BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

IN THE MATTER OF THE APPLICATION BY SCS CARBON TRANSPORT LLC FOR A PERMIT TO CONSTRUCT A CARBON DIOXIDE TRANSMISSION PIPELINE	**HP22-001** **DR. MATT LIEBMAN** **INITIAL PRE-FILED TESTIMONY IN SUPPORT OF LANDOWNER INTERVENORS**

Q: Please state your name and purpose for providing testimony in these proceedings.

A: My name is Matt Liebman. The purpose of my testimony is to provide the PUC information helpful when considering this proposed hazardous pipeline application. My primary areas of concern are soil degradation and reduced crop yields; minimal reductions in greenhouse gas emissions should this proposed hazardous pipeline be approved; and corruption of the ideal of public sacrifice for the public good.

Q: What experience, education, training, or background qualify you to provide opinions and your concerns as you have hearing?

A: I am a Professor Emeritus of Agronomy at Iowa State University and the Henry A. Wallace Endowed Chair for Sustainable Agriculture. Please see a summary of my education and experience in **Attachment No. 1,** my C.V.

Q: I ask you to assume that the four (4) main elements of proof that Summit has the sole burden to prove in these proceedings are a) that Summit will comply with all applicable laws and rules; b) that no aspect of Summit's proposed hazardous pipeline will pose a threat of serious injury to the environment, or to the social condition of current inhabitants or expected inhabitants in the siting area, or to the economic condition of current inhabitants or expected inhabitants in the siting area; c) that no aspect of Summit's proposed hazardous pipeline will substantially impair the health, safety, or welfare of the

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inhabitants; and d) that no aspect of Summit's proposed hazardous pipeline will unduly interfere with the orderly development of the region – with special consideration given to the views and positions of the governing bodies of affected local units of government. Of these factors, which are most relevant to your opinions here?

A: My opinions arguably touch each of these factors with the most direct relevance being that this proposed hazardous pipeline does pose a threat of serious injury to the environment and social conditions or both current and expected inhabitants in the siting area and to their economic condition for the reasons discussed below.

Q: Based upon your research, studies, education, background, training, and experiences do you have an opinion whether or not South Dakota landowners will suffer from soil degradation and reduced crop yields?

A: Yes, I do.

Q: And what is that opinion?

A: Subsoil compaction, the kind you can expect from pipeline related construction activities proposed here by Summit, reduces corn yields at least by 15% and soybean yields by 25% for at least several years after pipeline construction completion. I am also aware of evidence of reduced yields decades into the future based upon familiarity with farmers affected by pipeline constructed and put in service decades ago. I have serious concerns for any person with production agriculture land that would be affected should the Commission approve this application. It is my opinion that construction of this proposed hazardous pipeline would pose a threat of serious injury to the economic condition of persons along the proposed route in South Dakota and elsewhere. Additionally, such impacts are more likely than not going to substantially impair the welfare of the current inhabitants and unduly interfere with the orderly development of the regions affected. These opinions are my own and find support in recent peer reviewed research included here as **Attachment No. 2**.

Q: What if I asked you to assume Summit is offering – at least if you agree to sign their Easement Agreement – to pay for some percentage of yield loss for up to

three (3) years – would that change the opinions you just expressed and if so, why?

A: No, it would not. That doesn't change the scientific evidence backing my opinions. I am concerned for affected landowners that will most certainly be dealing with yield loss and therefore economic loss and damage years beyond the first three (3) following construction.

Q: What is your next opinion you would like the Commission to consider?

A: Capturing carbon dioxide generated during the process of fermentation at ethanol plants and then transporting it by pipelines through South Dakota and other states and storing it underground would have trivial effects on our nation's carbon dioxide emissions. Carbon dioxide emissions in the U.S. in 2020 were 110 times greater than the amount that might be captured at all our nation's ethanol plants under the most favorable projections. The use of ethanol in our cars contributes to greenhouse gas emissions, which exacerbate our ever-increasing climate crisis. Tailpipe emissions from U.S. vehicles in 2020 using gasoline blended with 10% ethanol (E10) were almost 25 times greater than the 43 million metric tons of carbon dioxide that could potentially be captured at all the nation's ethanol plants. Because vehicles using ethanol rather than regular gasoline typically get 4% to 5% fewer miles per gallon of fuel consumed, due to the lower energy content of ethanol, carbon dioxide emissions per mile traveled are as high or higher for ethanol blends as for pure gasoline.

Q: Why do you believe that is relevant to these proceedings?

A: Summit claims its project would allow the ethanol plants they partner with to sell their product at a premium in the growing number of states and countries that have adopted low carbon fuel standards. However, as stated above, this simply encourages greater use of a dirtier fuel which defeats Summit's stated purpose of carbon capture.

Q: Do you have any other opinions to share with the Commission?

A: Yes. Because the carbon dioxide transported that would be transported by Summit from ethanol plants for underground storage would hardly dent U.S. greenhouse gas emissions while incurring substantial damage to private land, I believe insufficient public benefit would accrue from allowing private pipeline projects to proceed using eminent domain. My understanding is that without an approved application by the South Dakota PUC there is no reason Summit would go through the entire condemnation process because there would be no need to obtain easements against landowners' interests.

Q: Have you written more extensively on your opinions we discussed here?

A: Yes, I have. **Attachment No. 3** to my testimony is a true and accurate copy of a July 29, 2022, joint article and research piece I prepared with others in opposition to these projects. I stand by the research and conclusions stated therein and incorporate those into my sworn testimony. I am competent to testify consistent with the above as necessary. I urge the PUC to carefully consider this testimony during the Hearing in this matter and in your deliberations. I further reserve the right to amend or modify these opinions upon presentation of any additional information that may justify such a change.

Dated June 15, 2023

/s/ Matt Liebman

Matt Liebman

Attachment No. 1

MATT LIEBMAN
615 11th Street, Ames, IA 50010, USA, mliebman@iastate.edu

EDUCATION

1986	Ph.D., University of California, Berkeley, CA (Botany)
1978	B.A. cum laude, Harvard University, Cambridge, MA (Biological Sciences)

PROFESSIONAL EXPERIENCE

2007-2021	Iowa State University, Ames, Iowa: Henry A. Wallace Endowed Chair for Sustainable Agriculture
2002-2021	Iowa State University, Ames, Iowa: Professor, Dept. of Agronomy
1998-2002	Iowa State University, Ames, Iowa: Associate Professor, Dept. of Agronomy
1993-1998	University of Maine, Orono, Maine: Associate Professor, Dept. of Plant, Soil and Environmental Sciences
1987-1993	University of Maine, Orono, Maine: Assistant Professor, Dept. of Plant, Soil and Environmental Sciences
2000, 2001, 2005	Wageningen University, Wageningen, The Netherlands: Visiting Scholar
1994-1995	University of California, Davis, California: Visiting Scholar

PROFESSIONAL RECOGNITION & SERVICE

• Dean's Citation for Extraordinary Contributions to the College of Agriculture and Life Sciences, Iowa State University (2022)
• Conservation Innovation Award, Soil and Water Conservation Society (2020)
• Organizing committee member and webinar moderator, National Academies of Science, Engineering, and Medicine, Food Forum (2020)
• Team Award, College of Agriculture and Life Sciences, Iowa State University (2018)
• Panel member, USDA Agriculture and Food Research Initiative, Pests and Beneficial Species in Agricultural Production Systems competitive grants program (2017)
• Committee member and co-author, Institute of Medicine/National Research Council of the National Academies–A Framework for Assessing Effects of the Food System (2013-2015)
• Spencer Award for Sustainable Agriculture, Leopold Center for Sustainable Agriculture (2013)
• Site reviewer, Long-Term Ecological Research program, National Science Foundation (2007, 2013)
• Sustainable Agriculture Achievement Award, Practical Farmers of Iowa (2013)
• Panel manager, USDA-NIFA Regional Approaches to Climate Change CAP competitive grants program (2010)
• Fellow, American Society of Agronomy (2009)
• Award for Achievement by an Organizational Team, Iowa State University Extension (2009)
• Outstanding Achievement in Research Award, College of Agriculture and Life Sciences, Iowa State University (2008)
• Chair, Graduate Program in Sustainable Agriculture, Iowa State University (2004-2007)
• Panel member, USDA National Research Initiative, Biology of Weedy and Invasive Species Program competitive grants program (2003, 2004, 2006)
• Pioneer Agronomy Professorship, Iowa State University (2001-2004)
• Vice-chair, Agroecology Section of the Ecological Society of America (2000-2004)
• Associate Editor: Weed Research (2009-present), Crop Science (1998-2005), Ecological Applications (1993-2002)

RESEARCH INTERESTS

General: Agricultural ecology with a focus on ways to (1) reduce dependence on agrichemicals and fossil fuels, and (2) improve soil, water, and wildlife conservation. *Specific:* Diversified cropping systems, organic matter amendments to soils, weed ecology and management, and the use of native perennial species for natural resource conservation and biofuel production.

PUBLICATIONS

Peer-reviewed journal articles, scientific letters, and book chapters: 176**;** >16,350 citations, h-index = 69 (as of June 2023) for a list, see: https://scholar.google.com/citations?hl=en&user=tylodlwAAAAJ

MENTORSHIP

Graduate students supervised directly: 15 M.S., 14 Ph.D.
Postdoctoral scientists supervised directly: 5

COMMUNITY SERVICE

• Instructor for Ames Parks and Recreation Department, Ames, IA (2000-2020)
• President, vice president, and member, Board of Directors, Wheatsfield Food Cooperative, Ames, IA (2008-2020)
• Committee member for nominations and recruitment, Wheatsfield Food Cooperative, Ames, IA (2021-present)
• Member, Board of Directors, Practical Farmers of Iowa (2021-present)

Attachment No. 2

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Soil Science Society of America Journal

ORIGINAL ARTICLE

Soil & Water Management & Conservation

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

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Assigned to Associate Editor Shannon Osborne.

Abstract

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

1 | INTRODUCTION

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

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

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

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

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

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

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

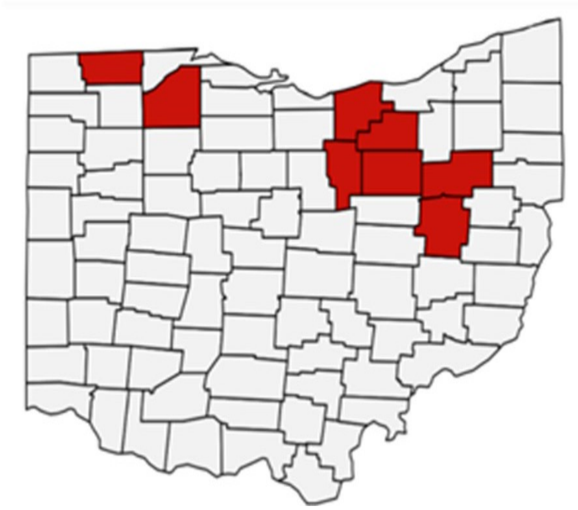

FIGURE 1 A map of Ohio with counties highlighted in red where sampling occurred for this study in 2020 and 2021

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

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

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

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

2.4 | Laboratory analyses

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

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

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

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

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

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

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

2.5 | Statistical analysis

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

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

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

Variable	Mean (standard error) ROW	ADJ	F-statistic 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

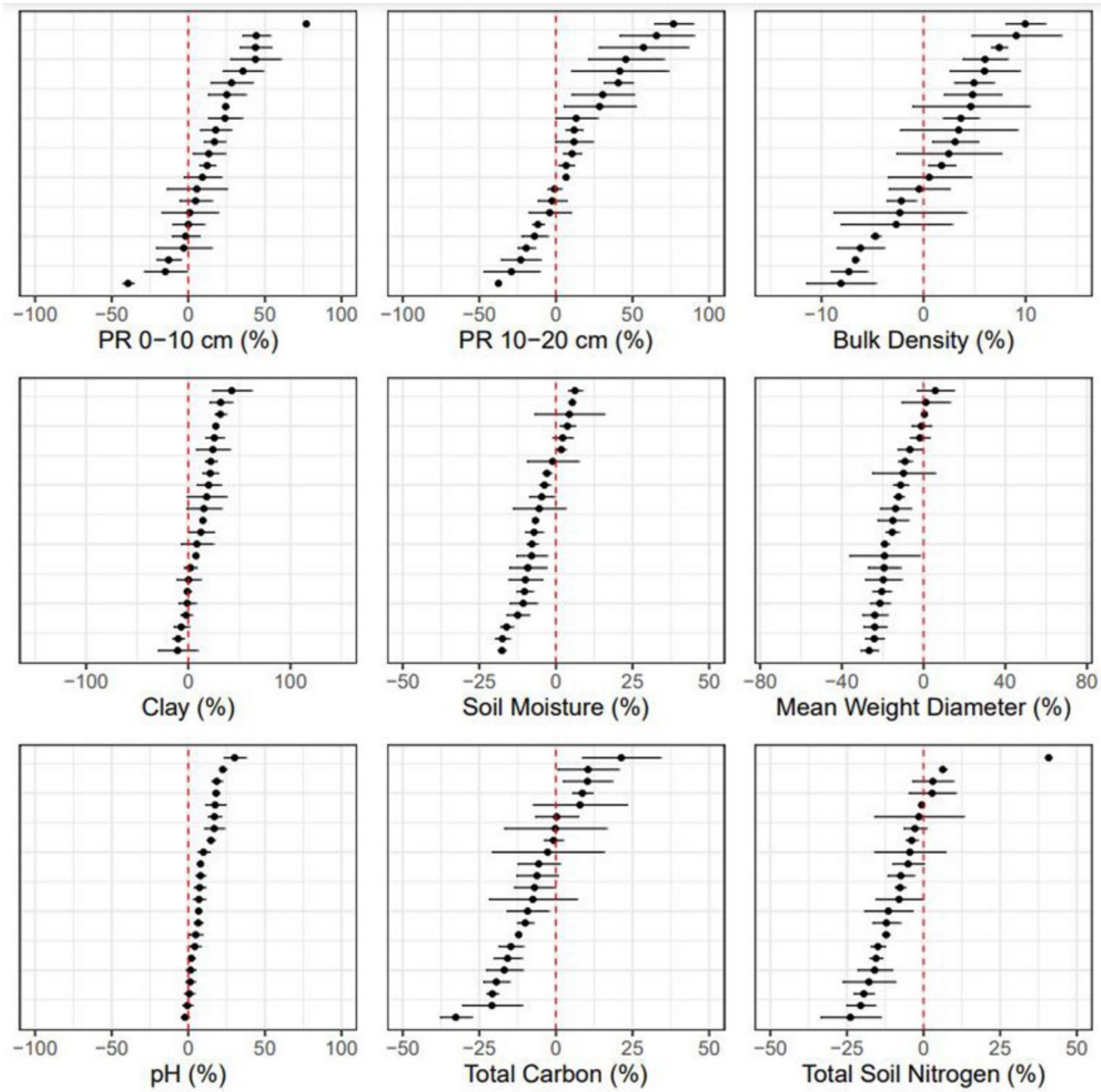

FIGURE 2 Average percent difference values for select soil properties between right-of-way (ROW) versus adjacent, unaffected areas (control, ADJ) across 23 sites. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing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

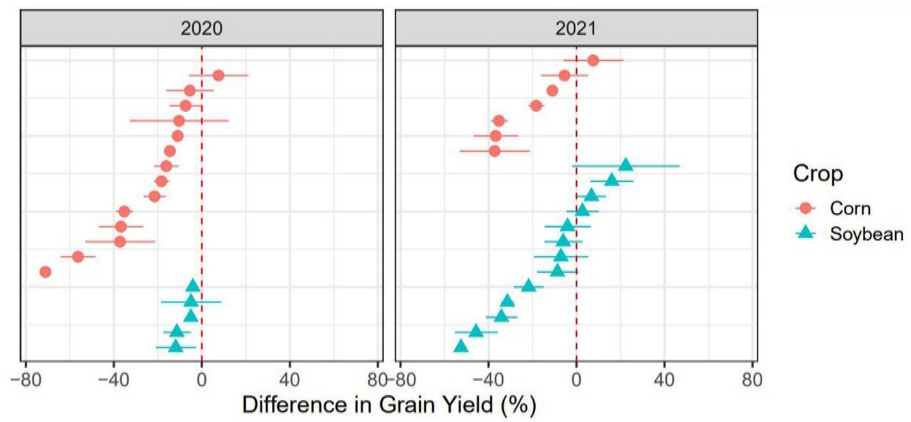

FIGURE 3 Average percent difference in crop yields in 2020 and 2021 between right-of-way (ROW) and adjacent (control, ADJ) sampling areas. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing the standard error among 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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Attachment No. 3

29 July 2022

To: Iowa Utilities Board, 1375 East Court Avenue, Des Moines, IA 50319

We write to express our opposition to issuing a permit for construction of the carbon dioxide (CO_2) pipeline proposed by Summit Carbon Solutions, Navigator CO_2 Ventures, and Archer Daniels Midland partnered with Wolf Carbon Solutions. Our science-based objections are four-fold and can be summarized as follows: (1) Building CO_2 pipelines in Iowa would lead to soil degradation in the crop fields and timberlands of many farmers and rural landowners and the resulting soil damage would reduce crop yields in construction areas for multiple years. (2) Capture of CO_2 during ethanol production would have very minor effects on U.S. greenhouse gas (GHG) emissions. (3) The amount of CO_2 captured during ethanol production would be a tiny fraction of what would be emitted from vehicle tailpipes. (4) Allowing profits to accrue to private pipeline companies using eminent domain would be an unacceptable corruption of the ideal of private sacrifice for public good.

Here, we provide more detailed information from relevant scientific and engineering studies.

Three companies–Summit Carbon Solutions, Navigator CO_2 Ventures, and Archer Daniels Midland partnered with Wolf Carbon Solutions–currently seek to build hundreds of miles of pipelines through the fields and timberlands of dozens of Iowa counties to carry CO_2 captured at ethanol manufacturing plants and perhaps, later, other industrial facilities. The CO_2 would be buried underground for permanent storage or used for 'enhanced oil recovery' by injecting it into oil wells. These activities are intended to reduce the discharge of CO_2, a greenhouse gas, into the atmosphere and slow the rate of climate change. Carbon dioxide is only one of the greenhouse gases of concern, but for the U.S., it comprises 79% of total GHG emissions when gases are considered based on their global warming potential (U.S. Environmental Protection Agency 2022). Substantial payments from taxpayers via the federal government would be given to CO_2 pipeline owners as part of a funding package for climate mitigation.

Building pipelines requires substantial disruption of the soil and vegetation in farm fields and timberlands. Crop yields can suffer for multiple years since soil heals slowly from the wounds inflicted by excavation, compaction, and back filling. ***A recent study conducted by Iowa State University scientists found that corn and soybean yields were reduced 15% and 25%, respectively, in the field zone affected by oil pipeline construction (Tekeste et al. 2021).*** Farmers are aware of this and consequently are reluctant to allow degradation of their land by pipeline construction. Given the link between land health and farm productivity and the paucity of relatively undisturbed forests and grasslands in Iowa, it would seem that a very large benefit to the public should accrue to offset the damage incurred from building private CO_2 pipelines through the fields and timber of hundreds of Iowa citizens.

About 15 billion gallons of ethanol are produced annually in the U.S., with the 42 plants in Iowa generating nearly 30% of that total. During the production of ethanol, CO_2 is emitted from the fermentation process and from the combustion of petrochemicals used to generate process heat. Fermentation is responsible for about 75% of the total CO_2 emissions from a corn grain ethanol facility (Hornafius and Hornafius 2015). The gas stream emitted during fermentation is nearly pure CO_2 and relatively easy to collect. Based on engineering and chemical analyses, 2853 metric tons of CO_2 are produced per million gallons of ethanol generated from corn grain (Hornafius and Hornafius 2015). Not all that CO_2 would be economically feasible to capture and place in a pipeline, but for present purposes, we assume that all of it could be. Thus, if the U.S. ethanol industry manufactured 15 billion gallons of ethanol, there would be about 43 million metric tons of CO_2 that could be captured and prevented from entering the atmosphere. For Iowa, that would translate to about 12.8 million metric tons of CO_2. (A metric ton is 2,205 pounds.) Those are large numbers, but they are small in comparison to the greenhouse gas emissions from vehicle tailpipes, from the entire U.S. transportation sector, and from the entire U.S. economy.

Combustion of fossil fuels in the transportation sector comprised the largest source of greenhouse gas emissions in the U.S. in 2020 (U.S. Environmental Protection Agency 2022). Combustion of a gallon of pure ethanol in a vehicle engine results in the release of 12.7 pounds of CO_2 from the tailpipe (Rosenfeld et al. 2018). Because ethanol has only two-thirds the energy content of gasoline and because of the configuration of most existing engines, the ethanol and gasoline are mixed, with E10 (i.e., 10% ethanol) being the most common version available at a filling station. Combustion of a gallon of E10 in a vehicle engine results in the release of 19.0 pounds of CO_2 from the tailpipe (Rosenfeld et al. 2018). According to the U.S. Energy Information Administration (2021), in 2020 U.S. motorists consumed 123.5 billion gallons of E10, which would have resulted in the release into the atmosphere of 1.06 billion metric tons of CO_2. ***Thus, for the U.S., tailpipe emissions from using E10 in 2020 were almost 25 times greater than the 43 million metric tons of CO_2 that could potentially be captured at all the nation's ethanol plants.*** Increasing the amount of ethanol blended with gasoline up to 15% (i.e., E15) would shift that figure only slightly. It should also be noted that because of ethanol's lower energy content, miles per gallon values for ethanol blended with gasoline are typically 4-5% lower than for pure gasoline. Consequently, ***CO_2 emissions per mile traveled are as high or higher for ethanol blends than for pure gasoline.***

The U.S. transportation sector, including cars, trucks, and airplanes, discharged 1.57 billion metric tons of CO_2 in 2020. Total CO_2 emissions by all activities in the U.S. that year were an estimated 4.72 billion metric tons (U.S. Environmental Protection Agency 2022). Based on those values, CO_2 emissions from the U.S. transportation sector would be 37 times greater than what might be captured at ethanol plants, while CO_2 emissions from the whole U.S. economy would be 110 times greater. ***Thus, the process of capturing CO_2 at ethanol plants, transporting it by pipelines through Iowa and other states, and storing it underground would have trivial effects on our nation's CO_2 emissions.***

Given the damage to Iowa farmland soils and crop yields and the absence of substantial environmental benefits to the Iowa public associated with CO_2 pipelines, we strongly oppose the use of eminent domain to facilitate construction of these pipelines by private companies in

Iowa. Issuance of permits for CO_2 pipeline construction would be a betrayal of public trust and a corruption of the ideal of private sacrifice for public good. Permitting should be denied.

Sincerely,

Linda D. Appelgate— Retired USDA/NRCS Resource Conservationist

Laura Belin— Editor and publisher of Bleeding Heartland

Patricia Boddy— PE, Agriculture Engineer, former director of Polk County Conservation, former deputy and interim director of Iowa DNR

Christine Curry— Environmental/conservation Advocate

Mike Delaney— Professor Emeritus, Environmental Sociologist

Cornelia B. Flora— Distinguished Professor of Agriculture and Life Sciences Emerita, Iowa State University

Liz Garst— Conservation farmland owner

Neil Hamilton— Emeritus Professor of Agriculture Law, Drake University

Chris Henning— Prairie Skye Productions, Farm Owner and Manager,
Environmental Advocate

Susan Judkins— Conservation Advocate

Matt Liebman— Professor Emeritus of Agronomy, Iowa State University

Mary Ellen Miller— Healthy Soils/Clean Water Advocate, Wayne County Soil & Water Conservation District Commissioner

David Osterberg— Professor Emeritus of Public Health, University of Iowa

Mark Rasmussen— Professor Emeritus, Iowa State University

Ralph Rosenberg— Former Executive Director, Iowa Environmental Council; Former Iowa State Representative and Senator

Larry A. Stone— Elkader, Iowa, Environmental Advocate, farmland owner

Tim Wagner— Iowa Coldwater Conservancy

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