacent areas in New York. The authors hypothesize this is due to uncontrolled soil mixing, increasing biological activity at depth, and decreasing biological activity in surface soils. Soil health scoring of these soils saw a significant decrease of soil quality, averaging a 27% decrease in soil function, as evaluated by the Cornell Soil Health Test. Root health ratings taken during this study were not significant.

3.5 | Crop yield and plant productivity responses

Decreases in plant biomass accumulation were common among almost all species reported, with average decreases in agricultural crop yields of 10.5, 33.2, 23.6, 6.2, and 10.8% for corn grain, corn silage, soybean, alfalfa, and small grains, respectively (Table 4, Figure 3). Corn grain yields were reduced up to 50% in the first 2 yr after installation on the ROW relative to control areas (Culley et al., 1981). After 10 yr, corn yields were still suppressed, with ROW crops only yielding 77% of control area yields. In silage corn, yields were reduced by roughly 40% in the 1st year following pipeline installation (Culley et al., 1981).

TABLE 4 Mean (range) percentage change of crop yield or vegetation productivity on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas (ADJ) across all studies

Ecosystem type	Plant community	No. of studies Total	Increase	No change	Decrease	Mean percentage change (range)	Citations
Agricultural crops	corn (grain)	5	0	1	4	−10.5 (−30.7 to 23.7)	2, 3, 5, 7, 26
	corn (silage)	2	0	0	2	−33.2 (−40.3 to −26.2)	3, 5
	soybean	3	0	0	3	−23.6 (−27.6 to −18.3)	2, 3, 5
	alfalfa	3	0	2	1	−6.2 (−22.2 to 1.91)	2, 3, 5
	small grains (barley, sorghum, wheat)	11	2	3	4	−10.8 (−67.6 to 32.0)	1, 2, 3, 5, 12, 16, 29
	raspberry	1	0	0	1	−45.6	33
	sunflower	1	1	0	0	8.1	34
Grasslands	prairie, grasses, shrubland	6	0	1	5	−56.8 (−85.7 to −24.8)	13, 14, 16, 25, 27, 31
Forests	forest	1	0	1	0	−1.7	15
Wetlands	wetland	2	0	1	1	−7.2 (−14.7 to 0.26)	14, 18

Note. Studies were classified as reporting an increase, no significant change, or decrease in the yield or productivity in ROW relative to ADJ. Positive and negative percentage changes indicate a respective increase and decrease in value over the ROW relative to the undisturbed areas. Citations refer to the study reference number listed in Table 1.

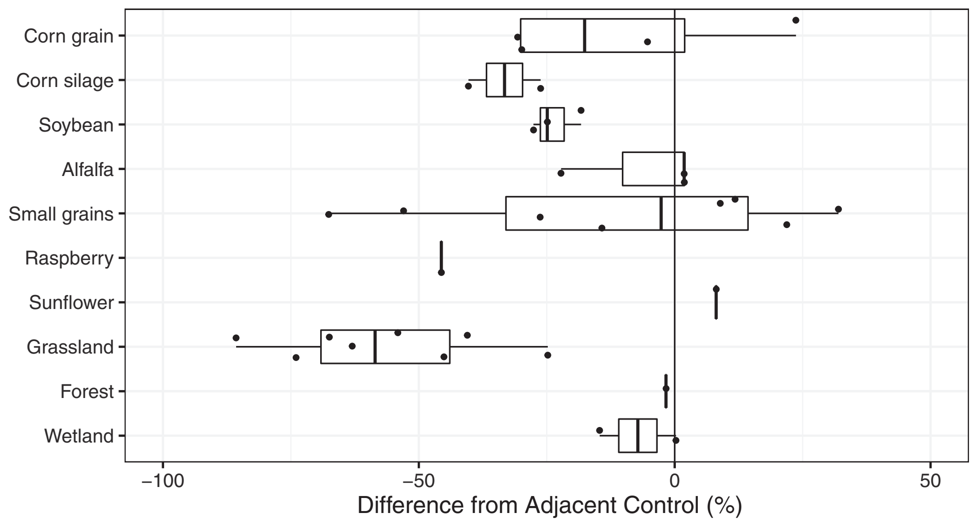

FIGURE 3 Percentage difference values for vegetative yields between right-of-way (ROW) vs. adjacent, unaffected areas (ADJ). Percentage differences were calculated with each study's paired replicate with the point representing the mean of each study's paired replicate with the point representing the mean of each study. Values on the left side of the solid line indicate a decrease in yield values when compared with adjacent values, while values on the right side indicate an increase in yield value

Neilsen et al. (1990) reported that, while corn emergence was not affected by pipeline installation, silking was delayed, corn plants were stunted, and yields were decreased on ROW. While fertilizer improved yield and accelerated silking times, the authors found that yield reductions in the ROW persisted and were greatest in areas with initially lower SOM and higher bulk density. Culley et al. (1981) and Landsburg and Cannon (1995) individually reported decreased yields in mixed soils within greenhouse studies, even when fertilized, causing both studies to conclude that fertilization alone could not fully remediate disturbed soils.

Soon, Rice, et al. (2000) reported decreased small grain yields in barley crops on ROW soils during the first harvest season after pipeline installation, but in the following 2 yr of the study, yields were comparable with that of undisturbed fields. Culley et al. (1981) found essentially no differences in small grain height within a 3-yr study period in Alberta, Canada, and only marginally different crop nutrient contents even when maturity was delayed, particularly in silage corn.

De Jong and Button (1973) found that wheat yields increased in Solonetzic soils, particularly over the trench area after remediation, which they attributed to trenching remediation measures which decreased bulk density and increased permeability and aeration. In this study, wheat yields were consistently higher over the trench, particularly for older pipelines. Zellmer et al. (1985) also found increases in wheat yields over the pipeline trench, and sorghum yields were not significantly different between ROW and adjacent areas. Similarly, Halmova et al. (2017) reported winter wheat yields increased over the trench, likely due to warmer soil conditions from pipeline temperatures. These authors reported that winter wheat yields over the trench were higher by 9.4–13.1%, and sunflower yields were higher by 8.1% compared with control areas.

Culley and Dow (1988) found that alfalfa yields increased slightly over the ROW compared with undisturbed area. Batey (2015) noted that, though claims for crop loss may not have been filed, crop loss still occurred in many areas, including with potato and raspberry. These losses could have been a result of increased moisture which contributes to increased incidence and severity of crop diseases like powdery scab in potato.

In nonagricultural soils, Kowaljow and Rostagno (2008) found that native shrubland faced difficulty in naturally revegetating disturbed areas, resulting in slow vegetation growth on-ROW compared with less disturbed areas, with lowest rates of vegetation present on the trench area. Desserud et al. (2010) found that invasive species like Kentucky bluegrass (*Poa pratensis* L.) dominated many of the native grass species in disturbed areas, while undisturbed sections had higher percentage cover by native fescue grass species. Xiao et al. (2014), Low (2016), and Xiao et al. (2017) found similar results, with invasive species thriving in disturbed areas, reducing plant diversity and resulting in difficulty of native species reestablishment after pipeline installation. Olson and Doherty (2012) found that, in naturally diverse wetland areas in Wisconsin, pipeline installation in these areas resulted in lower species richness and higher dominance of invasive species when compared with undisturbed wetland areas.

4 | CONCLUSIONS

As the number of pipeline installations around the world is projected to increase, land managers and the public would benefit from research quantifying changes in soil and plant ecosystem functions, such as analysis of soil microbial population composition and diversity following pipeline installation and the exploration of the use of remotely sensed imagery to predict vegetation changes over time and space. Specifically, managers need improved guidance on managing and improving soils post-disturbance, which could be supported by further remediation studies on pipeline-impacted areas.

Pipeline installations have occurred through the world and accordingly, research studies documenting the impacts of installation vary greatly in space and time, making drawing specific and consistent conclusions difficult. However, published research has demonstrated a general consensus that pipeline installations have resulted in lasting soil physical and chemical degradation and subsequent decreases in plant productivity. Commonly reported responses after pipeline installation includes increases in soil mixing (17.1%), compaction (bulk density: 12.6%, penetration resistance: 40.9%), increased erosion potential caused by decreased aggregate stability (−44.8%), alterations in electrical conductivity (109.4%), and decreased organic matter and organic C content (−20.8%). Additionally, pipeline installation has often been detrimental to agricultural crop yields and native vegetation in natural ecosystems, with yields averaging 6.2–33.2% lower on ROW areas compared with adjacent, undisturbed areas. However, remediation measures are major factors in the extent of disturbance and recovery potential. This literature review and quantitative synthesis provides clarity to the general degrading effect that pipeline installation has on natural resources including increased soil compaction and decreased vegetative productivity, which can often persist for decades following initial pipeline installation.

DATA AVAILABILITY STATEMENT

Data collected and used in this review were publicly available, and no new data were introduced in this report.

AUTHOR CONTRIBUTIONS

Theresa Brehm: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing. Steve Culman: Conceptualization; Formal analysis; Funding acquisition; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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CFAES

SCHOOL OF ENVIRONMENT AND NATURAL RESOURCES

Landowner Experiences with Natural Gas Pipeline Installations in Ohio

Steve Culman, Theresa Brehm, Doug Jackson-Smith

INTRODUCTION

Numerous natural gas pipelines have been installed in Ohio over the past decade to transport fracked petroleum from Eastern Ohio to other regions of the state for refinement or redistribution. These pipelines are essential components of Ohio's energy infrastructure and bring economic growth to the region. However, the installation process creates a large amount of disturbance that can have lasting impacts on soil and crops.

Here we report our findings from a landowner survey intended to capture the collective experiences of Ohio residents having pipelines installed on their land. We targeted three recently installed, independently operated pipelines in Ohio that varied in size. All three pipelines used best management practices for installation and remediation, including double lift excavation and deep ripping of subsoils. We believe this report provides a robust reflection of typical landowner experiences with current pipeline installation practices.

The Pipelines. The Rover, Utopia and Nexus pipelines are all three independently operated pipelines that were installed in 2016-2017, with installation completed in 2018 (Table 1). The Rover and Nexus pipelines were subject to eminent domain laws, while the Utopia pipeline was not federally regulated. All three pipelines had documents (Environmental Impact Agreements or Agricultural Impact Mitigation Agreements) that outlined double-lift installation techniques and site remediation practices post-installation, that would generally be considered 'best management practices'. These pipelines were installed in the northern part of Ohio, crossing over 20 counties throughout the state and had limited activities with feeder lines and compression stations in additional counties.

Table 1: Description of Rover, Utopia and Nexus pipelines.

Pipeline Name	Parent Company	Number of Lines	Diameter (inch)	Length in Ohio (mile)	Capacity (MCuM per day)	Ohio Counties Crossed	Year Construction Began	Year Construction Completed
Rover	Energy Transfer Partners	Dual	42	210	92.0	18	2016	2018
Utopia	Kinder Morgan	Single	12	264	6.0	13	2016	2018
Nexus	DTE Energy and Enbridge, Inc.	Single	36	209	42.5	13	2017	2018

Survey Methods. In the summer of 2021, Ohio State University sent 600 surveys total to landowners (200 for each pipeline). The landowners were randomly selected by dividing each pipeline into 200 equal distances, and then identifying landowners at each point using Landgrid, a subscription-service database that utilizes publicly available county auditor data. Landowners were mailed a 6-page survey with return postage and those that did not respond were mailed another survey two additional times over the next 6 months. 149 survey sample points were disqualified due to undeliverable addresses or responses from landowners that their property did not have a pipeline. Our total response rate was 31.5% (142 responses out of the remaining 451 addresses). These were distributed across the Rover (33.1%), Utopia (26.1%) and Nexus (40.8%) pipelines. This response rate gives us confidence that the experiences and opinions represented here are a reasonable reflection of the entire population of affected landowners. There were 22 Ohio counties with responses total (Figure 1). The average easement length was 2390 linear feet, but varied from landowners of 54 ft to 10,800 ft.

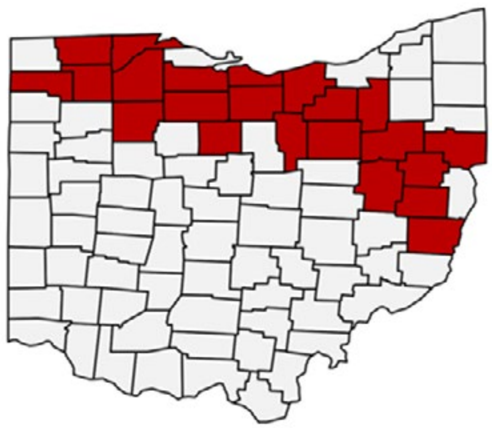

Figure 1. Ohio counties (red shaded) where landowners responded to survey.

Landowner Respondents. Nearly all of the survey respondents indicated they were *"Very familiar"* with what happened to their land over the past 5 years (87.9%) or were *"Somewhat familiar"* (9.9%). The majority of survey respondents both owned and operated the land (72.3%), while the remainder either owned but did not operate (24.1%) or did not own, but operated the land (2.1%).

Ecosystems Impacted. The vast majority of landowners who responded had land in agricultural production (95.7%) with only a small percentage not in agriculture (4.3%). Landowners commonly had a pipeline running through multiple fields or ecosystems. The majority of landowners (88.0%) had a pipeline installed in row-cropped fields (corn, soybean, small grain, hay), followed by forest (20.4%), grazed pasture (19.0%), wetlands (10.4%), and horticultural crops (1.4%).

INSTALLATION PROCESS

Previous pipeline studies have reported high rates of soil compaction following pipeline installations. We asked respondents if, *"During the installation process, were there times when soil conditions were not optimal, but pipeline installation continued?"*. The majority of respondents answered *"Yes"* to this question (71.8%, Figure 2). These responses were similar across all three pipelines (Figure 3).

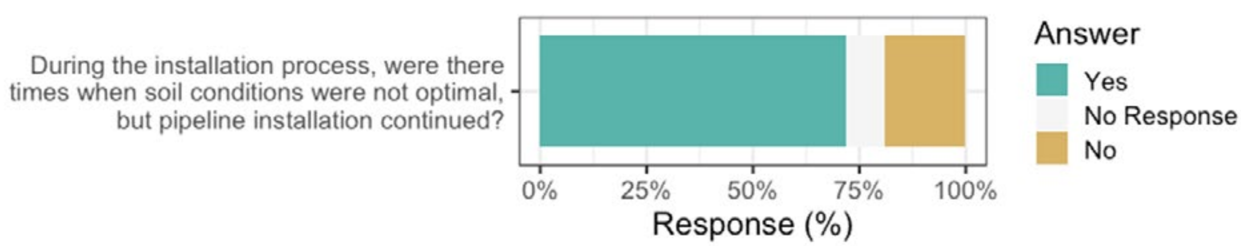

Figure 2. Percent of respondents indicating that soil conditions were not optimal during installation.

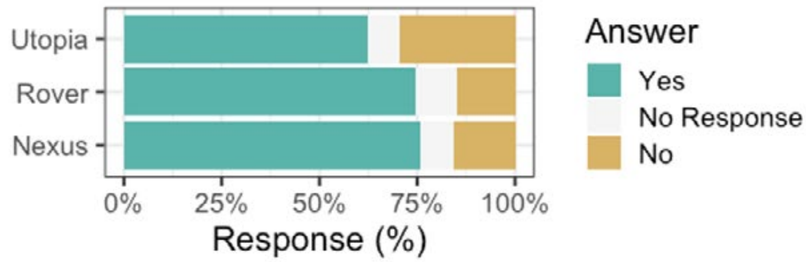

Figure 3. Percent of respondents indicating that soil conditions were not optimal during installation, by pipeline company.

Those who indicated that soil conditions were not optimal during installation were asked to rate how sub-optimal the conditions were (Table 2). Over half of the respondents (55.7%) said the soil conditions during installation were extremely sub-optimal (soil completely saturated). Again, these responses were similar across pipelines with most respondents ranking the conditions as *"Extremely sub-optimal"*: Nexus (48.8%), Rover (65.6%) and Utopia (54.5%).

Table 2. Ranking of the how sub-optimal soil conditions were during installation.

Slightly sub-optimal (Soils were still wet, and I would only drive on them if tasks were very important and time sensitive)	14.4%
Moderately sub-optimal (Soils were not fully saturated, but still tacky and too wet to drive on)	29.9%
Extremely sub-optimal (Soils were completely saturated, worked during or immediately after large rain events)	55.7%

Soils are highly susceptible to compaction when wet, and once compacted can take decades to recover. Compacted soils have impaired function as reduced water and gas exchange, restricted plant root growth and overall reduced productivity.

CROP YIELDS AFTER INSTALLATION AND REMEDIATION

Respondents were asked to report yields they had measured in areas over the pipeline relative to an adjacent, unaffected area. We received 52 paired yield measurements in corn, popcorn, soybean and wheat. All but one response indicated yield reductions over the pipeline right of way compared to an adjacent area (Figure 4). Yield reductions across crops ranged from 22% more yield to 100% less yield (total crop failure), with average declines across crops approximately 40 – 60% (Table 3). Across all reports, yields over pipelines were reduced 93 bushel/acre in corn, 2667 pound/acre in popcorn, 22.5 bushel/acre in soybean and 55.2 bushel/acre in wheat (Table 3).

Figure 4. Farmer-reported percent differences in crop yields between the pipeline and an adjacent, non-impacted area. Values on the left side of the red dotted line indicate a yield reduction over the pipeline when compared with adjacent areas, while values on the right side indicate an increase in yield.

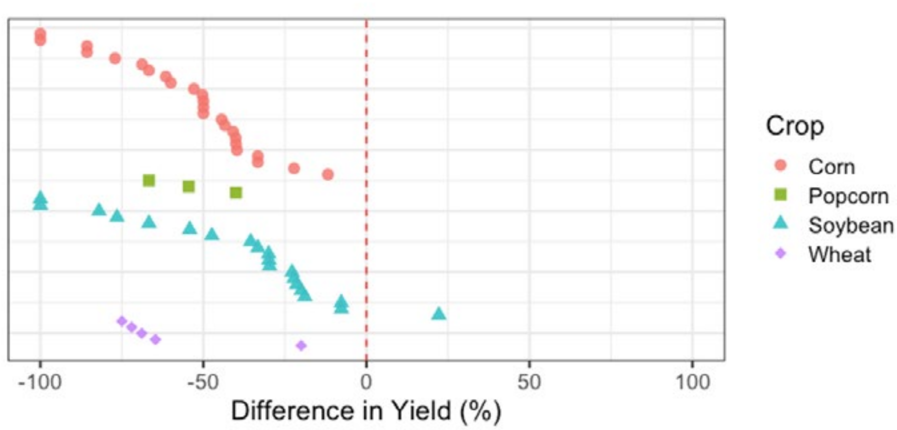

Table 3. Difference in farmer-reported grain yields by crop. The first row reports the average percent difference and the second row reports average actual yield difference.

	Corn (n = 24)	**Popcorn (n = 3)**	**Soybean (n = 20)**	**Wheat (n = 5)**
Average percent difference	-54.5%	-53.7%	-38.3%	-60.1%
Average total difference	-93.2 bu/acre	-2667 lbs/acre	-22.5 bu/acre	-55.2 bu/acre

In addition, twenty-seven respondents commented that they did not measure yields over the pipeline but noted stunted crop growth, reduced plant vigor and/or yield reductions over the pipeline relative to the non-impacted areas of the same field. Ten respondents indicated they had not cropped some fields yet due to ongoing site remediation. Four respondents commented that there were no differences in yield, while two said yields over pipelines were reduced in the first few years, but that yields were improving over the pipeline area.

IMPACT OF REMEDIATION

All three pipeline companies were expected to implement installation and remediation practices to minimize soil and plant disturbance. Three years after site remediation was complete, we asked, *"Do you feel that your land is generally back to the condition it was prior to pipeline installation?"* Only 17.6% of respondents indicated that things had returned to normal (Figure 5). By contrast, 82.4% of the respondents answered no to this question and indicated the following as reasons for making this statement: decreased crop yields or plant vigor (92%), increased soil compaction (82%), decreased rainfall infiltration (61%), increased soil erosion (52%), increased rock fragments (42%) and increased weeds (30%). Responses were similar across the three pipelines (Figure 6).

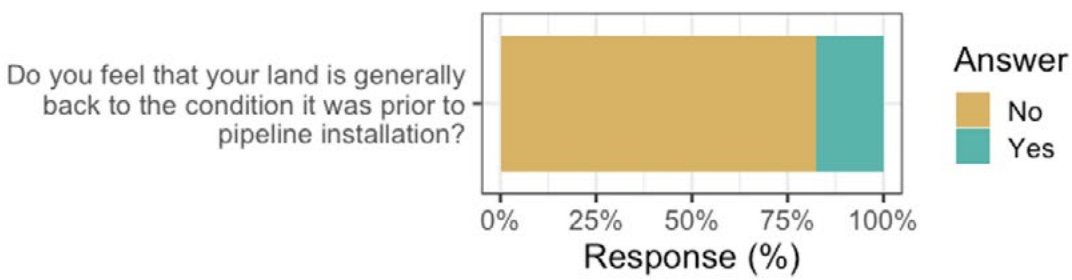

Figure 5. Percent of respondents indicating their land had generally returned to condition prior to installation.

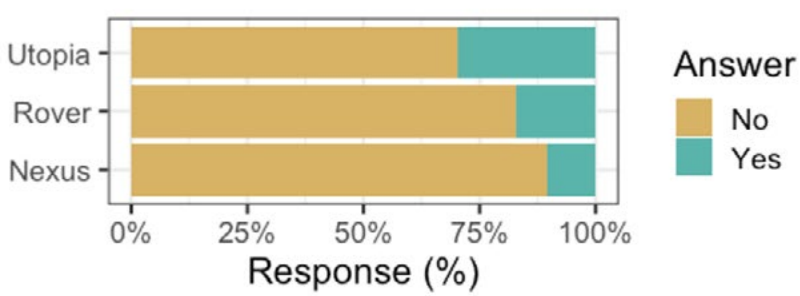

Figure 6. Percent of respondents indicating their land had generally returned to condition prior to installation, by pipeline company.

LANDOWNER PERSONAL EXPERIENCES

We asked landowners several questions about their personal experiences having pipelines installed on their land. Responses showed mixed experiences with landowners overall (Figures 7 and 8). The responses were roughly split when asked if they were treated fairly during the negotiation process: 46.2% agreed (strongly agreed or agreed) vs. 39.4% disagree (strongly disagreed or disagreed). The majority of respondents felt they were treated with respect by the installation crews, and that clear points of contact were established throughout the installation process. However, less than one-third (27.2%) agreed that the contract agreements outlining best management practices were followed properly on their land, compared to those who disagreed (37.6%; Figure 7). Interestingly, 3 out of 142 respondents from 2 different pipelines said they could sometimes smell gas over the installed pipeline.

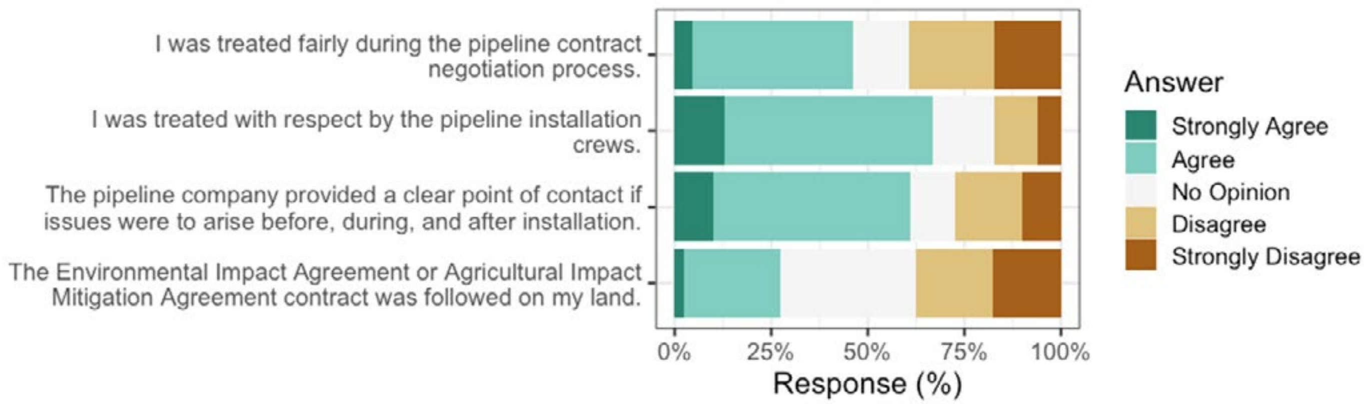

Figure 7. Percent of respondents who agree or disagree with statements about the negotiation and pipeline installation process.

When asked about their overall experience with having a pipeline installed on their land, the responses were mixed but mostly reflected negative experiences (Figure 8). Roughly half of the respondents (56.3%) were not satisfied with the experience compared to satisfied (31.9%) and a similar proportion felt they had a choice in signing the easement (30.1% agreed vs. 54.1% disagreed). About one-third of respondents (36.1%) felt that they were fairly compensated for the easement, while 46.6% did not feel fairly compensated. Finally, only a quarter (26.7%) would be open to negotiating a future easement compared with 55.6% who said they would not be open to another pipeline easement (Figure 8).

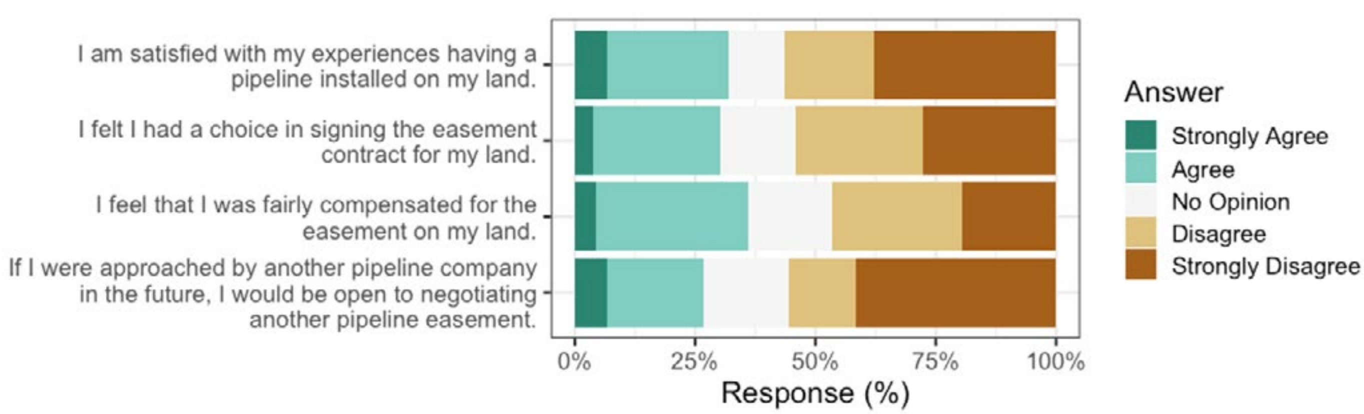

Figure 8. Overall landowner perceptions about the pipeline installation experience.

CONCLUSIONS

This survey responses here tell an important story of landowner experience and reflect what might be considered typical with contemporary pipeline installation. Despite the outlined best management practices, landowner responses suggest that these were not always followed and that many fields were worked when they were far too wet. This likely resulted in soil compaction and degradation in many fields and may be a primary reason crop yields have been reduced in most of the fields reported here. Three years after remediation was complete, 82% of respondents do not believe their land has been remediated back to the original condition, prior to pipeline installation. Additionally, less than half of respondents are satisfied with their overall experience of having a pipeline installed on their land.

This survey of farmer experiences largely reflects what our team measured on 29 farms across 8 Ohio counties in 2020 and 2021. We observed widespread soil degradation including increased compaction, increased subsoil mixing, decreased aggregate stability and decreased organic matter. This soil degradation reduced corn yields over pipeline right-of-way areas around 20% and soybean yields around 10%. Overall pipeline installation and remediation best management practices were insufficient to prevent soil degradation in the farms we sampled (Brehm, 2022).

Underground pipelines are an important aspect of Ohio's energy portfolio with more pipelines projected to be installed in the coming years. But farmers should be appropriately compensated for soil degradation and sustained crop yield losses from these activities. Current easement payments should likely be revisited, as all available evidence from Ohio suggests that degradation often persists for more than 3 or 4 years after installation and remediation is complete. Crop loss monitoring and soil remediation practices should be the focus of research efforts moving forward.

More information on this study can be found here, including reports as they become available:
https://go.osu.edu/pipeline-study

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