STATE OF NORTH DAKOTA

PUBLIC SERVICE COMMISSION

IN THE MATTER OF THE APPLICATION	)	
OF SCS CARBON TRANSPORT LLC FOR	)	Case No. PU-22-391
A CERTIFICATE OF CORRIDOR	)	
COMPATIBILITY AND ROUTE PERMIT	)	
FOR THE MIDWEST CARBON EXPRESS	)	
PROJECT IN BURLEIGH, CASS, DICKEY,	)	
EMMONS, LOGAN, MCINTOSH,	)	
MORTON, OLIVER, RICHLAND AND	)	
SARGENT COUNTIES, NORTH DAKOTA	)	

DIRECT TESTIMONY OF DR. MATT LIEBMAN
ON BEHALF OF
LANDOWNER INTERVENORS

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

A: My name is Dr. Matt Liebman. The purpose of my testimony is to provide the Public Service Commission (PSC) information helpful when considering this proposed hazardous pipeline application. My primary areas of concern are soil degradation, reduced crop yield, and minimal reductions in greenhouse gas emissions should this proposed hazardous pipeline be approved.

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

A: I am an Emeritus Professor of Agronomy and the former Henry A. Wallace Endowed Chair for Sustainable Agriculture at Iowa State University. I received a B.A. in Biological Sciences from Harvard University in 1978 and a Ph.D. in Botany from the University of California-Berkeley in 1986. Before joining the Iowa State University faculty in 1998, I was employed for 11 years as an assistant professor and then as an associate professor at the University of Maine. I became a fellow of the American Society of Agronomy in 2009, and I have served as an associate and subject editor for several scientific journals, including *Ecological Applications* (1993-2002), *Crop Science* (1998-2005), and *Weed Research* (2009-present). My research, teaching, and outreach activities have focused on ways to use ecological processes to create farming systems that are productive, profitable, resilient, and environmentally sound. As part of my professional activities, I have conducted research in the areas of crop production and crop protection, and I have reviewed a substantial amount of research and published literature on soil health, including the effects of pipeline construction on soils and plants.

Q: Please provide a general summary of research on soil health as it relates to this project.

A: As noted by soil scientists Fred Magdoff and Harold van Es, healthy soils occur when biological, chemical, and physical conditions are optimized. Healthy soils enable high crop yields. When soils are healthy, roots proliferate readily, water enters and is stored easily, plants have a sufficient nutrient supply, harmful chemicals are absent, and beneficial organisms are active and able to keep potentially deleterious ones in check.

Importantly, a soil's various properties are interrelated. For example, when a soil is compacted, there is a loss of the large pore spaces, making it difficult for precipitation to infiltrate, and for roots to grow to where water and nutrients are present, which increases vulnerability to drought conditions. Under high rainfall conditions, compaction can increase runoff and erosion and may promote soil waterlogging by restricting drainage. By reducing soil pore spaces containing oxygen, compaction may also reduce soil biological activity.

Q: Based upon your research, studies, education, background, training, and experiences do you have an opinion whether or not North 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, can reduce 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 PSC approve this application. It is my opinion that construction of this proposed hazardous pipeline would substantially impair the welfare of residents along the proposed route in North Dakota and elsewhere.

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 PSC to consider?

A: Capturing carbon dioxide generated during the process of fermentation at ethanol plants and then transporting it by pipelines 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: Have you written more extensively on your opinions we discussed here?

A: Yes, I have. **Attachment No. 1** 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 and submitted to the Iowa Utilities Board. I stand by the research and conclusions stated therein and incorporate those into my sworn testimony.

Q. Can you explain the research presented in Attachment No. 2?

A. Yes, underground pipelines are widely used to transport energy materials, but pipeline construction commonly causes disturbance to ecosystems. The authors note that "[d]ue to variability in pipeline installation practices and environments, drawing consensus about how pipeline installations typically impact ecosystems has been challenging." To address this information gap, as shown in **Attachment No. 2**, Brehm and Culman performed a systematic literature review drawing on 34 studies from eight countries that evaluated impacts of pipeline installation on soil properties and plant performance. The majority of studies found that pipeline installation resulted in soil degradation via increased compaction and soil mixing and decreased aggregate stability and soil carbon content relative to adjacent, undisturbed areas. Most of the studies reviewed also reported reductions in crop yields.

Q. In your opinion, what are the most significant findings contained in Attachment No. 2 as they relate to Summit's project?

A. In my opinion, the most significant findings are: (1) pipeline construction increased soil resistance to penetration (which is an indicator of soil compaction and impedance of root growth); (2) decreased soil aggregate stability (which is an indicator of loss of beneficial soil structure and increased erosion potential); (3) increased soil temperature; and decreased water infiltration; (4) average reductions in corn grain and soybean yields were 10.5% and 23.6%, respectively; and (5) in some studies, crop yield reductions were found to persist at least 10 years after pipeline construction. The authors concluded that pipeline construction generally has degrading effects on soils and vegetation, "which can often persist for decades following initial pipeline installation."

Q. Can you explain the research presented in Attachment No. 3?

A. Degradation of soil resources, including increased soil compaction, and decreased crop yields have been common outcomes of underground pipeline installation. However, much of the research documenting how pipeline installation affects soils and crops was conducted before contemporary best management practices were developed and implemented. Consequently, Brehm and Culman conducted a study in 2020 and 2021 to evaluate the impacts of pipeline installation on soils and crops at 29 farm field sites across eight Ohio counties after a 4-5-year remediation period. The remediation period coincided with the end of landowner compensation by pipeline companies.

Q. In your opinion, what are the most significant findings contained in <u>Attachment No. 3</u> as they relate to Summit's project?

A. Brehm and Culman reported that they 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 areas compared with adjacent areas." Furthermore, they noted that "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." Brehm and Culman concluded that "current best management practices of pipeline installation and remediation employed by three companies were insufficient to combat widespread soil degradation and crop yield loss."

Q. Are the findings in the two studies representative of other published research in this field?

A. Brehm and Culman's findings are consistent with the results of other studies I've read. For example, Dr. Teskeste and his colleagues at Iowa State University investigated the impacts of constructing the Dakota Access oil pipeline and reported that corn and soybean yields were reduced 15% and 25%, respectively, in pipeline right of way areas relative to adjacent zones not subject to pipeline construction machinery. Deep subsoil tillage was unable to fully relieve soil compaction incurred by pipeline construction. *See* Tekeste et al. (2021), "Effect of subsoil tillage during pipeline construction activities on near-term soil physical properties and crop yields in the right-of- way." *Soil Use and Management*, doi:10.1111/sum.12623.

Q. Please describe the available research on soil compaction from heavy machinery and its effects on soil health and crop yields.

A. Trafficking by heavy machinery when soil moisture levels are above a soil's plastic limit often results in compaction, poor soil structure, low crop productivity. Soil bulk density and cone penetration resistance typically increase, while soil water storage typically decreases. Consequently, crop root growth and crop uptake of water and nutrients are depressed, resulting in lower yields. Subsoil compaction due to heavy machinery operations is difficult to alleviate, even with deep tillage.

Q. Please describe the available research on the effects of pipeline construction in wet conditions and its effects on soil health and crop yields.

A. A soil's moisture holding capacity, drainage rate, and plastic limit are strongly affected by soil particle size distribution, commonly called soil texture. In general, clay soils and loam soils stay wetter for longer and have lower plastic limits than do sandy soils. When soil moisture content is above a soil's plastic limit, soil is readily compacted by machinery traffic and operations. When soil moisture content is below the plastic limit, a soil is relatively resistant to compaction and is friable, i.e., it crumbles and breaks into crumbs when squeezed. The amount of moisture that can be present without serious risk of compaction from machinery is greater for a sandy soil than for a high clay soil or a loam soil. Prevention of soil compaction is important for protecting crop yields.

Q. What soils are the most susceptible to compaction?

A. Soils that are relatively high in clay and silt particles are most susceptible to compaction.

Q. What seasonal conditions produce the most compaction?

A. Wet soil conditions in the spring and fall are associated with the highest risks of soil compaction from traffic by heavy machinery.

Q. How long do you expect soil compaction from this pipeline project to affect crop yields for farmers and landowners?

A. Based on the scientific literature I have read, I expect crop yields to be depressed on many farms for at least five years after completion of pipeline construction. Results of some studies indicate that crop yield reductions due to pipeline installation can persist for 10 or more years.

Q. What soil conditions are most appropriate for excavation and heavy machinery operation.

A. The appropriate timing and appropriate status of soil conditions for field traffic and operations by heavy equipment are strongly influenced by soil texture, i.e., the relative proportions of clay, silt, and sand particles. In general, fine textured soils (those with a high proportion of clays and fine silt particles) retain more moisture for a longer period than do coarse textured soils (those with a high proportion of sand particles). When soil moisture content is above a soil's plastic limit, soil is readily compacted by machinery traffic and operations. When soil moisture content is below the plastic limit, a soil is relatively resistant to compaction and is friable, i.e., it crumbles and breaks into crumbs when squeezed. A simple "ball test" can be used to assess a soil's moisture status with regard to susceptibility to compaction. A handful of soil is taken from the area that would be subject to machinery traffic and the handler tries to shape it into a ball. If it molds easily and sticks together, or if it can be squeezed into a long thread, the soil is too wet for machinery operations. If it crumbles readily, it is probably dry enough for field traffic, tillage, and heavy machinery operations..

Q. What are your recommended requirements for pipeline contractors during and after construction for avoiding soil compaction, crop damage, and yield loss?

A. Trafficking soon after a rainfall event can create irreversible soil compaction and long-term crop yield depression. The appropriate number of days to wait after rainfall should be determined by a soil ball test, described above, or other means of assessing soil physical conditions with regard to plasticity and friability. Topsoil should be separated from subsoil during removal and the two strata should be replaced carefully to prevent mixing.

Q. What type of rain event is significant enough to result in soil compaction and tile damage in and near the pipeline construction area?

A. Soil moisture status is a function of soil texture, which affects water retention, evaporation, drainage, and plasticity. Soil moisture is also affected by previous and current precipitation inputs. Thus, the effects of a single type of rain event are context dependent. Assessment of soil moisture status and plasticity should take place after any rainfall event and before possible commencement of any equipment operations.

Q. What amount or level of pre-existing soil moisture should result in a halt of construction activities?

A. Again, the level of soil moisture that defines a soil's plastic limit is strongly affected by soil texture and other factors. Construction activities should be conducted when soil tests indicate that a soil is friable, not plastic.

Q: Do you have any further statements you would like the PSC to consider?

A: Yes, **Attachment No. 4** is a transcript of the testimony I provided before the Iowa Utilities Board regarding the Summit project that I believe has relevance to proceedings in North Dakota.

Q: Are all of your statements and opinions rendered here, including in your Attachments, given to a reasonable degree of professional certainty and based upon your education, experience, background, and training?

A: Yes. I am competent to testify consistent with the above as necessary. I urge the PSC 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.

/s/ Dr. Matt Liebman

Dr. Matt Liebman

State of Iowa)

) ss.

County of Story)

I, Matt Liebman, being first duly sworn on oath, depose and state that I am the person identified in the above Pre-Filed Direct Testimony that I have caused to be prepared and I am familiar with the contents therein and competent to testify on these matters. My Pre-Filed Direct Testimony found in the foregoing pages is true and correct to the best of my knowledge.

Matt Liebman

Subscribed and sworn to before me, a Notary Public in and for said County and State this

13th day of May, 2024

NOTARIAL SEAL IOWA
AMANDA MATTHEWS
COMMISSION NUMBER 819237
MY COMMISSION EXPIRES
July 31 2025

Notary

Notary Public Commission expires: July 31 2025

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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 CO2 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 CO2 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 CO2 during ethanol production would have very minor effects on U.S. greenhouse gas (GHG) emissions. (3) The amount of CO2 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 CO2 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 CO2 captured at ethanol manufacturing plants and perhaps, later, other industrial facilities. The CO2 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 CO2, 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 CO2 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 CO2 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, CO2 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 CO2 emissions from a corn grain ethanol facility (Hornafius and Hornafius 2015). The gas stream emitted during fermentation is nearly pure CO2 and relatively easy to collect. Based on engineering and chemical analyses, 2853 metric tons of CO2 are produced per million gallons of ethanol generated from corn grain (Hornafius and Hornafius 2015). Not all that CO2 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 CO2 that could be captured and prevented from entering the atmosphere. For Iowa, that would translate to about 12.8 million metric tons of CO2. (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 CO2 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 El0 (i.e., 10% ethanol) being the most common version available at a filling station. Combustion of a gallon of El0 in a vehicle engine results in the release of 19.0 pounds of CO2 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 El0, which would have resulted in the release into the atmosphere of 1.06 billion metric tons of CO2. ***Thus, for the U.S., tailpipe emissions from using El0 in 2020 were almost 25 times greater than the 43 million metric tons of CO2 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, ***CO2 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 CO2 in 2020. Total CO2 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, CO2 emissions from the U.S. transportation sector would be 37 times greater than what might be captured at ethanol plants, while CO2 emissions from the whole U.S. economy would be 110 times greater. ***Thus, the process of capturing CO2 at ethanol plants, transporting it by pipelines through Iowa and other states, and storing it underground would have trivial effects on our nation's CO2 emissions.***

Given the damage to Iowa farmland soils and crop yields and the absence of substantial environmental benefits to the Iowa public associated with CO2 pipelines, we strongly oppose the use of eminent domain to facilitate construction of these pipelines by private companies in

Iowa. Issuance of permits for CO2 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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REVIEW

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

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Assigned to Associate Editor Joshua McGrath.

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

	No. of studies				Mean percentage	
Property	Total	Increase	No change	Decrease	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.

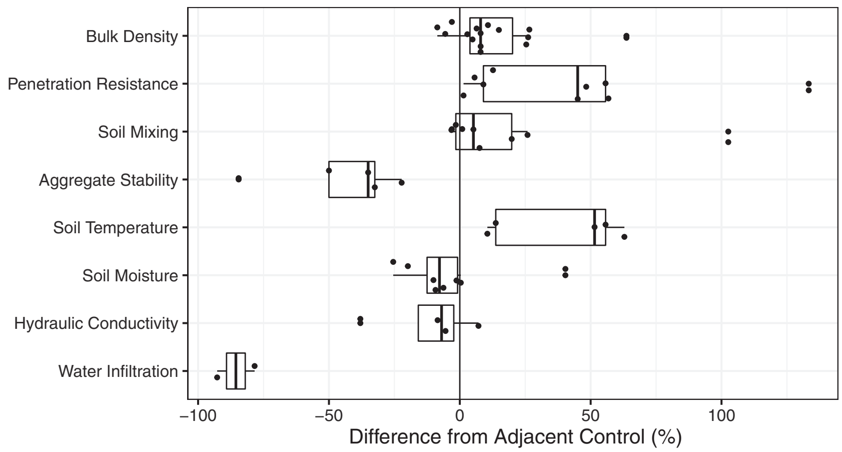

FIGURE 1 Percentage difference values for select soil physical properties between right-of-way vs. adjacent, unaffected areas. Points represent mean percentage difference of each study with boxplots representing the distribution of values. Positive and negative values indicate a respective increase or 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				Mean percentage change (range)	Citations
	Total	Increase	No change	Decrease		
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

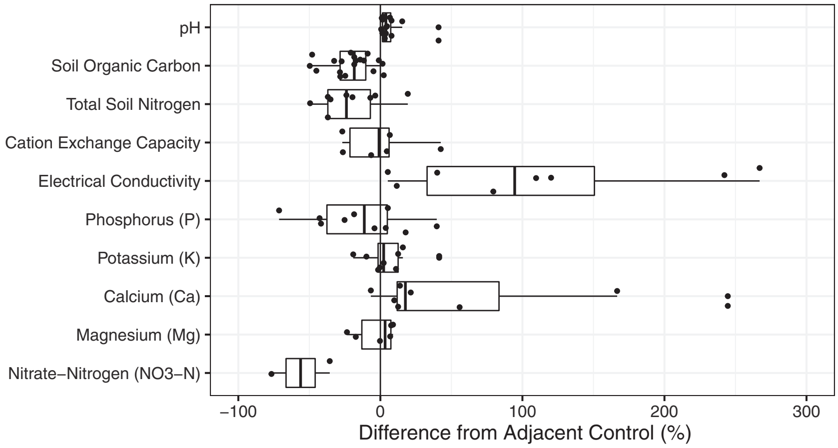

FIGURE 2 Percentage difference values for select soil chemical properties between right-of-way vs. adjacent, unaffected areas. Points represent mean percent difference of each study with boxplots representing the distribution of values. Positive and negative values indicate a respective increase or in 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.

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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

		No. of studies				Mean percentage	
Ecosystem type	**Plant community**	**Total**	**Increase**	**No change**	**Decrease**	**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.

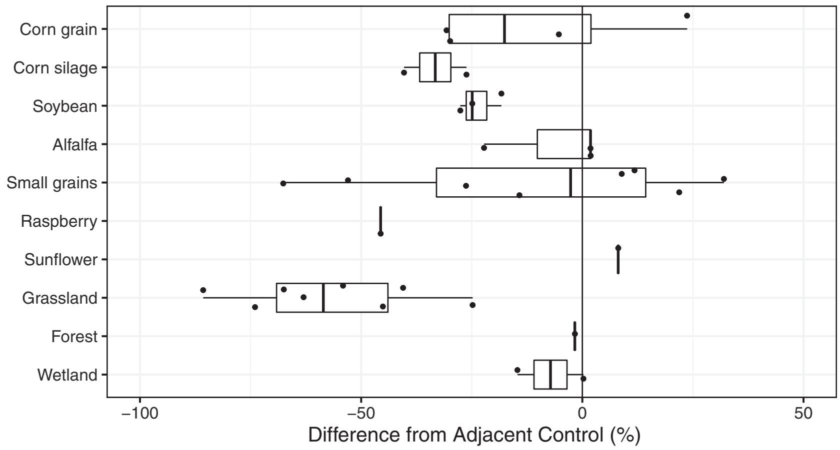

FIGURE 3 Percentage difference values for vegetative yields between right-of-way (ROW) vs. adjacent, unaffected areas (ADJ). Percentage differences were calculated with each study's paired replicate with the point representing the mean of each study's paired replicate with the point representing the 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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Soil degradation and crop yield declines persist 5 years after pipeline installations

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Abstract

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

1 INTRODUCTION

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

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

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

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

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

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

Core Ideas

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

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

2 MATERIALS AND METHODS

2.1 Site description

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

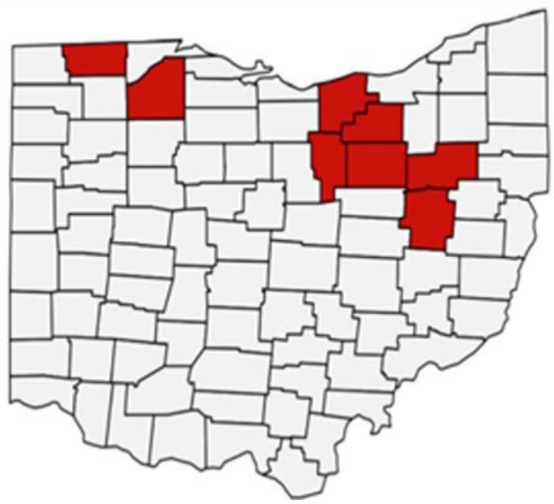

FIGURE 1 A map of Ohio with counties highlighted in red where sampling occurred for this study in 2020 and 2021

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

Final field sites were selected to represent diverse geographic locations, soil types, and topographies. Mean annual temperature for this region is ~ I 0°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.) Men-.] 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**	**Year2**	**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	Aguie Fragiudalfs	Yes
Site 5	Medina	Nexus	Corn silage	Not sampled	Oshtemo	Typic Hapludalfs	Yes
Site 6	Wayne	Utopia	Corn	Soybeans	Canfield	Aguie Fragiudalfs	Yes
Site 7	Wood	Nexus	Soybeans	Not sampled	Hoytville	Mollie Epiagualfs	Yes
Site 8	Wayne	Rover	Soybeans	Corn	Wooster Riddles	Typic Hapludalfs	Yes
Site9	Wayne	Utopia	Corn	Not sampled	Canfield	Aguie Fragiudalfs	Yes
Site 10	Lorain	Nexus	Corn	Not sampled	Chili	Typic Hapludalfs	Yes
Site 11	Lorain	Nexus	Not sampled	Soybeans	Mahoning	Aerie Epiagualfs	Yes
Site 12	Lorain	Nexus	Soybeans	Corn	Mahoning	Aerie Epiagualfs	Yes
Site 13	Lorain	Nexus	Soybeans	Not sampled	Mahoning	Aerie Epiagualfs	Yes
Site 14	Wayne	Rover	Corn	Corn	Luray	Typic Argiaguolls	Yes
Site 15	Wayne	Utopia	Corn	Soybeans	Fitchville	Aerie Endoagualfs	Yes
Site 16	Stark	Rover	Soybeans	Not sampled	Seabring	Typie Endoagualfs	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	Aerie Ochragualfs	Yes
Site 22	Ashland	Rover	Corn	Soybeans	Bogart	Aguie Hapludalfs	Yes
Site 23	Wayne	Utopia	Corn	Soybeans	Ravenna	Aerie Fragiagualfs	Yes
Site 24	Fulton	Rover	Not sampled	Corn	Colwood	Typic Haplaguolls	No
Site 25	Fulton	Rover	Not sampled	Soybeans	Kibbie	Aguollic Hapludalfs	No
Site 26	Fulton	Rover	Not sampled	Corn	Millgrove	Typic Argiaguolls	No
Site 27	Fulton	Rover	Not sampled	Corn	Gilford	Typic Haplaguolls	No
Site 28	Fulton	Rover	Not sampled	Soybeans	Granby	Typic Haplaguolls	No
Site 29	Fulton	Rover	Not sampled	Corn	Sloan	Fluvaguentic Haplaguolls	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, RS 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 Oto 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
	Kinder Morgan	[illegible]					[illegible]	[illegible]
	DTE Energy and Enbridge, Inc.	[illegible]					[illegible]	[illegible]

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.

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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 x *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):

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

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 Sl). Within the ROW, PR increased an average of 15.3% (ranged -39.3% to 77.0%) between O 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 O 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 O 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 x Trt
Penetration resistance (MPa)					
0-10 cm	2.6 (0.1)	2.3 (0.1)	12.0***	23.0****	3.5[illegible]
10-20cm	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)	[illegible]	22.4[illegible]	1.5
Texture (g kg^{-1})					
Clay	201.6 (8.6)	176.6 (6.9)	20.9[illegible]	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.[illegible]**
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.[illegible]	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

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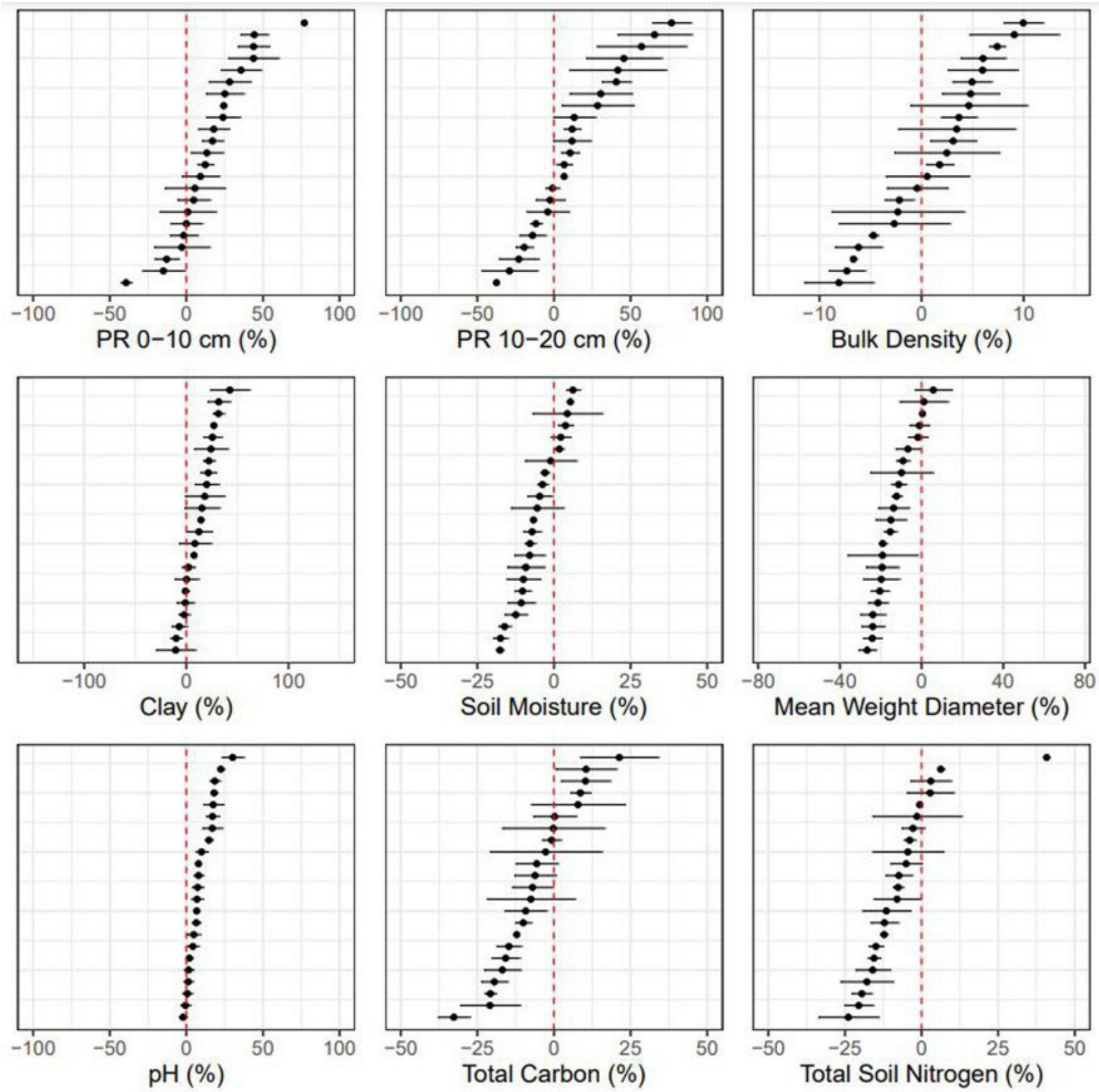

FIGURE 2 Average percent difference values for select soil properties between right-of-way (ROW) versus adjacent, unaffected areas (control, ADJ) across 23 sites. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing 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 of0--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 of0.8 cmolc 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).

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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 x Trt**
Soil pH	6.7 (0.1)	6.1 (0.1)	110.0·•··1....,.	15.8****	3.3**'1":'
OM (g kg^{-1})	19.6 (0.7)	20.2 (0.7)	1.4	14.1****	1.6
CEC (cmolc 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 x 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 (Mgha l)	Year	ROW	ADJ	Trt	Site	Site x 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 O.OOL.
****Significance reported as 0.0001.

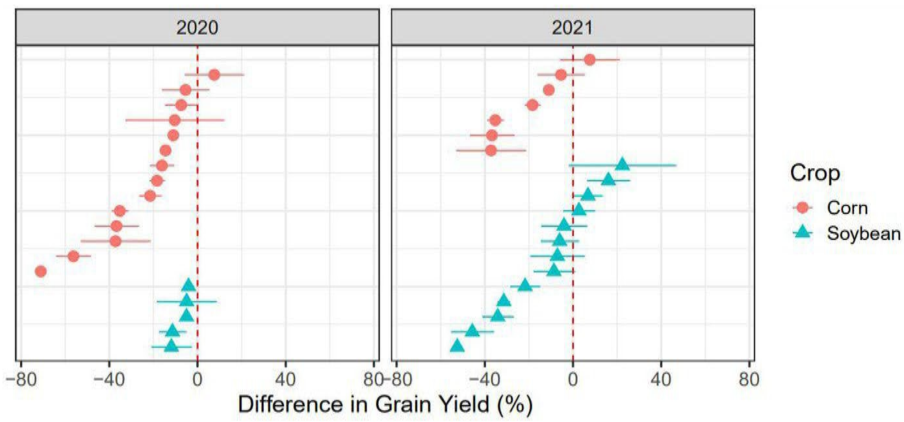

FIGURE 3 Average percent difference in crop yields in 2020 and 2021 between right-of-way (ROW) and adjacent (control, ADJ) sampling areas. Percent differences were calculated on each paired replicate with the point representing the mean of each site and error bars representing the standard error among 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; Zeg-eye 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 of0.61 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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THE WITNESS: All right. Is this good?

BOARD CHAIR HELLAND: You're doing great. Go ahead and raise your right hand.

MATT LIEBMAN,

called as a witness by the Counties, being first duly sworn by Board Chair Helland, was examined and testified as follows:

BOARD CHAIR HELLAND: Thank you.

Mr. Whipple.

DIRECT EXAMINATION

BY MR. WHIPPLE:

Q. Are you the same Matt Liebman who caused direct testimony and Exhibits 1 and 2 to be filed in this matter on July 24, 2023, and surrebuttal testimony to be filed on September 1, 2023?

A. I am.

Q. Do you affirm that testimony as if you were asked the same questions here today?

A. I do --

BOARD CHAIR HELLAND: Hold on. We'll have our technical folks help us out here.

A. I do affirm.

MR. WHIPPLE: Are we working? Should I keep going?

BOARD CHAIR HELLAND: It's working. We'll have a mic here on hand as a backup. It looks like it's working now.

BY MR. WHIPPLE:

Q. Do you have any additions or corrections to make to that testimony?

A. Not at the present time.

MR. WHIPPLE: In that case, Your Honor, I move the testimony and exhibits sponsored by Dr. Liebman.

(Liebman Direct Exhibits 1 and 2 were offered into evidence.)

BOARD CHAIR HELLAND: Is there objection?

MR. LEONARD: Yes, Your Honor. We object to the admissibility of the surrebuttal.

The Board doesn't allow for surrebuttal testimony, and it's traditional for this Board or, frankly, before any Court that the applicant would be the party that gets the last word.

Surrebuttal testimony filed after our deadline for our rebuttal testimony gives the Counties the last word on this subject, so we would object to the admissibility of the prefiled surrebuttal testimony.

MR. WHIPPLE: May I respond, Your Honor?

BOARD CHAIR HELLAND: Yes. Go ahead,

please.

MR. WHIPPLE: Your Honor, Dr. Liebman's surrebuttal is directed at the testimony of Mr. DeJoia, who was not identified in direct testimony and whom, under the Board's procedural order, the Counties did not have any opportunity to do any direct examination of Dr. Liebman with regard to.

And so rather than at hearing request latitude on direct examination, the Counties thought it more fair to identify and file ahead of time in written form so that Summit could see the rebuttal testimony of Dr. Liebman, and then they had the opportunity, then, when they called Mr. DeJoia to have Mr. DeJoia respond to anything that Mr. Liebman had in his surrebuttal.

So we, for that reason, request the Board to accept the surrebuttal of Dr. Liebman.

BOARD CHAIR HELLAND: Mr. Long?

MR. LONG: OCA strongly supports admission of Mr. Liebman's surrebuttal. While -- Even if Summit is to get the last word, the other parties need to be given an opportunity to respond to things, and as Mr. Whipple pointed out, Mr. Liebman's surrebuttal testimony is in response to the testimony of -- the rebuttal testimony of a witness who had not addressed the topic or even filed direct testimony.

The Board has the authority to provide for efficient proceedings, and I believe that the way Mr. Whipple and the Counties handled this is appropriate because by prefiling it, they largely took away any element of surprise to Summit.

The alternative would be for them to do additional direct, in which case Summit wouldn't have even had the benefit of reading and knowing in advance what was going to happen.

BOARD CHAIR HELLAND: Okay. Thank you.

The objection is noted. The Board will admit the evidence and give it the weight due.

(Liebman Direct Exhibits 1 and 2 were admitted into evidence.)

MR. WHIPPLE: Your Honor, just for clarification, you are granting admission of all of the testimony and exhibits of Mr. Liebman?

BOARD CHAIR HELLAND: Correct.

MR. WHIPPLE: In which we tender Dr. Liebman for cross-examination, Your Honor.

BOARD CHAIR HELLAND: Just to clarify, Mr. Long, do you have a comment on the objection, or did you want to go first?

MR. LONG: When called on, I would like to participate in the cross-examination.

BOARD CHAIR HELLAND: It looks like you're first.

MR. LONG: Thank you. I do have something I would like to introduce at the hearing. If I have to separately file it as a hearing exhibit, I will.

I note that it was previously filed as Affidavit of Mehari Tekeste, Ph.D. -- I hope I pronounce the name correctly -- filed by Kristi Harschbarger on behalf of the Iowa Association of Counties on August 3rd.

So I have paper copies to distribute, and I would like to ask the witness about this. While we're getting ready for that, I'm also going to be asking the witness about OCA Hearing Exhibit 4, which was introduced and moved into the record yesterday, and we filed it.

Well, I'm not sure if it's actually come through yet, but it was the response to OCA Data Request No. 69. I believe it was introduced into the record yesterday as OCA Hearing Exhibit 4.

(Brief pause.)

MR. LONG: And I would also ask, if it's appropriate at this time, for a point of order about how I should handle this. I would like to actually get this affidavit admitted into the record.

Does that mean I need to move it as an OCA hearing exhibit, or can I simply refer to it in the EFS record, since it's already been filed, and ask that it be officially admitted in the record in this case?

BOARD CHAIR HELLAND: A motion would be preferable.

MR. LONG: I will treat it as a hearing exhibit, then. I'm going to discuss it with the witness, but I offer it as OCA Hearing Exhibit 5.

CROSS-EXAMINATION

BY MR. LONG:

Q. Does this witness have this affidavit?
A. From Dr. Tekeste?
Q. Yes.
A. Yes, in front of me here. I've read it previously.
Q. I was just going to ask: Have you read this?
A. I have.
Q. Can you tell us -- Okay.

MR. LONG: I would now like to move introduction of this affidavit as OCA Hearing Exhibit No. 5.

(OCA Hearing Exhibit 5 was offered into evidence.)

BOARD CHAIR HELLAND: Objections?

MR. LEONARD: Object to foundation and hearsay. It's the affidavit of somebody who is not here.

BOARD CHAIR HELLAND: Thank you.

Mr. Meyer, did you have an objection?

MR. MEYER: No.

BOARD CHAIR HELLAND: You're all right. Just double-checking.

The Board will admit OCA Hearing Exhibit 5 and give it the weight due.

(OCA Hearing Exhibit 5 was admitted into evidence.)

BY MR. LONG:

Q. Mr. Liebman, have you reviewed this?

A. Have I?

Q. Have you reviewed this affidavit? Maybe I already asked you that.

A. From Dr. Tekeste?

Q. Yes.

A. Yes, I have.

Q. And can you tell us how it informs or relates to your prefiled testimony, including the surrebuttal?

A. Sure. What this document puts forward is the results of -- can we hear? Yeah. The results of laboratory tests where soil samples were brought inside, and the period of time required for them to drain to a moisture content where they could support field traffic without damaging soil structure was determined, and based on these laboratory tests inside, Dr. Tekeste recommended that a period of three days after rainfall would be appropriate to wait before resuming field operations.

And I would just point out that this is a laboratory study and that moisture conditions in the field, as affected by temperature and other factors, can be quite different than standardized conditions in the indoor laboratory.

Q. For construction of this pipeline, do you think that a laboratory test is going to be helpful to the county inspector who will be on the scene and making decisions about construction activity?

A. I think it might provide a general guideline, but in terms of making a decision about whether or not to move ahead with construction activities on any given day on any given site with different soil conditions of sand versus silt versus clay, I think the inspector needs to be able to make a determination on-site at that time.

Q. And is that why you recommended the -- I believe it's called the ball test in your prefiled testimony?

A. Yes, it was. So the recommendation of using the ball test is from two agricultural soil scientists who are very well known, Harold Ennis and Frederick Magdoff, who have written extensively on the relationship between soil quality and crop productivity, and what they were referring to was a test that farmers and others under field conditions could rapidly determine whether soil was too wet to work with. In other words, it could be compacted, and the long-term productivity of that soil would be reduced by the presence of heavy agricultural machinery or construction machinery.

So that ball test, which basically involves taking a small, golf ball-size amount of soil in your hand and squeezing it and seeing if it forms a ribbon, is a way of determining whether the soil is sticky and, therefore, too wet to support heavy traffic, or if it's friable and comes apart and it's dry enough and has the structure necessary to support heavy machinery. So that's why I recommended the ball test.

There are other things that have been recommended. One is called the ribbon test, which is very similar to the ball test, and there are other instruments that could be used, but my concern about using instruments is that the time necessary to determine soil conditions relative to proceeding with field operations might be protracted, right?

If an inspector is on-site, they need a test that allows them to make a rapid determination if soil conditions are appropriate for the presence of machinery.

Q. I'd like to clarify your opinion on that. So are you saying that it's your opinion that other field tests, including field tests using special testing equipment, might require a waiting period or some other time for the test to be performed?

A. It would depend on the equipment and the particular procedure being used, but I guess my criterion, as an agronomist, is: Can we make a determination about the suitability of field conditions based on --

BOARD CHAIR HELLAND: Hold on.

A. -- measurements that we can make in the field.

BOARD CHAIR HELLAND: The court reporter

got it, which is good, but I'm not sure the online stream picked it up. So let's swap out your mic again.

A. The point I was trying to make is that I think, as an agronomist, my concern is about protecting the long-term productivity of soil and preventing nearly irreversible compaction due to the presence of heavy machinery under unsuitably wet conditions.

So to the extent that we can rapidly determine the soil condition and make a decision about moving forward with field operations, be it farming or pipeline construction, I think the criterion has to protect soil by making a rapid on-site determination.

BY MR. LONG:

Q. Thank you. Now, I may be referring to OCA Hearing Exhibit 4, which was introduced yesterday when OCA's witness, Scott Bents, was testifying on the stand.

Did you observe the cross-examination of Mr. Bents yesterday?

A. I was here, yes.

Q. Do you recall that there was a discussion in which Mr. Bents suggested that perhaps the ball test you proposed should be -- Let me rephrase. In which Mr. Bents suggested that perhaps the test should be split up such that the ball test you proposed should be used to make a decision about whether to begin construction on a particular site and open a parcel, and that perhaps a more lenient standard, including potentially the 30 percent standing water standard suggested by Mr. DeJoia and referenced in OCA Hearing Exhibit 4, should be used once the trench has been opened to determine whether construction should continue?

Do you recall that discussion?

A. Thank you for reminding me. As an agronomist, I've had personal experience with soil compaction and its reduction of crop yields, and I believe that if 30 percent of the subsurface soil was covered with water, it would be too wet to proceed with field work.

Q. Understood. I believe Summit's -- I believe it -- Well, I'm not going to speak for Summit's witness, but my question to you is: Do you believe it would be appropriate to break up the test that the inspector should use like Mr. Bents suggested?

What I mean is: Should there be one perhaps stricter test when you're deciding whether to open a trench on a parcel you haven't gotten to yet, and should there be another more relaxed test when you're deciding whether to halt construction because of wet conditions on a parcel that already has a trench open?

A. From the standpoint of protecting long-term soil productivity, subsoil is much more difficult to remediate once it's compacted than topsoil. So, if anything, the standard should be more conservative for the subsoil than for the surface soil.

Deep ripping of subsoil after it's been compacted has been repeatedly shown to be insufficient to restore the productivity of the soil. So with regard to different tests for the surface soil and the subsoil, I would say I would be at least as conservative for the subsoil and perhaps more conservative than with topsoil, which is easier to remediate.

MR. LONG: Okay. Thank you. Those are my only questions for this witness.

BOARD CHAIR HELLAND: Mr. Meyer?

CROSS-EXAMINATION

BY MR. MEYER:

Q. Dr. Liebman, do you have an opinion as to whether this project will be irreversibly detrimental to Iowa crop production in terms of soil capacity?

A. Yeah, I do have an opinion based on work that was done at Iowa State University when the Dakota Access pipeline was constructed, and the effects on soils and crop productivity were followed for five years, and then work done by two scientists at Ohio State University looking at 29 sites where three different pipeline companies had construction activities across corn and soybean fields.

Based on those studies, it would appear that the use of best management practices for pipeline construction as they exist today, which I understand to be what's called double-lift -- separating topsoil from subsoil when the pipeline is installed, and then using deep tillage on subsoil following pipeline installation -- the adjacent areas are ripped with heavy agricultural machinery to loosen the subsoil. Those procedures are insufficient to overcome yield reductions for a period of at least five years.

So I think all the literature I've looked at has indicated that it's very difficult to remediate compaction of subsoil, even with deep ripping. Stirring the soil up with heavy agricultural machinery to break up compaction is not sufficient to return the depth of the rooting zone to what it is in undisturbed, non-pipeline areas.

So at least for five years following construction -- and some older literature would indicate for decades following pipeline construction -- you can see a reduction in crop yield that can be related to subsoil compaction, loss of porosity in the soil, which impedes the growth of roots, which is particularly important in dry years, and roots are part of the plant that need to respire. So access to soil pores that contain oxygen is actually a way to make healthy crop plants, and when you compress soil, that porosity is lost, and root function is reduced.

So typically what we see in studies that have been done in Iowa, Ohio and other parts of the world is that crop yields are reduced on the order of 10 to 30 percent for at least five years following pipeline construction.

Q. And then you had referenced some longer term, decades, perhaps. Is there any way to quantify that loss?

MR. LEONARD: Objection.

BOARD CHAIR HELLAND: State your objection.

MR. LEONARD: Back to friendly cross. This is not cross-examination. It's direct examination.

The first question was, in fact, direct examination. It asked an expert witness if he had an expert witness opinion in this matter, which, of course, is included in his prefiled direct testimony.

This particular witness also was given latitude to file surrebuttal testimony, so having Mr. Meyer question Mr. Whipple's witness about topics which are already addressed in his direct testimony is not cross-examination. It's repetitive, and it should not be permitted.

BOARD CHAIR HELLAND: Mr. Meyer, do you have a response, or Mr. Whipple, whomever?

MR. MEYER: Your Honor, I'll take a run at it first. I'm just asking him to clarify an answer that he's given to a previous question.

BOARD CHAIR HELLAND: Mr. Whipple?

MR. WHIPPLE: Your Honor, I'm reminded about the admonition of friendly cross the Board admonished at the beginning of the hearing. I believe at this point we're not engaged in duplicative testimony, and I think at this point Mr. Meyer's questions are adding value to the record and not slowing down the hearing or being repetitive.

So to the extent that is the Board's determination about friendly cross, I think we haven't crossed that line at this point.

BOARD CHAIR HELLAND: Mr. Meyer, if you need to make a clarification, please make it brief and move to testimony not already -- or questions not already covered. We do need to limit friendly cross, and we will be limiting friendly cross.

MR. MEYER: Your Honor, this is my last question.

BY MR. MEYER:

Q. So you talked about loss over a five-year period. Ten to 30 percent, I believe, is what you said.

Any way to quantify or qualify over the decades that you've seen studies show that there will be a residual loss for that length of time?

A. I don't think we know how long the losses due to compaction will occur, given best management practices that have been in place for a relatively short amount of time. Double-lifting, separating topsoil and subsoil, and deep ripping, those are relatively new practices maybe within the last decade, so the long-term studies following those kinds of practices have not collected the data that would allow us to project into the future.

Older studies where those type of

double-lift practices and deep soil ripping were not necessarily in place would indicate that compaction limits yields for in some cases more than one or two decades, but we don't have data yet on current engineering, procurement and construction management remediation programs for pipeline construction to make a projection about what would happen to crop productivity.

MR. MEYER: Thank you. I pass the witness.

BOARD CHAIR HELLAND: Thank you.

Ms. Gruenhagen?

MS. GRUENHAGEN: Thank you, Your Honor.

CROSS-EXAMINATION

BY MS. GRUENHAGEN:

Q. I've crossed off quite a few of my questions here, but I do have a few left.

You talk about the difference between clay and sandy soil. Where -- Are you familiar with the proposed pipeline route?

A. Not the specifics.

Q. Then I'll just ask you more generally. Where in the state is clay soil more predominant?

A. Certainly in the north-central portion of the state has silty clay loam, heavier textured soils on the Des Moines loam from, say, Minnesota, down to

Des Moines in the central portion of the state.

When you move to the western portion of the state, there are more loess soils, wind-blown silts, which have a different texture than heavier central/ north-central Iowa soils.

So the extreme southern part of the state has quite heavy clay along the Missouri border.

Q. On page, 7, line 3 of your direct testimony, you talk about soil compaction caused by heavy machinery and heavy equipment. Would you have the same concerns with foot traffic in the easement?

A. With foot traffic?

Q. Yes.

A. Foot traffic can compact soil, but typically, you know, pipelines are not being constructed by people with shovels. They're being done with people using large excavating equipment and soil-moving trucks and that sort of thing.

Q. Would you have concern with a vehicle like the size of an ATV running along that easement during the wet conditions?

A. Any kind of vehicle of sufficient weight and narrow enough tires can do quite a bit of damage to soil through compaction. So it's a question of not just the mass, weight of the vehicle but the

distribution of weight on its tires.
That's why when you see big, heavy machinery, it's typically with double-wides or larger Caterpillar treads to distribute the load.
Q. Would you have the same concern with a pickup truck; like, a one-ton pickup truck with soil compaction?
A. You can do damage to soil structure with a pickup truck, but the amount of damage is probably less than very heavy machinery under wet soil conditions.
Q. So if there were construction activities that would only necessitate those smaller kind of vehicles and the weight was distributed properly on the tires, would you have the same concerns about soil compaction?
A. I'd have to know the axle loads and figure out how much -- how many pounds per square inch were being exerted on the soil.
Small tractors can do quite a bit of damage, if they have narrow tires. It's really a physical function of how you distribute the load on the soil surface.
Q. Okay. And you said you reviewed the Ag Impact Mitigation Plan?

A. Can you repeat that?
Q. I believe you testified you have reviewed the Ag Impact Mitigation Plan that Summit has proposed?
A. Yes, I have read that.
Q. Okay. Do you recall the part of the plan that talks about removing the topsoil and allowing construction to continue in the subsoil?
A. Yes, and specifically in reference to the amount of water on the right-of-way.
Is that what you're referring to?
Q. It's with regard to wet conditions and allowing the -- allowing construction to continue if the topsoil has been stripped off and stockpiled.
A. Right. Yeah, I would say, as an agronomist, the subsoil is more vulnerable to degradation by machinery. So I would be very hesitant to recommend going ahead with all kinds of potentially compacting activities when the subsoil is exposed.
Again, it's very difficult to remediate compaction in subsoil. It's easier to remediate compaction in topsoil.
So I'm concerned that proceeding with field operations, when soil is too wet to sustain heavy loads without being compacted, would lead to subsoil

degradation.
Q. So the concerns you've expressed about constructing in wet conditions extends to the subsoil as well?
A. Yes.
Q. Okay. I believe it was Mr. DeJoia who testified about using cover crops in the easement area to help it recover. Do you see that as one way to help that soil recover?
A. It's definitely a good thing to do. I don't think that you can relieve subsoil compaction with cover-cropping to a sufficient degree to return corn and soybean production to the level it was before the soil was disturbed by the pipeline construction.
Q. You talked about deep ripping already. We just talked about cover crops.
Is there anything that you would recommend to help reduce compaction?
A. So the agronomic view of compaction is it's better to avoid compaction than try to remediate it. The single most important thing, with regard to avoiding compaction, is not working in excessively wet field conditions.
Q. Thank you. And then we talked about the ball test, and you said it's a more rapid test. How

long does it take to conduct a ball test?

A. As long as it takes to take a handful of soil, form it into a small ball and press it between your thumb and forefinger to see if it sticks together as it's extended or if it falls apart and is friable.

Q. If there's a 40-acre parcel, would you think -- I guess, would you recommend that there be repetitions of that test across that parcel?

A. Sure, particularly if there's a slope and what they call a catena of soils. Typically what you find on the slope and what's at the bottom of the slope differs in soil texture than what's at the mid-slope or upper-slope positions.

So as you're walking across a field, if you sense that some areas are sandier and some areas are heavier than others, it would be good to test in the same way as when you do a soil test to determine fertility conditions. You want to make sure you take an adequate sample of the variation within the field.

Q. If I'm understanding you correctly, if it looks like the soil types are different across the field, you would need to repeat that ball test?

A. Absolutely, yes, and I think farmers have a good idea of that by looking at their soil maps.

Virtually every farm is now, you know, clear about what soil types are present across fields, and people make adjustments in their field operations in fertility and other matters based on variations in soil within a field.

MS. GRUENHAGEN: Thank you. That's all the questions I have.

BOARD CHAIR HELLAND: Thank you.

Mr. Jorde?

MR. JORDE: Yes. Thank you.

CROSS-EXAMINATION

BY MR. JORDE:

Q. Doctor, you used the phrase -- I think it was, like, "extremely wet conditions," and are you saying that the ball test is the most appropriate test to determine if they're extremely wet, or is there, for instance, I mean, if X amount of rainfall, then construction shouldn't happen?

How do you go about determining that?

A. Okay. So a number of things determine the moisture status of the soil. One of them is the amount of rainfall and how long ago it occurred, and another thing is the texture of the soil.

So by "texture" I mean how much of it is sand, which is relatively coarse and drains quickly;

how much is silt and clay, which are finer soil particles and drain more slowly. Then, of course, there's slope and a whole variety of other things including temperature, which would influence evaporation of moisture from the soil surface.

So there is no universal recommendation about when soil is ready for machinery operations to recommence or to begin to begin. What I'm recommending is something that is relatively rapid so that farmers or inspectors on-site could make a determination of whether it's too wet to proceed or whether we can go ahead.

And I think those are -- that determination is contextual on the soil type, on the recent rainfall history, the topography, and if you don't have something that you can make a rapid determination in the field about whether to go ahead or not, I think it's a problem.

Q. But would you agree that there's certain conditions of wet soil, I mean, like pooling of water, where it's obvious that construction is maybe not wise or shouldn't happen? Are you stating that the ball test should be kind of the definitive test to determine that?

A. I don't know if it should be the definitive test or not. I think it's a useful way of determining whether soil conditions are appropriate for the passage of heavy machinery over the ground, and I fully recognize that there could be other means of determining soil conditions with regard to their suitability for the field operations in pipeline construction.

All I'm suggesting is that it would behoove the farmer, who is going to work with the field later, to avoid compaction, and to the extent that an inspector or a pipeline constructor can rapidly determine whether soil conditions are appropriate or not, I think the ball test is one way to go.

Q. Is there a universal depth of topsoil? When we say "topsoil" -- that term is used a lot -- I mean, can you give me -- is that 1 inch, 2 inches, 6 inches? What is the topsoil?

A. For our purposes today, I'll say the top 8 to 10 inches, but the technical definition of the O and A horizons would indicate that the so-called topsoil would vary depending on the soil series and the local erosion conditions.

Q. And then the subsoil, how deep typically is subsoil?

A. Well, in Iowa it can be extremely deep.

You go out to the loess hills, it's maybe tens of feet thick. On the Des Moines loam, you know, it could be 4 to 6 feet.

Q. Did you say loess hills?

A. The western portion of Iowa.

Q. Did you say "west" or "loess"?

A. Loess.

Q. How do you spell that?

A. L-o-e-s-s.

Q. You mentioned Dakota Access. Have you reviewed any of the photographs and kind of the working in wet conditions that was going on in Dakota Access?

A. Just anecdotally. The documents I referred to were several scientific publications by scientists at Iowa State University who had been contracted to look at the effects on soil and crop productivity following construction of the Dakota Access pipeline on Iowa State University land, and they've had three or four publications that I've looked at.

They had some photographs of the actual pipeline construction there. They diagrammed the right-of-way for the pipeline and divided it into different zones where there was about a 15-foot area where the pipeline was being directly inserted, and then there were adjacent areas where heavy machinery was passing, where soil was piled up, and that general right-of-way was on the order of 125 to 150 feet wide.

MR. JORDE: Can I have staff please pull up Exhibit 579 and go to page 49 of that?

(Brief pause.)

BY MR. JORDE:

Q. Sir, would you agree that although there might be a ball test or field test that you can actually do, when confronted with situations like -- where it's so obvious where water is pooling and there's standing water that a ball test might not necessarily be necessary?

A. That would be my opinion.

Q. Okay. So you would agree that visual inspection of essentially the obvious, such as shown in this photograph here, that -- I mean, would you say the inspector should be given the power to be able to make construction decisions regardless of whether or not they use a ball test in conditions like this?

A. If the criterion is large amounts of standing water, yes.

MR. JORDE: Okay. All right. Thank you. I don't have anything further, Doctor.

BOARD CHAIR HELLAND: Mr. Leonard, and then

Mr. Taylor.

CROSS-EXAMINATION

BY MR. LEONARD:

Q. Just a brief couple of questions, Dr. Liebman.

You mentioned a couple times some work Iowa State did with respect to the reclamation process for the Dakota Access pipeline; is that right?

A. Yes.

Q. Is it your understanding that the Dakota Access pipeline is a 30-inch diameter crude oil pipeline?

A. Yeah. I don't think the remediation practices have any relationship with the diameter of the pipe.

Q. Okay. Do you think that the size of the trench, both in terms of the width and depth, may be different for a 30-inch pipe as opposed to, for example, a 6-inch pipe?

A. So the burial of the Dakota Access pipeline, if I recall correctly from Dr. Tekeste's paper, was on the order of about 4 feet.

Q. Correct. To the top?

A. And this pipeline that Summit has proposed is near 4 feet, correct.

Q. Correct. How deep do you want to dig a trench for a 30-inch pipe to be 4 feet deep to the top of the pipe?

A. Four feet plus 30 inches.

Q. Okay. Now let's do the same thing with a 6-inch pipe.

Four feet plus 6 inches?

A. Okay.

Q. So my question is: Is it fair to assume that digging a trench for a 30-inch pipe, that trench may have to be wider and deeper, for instance, than for a 6-inch pipe?

A. Okay. So I mentioned before that in the study done at Iowa State University, they looked at the entire right-of-way zone; not just in the trench that was about 15-feet wide, but in the adjacent areas that added about another 60 feet on either side. Those adjacent areas showed reduction in the same yield due to compaction that were nearly equivalent to the zone where the pipeline was inserted.

So a 15-foot zone where the pipeline was buried, whether it was 4 feet plus 30 inches or something less than that, gave reductions in yield that were very similar to the areas where heavy machinery was moving alongside that trench or soil was

being stacked and then moved around.
So the point is: I'm not sure that the trench depth is anywhere near as important as the movement of heavy machinery adjacent to that trench.
Q. I understand your answer, and my next question is: Is it possible that the equipment needed to dig a trench for a 6-inch pipeline might be lighter than that needed to dig a trench for a 30-inch pipeline?
A. I'm not a construction engineer, so I can't answer that.
MR. LEONARD: Okay. No further questions.
BOARD CHAIR HELLAND: Thank you.
Mr. Taylor?
MR. TAYLOR: Thank you.

CROSS-EXAMINATION

BY MR. TAYLOR:
Q. I went to Iowa State University, but I never took any agronomy courses, so help me out here.
Back in the Dakota Access case, I thought the understanding was that the topsoil was more important for productivity than the subsoil, and that's why the topsoil had to be carefully separated from the subsoil. Can you clarify that for me?
A. Okay. I'll try. So topsoil has certain

characteristics. Like, it has more organic matter than subsoil. Topsoil provides much of the fertility to crops.

Topsoil is very important for providing a medium for rainfall to infiltrate into the soil. If it's abused and you get a lot of runoff, you get potentially flooding and some erosion. Topsoil has more microbial activity, which cycles nutrients and also protects crop roots from diseases.

Subsoil is very important with regard to rooting depth. Roots explore soil. As topsoil dries out, they go deeper to look for moisture. They grow to greater depths.

If they're impeded because of compaction or because the soil just isn't that deep before you hit bedrock, the amount of moisture available to the crop is limited relative to a soil profile, which is easily penetrated by roots because it hasn't been compacted.

In a wet year, it may not matter too much. In a dry year where roots become more reliant on exploring the subsoil to take up needed moisture, you can see marked effects of soil compaction on crop productivity.

MR. TAYLOR: Thank you. That's all the questions I have.

BOARD CHAIR HELLAND: Thank you.

Any questions from the Board?

BOARD MEMBER MARTZ: Dr. Liebman, you said earlier that you would be even more conservative with the subsoil conditions versus topsoil with regards to work during wet conditions. Earlier we heard from Mr. DeJoia in his testimony here, and he stated that his concern was more the topsoil and getting it back onto the ground as quickly as possible due to concerns about its structure and microbial activity.

So what is your opinion on that, kind of the push-and-pull between those two objectives?

THE WITNESS: I think both topsoil and subsoil need to be protected. I think the issue, as I indicated earlier, is that it's much more difficult and it may be nearly impossible to remediate compaction in subsoil relative to topsoil.

Topsoil is subject to improvement through freezing and thawing and tillage and the application of organic materials like cover crops or other types of organic amendments. So you can restore the productivity of topsoil over a period of a couple years, but the compaction done on subsoil is very difficult to alleviate in study after study.

So that was my -- that was the motivation for me to make the comment that I think the -- the approach taken for protecting subsoil needs to be conservative.

BOARD MEMBER MARTZ: Just to restate, so if the protection of that subsoil results in that topsoil being removed for a longer or significant period of time, you would still say it's more important to be more conservative with the subsoil?

THE WITNESS: Yes.

BOARD MEMBER MARTZ: Thank you. No further questions.

BOARD MEMBER BYRNES: Thank you, Dr. Liebman. The first thing I just want to clarify a little bit -- and it's more a definition, if you will. I think maybe you just touched on it with Board Member Martz. You stated -- Earlier in your testimony here today, you used the term "nearly irreversible compaction." So that just applies to the subsoil, or are we talking -- Just clarify what you're referring to.

THE WITNESS: If you separated the topsoil from the subsoil, the subsoil hasn't moved, right? The subsoil is what's remaining after the topsoil has been scraped off. So the protection of topsoil in a pile is important, but my opinion is that if it hasn't been abused too much, it can be pretty fully remediated within a period of several years.

The subsoil, which hasn't moved, it might have been stirred up by deep tillage, deep ripping but has been subjected previously to heavy machinery, I don't think that it's that easy to overcome the compaction that takes place there. All the studies I've looked at have shown pervasive effects of having machinery on the structure of subsoil that lasts for multiple years. So my concern is protection of the subsoil in addition to protection of the topsoil.

I don't want that topsoil to go away. It's Iowa's most important agricultural asset, but I believe that the separation of the two strata, the top and bottom, is an important thing to do.

That double-lift technique is good, and if heavy machinery is trafficking across the subsoil, I think it's going to be difficult, if that traffic occurred under excessively wet conditions, to fully remediate the subsoil.

BOARD MEMBER BYRNES: Just for the record to clarify -- I feel like the definition may be a little bit fluid -- what is your definition of "subsoil"?

THE WITNESS: Okay. So in a technical way, soils are divided to an O horizon, which is the organic matter at the very top. An A horizon is typically the area where roots proliferate close to the soil's surface and might be plowed, if it was subject to tillage. That area might be a total of 10 inches deep in colloquial parlance for topsoil.

Below that 10-inch layer, below that at maybe 12 inches, I think we're talking about B and C horizons where soil typically has more clay, and there's less organic matter.

BOARD MEMBER BYRNES: So the subsoil would be B and C?

THE WITNESS: Yep, below, let's say, 10 to 12 inches.

BOARD MEMBER BYRNES: Okay. Thank you for clarifying that.

THE WITNESS: Yes. The rooting depths for crops in Iowa can be very deep, like, on the order of 6 to 10 feet, which is really important in a dry year.

BOARD MEMBER BYRNES: That was going to be my next question. So since you are an agronomist, you also study the impacts of the crops on the soil.

So for the record typically in a corn plant we can see root depth of?

THE WITNESS: Well, you can measure them.

For the furthest extension of a corn root, you can probably find it to 4 or 5 feet on many good Iowa soils.

BOARD MEMBER BYRNES: Soybeans?

THE WITNESS: Maybe shallower. Three to 4 feet on typical soils.

BOARD MEMBER BYRNES: Okay. And we have had -- So we're entering Week 4 of this hearing. We have had a lot of conversations around field tile and field tile being a concern with this pipeline.

Have you or any of your colleagues at Iowa State University or even colleagues at other institutions, do you know of or are you aware of any research that's also done on the impacts of installing field tile when it comes to compaction of this farmland?

THE WITNESS: The machinery used to install field tile now, the perforated plastic pipe, even the fairly wide pipes makes a very narrow trench. And I'm familiar with a couple of excavating contractors who do tiling work, and I've seen the machinery they work with, which is laser-guided and moves very quickly. The trenches are very narrow. So the zone that has been disturbed through the installation of these pipes is on the order of several-feet wide rather than a working area of, say, 125 feet. Okay?

So when I look at a field that's been tiled, I can see the placement of the tile because that area of the field typically dries out faster immediately over the tile, and the reduction in moisture in a dry year might need, say, a corn plant to be shorter immediately over the tile. On the other hand, in a wet year the corn plant might benefit from greater drainage right over a tile.

What tile does is it improves the performance of the corn plants adjacent to the tile because water is moving out and providing more oxygen space in the soil between the tiles, right? The water is moving laterally and then draining out of the field.

So the installation of the tile, even though there may be a slight reduction in some years immediately over the tile, leads to greater productivity in many years, and that's why farmers are interested in spending $700 to $1,000 an acre to put the tile in, because productivity under the types of wet spring conditions we have typically improve with tiling. That's different than compacting a 125-feet-wide width with heavy machinery.

Tile machines are large. They're heavy,

but they often now have Caterpillar treads to distribute the load, and the tile pipe itself is inserted in a very narrow band of disturbance.

So I think, based on my experience and what I've read in terms of the effective tiling on land productivity, tiling typically increases the per-acre yields; whereas, pipeline construction, at least for some period of time following the construction of the pipeline, decreases crop productivity.

BOARD MEMBER BYRNES: And you are probably aware that after -- None of us, as Board members, were present when land restoration rules were changed, but after Dakota Access, Chapter 9 rules on land restoration were changed. Did you or anyone else at Iowa State make any contributions to that rulemaking change?

THE WITNESS: I did not, but I can't say whether or not Iowa State scientists contributed to that. I would expect that their expertise would be at least consulted.

BOARD MEMBER BYRNES: And I guess one other item.

So going back to the topsoil and the worry of irreversible compaction to the subsoil, what would be your recommendation? So keeping in mind something like Chapter 9 and land restoration rules, what would be a recommendation that you would have, if Chapter 9 were to be modified down the road, to help with that potential irreversible compaction of the subsoil?

THE WITNESS: Everything I've learned from my personal experience and from reading scientific literature would indicate that avoiding the problem is better than trying to remediate the problem, and the single most important way to avoid soil compaction is to not allow heavy traffic on excessively wet soil.

Those are -- You know, a high load on soil that's too wet leads to the increase in both density, the loss of porosity and difficulties with root penetration. So the single most important thing to do is not get yourself into that situation to begin with.

BOARD MEMBER BYRNES: So you're not saying don't do infrastructure projects? You're saying when a project is done, pay attention to the moisture content in which the project is being conducted?

THE WITNESS: So if you have a pipeline construction project, even if moisture conditions are quite suitable for heavy field traffic and even if you use double-lift procedures, separating topsoil and subsoil, and even if you deep-rip the subsoil to increase infiltration, I think you may see a reduction in crop yield following the completion of the pipeline project just because heavy machinery exerts a load on soil.

Right now compaction is considered by many agronomists to be sort of the silent yield reducer across very many acres of American field crops just because people are using larger and larger machinery.

So I can't guarantee that following good management practices -- Based on not being in the field when it's excessively wet, I can't guarantee that that will protect crop yields, but I think it's the first step towards moving towards minimal impact on agricultural yields.

BOARD MEMBER BYRNES: So just one last thing. So we have listened to a lot of conversation about wet conditions.

So just to be clear for the record and then it's -- again, that's a term that's hard to define, but based on your expertise, what is your recommendation or your definition of "wet conditions"?

THE WITNESS: Okay. So, again, as I mentioned before, it's contextual on: What are the sizes of the soil particles? Sand, which is a larger soil particle, drains quickly. Silt and clay, which are smaller soil particles, drain much more slowly.

The amount of water that you can tolerate in a sandy soil without doing damage to soil over the longer term after heavy machinery has passed, the amount of water you can tolerate is larger in a sandy soil than in a clay soil. So it depends on what kind of soil you're dealing with.

Soil scientists classify many different textures of soil in Iowa, and that's why having some sort of empirical way of determining whether the soil is friable and breaks apart and, therefore, could support heavy agricultural or construction machinery, or if it binds together when you squeeze it like kids do, right? They make mud pies. That's too wet.

So if you have a sandy soil, what's too wet? Well, the moisture content might be a poor indicator, but the fact that it breaks apart and allows it to crumble would be, perhaps, a better indicator than actually measuring, you know, is it 40 percent moisture content, all right?

So what I'm trying to say here is it really depends on the type of soil, and the drainage of that soil will be dependent on the relative balance of silt, clay and sand.

BOARD MEMBER BYRNES: All right. Those are all the questions I have. Thank you, sir.

BOARD CHAIR HELLAND: Mr. Whipple for redirect?

MR. WHIPPLE: No redirect, Your Honor.

BOARD CHAIR HELLAND: Thank you. You may step down, Doctor. Thank you.

Mr. Whipple, you can call your next witness.

MR. WHIPPLE: Thank you, Your Honor. At this time the Counties call Cole Kruizenga.

BOARD CHAIR HELLAND: Good morning.

THE WITNESS: Good morning.

BOARD CHAIR HELLAND: Go ahead and move the microphone wherever you need it. Just make sure you're speaking into the microphone. Thank you.

Go ahead and raise your right hand.

COLE KRUIZENGA,

called as a witness by the Counties, being first duly sworn by the Certified Shorthand Reporter, was examined and testified as follows:

BOARD CHAIR HELLAND: Thank you.

Mr. Whipple?

DIRECT EXAMINATION

BY MR. WHIPPLE:

Q. Are you the same Cole Kruizenga who caused direct testimony and Exhibits 1 through 3 to be filed