Evaluating the effects of underground pipeline installation on soil and crop characteristics throughout Ohio, USA

Thesis

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Abstract

Oil and natural gas pipelines are essential to the transport of energy materials, but construction of these pipelines commonly causes major disturbance to ecosystems. Due to variability in pipeline installation practices and environments, drawing consensus about how pipeline installations typically impact agricultural ecosystems has been challenging. Here, we conducted a systematic literature review and quantitative analysis of current pipeline studies to determine the magnitude of soil and vegetative responses to pipeline installation and found detrimental impacts to both soil and vegetation variables, including compaction, aggregate stability, and plant biomass. However, best management practices and remediation timeframes vary between studies. Thus, the objective of this study was to determine impacts of pipeline installation on Ohio soil and crop characteristics after a 4- to 5-year remediation period across three independent pipeline installations: the Rover, Utopia, and Nexus pipelines. We performed a 2-year on-farm study in 2020 and 2021 over 29 sites in 8 Ohio counties, directly comparing right-of-way (ROW) and adjacent, unaffected areas (ADJ) of the same agricultural fields. Soil physical, chemical, and biological properties were evaluated, as well as yield and stand counts for field corn, corn silage, and soybean. Detrimental impacts to soil physical characteristics which occurred during pipeline installation persisted through this study period, while variable impacts to soil chemical properties were observed on an individual

site basis. Finally, satellite image-derived normalized difference vegetation index (NDVI) was used to analyze if ROW versus ADJ differences in agricultural crop yields can be evaluated in a less time- and labor-intensive process compared with traditional on-farm sampling methods. Various soil and yield metrics show that degradation of agricultural land persists past the 4- to 5-year remediation period suggested by pipeline companies.

Dedication

I would like to dedicate this thesis to the memory of my grandmother, who passed away during the writing of this document. She was an incredibly strong, independent farming mother, and her passion for family and her community is a driving force in how I attempt to treat other people on a daily basis. Thank you for your constant support, baking advice, and sweet hugs. I'll miss you forever.

Acknowledgments

A thesis project is not merely written by a single individual; rather, it is written by a team of people constantly supporting the author. I would like to particularly thank my advisor, Steve Culman, for his constant support over the last two years. COVID-19 has made this process both exceptionally interesting and difficult, but your mentorship, guidance, and passion for the people impacted by the science we've conducted has pushed me to think about science in a different way. My committee members, Scott Demyan and Sami Khanal have also been incredible sources of knowledge and support throughout this process as well. Thank you.

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Field of Study

Major Field: Environment and Natural Resources

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Chapter 1. Literature Review and Quantitative Synthesis

Introduction

Transportation of energy resources such as oil and natural gas has been a longstanding issue for many civil engineers and energy suppliers. As such, underground pipelines have developed into a safe and effective method of material transport, with pipeline infrastructure systems now in 130 countries and on every continent (CIA 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 Canada, Russia, and China following, each with over 100,000 kilometers of pipelines (CIA World Factbook Staff, 2021). In the United States alone, there are roughly 486,400 kilometers of natural gas transmission pipelines and 3,641,260 kilometers of natural gas distribution pipelines (Bureau of Transportation Statistics Staff, 2021; U.S. PHMSA Staff, 2021).

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 pipelaying machinery traffic occurs, and a pile area where topsoil and subsoil are staged, in separate areas, while the pipeline is laid (Figure 1.1). The total area of each pipeline's ROW can 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". Current best practices now ensure topsoil and subsoil are lifted from the trench area individually, then stored separately, known as a "double lift," to maintain proper separation during the installation process. Double lifts decrease the rates of soil mixing between horizon layers, which often differ in texture, porosity, organic matter content, soil chemistry, and overall soil function. Additionally, current best management practices suggest surface and deep subsoil ripping after pipelines have been laid to decrease long-term effects of compaction on agricultural or natural landscapes.

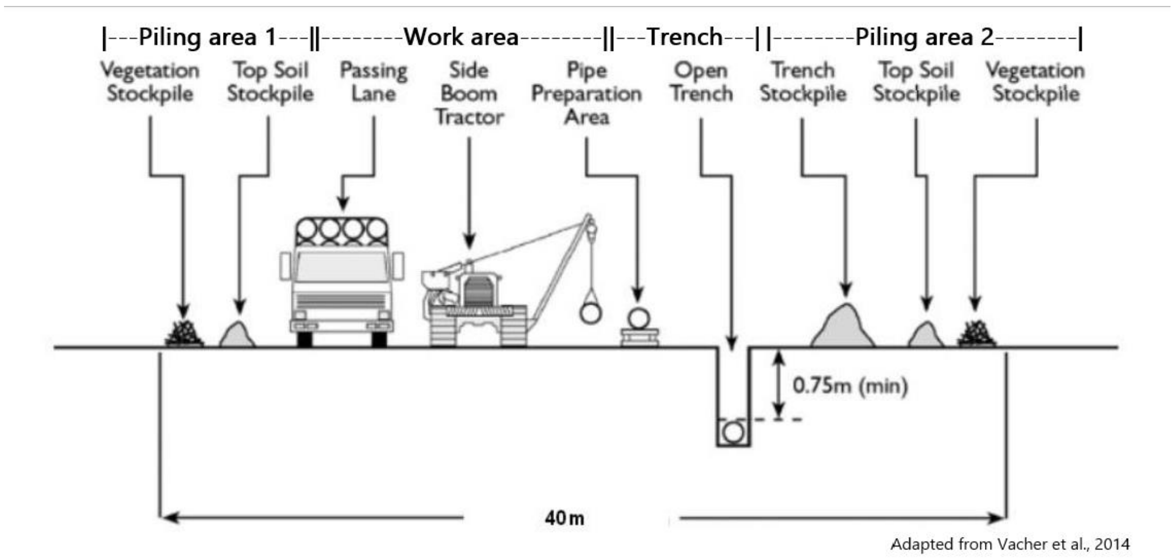

Figure 1.1: A schematic of the pipeline installation process, detailing multiple piling storage areas utilizing a double lift method for soil extraction, the work area or road, and the pipeline trench. Figure adapted from Vacher et al., 2014.

Despite the extensive infrastructure already in place in many countries, thousands of miles of pipelines are still being installed globally each year (CIA World Factbook, 2021). These installations have cut through numerous ecosystems such as pastures, wetlands, forests, and agricultural fields to connect the global energy infrastructure. 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 alter the growing environment for vegetation in ROW areas compared to 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.

Given the site-specific nature of pipeline installations, there is a lack of clear understanding and consensus regarding the overall impacts of these installations on soil properties and plant communities. Landsburg and Cannon (1995) reviewed the impact of pipeline disturbance via overstripping topsoil within native rangelands of southeastern Alberta, but this report is limited in scope and excludes more recent information that has emerged over the past 25 years.

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 i) comprehensively compile research studies reporting impacts of pipeline installation on soil and plant properties, and ii) synthesize and quantify the collective mean percent change that pipeline installations had on reported soil and plant properties in these studies.

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 December 15, 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.

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 non-disturbed adjacent areas, with statistical significance used from the original studies at $p < 0.05$ or $p < 0.1$ levels. For studies that reported a statistical increase or decrease in a soil or plant variable, the percent 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. Then a percent difference for each variable within each study was calculated using Equation (1.1):

$$\% \, difference = \left(\frac{ROW - ADJ}{ADJ}\right) * 100$$

Percent difference was used as a way to standardize values across soil types, ecosystems, and management styles, as well as to assess the directionality and magnitude of response. Finally, for each soil and plant variable, a mean percent difference value (and range) across studies were calculated independently for studies documenting an increase and for studies documenting a decrease in values with pipeline installation.

Results and Discussion

Characteristics of Pipelines Studied

In total, 34 peer-reviewed or scholarly papers were found from eight countries (Table 1.1). 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 in 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 wheat (*Triticum aestivum*), corn (*Zea mays*), soybean (*Glycine max*), alfalfa (*Medicago sativa*), cereal grains such as sorghum (*Sorghum bicolor*) and barley (*Oryza sativa*), potato (*Solanum tuberosum*), raspberry (*Rubus idaeus*), and sunflower (*Helianthus annuus*).

The age of pipelines studied ranged from during the installation process to 53 years post-installation but averaged 8.7 years after installation. Most pipelines were studied within 10 years 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 type of lift used. For example, many studies in northern Canada reported single lift installations as a result of thinner topsoil layers compared to many other areas of the world. 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.

Table 1.1: Published scientific and governmental studies found evaluating the impacts of pipeline installation on soil and plant properties.

Study Reference Number	Country	State/Province	Citation	Number 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	Nielsen 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 et al. (2000a)	1	3	Chemical, biological	Above and belowground biomass, grain macronutrients
12		Alberta	Soon et al. (2000b)	1	3	Physical, chemical	Not reported
13		Alberta	Desserud et al. (2010)	14	7-40	Physical	Mean % 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 % cover, species presence, coverage, diversity, quality, proportional species abundance
19		New York	Schindelback and van Es (2012)	1	1	Physical, chemical, biological	Not reported

Table 1.1, Continued

20		Wyoming	Gasch et al. (2016)	4	1, 5, 36, 55	Physical, chemical, biological	Total % 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 % 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

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 (Figure 2.1).

Soil Physical Properties

Compaction

Of the 26 studies reporting compaction via bulk density or penetration resistance, 17 documented significant increases in rates of compaction on the ROW compared to control areas. However, 8 studies showed no change in compaction and 1 study reporting a decrease in bulk density (Table 1.2). In studies with increased compaction, bulk density increased an average of 19.7% (4.9-63.7%) and penetration resistance increased an average of 51.6% (9.0-133%) (Table 1.2). 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 to 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.

A study by 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, USA, ROW soil had bulk densities 63% higher than adjacent areas (Olson & Doherty, 2012). Antille et al. (2015) found that soil compaction within lease areas increased by approximately 10% compared to undisturbed fields ($p < 0.05$). Additionally, surface compaction from 0-40 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 percent 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 to 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 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 & van Es (2012) found that decompaction efforts after pipeline installation decreased surface and subsurface hardness by -3.0% and -11.0%, respectively, within agricultural soils. Turner (2016) found 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.

Soil mixing

Soil mixing via changes in soil texture and particle size distribution increased by an average of 39.0% in 24 of the 28 studies, with a range of increase from 7.6% to 102.6% (Table 1.2). Evidence of soil mixing can often be seen through higher clay content in surface horizons, decreased soil carbon, and visible changes in soil color as a result of soil churning or mixing. These effects are typically long-lasting. For example, de Jong & Button (1973) documented that soil mixed from pipeline installation 10 years 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. 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 (Wester et al., 2019).

Table 1.2: Mean percent change of various soil properties on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas. 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 percent 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 1.1.

		Studies with Increases			Studies with No Change		Studies with Decreases		
Soil Property	**Total Number of Studies**	**n**	**Mean % Increase (Range)**	**Citations**	**n**	**Citations**	**n**	**Mean % Decrease (Range)**	**Citations**
Compaction via Bulk Density	16	10	19.7 (4.9-63.7)	2, 3, 4, 7, 11, 18, 22, 23, 29, 33	5	1, 5, 6, 15, 20	1	-3.0	16
Compaction via Penetration Resistance	10	7	51.6 (9.0-133.3)	2, 3, 18, 22, 23, 29, 31	3	1, 11, 19	0		
Soil Mixing via Texture and Particle Size Distribution	28	24	39.0 (7.6-102.6)	1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 25, 26, 28, 29, 33	4	9, 13, 24, 30	0		
Aggregate Stability	12	0			0		12	-43.6 (-22.2)-(-84.5)	2, 3, 10, 13, 18, 19, 21, 28, 32, 29, 15, 30
Coarse Fragments/Rocks	7	6	[a]	2, 4, 9, 19, 24, 25	1	17	0		
Soil Temperature	5	5	35.7 (10.5-62.9)	8, 9, 15, 26, 34	0		0		
Soil Moisture	8	1	40.4	20	3	1, 6, 22	4	-13.2 (-1.3)-(-25.4)	9, 11, 18, 34
Hydraulic Conductivity	6	1	7.1	16	3	17, 19, 24	2	-23.2 (-8.5)-(-38.0)	2, 5
Infiltration Capacity	3	0			0		3	-85.6 (-78.4)-(-92.7)	28, 29, 31
pH	19	9	11.3 (3.1-41.0)	1, 2, 3, 5, 6, 15, 17, 19, 20	10	4, 9, 10, 11, 16, 21, 25, 26, 29, 31	0		
Organic Matter/Soil Carbon	21	0			4	7, 12, 15, 17	17	-24.4 (-4.9)-(-49.7)	2, 3, 4, 5, 6, 9, 10, 16, 19, 20, 24, 25, 26, 28, 29, 31, 33
Total Soil Nitrogen	11	2	593.0 (19.3-1166.7)	15, 21	0		9	-23.6 (-3.6)-(49.5)	2, 3, 5, 7, 12, 20, 24, 26, 31
Cation Exchange Capacity	7	1	42.5	5	4	15, 16, 17, 29	2	-26.6 (-26.4)-(-26.8)	1, 3
Electrical Conductivity	9	7	131.8 (11.5-267.0)	1, 4, 6, 11, 20, 21, 31	2	16, 29	0		
Nitrate-Nitrogen [b]	2	0			0		2	-35.6	1, 19
Phosphorus (P) [c]	12	1	39.7	15	8	2, 10, 16, 17, 19, 21, 24, 26	3	-46.4 (-25.2)-(-71.3)	1, 3, 31
Potassium (K) [c]	13	3	21.6 (11.0-41.4)	1, 5, 10	8	2, 4, 16, 17, 21, 24, 26, 29	2	-14.5 (-9.8)-(-19.1)	3, 19

Table 1.2, Continued

Calcium (Ca) [c]	9	6	83.5 (12.5-244.6)	4, 5, 6, 10, 11, 16	3	17, 21, 29	0		
Magnesium (Mg) [c]	9	3	363.0 (316.0-410.0)	6, 16, 21	4	11, 17, 19, 29	2	-20.4 (-17.3)-(-23.5)	5, 10
Sodium (Na) [c]	7	5	343.9 (211.8-469.0)	4, 6, 11, 16, 21	1	29	1	-16.5	10
Sulfur (S) [c]	5	4	612.5 (57.9-1516.7)	4, 6, 15, 21	0		1	-54.2	11

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

[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

Aggregate stability and erodibility potential

All 12 studies that measured pipeline installation impacts on aggregate stability found significant decreases, with an average reduction of 43.6% and ranging from 22.2 to 84.5% (Table 1.2). Evidence of subsidence, or the gradual settling or sinking of the Earth's surface, in ROW areas has been documented by Vacher et al. (2016), which states that depressions in disturbed fields after pipeline installation measured between 10-20 cm below the average slope of the adjacent study area. 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 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 percent organic carbon 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 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 increases near rivers and in areas of high seismic activity, a highly relevant topic in Azerbaijan, where the study was conducted. 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%.

Exposed coarse rock fragments

Increased amounts of coarse fragments were found in 6 of the 7 studies conducted, while 1 study reported no significant change between the ROW and adjacent areas (Table 1.2). 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.

Soil temperature

Increased soil temperature was documented by 5 out of 5 studies, with an average increase in temperature of 35.7% along ROW compared to adjacent areas (Table 1.2). 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 to 3.4°C higher than soils farther away from the pipeline. Comparatively, Shi et al. (2015) reported a 1.0 to 2.0°C increase in temperature along ROW areas in western China.

Soil moisture, hydraulic conductivity, and water infiltration capacity

Decreases in soil moisture were reported in 4 out of 8 studies, with an average decrease of 13.2% (Table 1.2). Notably, Halmova et al. (2017) attributed this decrease in gravimetric soil moisture to increases in soil temperature along the ROW. 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).

Hydraulic conductivity of soils over the ROW was decreased in 2 of 6 studies, with an average decrease of 23.2%, largely connected to compaction and permeability alterations in the soil, and studies report that remediation measures post-installation are key to the resulting effects on soil hydrology (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 to 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 tenfold in ROW soils compared to 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, likely due to soil mixing and remediation measures which decreased bulk density compared to pre-installation.

Between the studies which analyzed water infiltration capacity, there was an average decrease of 85.6% across all 3 studies (Table 1.2). 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 are apparent through decreased water infiltration rates, decreased saturation percentage, decreased total porosity, decreased water holding capacity, and decreased total soil moisture occurred (Culley et al., 1982; Culley & Dow, 1988; Landsburg & Cannon, 1989; Olson & Doherty, 2012; Antille et al., 2015).

Soil Chemical Properties

pH

No significant change in soil pH following pipeline installation were found in 10 out of 19 studies (Table 1.2). However, 9 studies, including Zellmer et al. (1985) and Naeth et al. (1987) observed relatively uniform soil pH levels throughout the entire soil profile as a result of extreme soil mixing. This was commonly found in studies though rates of increase were largely determined by inherent soil pH, with an average increase in pH of 11.3% (Table 1.2). De Jong and Button reported surface pH generally increased 0.5 for 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, Arshad, et al. (2000) found that pH was highest in the year after installation, and continuously decreased in years following. In a forest study, Turner (2016) found that pH was highly linked with tree species.

Organic matter and soil carbon

An average decrease of 24.4% in soil organic matter (SOM) or soil organic carbon (SOC) occurred in 17 of 21 studies (Table 1.2). Increases in either organic matter or soil carbon were not found in any study. 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 0-15 cm, paired with an increase in SOC from 15-30 cm, compared to no changes in undisturbed fields. Likewise, Schindelback and van Es (2012) found a decrease of SOC by 44%, measured from 0-15 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 to trenches.

Additionally, Soon, Arshad, et al. (2000) reported a SOC decrease of 12% in a work area three years following pipeline installation. In a continuous study for 10 years after a pipeline installation in Ontario, Canada, Culley and Dow (1988) reported that there were still lower SOM levels on the ROW compared to undisturbed fields. When studying a pipeline almost 50 years 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 to a control area. 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. 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.

Nitrogen

Similar to SOM, total soil nitrogen (TSN) often decreases with disturbance. Across 11 total studies reporting TSN, 9 documented decreases that averaged 23.6% (Table 1.2). Culley et al. (1981) found that TSN decreased within the 0-15 cm range but increased from 15-30 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 years of analysis, Culley and Dow (1988) reported ROW soils still contained 23.9% less TSN than undisturbed fields. Landsburg and Cannon (1995), Soon, Arshad, 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 2 accounts of increases in TSN were reported, though Wester et al. (2019) found an increase of 1166.7% in TSN, which the authors concluded was a result of the erosion control measures applied to the ROW compared to adjacent areas, rather than an inherent increase in TSN derived from pipeline installation.

Cation exchange capacity

Cation exchange capacity (CEC) was inconsistently impacted with pipeline installations, with 4 out of 7 studies reporting no change, 1 study reporting an increase in CEC, and 2 studies reporting a decrease in CEC within the ROW (Table 1.2). Culley et al. (1982) reported a decrease in CEC within ROW agricultural soils compared to undisturbed fields follow 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 years after pipeline installation.

Electrical conductivity

In total, 7 out of 9 studies reported a significant increase in electrical conductivity (EC), with an average increase of 131.8% along ROW areas compared to adjacent areas (Table 1.2). Zellmer et al. (1985) found increasing sodium levels within the trench compared to off-ROW soils, suggesting sodium increases were due to soil horizon mixing. Similarly, Naeth et al. (1987) reported sodium adsorption rates up to 5 times higher in the trench compared to a control area. However, Landsburg and Cannon (1995) reported that EC levels returned to pre-disturbance levels within 5 years of pipeline installation, beginning first at surface levels, then moving deeper as a result of leaching. De Jong and Button found that EC increased with depth, particularly in Solonetzic soils with newly installed pipelines. Similarly, Soon, Arshad, et al. (2000) reported that EC levels were appreciably higher at deeper levels, from 50-100 cm, but the decrease after installation time Landsburg and Cannon (1995) reported was not confirmed through this study.

Available nutrients

Compared to carbon and nitrogen 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 1.2). On average, alterations to phosphorus, potassium, and magnesium nutrient levels were not significantly different from adjacent areas. De Jong and Button (1973) reported a decrease in phosphorus (P) and potassium (K) with depth, indicating mixing of topsoil horizons, where available nutrients are generally elevated, with subsoil, where nutrients are limited. Soon, Arshad, et al. (2000) also noted that K decreased with depth in their study in Alberta, Canada.

In comparison, increases in calcium 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 calcium-rich subsoil closer to the surface (Culley at al., 1981; Zellmer et al., 1985; Landsburg, 1989; Soon, Arshad, et al., 2000). In a 10-year study performed by Culley and Dow (1988), these findings were confirmed, stating that surface soils were increasingly calcareous compared to undisturbed fields. Additionally, Mg, Na, and S were found to increase in surface soils and with depth following pipeline installation (Landsburg, 1989; Soon, Arshad, et al., 2000).

Soil Biological Properties

Little research has been conducted regarding impacts of pipelines on biological soil properties. Soon, Rice, 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, USA. Conversely, Schindelbeck and van Es (2012) found significant decreases of 73% in biologically active C (permanganate oxidizable C) in pipelined 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.

Crop and Plant Yield Responses

Decreases in plant biomass accumulation were common among almost all species reported, with average decreases in agricultural crop yields of 10.6, 33.3, 23.6, 22.2, and 40.3% for corn grain, corn silage, soybean, alfalfa, and small grains, respectively (Table 1.3). Corn grain yields were reduced up to 50% in the first two years after installation on the ROW relative to control areas (Culley et al., 1981). After 10 years, 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 first year following pipeline installation (Culley et al., 1981).

Table 1.3: Mean percent change of crop yield or vegetation productivity on pipeline right-of-way (ROW) areas relative to adjacent, undisturbed areas. 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 percent 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 1.1.

			Studies with Increases			Studies with No Change		Studies with Decreases		
Ecosystem Type	**Plant community**	**Total Number of Studies**	**n**	**Mean % Increase (Range)**	**Citations**	**n**	**Citations**	**n**	**Mean % Decrease (Range)**	**Citations**
Agricultural Crops	Corn (grain)	5	0			1	26	4	-10.6 (-5.3)-(-30.7)	2, 3, 5, 7
	Corn (silage)	2	0			0		2	-33.3 (-26.2)-(-40.3)	3, 5
	Soybeans	3	0			0		3	-23.6 (-18.3)-(-27.6)	2, 3, 5
	Alfalfa	3	0			2	2, 3	1	-22.2	5
	Small grains (wheat, barley, sorghum)	10	1	27.0	16	3	1, 2, 12	4	-40.3 (-14.2)-(-67.6)	2, 3, 5, 29
	Raspberries	1	0			0		1	-45.6	33
	Sunflower	1	1	8.1	34	0		0		
Grasslands	Prairie, grasses, shrubland	6	0			1	14	5	-43.2 (-24.8)-(-63.0)	13, 16, 25, 27, 31
Forests	Forest	1	0			1	15	0		
Wetlands	Wetland	2	0			1	14	1	-14.7	18

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 yields on ROW soils during the first harvest season after pipeline installation, but in the following two years 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 three-year 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 to 13.1%, and sunflower yields were higher by 8.1% compared to control areas.

Culley and Dow (1988) found that alfalfa yields increased slightly over the ROW compared to 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 potatoes.

In non-agricultural soils, Kowaljow and Rostagno (2008) found that native shrubland faced difficulty in naturally revegetating disturbed areas, resulting in slow vegetation growth on-ROW compared to 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*) dominated many of the native grass species in disturbed areas, while undisturbed sections had higher percent 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, USA, pipeline installation in these areas resulted in lower species richness and higher dominance of invasive species when compared with undisturbed wetland areas.

Conclusions

Pipeline installations have occurred through the world and accordingly, research studies documenting the impacts of installation vary greatly in space and time. As a result, making direct comparisons between different pipeline installations or drawing specific and consistent conclusions can be difficult. However, published research has demonstrated a general consensus that pipeline installations across the world 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, compaction, increased erosion potential, alterations in pH, and decreased organic matter and organic carbon content. Additionally, pipeline installation has often been detrimental to agricultural crop yields and native vegetation in natural ecosystems. 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 effects that pipeline installation has on natural resources, the magnitude of these effects and how long these effects can persist. This is particularly important information for land managers to consider when approached to sign easement contracts for future pipeline installations.

As the number of pipeline installations around the world is projected to increase, particularly through fertile agricultural lands, more studies are needed to fully understand impacts of pipeline installations and which installation practices most effectively mitigate soil degradation. Perhaps equally important, identifying cost-effective practices to remediate degraded soils and plant communities remain a priority. This research could benefit land managers as well as the general public through better understanding of how soil ecosystem functions are altered after severe disturbance, with an emphasis on managing and improving soils post-disturbance.

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Chapter 2. Evaluating the effects of pipeline installation on soils and field crops in Ohio

Introduction

Underground gas pipelines have developed into a safe and effective method of material transport, with pipeline infrastructure systems now in 130 countries and on every continent (CIA World Factbook Staff, 2021). The United States has the most extensive oil and natural gas pipeline system in the world, with roughly 486,400 kilometers of natural gas transmission pipelines and 3,641,260 kilometers of natural gas distribution pipelines (Bureau of Transportation Statistics Staff, 2021; U.S. PHMSA Staff, 2021).

Pipeline installation occurs within a right-of-way (ROW) or easement area, containing three major components: 1) a trench where the pipe is laid, 2) a work area where pipe laying machinery traffic occurs, and 3) a pile area where topsoil and subsoil are staged, in separate areas, while the pipeline is laid. The total area of each pipeline's ROW can differ depending on pipeline installation, pipe size, and installation depth (Batey, 2015). 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 et al., 1997; Landsburg & Cannon, 1995; Zellmer et al., 1985). Current best practices ensure topsoil and subsoil are lifted and separated 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 & Dougherty, 2012; Shi et al., 2014).

Land where pipelines have been installed face potentially long-lasting degradation on soil and vegetation resources due to heavy machinery traffic, ineffective soil lifting via single or double lift techniques, and inadequate site remediation after pipeline installation (Batey, 2015; de Jong & Button, 1973; Tekeste et al., 2020). Culley et al. (1982) reported 55.7% greater soil compaction in the ROW compared with an adjacent, undisturbed part of the field. Similarly, in a wetland study from Wisconsin, compaction in ROW areas increased 63.7% compared with undisturbed areas (Olson & Dougherty, 2012). Conversely, no significant change in bulk density was seen from 0-60 cm in depth when comparing 13 different pipelines installed in Saskatoon, Canada, ranging in age from 0-11 years after installation (de Jong & Button, 1973; Culley and Dow, 1988). However, knowing the thickness, depth, and severity of initial compaction as well as subsequent remediation actions taken are essential to understanding longevity of soil compaction on disturbed areas, with remediation typically occurring over decades rather than several years (Batey, 2009; Spoor, 2006). Soil compaction following pipeline installation may be short-lived, but how long it takes for pipelined soils to return to their previous state is largely unknown.

Evidence of soil horizon mixing with pipeline installation has been widely documented in the literature, with 24 of 28 studies documenting an average change of

39.0% in particle size density and soil textural changes (Chapter 1). Naeth et al. (1987) reported a 102.6% increase in clay content within 7.6 cm of the surface, while Culley and Dow (1988) observed a 25.9% increase in clay content from 0-30 cm. While double lift installation techniques are suggested to mitigate soil horizon mixing and subsequent detrimental impacts to soil and vegetation, few studies have been examined these differences, particularly as best management practices continue to evolve and improve (Desserud et al., 2010; Soon, Arshad, et al., 2000; Tekeste et al., 2020).

Soil organic matter (SOM) and soil organic carbon (SOC) typically decrease immediately following pipeline installation, with an average decrease of 16.8% and 31.0 for SOM and SOC, respectively, over 17 studies (Chapter 1, Culley & Dow, 1988; Naeth et al., 1987; Shi et al., 2014). Total soil nitrogen followed a similar trend, decreasing 23.6% across 9 independent studies (Chapter 1).

Crop yields and plant productivity following pipeline installation typically experience declines, with average decreases of field crops from reported studies between 10.6-40.3% (Chapter 1). Within three years of pipeline installation in Ontario, Canada, ROW corn grain yields were 29.9% lower than adjacent areas, and this trend continued, with a 23.7% yield decrease persisting for 10 years following installation (Culley et al., 1982; Culley & Dow, 1988). However, no significant decreases in corn grain yields were documented between three gas and oil pipelines in central China (Shi et al., 2015). Pipeline installation reduced corn silage and soybean yields by over 40% and 27.6% three years after installation (Culley et al. 1982) and 26.2% and 24.9% after 10 years (Culley and Dow, 1988), respectively. Alfalfa yields were not impacted in the first three years

(Culley et al. 1982) but were reduced 22.2% after 10 years (Culley and Dow, 1988). In these studies, small grains (winter wheat, barley, mixed cereals) had reduced ROW yields of between 11.8-67.6% (Culley et al., 1982; Culley & Dow, 1988). Comparatively, Zellmer et al. (1985) documented both wheat and sorghum yield increases of 21.9% and 32.0%, respectively, within four field sites in a pipeline ROW in Oklahoma. Declines in crop yields have not been universally found however, as instances of no differences in wheat and barley have also been reported (Culley et al., 1981; de Jong & Button, 1973; Soon, Rice, et al., 2000).

In order to decrease long-term effects of compaction on agricultural and natural landscapes, current best management practices suggest remediation activities like surface and subsoil ripping after pipelines have been laid (Batey, 2015; Tekeste et al., 2019; Tekeste et al., 2020). However, the literature supporting these suggestions on individual pipelined areas are minimal in number and dated, with much of the previous research on this topic being conducted prior to the development of new best management practices like double lift techniques (Chapter 1).

In recent years in Ohio, it has become common practice for many natural gas and oil companies to compensate farmers and landowners for only 3 to 4 years after pipeline installation is completed, with compensation decreasing 25% each year (Nexus Staff, 2016; Rover Staff, 2016). Thus, 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. Therefore, by the fifth year following pipeline construction, many farmers and landowners are receiving no compensation for crop losses following pipeline installation. The basis of this 4–5-year compensation timeframe is not aligned with previous studies which have documented lasting deleterious effects on soils and crops for at least a decade.

Underground oil and natural gas pipelines are essential to global energy operations, but previous studies have commonly reported soil degradation and crop yield decreases following installation. Current best management practices have improved from single lift to double lift technologies in recent decades, and extensive site remediation practices are now commonly implemented after installation. Because construction, installation, and remediation practices often vary between pipeline parent companies, construction crews, soil types, and climatic events, attempting to generalize the impacts of pipeline installation using current best management practices requires evaluating multiple pipelines over a diverse soils and environments.

The objective of this study was to evaluate the impact of pipeline installation on Ohio soils and field crops after a 4- to 5-year remediation period. Here, we examined three independently operated pipelines constructed and remediated using current best management practices. We report corn and soybean yields and a suite of soil properties from 29 fields across eight Ohio counties to assess if impacts persist after site remediation is complete.

Material and Methods

Pipeline Description

We selected three recently installed pipelines to study in northern Ohio; the Rover, Utopia, and Nexus pipelines are all natural gas pipelines installed between 2016-2017 (Table 2.1).

Table 2.1: 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 (MCuM per day)**	**Ohio Counties Crossed**	**Year Construction Began**	**Year Construction Completed**
Rover	Energy Transfer Partners	Dual	107	338	92.03	18	2016	2018
Utopia	Kinder Morgan	Single	30	425	5.95	13	2016	2018
Nexus	DTE Energy and Enbridge, Inc.	Single	91	336	42.48	13	2017	2018

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.

Mean annual temperature for this region is ~10°C, with a mean annual precipitation of ~900-1000 mm (NOAA Staff, 2021a). Soils in this region commonly developed over glacial limestone or lake sediments, depending on proximity to Lake Erie, which borders much of the northern portion of Ohio (Barker, et al., 2017).

All three pipelines were constructed within a 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 (AIMP) from Rover and Nexus pipelines state these pipelines were installed at a depth of roughly 1 meter, 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; Rover Staff, 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 following pipeline installation occurred via deep ripping at a depth of 45 cm, and re-establishment of herbaceous vegetation on the ROW followed within all pipeline-disturbed areas for Rover and Nexus. Environmental Impact Statements were not made publicly available for the Utopia pipeline.

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, and Ohio Farm Bureau, landowners, and 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 (C.O.R.N.) newsletter, to create broader awareness of the research project and develop engagement opportunities. Postcard invitations to participate in this study were mailed to farmers and landowners along the three pipelines, detailing the objective of the study and requesting landowners to participate.

Final field sites were selected to represent diverse geographic locations, soil types, and topographies. Selected fields were planted with grain crops in 2020 and planned to be in grain crops for the 2021 growing season. Grain crops included corn, corn silage, and soybean, which occupy over 3.4 million hectares in Ohio, or 63% of farm area (USDA-NASS Staff, 2021). Twenty-three field sites were identified for analysis during 2020, and 20 field sites were identified 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 2.1) including 20 different USDA soil series (Table 2.2) and were divided between Rover (n=15), Utopia (n=7), and Nexus (n=6) pipelines.

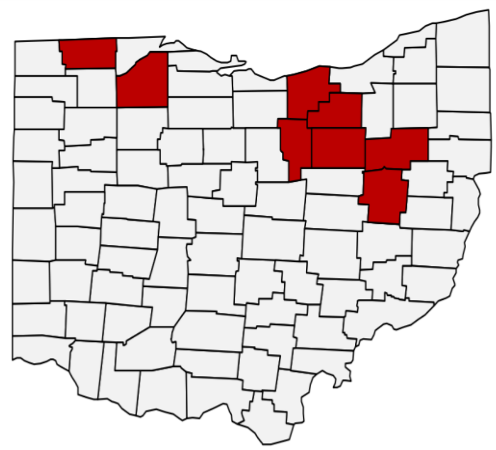

Figure 2.1: A map of Ohio with counties highlighted in red where sampling occurred for this study in 2020 and 2021.

Table 2.2: Description of all pipeline sites sampled including crops harvested per year and soil classifications.

			Crop		Soil Classification		
Site ID	County	Pipeline	Year 1	Year 2	Soil Series	Soil Series Subgroup	Soil sampled
Site 1	Wayne	Rover	Silage corn	Soybeans	Wooster Riddles	Ultic Hapludalfs	Yes
Site 2	Wayne	Utopia	Corn	Soybeans	Wooster Riddles	Ultic Hapludalfs	Yes
Site 3	Wayne	Rover	Corn	Soybeans	Chili	Typic Hapludalfs	Yes
Site 4	Wayne	Rover	Corn	Soybeans	Canfield	Aquic Fragiudalfs	Yes
Site 5	Medina	Nexus	Silage corn	Not sampled	Oshtemo	Typic Hapludalfs	Yes
Site 6	Wayne	Utopia	Corn	Soybeans	Canfield	Aquic Fragiudalfs	Yes
Site 7	Wood	Nexus	Soybeans	Not sampled	Hoytville	Mollic Epiaqualfs	Yes
Site 8	Wayne	Rover	Soybeans	Corn	Wooster Riddles	Typic Hapludalfs	Yes
Site 9	Wayne	Utopia	Corn	Not sampled	Canfield	Aquic Fragiudalfs	Yes
Site 10	Lorain	Nexus	Corn	Not sampled	Chili	Typic Hapludalfs	Yes
Site 11	Lorain	Nexus	Not sampled	Soybeans	Mahoning	Aeric Epiaqualfs	Yes
Site 12	Lorain	Nexus	Soybeans	Corn	Mahoning	Aeric Epiaqualfs	Yes

Table 2.2, Continued

Site 13	Lorain	Nexus	Soybeans	Not sampled	Mahoning	Aeric Epiaqualfs	Yes
Site 14	Wayne	Rover	Corn	Corn	Luray	Typic Argiaquolls	Yes
Site 15	Wayne	Utopia	Corn	Soybeans	Fitchville	Aeric Endoaqualfs	Yes
Site 16	Stark	Rover	Soybeans	Not sampled	Seabring	Typic Endoaqualfs	Yes
Site 17	Stark	Utopia	Corn	Not sampled	Sparta	Entic Hapludolls	Yes
Site 18	Tuscawaras	Rover	Not sampled	Not sampled	Chili	Typic Hapludalfs	Yes
Site 19	Tuscawaras	Rover	Not sampled	Not sampled	Elkinsville	Ultic Hapludalfs	Yes
Site 20	Tuscawaras	Utopia	Corn	Not sampled	Elkinsville	Ultic Hapludalfs	Yes
Site 21	Ashland	Rover	Corn	Soybeans	Jimtown	Aeric Ochraqualfs	Yes
Site 22	Ashland	Rover	Corn	Soybeans	Bogart	Aquic Hapludalfs	Yes
Site 23	Wayne	Utopia	Corn	Soybeans	Ravenna	Aeric Fragiaqualfs	Yes
Site 24	Fulton	Rover	Not sampled	Corn	Colwood	Typic Haplaquolls	No
Site 25	Fulton	Rover	Not sampled	Soybeans	Kibbie	Aquollic Hapludalfs	No
Site 26	Fulton	Rover	Not sampled	Corn	Millgrove	Typic Argiaquolls	No
Site 27	Fulton	Rover	Not sampled	Corn	Gilford	Typic Haplaquolls	No
Site 28	Fulton	Rover	Not sampled	Soybeans	Granby	Typic Haplaquolls	No
Site 29	Fulton	Rover	Not sampled	Corn	Sloan	Fluvaquentic Haplaquolls	No

Field Soil and Crop Sampling

This study took place as a replicated but not randomized complete block design with direct comparison between the right-of-way (ROW) transect and an adjacent, unaffected area (ADJ) within the same field for each site. 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 at least 30 m apart and roughly 3 m away from trench centerline), were identified as ROW sampling locations and GPS coordinates were recorded. Sampling directly over the pipeline trench was avoided because more intense decompaction efforts are sometimes made in this area by installation crews as compared with the majority of the ROW. Trench, road area, and piling areas were all determined to be a part of the pipeline ROW, so effort was made to locate adjacent sampling areas avoiding all previously disturbed construction zones. From each of the ROW sampling points, an adjacent (ADJ), undisturbed sampling point was identified directly off the ROW, making a total of three adjacent sampling points to serve as a control (Figure 2.2). Therefore, each field was made up of six sampling areas, 3 ROW paired with 3 ADJ.

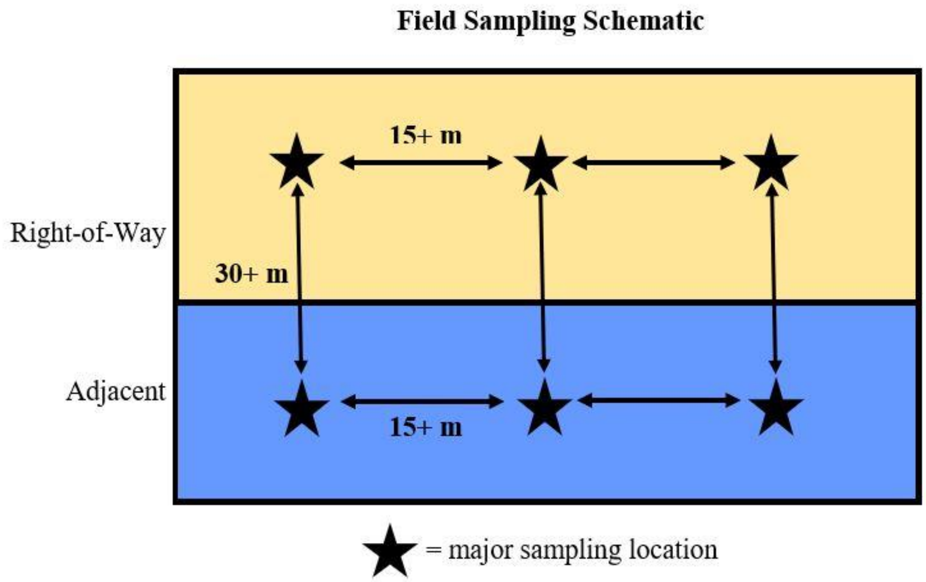

Figure 2.2: Example field sampling schematic, detailing the six (6) major sampling points taken at each field site between the right-of-way (ROW) and adjacent, unaffected areas (ADJ).

A 12 m^2 sampling area surrounding each of the six sampling points was demarcated. Within this sampling area, ten 2.5 cm soil cores were collected from 0-20 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, Woodstock, IL) within each sampling area. Twelve independent penetrometer readings were taken at 0-10 and 10-20 cm, and an average reading was later 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. Plant biomass and stand count data were taken in both years at a total of 23 sites across 7 counties, and 20 sites across 4 counties in 2020 and 2021, respectively (Table 2.2).

Laboratory Analyses

Collected soils were weighed to determine total mass at field moisture. Soils were 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. 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 40°C for 72 hr.

Aggregate stability was measured via wet sieving by Yoder (1936). Four aggregate size classes were measured: >2000 µm, 250–2000 µm, 53–250 µm, 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 min^{-1}. 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 a X,Y Autosampler (PIKE Technologies, Inc., Madison, WI) equipped with a deuterated triglycine sulfate (DTGS) detector, coupled with a Nicolet iS50 spectrometer with a diffuse reflectance accessory (Thermo Fisher Scientific Inc., Waltham, MA). 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) to generate the spectral replicates that were further averaged prior to peak area analysis and predictions. The spectral readings were randomly located within a 3 mm diameter circle in the central position of each well configured in AutoPro™ software (Pike Technologies Inc., Madison, WI).

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 hr), 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 minutes at 180 oscillations min^{-1}. After shaking, samples were autoclaved at 121°C for 30 minutes. Samples were allowed to cool to room temperature before being resuspended by being shaken again for 3 minutes at 180 oscillations min^{-1}. A 1.5 mL subsample was collected, transferred to a 2 mL centrifuge tube, and subsequently centrifuged at 10,000 x *g* for 3 minutes. Ten µL 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 minutes. 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-hour aerobic incubation period was determined using the Franzluebbers et al. (2000) method. Ten g 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 hours. Following the incubation period, a 1 mL air sample from each tube was collected with a syringe and injected into a LI–820 infrared gas analyzer (LICOR, Biosciences) to determine the CO2 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 oscillation min^{-1} for 2 minutes, then left to settle for 10 minutes. 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.

Plant biomass and stand count data were taken in both years at a total of 20 sites across 7 counties in 2020, and 20 sites across 6 counties in 2021, with 13 sites sampled in both years (Table 2.2). The method of crop sampling varied depending on the crop planted at each site. All three crops (corn, silage corn, and soybean) were hand harvested, oven dried for seven days at 49°C, and calculated on an area basis. Field corn ears were collected by hand from 12 m^2 (3 linear m of 4 rows with 0.76 m spacing) the first year and 6 m^2 (1.5 linear m of 4 rows with 0.76 m spacing) the second year of sampling. All corn ears from the sampling area were counted, whole cobs were dried, and corn ears were hand-shelled. Silage corn was collected from 7.2 m^2 (1.8 linear m of 4 rows with 0.76 m spacing), by clipping each plant at the brace root level and harvesting the whole plant. Number of plants were counted and whole plants were oven dried. Soybean plant biomass was collected from 5.4 m^2 (1.8 linear m of 3 rows, spaced at 0.19 m and 0.38 m). Whole plants were counted, clipped at ground level, then oven dried and hand-shelled. Oven-dry weights of field crops were multiplied by a standard moisture at harvest (15.5, 67, 13% for corn grain, corn silage, and soybean, respectively) to determine yield.

Statistical Analysis

Statistical analysis was conducted using SAS v. 9.4 (Cary, NC) and R version 4.1.1 (R Foundation for Statistical Computing, Vienna, Austria) 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 right-of-way (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 the following Equation (2.1):

$$\% \, Difference = \frac{(ROW - ADJ)}{ADJ} \times 100$$

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. This type of calculation was utilized to accommodate and standardize differences in soil type, microclimate, vegetation type, management history, and remediation methods between field sites. Some values for coarse fragments were originally zero, so 0.001 was added to this value to enable percent difference calculations. All figures were generated using the “ggplot2” package in R.

Results & Discussion

Soil Physical Characteristics

Penetration Resistance

Penetration resistance (PR) was significantly higher in pipeline ROW relative to the adjacent soils in the 0-10 cm depth but was not statistically different at the 10-20 cm depth (Table 2.3). Within the ROW, PR increased an average of 15.3% (ranged -39.3% to 77.0%) between 0-10 cm and 13.6% (ranged -37.5% to 76.7%) between 10-20 cm relative to ADJ (Figure S1, Table S1).

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 1,656 PR observations per depth across all sites, there were significantly more missing observations from 0-10 cm in the ROW (n=75) relative to the ADJ (n=47, p=0.009). Similarly, there were significantly more missing observations from exceeding 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 adjacent, unaffected areas of the same field.

This finding is consistent with similar studies over the last 40 years. Over the course of two years following installation of a pipeline in central Iowa, Tekeste et al.

(2020) found that PR on ROW soils increased an average of 38.7% and 51.3% in conventional tillage and no-tillage systems, respectively when compared with a control. Additionally, Culley et al. (1982) reported a 55.7% increase in cone index PR within ROW soils compared with undisturbed areas between 0-30 cm in 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).

Table 2.3: Mean (standard error) and F-statistics of soil physical characteristics in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites.

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

[1] Significance is reported as ****=0.0001, ***=0.001, **=0.01, and *=0.05.

Texture

Significant changes in soil texture were found in 6 sites, 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 2.3). Significant increases to clay content occurred in 6 of the 23 sites measured, compared with only 1 and 2 sites showing silt and sand increases, respectively (Table S2). As clay content increased, there was a paired decrease in silt content in 4 sites, with an average decrease of 12.1 g kg^{-1} across all 23 sites sampled. Overall, sand content was not significantly affected by pipeline installation (Table 2.3).

Increases in surface soil clay concentration, decreases in soil carbon stocks, and visible changes in soil color among horizons have been reported (e.g., 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 adjacent 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, often determined by the landowner's or farmer's best judgment and can at least partially explain site-by-site differences. For example, the landowner of Site 4 specifically requested the Rover pipeline company to regrade the pipeline ROW and fill in subsidence with several dump truck loads of high-quality peat-derived topsoil. Thus, Site 4 had a much different and higher quality backfill than many other sites sampled here, which often had subsidence backfilled with a material of the pipeline company's choosing. Anecdotal evidence from landowners stated this backfill was often "low-quality", contained high rates of weed seed, and was a significantly different texture than native soil materials, which is also partially evidenced within our individual site data (Table S3). Overall, it was evident that soil mixing between topsoil (A horizon) and subsoil (B horizon) occurred at most sites, indicating that the best management practice of double lift excavation used by each pipeline company were insufficient to eliminate degradation of soil structure and horizonization.

Aggregate Stability

Aggregate stability was significantly decreased under ROW sites relative to ADJ in both macroaggregate size classes (>2000, 250-2000 μm) and significantly increased in microaggregates (53-250 μm) and the silt and clay fraction (<53 μm) (Table 2.3). Macroaggregate prevalence significantly decreased overall within ROW soils, with average mean weight diameter (MWD) decreasing by 13.6% (ranging from -24.1% to 5.7%) across all sites when comparing ROW versus ADJ areas (Figure S2, Table S4). Indicatively, microaggregate prevalence increased in almost half of sampling sites (Table S2). The size class distribution of soil aggregates illuminates 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). McDowell et al. (2006) reported preferential loss of P with decreasing aggregate size in a 35-week ryegrass experiment analyzing water soluble P, inorganic and organic P fractions, and P contained in leachate within soils of different aggregate size classes. Additionally, Trivedi et al. (2015) observed different bacterial phyla within various aggregate size classes, which indicates niche bacterial ecosystems when comparing micro- and macropores. This study found that variability in these bacterial phyla influence C availability and degradation rates differently, depending on the size of aggregates where bacteria are located. 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 (Vacher et al., 2016).

Moisture

Gravimetric soil moisture at sampling time decreased an average of 11.5 g kg^{-1} across all 23 sites measured (Table 2.3), with an average percent difference of -6.3% across all sites including values ranging from -17.8% to 6.2% (Figure S1). A possible driving factor for the variability observed is the maintenance and repair of tile drainage following pipeline installation on a site-by-site basis. At Sites 12 and 19, where tile drainage was not sufficiently repaired, soil moisture was higher in ROW areas relative to ADJ areas. In several other sites where tile drainage was repaired, ROW areas now report significantly lower soil moisture than ADJ areas (Table S1). While tile drainage is an important factor in hydrologic conductivity and water flow in northern Ohio, other factors such as soil temperature, aggregate stability and size, porosity and soil texture can also influence soil moisture in pipelined areas. While soil temperature was not measured in this study, studies within the Slovak Republic and western China both report soil temperatures increasing in ROW soils anywhere between 1.0 and 3.4°C when compared with areas farther from the pipeline trench (Halmova et al., 2017; Shi et al., 2015). Notably, Halmova et al. (2017) explicitly attribute decreases in gravimetric soil moisture to increases in ROW soil temperatures from pipeline heating. Alternatively, Culley et al. (1982) found that hydraulic conductivity on ROWs decreased by an average of 38% compared to undisturbed fields, denoting that total porosity decreased, but drainable porosity remained the same, and volumetric water content was similar between ROW and undisturbed fields. This may indicate that a combination of aggregate size and stability, along with metrics of temperature and compaction via penetration resistance or bulk density, could be indicators of how a disturbed soil will retain moisture over a period of time.

Rocks

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 2.3). 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.

Soil Chemical Characteristics

pH

Soil pH significantly increased in ROW soils in 8 of 23 sites measured when compared with ADJ areas (Table S2), with an average increase of 0.6 across all sites (Table 2.4). Given the largely acidic subsoils within the counties sampled, the increase in pH is likely due to agricultural lime applied as a remediation tactic, rather than true site remediation. De Jong and Button (1973) did report pH increases between 0.5-1.0 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 (e.g., Harper & Kershaw, 1997; Ivey & McBride, 1999; Kowaljow & Rostagno, 2008; Shi et al., 2015; Zellmer et al., 1985). Soon, Arshad, et al. (2000) stated that pH was highest in the year following pipeline installation, while continuously decreasing in subsequent years.

Table 2.4: 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[2]**		
Variable	**ROW**	**ADJ**	**Trt**	**Site**	**Site*Trt**
Soil pH	6.7 (0.1)	6.1 (0.1)	110.0****	15.8****	3.3****
OM (g kg^{-1})	19.55 (0.69)	20.22 (0.72)	1.4	14.1****	1.6
CEC ($cmol_c$ kg^{-1})	11.5 (0.5)	10.7 (0.5)	5.6*	18.3****	3.8****
Total C (g kg^{-1})	12.27 (0.51)	13.22 (0.49)	7.8**	22.2****	1.0
Total Soil N (g kg^{-1})	1.31 (0.04)	1.42 (0.04)	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***

[2] Significance is reported as ****=0.0001, ***=0.001, **=0.01, and *=0.05.

Cation Exchange Capacity (CEC)

There was an average increase in CEC of 0.8 $cmol_c$ kg^{-1} in ROW soils compared with ADJ soils across all sites (Table 2.4), which likely results from increasing clay content in ROW areas. Cation exchange capacity significantly increased at 3 sites, while showing significant decreases at 1 site, with slight variation between sites and soil types (Table S2). This finding follows a similar trend seen in pipelined soils in Ontario, Canada, where Culley et al. (1988) reported a 42.5% increase in CEC between ROW and ADJ soils following 10 years of remediation activities. However, in a similar study in Alberta, Canada, researchers reported a 26.4% decrease in CEC among ROW soils compared with ADJ soils in single lift pipelines ranging from 1-11 years in remediation (de Jong & Button, 1973).

Soil Organic Carbon (SOC) and Total Soil Nitrogen (TSN)

Soil organic carbon (SOC) within the ROW decreased an average of 0.95 g kg^{-1} when compared with adjacent, unaffected areas (Table 2.4). This equated to an average SOC decrease of 6.54%, ranging from -32.68% to 21.30% across all sites (Figure S3, Table S5). Total soil N (TSN) decreased an average of 0.11 g kg^{-1} in ROW soils compared with ADJ areas (Table 2.4). These decreases were significant within 7 of the 23 sites measured, while 2 sites documented significant increases (Table S2).

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 soil organic carbon (SOC), respectively. However, no significant differences were found between ROW and ADJ SOC rates in study in the boreal plains of Alberta, Canada (Soon, Rice, et al., 2000). Thus, soil carbon stocks are slightly variable between sites and soil types but do tend to decrease overall in response to pipeline installation, even following a multi-year remediation period. Our data on decreasing TSN is consistent with much of the literature on pipeline disturbances (Landsburg & Cannon, 1995; Shi et al., 2014; Shi et al., 2015; Soon, Arshad, et al., 2000). Namely, Culley et al. (1982) found that TSN decreased in surface soils (0-15 cm) over pipelines but increased in subsurface soils (15-30 cm). Even following a 10-year remediation period, a 23.9% TSN reduction in ROW soils compared with adjacent soils still occurred (Culley & Dow, 1988). When analyzing a gas pipeline installation site in Northern Chebut, Argentina, researchers also documented a 49.5% decrease in TSN when comparing a clearcut ROW and adjacent, undisturbed steppe mounds (Kowaljow & Rostagno, 2008).

Mehlich-3 Extractable Nutrients

Mean 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 2.4). Mehlich-3 extractable nutrients were significantly increased over pipeline ROW ($p < 0.05$) for every macronutrient, except for phosphorus which decreased over the ROW

(Table S6, Figure S4). Increases in calcium and magnesium values were likely artificially elevated as a response to widespread agricultural liming practices by farmers at most sampling sites, but could also be caused by soil horizon mixing, where subsoil and bedrock materials high in Ca and Mg were brought to the surface and weather rapidly.

These findings are consistent with previous studies that documented decreases in P ranging from 25.2-71.3% in ROW soils compared with ADJ areas (Culley et al., 1982; de Jong & Button, 1973; Kowaljow and 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 in 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).

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 2.5). Pipeline installations did not affect POXC values across all sites (Table 2.5), although three individual sites were significantly decreased over the ROW, with percent differences ranging from -28.1% to 44.5% (Table S2, Figure S3). 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 S7, Figure S3).

Table 2.5: 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[3]**		
Variable	**ROW**	**ADJ**	**Trt**	**Site**	**Site*Trt**
POXC (mg kg^{-1})	413.0 (14.0)	424.7 (11.5)	1.1	9.5****	2.0*
Protein (g kg^{-1})	3.7 (0.1)	4.2 (0.1)	25.5****	5.6****	1.4
Respiration (mg kg^{-1})	37.9 (2.7)	46.3 (4.1)	10.6**	15.7****	2.3**

[3] Significance is reported as ****=0.0001, ***=0.001, **=0.01, and *=0.05.

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 and van Es, 2012). In this study, authors concluded that soil function in ROW soils decreased by an average of 27% when compared with unaffected soils, as evaluated by the Cornell Soil Health Test. 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 where microbial populations reside are dramatically altered, and that microbial activity within ROW soils will likely equilibrate over time as populations adapt to changing soil conditions (Vermeirer et al., 2018). While the differences in biological and biochemical characteristics in this study remain small, the combination of these factors can paint a larger picture of the microbial population and its activity within pipelined soils. Abundance and activity of microbes may be independently affected by pipeline installation. Decreased respiration values indicate a suppression of microbial activity, whereas POXC as a measure of labile carbon, or an indicator of microbial food source, in a soil remain unaffected. It is possible that ROW soil mixing could be disrupting microbial "hotspots" of activity near root channels and incorporated soil organic matter (Wang, Liu, Kuzyakov, et al., 2020; Zegeye et al., 2019), so microbes may be physically disconnected from their carbon source, which reduces microbial activity and thus respiration, while leaving POXC unchanged.

Crop Yield and Stand Count

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 2.6, Table S8). This translates to a 2020 yield decrease of 23.8% and a 2021 yield decrease of 19.5% in ROW yields compared with ADJ yields (Figure 2.3). Similarly, corn silage yield in 2020 decreased by 25.53 Mg ha^{-1} (28.8%) in 2020, ranging from -52.51 to 1.30 Mg ha^{-1} (Figure 2.3, Table S9). Comparatively, soybean yields were not significantly different during 2020, with only a 7.4% decrease in ROW yields compared with ADJ. However, during 2021, soybean yield decreased by an average of 0.61 Mg ha^{-1}, ranging from -2.25 to 0.88 Mg ha^{-1} (Table 2.6, Table S11). This decline equates to a 12.6% decrease in ROW soybean yields compared with ADJ areas (Figure 2.3). Overall, corn grain and silage were 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 (Table 2.8).

Table 2.6: Mean (standard error) and F-statistics of yields for field corn, corn silage, and soybean in 2020 and 2021 across Ohio field sites.

		Mean (Standard Error)		**F-Statistic[4]**		
Crop (Mg ha^{-1})	**Year**	**ROW**	**ADJ**	**Trt**	**Site**	**Site*Trt**
Corn	2020	8.69 (0.71)	11.96 (0.55)	132.3****	35.1****	6.3****
	2021	6.52 (0.52)	7.86 (0.34)	28.6****	18.6****	3.6*
Corn Silage	2020	52.26 (1.98)	77.79 (7.28)	47.9***	19.6**	21.0**
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****

[4]Significance is reported as ****=0.0001, ***=0.001, **=0.01, and *=0.05.

Table 2.7: Mean (standard error) and F-statistics of stand count at harvest of right-of-way (ROW) and adjacent (control) areas for field corn, corn silage, and soybean in 2020 and 2021 across Ohio field sites.

		Mean (Standard Error)		**F-Statistic[5]**		
Stand Count per Harvested Area	**Year**	**ROW**	**ADJ**	**Trt**	**Site**	**Site*Trt**
Corn	2020	66.1 (3.0)	71.8 (2.8)	18.2****	4.0***	6.7****
	2021	76.2 (2.2)	79.6 (3.0)	0.1	9.7****	2.9*
Corn Silage	2020	22.7 (2.8)	23.2 (1.8)	0.1	0.0	6.1*
Soybean	2020	60.3 (3.5)	60.3 (3.2)	0	8.0***	1.8
	2021	59.3 (3.3)	63.4 (2.7)	0.7	20.0****	1.7

[5] Significance is reported as ****=0.0001, ***=0.001, **=0.01, and *=0.05.

Table 2.8: Number of significant ($p < 0.05$) increases or decreases in right-of-way (ROW) field corn, corn silage, and soybean yields for two sampling years (2020, 2021) compared with adjacent, unaffected areas.

			Yield		**Stand Count at Harvest**	
Crop	**Year**	**Total Field Sites**	**Increases**	**Decreases**	**Increases**	**Decreases**
Corn	2020	13	0	10	0	4
	2021	7	0	5	1	0
Corn Silage	2020	2	0	1	0	0
Soybean	2020	5	0	0	0	0
	2021	13	0	4	0	2

Stand counts at harvest were similar or slightly decreased between most field corn, corn silage, and soybean crop-year combinations, indicating that, while a comparable number of plants were growing in an area for these crops, the harvestable yields from these plants were lower within ROW areas when compared with ADJ areas (Tables 2.7, 2.8). In both corn and soybean, this was often observed as shorter plants with weaker stalks, each containing either a smaller ear of corn or fewer pods containing a smaller number of soybeans.

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 (e.g., 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 two years of pipeline installation, while still maintaining a 23.7% yield decrease 10 years following pipeline installation (Culley & Dow, 1988). Additionally, in the same study, corn silage yields decreased by roughly 40.3% in the first year following installation, and by 26.2% after 10 years. 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 4–5-year recovery period, corn grain and silage yields at our sites are still significantly lower than adjacent, unaffected areas within the same field, showing that yield declines persist for years following installation. Similarly, Culley and Dow (1988) reported soybean yield decreases of 24.9% following 10 years of recovery from pipeline installation. While soybean yield decreases were smaller in our study, these effects were persisted through varying levels of precipitation and across soil types.

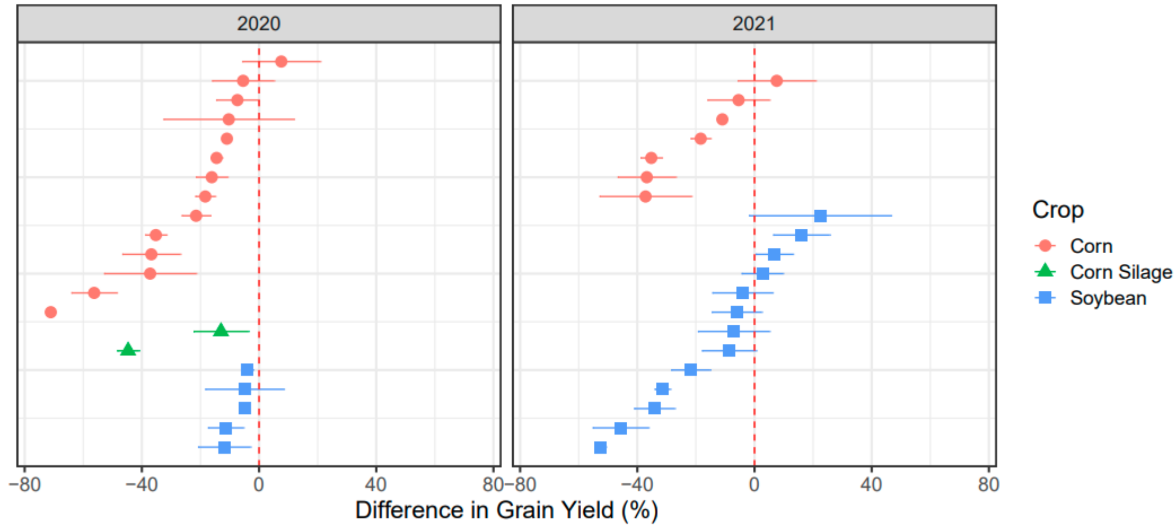

Figure 2.3: Average percent difference in crop yields in 2020 and 2021 between right-of-way (ROW) and adjacent (control) sampling areas. Percent differences were calculated with each paired replicate with the point representing the mean of each site and error bars representing the standard error among 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.

Conclusions

Across a diverse set of farms and soil types in 8 counties across northern Ohio, soil characteristics and crop yields were still detrimentally impacted following a 4–5-year recovery period on three recently installed, double lift pipelines. Soil physical characteristics like penetration resistance and aggregate stability indicate that large-scale compaction prevails at almost all sites evaluated in this study. Future degradation via wind and water erosion may become points of concern in ROW areas if the current degradation legacy is not addressed and remediation in both soil and vegetation indices are not achieved. Likely, a combination of physical compaction and soil mixing resulted in degradation of other measured soil chemical and biological properties reported here. Alterations to CEC, total C and N, and Mehlich-3 extractable nutrient availability following pipeline installation documented here will likely impact vegetative growth and vigor into the immediate future, if not properly remediated. 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 sometimes temporally and spatially overlapped.

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. However, the continued detrimental impacts to both soil characteristics and agricultural crop yields following pipeline installation, as documented in this study, 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 not sufficient preventative measures to mitigate soil degradation and crop yield losses. Likely, the answer is a combination of these factors, rather than a result of solely one or the other. Research on longer timescales across a diverse set of pipelines is needed to continue to document the longevity of contemporary pipeline installation practices on soil and crop characteristics.

Future pipeline installation sites would benefit from the development of a formal nation-wide regulatory document regarding specific pipeline installation practices which must be followed by each pipeline installation and remediation crew, in addition to the currently existing "Plans and Procedures" document from the Federal Energy Regulatory Commission. In this way, all pipeline construction projects would be completed following the same standards, and deviations from written Environmental Impact Statements and Agricultural Impact Mitigation Plans can be more easily identified and remediated across sites. Organizations such as the Federal Energy Regulatory Commission, which currently requires submission of Environmental Impact Statements for each new federally regulated pipeline construction, could be instrumental in development of this document. Adherence to Environmental Impact Statements and Agricultural Impact Mitigation Plans are essential to mitigating persisting impacts as underground pipeline installations continue to occur in agricultural areas.

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Chapter 3. Impact of pipeline installation on normalized difference vegetation index (NDVI) values and crop yields

Introduction

Optical remote sensing via satellite imagery can provide a rapid timescale, high resolution snapshot of the world through use of visible, near infrared, and short-wave infrared sensors which form images of the earth via reflectance of solar radiation on ground targets (Liew, 2001). In this way, specific targets such as bodies of water or varying levels of vegetative cover can be differentiated from each other by varying spectral reflectance signatures. Remote sensing using imagery derived vegetation indices such as normalized difference vegetation index (NDVI), has been used in agriculture and environmental monitoring, and has become a powerful tool to propel precision agriculture forward in recent decades (Ghassemian, 2008; Haboudane et al., 2004; Meyer & Camargo Neto, 2008). NDVI is calculated from the following Equation (3.1), where NIR is near-infrared light, and R is visible red light:

$$NDVI = \frac{(NIR - R)}{(NIR + R)}$$

Because chlorophyll in a healthy plant absorbs most visible red light, and the cellular structure of a healthy plant reflects most near infrared light, NDVI can provide insight to photosynthetic processes occurring in plants. Higher NDVI values indicate more robust plant growth, while lower NDVI values can indicate unhealthy vegetation. Specifically, Wu et al. (2008) utilized NDVI to predict chlorophyll content in winter wheat, and determined wavelengths considered in NDVI metrics (e.g., 670, 800 versus 705, 750). Additionally, nutrient depletion and water availability in plants can also be predicted via NDVI, with more stressed plants incurring a lower reflectance than non-stressed plants (Peñuelas et al., 1994). Normalized difference vegetation index bands can also effectively be used to predict agricultural crop properties like wet biomass, leaf area index, plant height, and yield (Atzberger, 2013; Khanal et al., 2018; Kushal, et al., 2021; Thenkabail et al., 2000).

Remote sensing via NDVI can also be helpful to determine land use/land cover changes over time, as NDVI is the most commonly used vegetation index for determining land use (Atzberger, 2013; Ayala-Silva & Twusami, 2002; Platt et al., 2016). For example, Perreault et al. (2017) reported remote sensed NDVI as an effective way to measure wetland vegetation stability and land cover changes following disturbance of permafrost regions of the Arctic tundra. Additionally, researchers were successful in determining land use/land cover changes over a 7-year period in the northern Eurasian Grain Belt, where transitions of both localized agricultural abandonment and agricultural intensification were observed in different regions of the same study area (Wright et al., 2012).

Land cover changes following installation of underground oil and natural gas pipelines are common, but the longevity of these vegetation alterations, particularly across a large geographical sampling area, is not well documented (Culley & Dow, 1988; de Jong & Button, 1973; Shi et al., 2015). Underground pipelines are installed within a right-of-way (ROW) area, which often includes a trench, road or work area, and piling areas for varying soil horizons. Recent documentation from pipeline companies suggests site remediation, including appropriate revegetation, could be completed within 4-5 years of initial installation proceedings, though this timeline is not often sufficient for complete site remediation to occur (Chapter 2). Additionally, collection of on-farm data regarding pipeline disturbance is time- and labor-intensive, particularly considering multi-year studies which are often needed when considering remediation efficacies over time.

Remote sensing techniques using NDVI reflectance were suggested by Bayramov et al. (2016) to estimate vegetation change and soil erosion risk in pipeline-disturbed areas of Azerbaijan, where bare land, sparse vegetation, and dense vegetation cover were estimated successfully using data from high-resolution multispectral satellites. A significant land cover change of 10% was also documented in an environmental change analysis conducted in pipeline-impacted areas of the Taranaki region within New Zealand (Huisman & Gharibi, 2015).

Here, we investigate the use of NDVI estimated using Sentinel satellite images (10 m resolution) from June-August of 2020 and 2021 to document changes in agricultural crop yields over a two-year period and relate these findings to crop performance (Chapter 2). We are motivated to scale up our intensive on-farm measurements on a select number of sites (Chapter 2) to a larger area and assess the impact of recent pipeline installations across Ohio. The specific objective of this study was to evaluate the impact of pipeline installation on field crop NDVI values and determine the ability of NDVI values to predict crop grain yields.

Methods

Study areas and On-Farm Experimental Design

This study used the same farm fields reported in Chapter 2 and sampled in 2020 and 2021 growing seasons where crops were grown (n=40 crop-year combinations. A replicated but not randomized complete block design was utilized to compare grain yields of corn grain, corn silage, and soybean in fields where the Nexus, Rover, and Utopia pipelines were installed between 2016-2017. Right-of-way (ROW) and adjacent, unaffected areas (ADJ) were each sampled in three paired replicates, equating to six sampling areas per site (Figure 3.1). Adjacent areas were considered a control, as these areas had not been visibly disturbed by pipeline installation. GPS coordinates were documented within each sampling area, for a total of 174 unique sampling locations over the two-year study period.

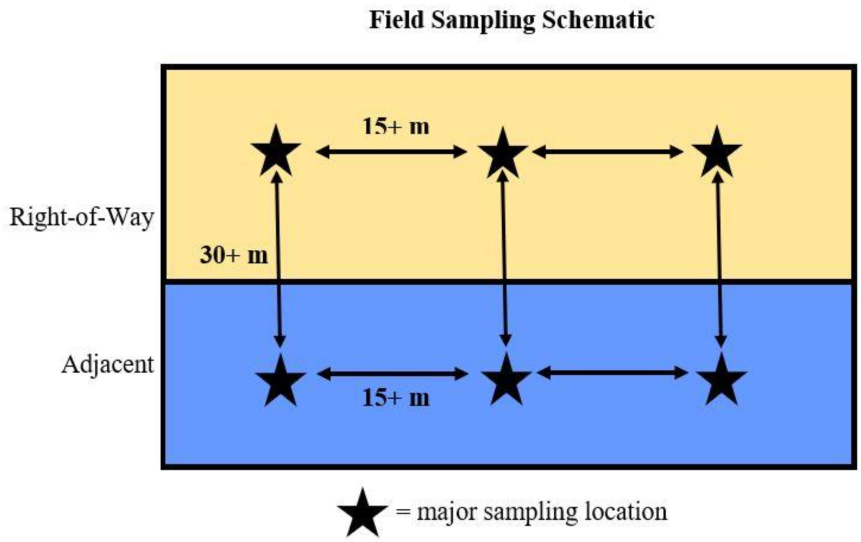

Figure 3.1: Example field sampling schematic, detailing the six (6) major sampling areas taken at each field site between the right-of-way (ROW) and adjacent, unaffected areas (ADJ).

Grain yields were hand-harvested from each location, with the method of sampling varying depending on crop. Yields from each crop were hand-harvested, oven dried for seven days at 49°C, and calculated on an area basis. Corn grain was collected from 12 m² (3 linear m of 4 rows with 0.76 m spacing) the first year and 6 m² (1.5 linear m of 4 rows with 0.76 m spacing) the second year of sampling. All corn ears from the sampling area were counted, whole cobs were dried, and corn ears were hand-shelled. A 7.2 m² (1.8 linear m of 4 rows with 0.76 m spacing) area was used to collect silage corn in 2020, where plants were collected by clipping each plant at the brace root level and harvesting the whole plant. The number of plants were counted prior to being oven dried. No corn silage sites were sampled in 2021. Soybean yield was collected from 5.4 m² (1.8

linear m of 3 rows, spaced at 0.19 m and 0.38 m), and whole plants were clipped at ground level, counted, then oven dried and hand-shelled. Dry yield values were then adjusted to a standard moisture of 155, 670, and 135 g kg^{-1} for corn grain, corn silage, and soybean, respectively.

Remote Sensing Data Collection and Preprocessing

ArcGIS Pro v. 2.9 (Redlands, CA) was used to develop a 1-mile buffer zone around each of the Rover, Utopia, and Nexus pipeline paths spanning the state of Ohio. Depending on the site, temporary ROW widths ranged from 50-150 feet total, with most work occurring within 75 feet of the centerline of each pipeline. Thus, ROW sampling points were designated within a 75 feet boundary of the pipeline centerline, and ADJ sampling points occurred between 150-200 feet from the pipeline centerline to create an "area boundary" for later satellite imagery collection. Coordinates of field sampling locations were organized into a point format (i.e., latitude, longitude) and exported as a shapefile.

Site coordinates, area boundary shapefiles, and KMZ files documenting each individual pipeline path, were uploaded to Google Earth Engine (GEE), an open-source data computing platform, for preprocessing and analysis. High spatial resolution Sentinel-2 satellite imagery (collected in 10-day cycles at 10 m resolution) with less than 20% cloud cover was collected for each pipeline during peak crop growth times (June 1-August 31) of both 2020 and 2021. A JavaScript-based Google Earth Engine Code Editor was used to correct for atmospheric interference and shadowing. Normalized difference vegetation index values (wavelengths ranging from 650-680 and 785-900 for red and near infrared bands, respectively) over the three-month period were averaged to document minimum, maximum, mean, and standard deviation NDVI bands and maps for each pipeline-year combination.

Data Analysis

Data analysis was conducted in R version 4.1 (R Foundation for Statistical Computing, Vienna, Austria). Packages used for analysis and graphing included readxl, ggplot2, tidyverse, and gapminder. 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 (6 observations per site-year, 40 site-year combinations, n=240 observations), as well as across sites in a two-way factorial with treatment and site in the model for each crop A percent difference calculation between the right-of-way (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 the following Equation (3.2):

$$\% \, Difference = \frac{(ROW - ADJ)}{ADJ} \times 100$$

Percent differences were calculated for each site-replication combination, and means and standard errors were calculated from the three replicate observations for each site-treatment combination. This type of calculation was utilized to accommodate and standardize differences in soil type, microclimate, vegetation type, management history, and remediation methods between fields.

Data are presented in three main ways: 1) mean, standard error, and F-statistic of NDVI values across treatments (ROW and ADJ) for all crop-year combinations, 2) mean, standard error, and F-statistic of NDVI for all pipeline-year combinations, and 3) a comparison of ROW vs. ADJ mean NDVI values compared with on-farm yield data for all crop-year combinations.

Results

Influence of Crop, Year and Pipeline Company on NDVI Values

Mean NDVI in the ROW across all sites and cropping types decreased 0.07 during 2020 and 0.06 in 2021 compared with ADJ sampling areas, which indicates lower vegetation greenness in ROW areas in both sampling years (Table 3.1, Figure 3.2). Corn silage was most impacted, with a mean NDVI decrease of 0.14 during 2020, while corn and soybeans respectively decreased an average of 0.08 and 0.02 in 2020, and 0.03 and 0.07 in 2021 (Table 3.1). Differences in NDVI due to pipeline installation (treatment) and site were both highly significant with the treatment representing a larger source of variability relative to site in 3 out of 5 crop-years (Table 3.1).

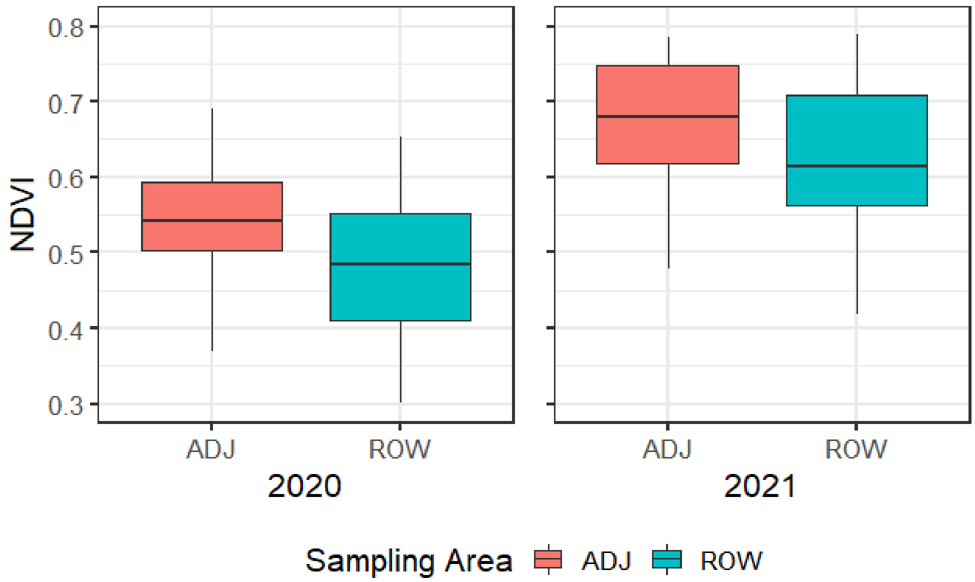

Figure 3.2: Distribution of normalized difference vegetation index (NDVI) values over pipeline right-of-way (ROW) and adjacent (ADJ), undisturbed areas during 2020 and 2021. Values represent treatment distributions for all pipelines (Rover, Utopia, and Nexus) and crops within a given year.

Table 3.1: Mean, standard error (SE), range, and F-statistic of NDVI reflectance values for right-of-way (ROW) and adjacent (ADJ), unaffected areas of the corn, corn silage, and soybean crops in 2020 and 2021.

		ROW		ADJ		F-Statistic[6]		
Crop	**Year**	**Mean (SE)**	**Range**	**Mean (SE)**	**Range**	**Trt[7]**	**Site**	**Site*Trt**
Corn	2020	0.45 (0.02)	0.28-0.63	0.53 (0.01)	0.36-0.63	140.94****	41.67****	7.87****
	2021	0.63 (0.01)	0.54-0.73	0.66 (0.01)	0.57-0.75	19.55**	40.22****	4.66**
Corn Silage	2020	0.52 (0.03)	0.43-0.53	0.66 (0.02)	0.63-0.66	762.61****	377.95****	185.29****
Soybean	2020	0.52 (0.02)	0.41-0.63	0.54 (0.01)	0.46-0.66	9.21***	39.27****	1.47
	2021	0.62 (0.02)	0.42-0.81	0.69 (0.02)	0.48-0.82	65.64****	37.93****	7.15****

[6] Significance is reported as ****=0.0001, ***=0.001, **=0.01, and *=0.05.
[7] Note: Trt – Treatment; pipelines type is considered as a treatment effect.

Examining sites individually revealed that decreases in NDVI were nearly universal for all crops (Figure 3.3, Table S10). Percent change in NDVI for 2020 sampling ranged from -37.14 to 4.79% for corn, -30.11 to -9.80 % for corn silage and -11.78 to -0.04% for soybean (Figure 3.3). Similarly, 2021 percent change in NDVI ranged from -37.14 to 4.79% for corn and -37.15 to 1.97% for soybean (Figure 3.3). In combining mean NDVI for both 2020 and 2021, average decreases 11.11% were seen for corn, 19.96% for corn silage, and 8.58% for soybean. Although the total sites in corn varied greatly between the two years, corn NDVI values were more negatively impacted by pipeline installation in 2020 relative to 2021, with a majority of sites experiencing a > 12.5% decline (Figure 3.3).

Evaluation of the impact of individual pipelines on NDVI values revealed differences between pipelines (Table 3.2, Figure 3.4). Average NDVI values decreased in ROW areas relative to ADJ in all pipelines and crops, except for Nexus in corn and soybean (Table 3.2). Rover and Utopia pipelines had consistently lower NDVI within ROW areas compared with ADJ sampling areas, with an average decrease of 0.06, 0.20, and 0.06 for Rover corn, corn silage, and soybeans, respectively (Table 3.2, Figure 3.4). Corn and soybean NDVI in the Utopia ROW were both an average of 0.09 lower than ADJ areas (Table 3.2).

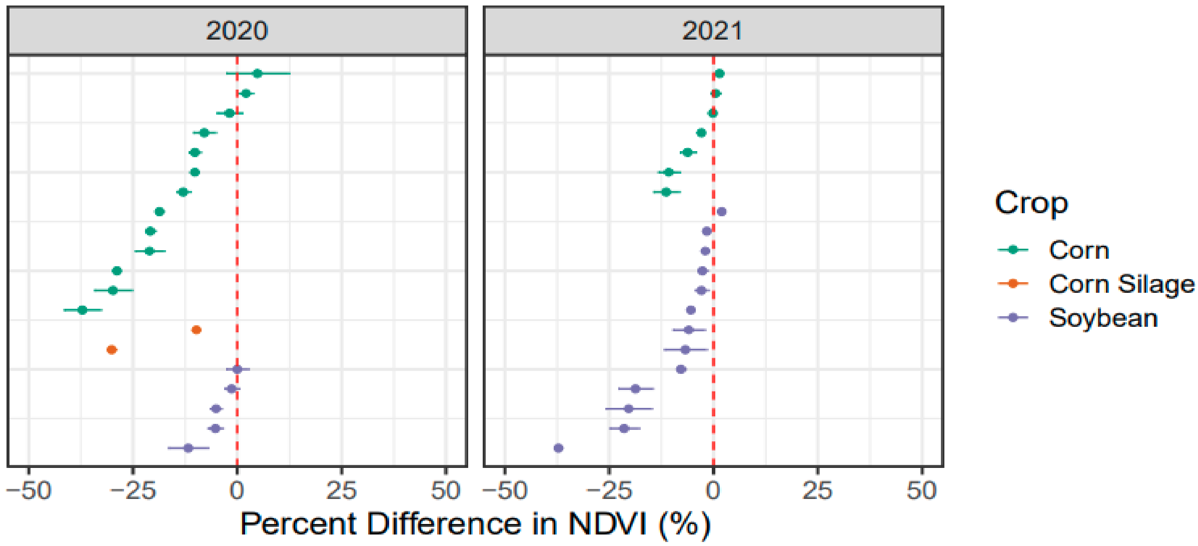

Figure 3.3: Average percent difference values for normalized difference vegetation index (NDVI) between right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across sites in 2020 and 2021. Percent differences were calculated with each paired replicate with the point representing the mean of each 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 NDVI when compared with adjacent values, while values on the right side indicate an increase in NDVI.

Interestingly, even when mean NDVI were similar between ROW and ADJ, ROW values often had a lower minimum range than ADJ areas, indicating more variability within and between sites in ROW areas (Table 3.2). For example, corn on the Rover pipeline had a minimum NDVI value 0.14 below that of the lowest ADJ value, and soybean on the Utopia pipeline was 0.18 lower than ADJ minimum values. Comparatively, the maximum range of NDVI values are similar across crop-year combinations in each pipeline, with the exception of corn silage where only one site was sampled per pipeline, resulting in more variability between ROW and ADJ sampling areas compared with other crops which had higher rate of sites included per crop (Table 3.2).

Table 3.2: Mean, standard error (SE), range, and F-statistics of normalized difference vegetation index (NDVI) reflectance values for right-of-way (ROW) and adjacent (ADJ), unaffected areas of the Rover, Utopia, and Nexus pipelines over both 2020 and 2021.

		ROW		**ADJ**		**F-Statistic[8]**		
Pipeline	**Crop**	**Mean (SE)**	**Range**	**Mean (SE)**	**Range**	**Trt**	**Site**	**Site*Trt**
Nexus	Corn	0.61 (0.03)	0.46-0.73	0.60 (0.03)	0.48-0.72	0.71	178.57****	0.36
	Corn Silage	0.60 (0.00)	0.60-0.61	0.67 (0.01)	0.66-0.68	178.84**		
	Soybean	0.55 (0.03)	0.41-0.78	0.56 (0.03)	0.46-0.77	2.85	115.09****	1.61
Rover	Corn	0.54 (0.02)	0.34-0.71	0.60 (0.01)	0.48-0.75	15.02***	9.35****	1.14
	Corn Silage	0.44 (0.01)	0.44-0.45	0.64 (0.01)	0.63-0.65	543.46**		
	Soybean	0.60 (0.02)	0.42-0.81	0.66 (0.02)	0.48-0.82	39.96****	36.8****	3.42**
Utopia	Corn	0.43 (0.03)	0.28-0.63	0.52 (0.02)	0.37-0.63	71.53****	56.06****	7.44***
	Soybean	0.63 (0.04)	0.47-0.74	0.74 (0.03)	0.65-0.77	53.16****	17.37***	28.92****

[8] Significance is reported as ****=0.0001, ***=0.001, **=0.01, and *=0.05

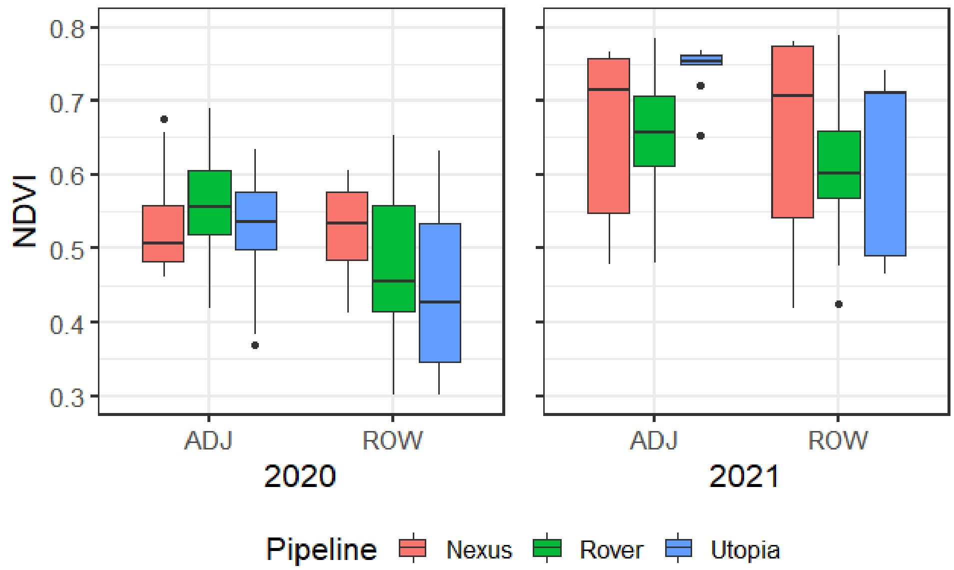

Figure 3.4: Distribution of normalized difference vegetation index (NDVI) values over the pipeline right-of-way (ROW) and adjacent (ADJ), undisturbed areas for the Nexus, Rover, and Utopia pipelines. Values represent all crops (corn, corn silage, and soybean) for 2020 and 2021.

Relationship between NDVI and Crop Yield

When comparing on-farm, hand-harvested crop yields to mean NDVI over both sampling years, a weak positive correlation can be seen for corn, with R^2 values of 0.16 and 0.09 for 2020 and 2021 respectively, and a 2020 corn silage R^2 value of 0.20 (Table 3.3, Figure 3.5). However, soybean NDVI-yield correlations are more complex. Increasing soybean yields during 2020 are associated with decreased NDVI values, whereas a seemingly negligible correlation between NDVI and yield occurs in soybean during 2021. However, Site 28 accounts for high variability during 2021, with a combination of high yields and low NDVI values (Figure 3.5). When excluding this site from the linear regression analysis for 2021, a much stronger correlation between NDVI and yield was found, with an R^2 of 0.20 (Table 3.3, Figure 3.6). Overall, NDVI-yield correlations do exist between crop-year combinations, though a significant relationship between yield and NDVI on a site-to-site basis was not established.

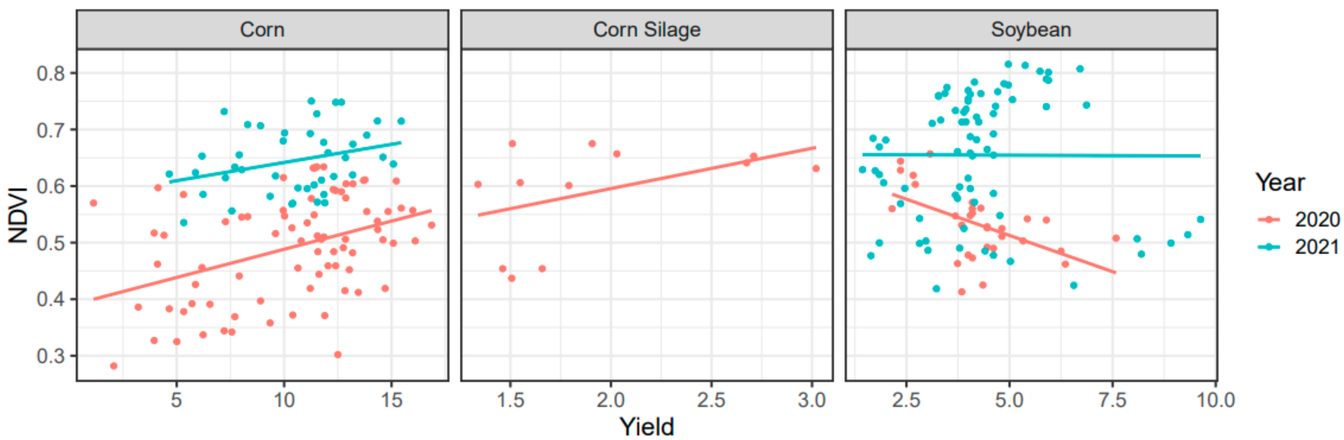

Figure 3.5: Relationships between crop yields and normalized difference vegetation index (NDVI) from the same sampling areas in 2020 (red points) and 2021 (blue points) for all sites by crop. Yields for all crops are reported as Mg ha $^{-1}$. Linear regression equations are found in Table 3.3.

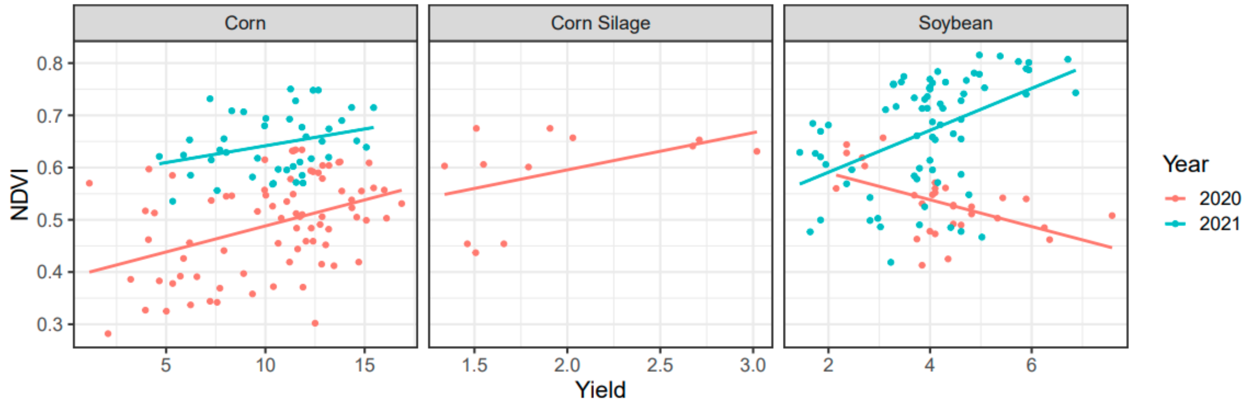

Figure 3.6: Relationships between crop yields and normalized difference vegetation index (NDVI) from the same sampling areas in 2020 (red points) and 2021 (blue points) for all sites except Site 28 by crop. Yields for all crops are reported as Mg ha $^{-1}$. Linear regression equations are found in Table 3.3.

Table 3.3: Linear regression equations and R^2 values comparing yield and NDVI for each crop yield-year combination.

Crop	**Year**	**Linear Regression Equation**	**R^2**
Corn	2020	y= 0.389x + 0.00063	0.16
	2021	y=0.577x + 0.00040	0.09
Corn Silage	2020	y=0.453x + 0.00016	0.20
Soybean	2020	y=0.641x - 0.00161	0.28
Including Site 28	2021	y=0.656x - 0.000017	0.00
Excluding Site 28	2021	y=0.511x + 0.00252	0.21

Discussion

Our NDVI values follow trends of estimated NDVI for crop performance, with disturbed areas often having lower reflectance rates compared with undisturbed areas (Cuca & Agapiou, 2017; Hao et al., 2020; Ji et al., 2021). In a study of the Shaanxi Province of China, Wang, Liu, Liu, et al. (2020) reported a significant decrease in NDVI with land use changes of farmland being converted to construction areas over an 18-year period. However, over time, these decreasing trends were minimized as restoration and remediation practices occur on disturbed lands. In a pipeline-disturbed area of Azerbaijan, researchers were able to document a significant decrease in bare land from 2007 to 2012, with a combined increase in sparse vegetation such as shrubs, grasslands, and senescing crops and dense vegetation like crops and trees (Bayramov et al., 2016). The authors concluded that increasing NDVI values across land cover types correlated with increasing vegetation density on pipeline-impacted areas.

More extreme decreases in corn yields during 2020 may be a factor of precipitation, as average precipitation in Ohio from June-August of 2020 was extremely low, with precipitation increasing slightly in August (NOAA Staff, 2021b). Based on the National Oceanic and Atmospheric Administration (NOAA) Statewide Precipitation ranking system, with 1 being the driest period recorded since data collection began in 1895, and 128 being the wettest, Ohio only ranked 29 in 2020, with this region considered to be in a drought during the June-August growing season (NOAA Staff, 2021b). Comparatively, precipitation from June-August of 2021 was above average, ranked 113 (NOAA Staff, 2021b). As corn can be extremely susceptible to drought, with between 2.1-8.0% yield reductions per day of stress during growing periods between pollination and dent, more severe corn yield reductions seen in 2020 may be a factor of precipitation, as compared with higher overall NDVI values seen in corn from 2021 (Lauer, 2018). Comparatively, drought-stressed soybean plants can flower again and initiate pod setting, even into the mid seed filling stage, so increased rainfall in August

2020 may have been a factor in increased soybean yields in this crop-year combination which were not reflected in NDVI values across the growing period (Licht & Clemens, 2020). Because later flowering of soybean crops can occur late in the growing season if increased precipitation occurs, NDVI from June-August may have captured drought-stressed soybean crops during the driest part of the growing season, while our hand-harvested sampling method captured soybean yield data following the late flowering process after yields may have rebounded from the drought. Additionally, prior studies have also shown a weaker correlation or non-linear response between NDVI and soybean yield, as compared with other field crops like corn, particularly during the middle of the growing season (Johnson, 2016, Xu & Katchova, 2019)

Additionally, the lack of correlation between NDVI and soybean yield for Site 28 is difficult to explain (Figure 3.5). Coordinates of on-farm sampling areas match with geographic coordinates utilized in NDVI data collection, but stand counts for this site specifically are not available for reference due to misplacement of stand count reports during yield processing for this site. However, when considering Site 28 as an outlier (Figure 3.6, Table 3.3), a much stronger relationship between NDVI-yield modelling exists in 2021, which is much more closely correlated with results from other crop-year combinations.

Our attempt to link NDVI with crop yield data are a promising start but have limitations. The lack of strong correlation in the NDVI-yield regression model (Figure 5) indicates more work must be done to gather more precise remotely sensed data. In this study, NDVI were gathered from a 3-month growing period of June-August, but on-farm sampling did not occur at sites until September-November. While mid-growing season is generally perceived as the most accurate time to collect NDVI data (Khanal et al., 2020), some bare soil may still have been visible in satellite data collected in early June, particularly if strong vegetative growth did not occur in the earlier NDVI sampling time but occurred later in the year. While averaging NDVI over the 3-month sampling period assists in smoothing irregularities between timepoints, influences from lack of strong vegetative growth in the early part of the growing season may still influence overall values, particularly in 2020 when sampling areas were in a drought.

Thus, future work on this project should examine how NDVI changes between periods of the growing season will influence NDVI values and treatment differences. Additionally, to extrapolate the limited, but intensive on-farm data we collected to a larger state-wide scale we will systematically sample agricultural areas along each of the three pipelines, following a similar pattern of comparing ROW and ADJ areas. Comparing NDVI from prior to pipeline installation, as well as every year since, will provide a clearer picture of the revegetation and remediation processes on pipeline-disturbed agricultural lands, and may indicate trends of how long it will take for vegetation on pipelined lands to meet pre-disturbance levels.

Conclusions

Remote sensing is a possible avenue for more effective management of time and labor resources relative to data collection by hand. NDVI analysis suggests that ROW areas have a lower reflectance, and thus vegetation greenness, than adjacent, unaffected areas of the same agricultural fields. Our work here establishes a weak but positive correlation between NDVI and crop yields in most crop-year combinations. Precipitation rates may have played a factor in soybean NDVI-yield relationships over both sampling years, while corn and corn silage had more consistent correlations between NDVI and yield across precipitation rates. Future work to effectively investigate the relationship between NDVI and yield loss on pipeline-disturbed areas will hopefully bring additional insights, particularly on a larger scale, including additional sites which were not originally included in the previous field-based study. Because optical remotely sensed data are preserved for years and openly accessible, NDVI data can continue to be used to compare yields over years, rather than just a limited snapshot presented here.

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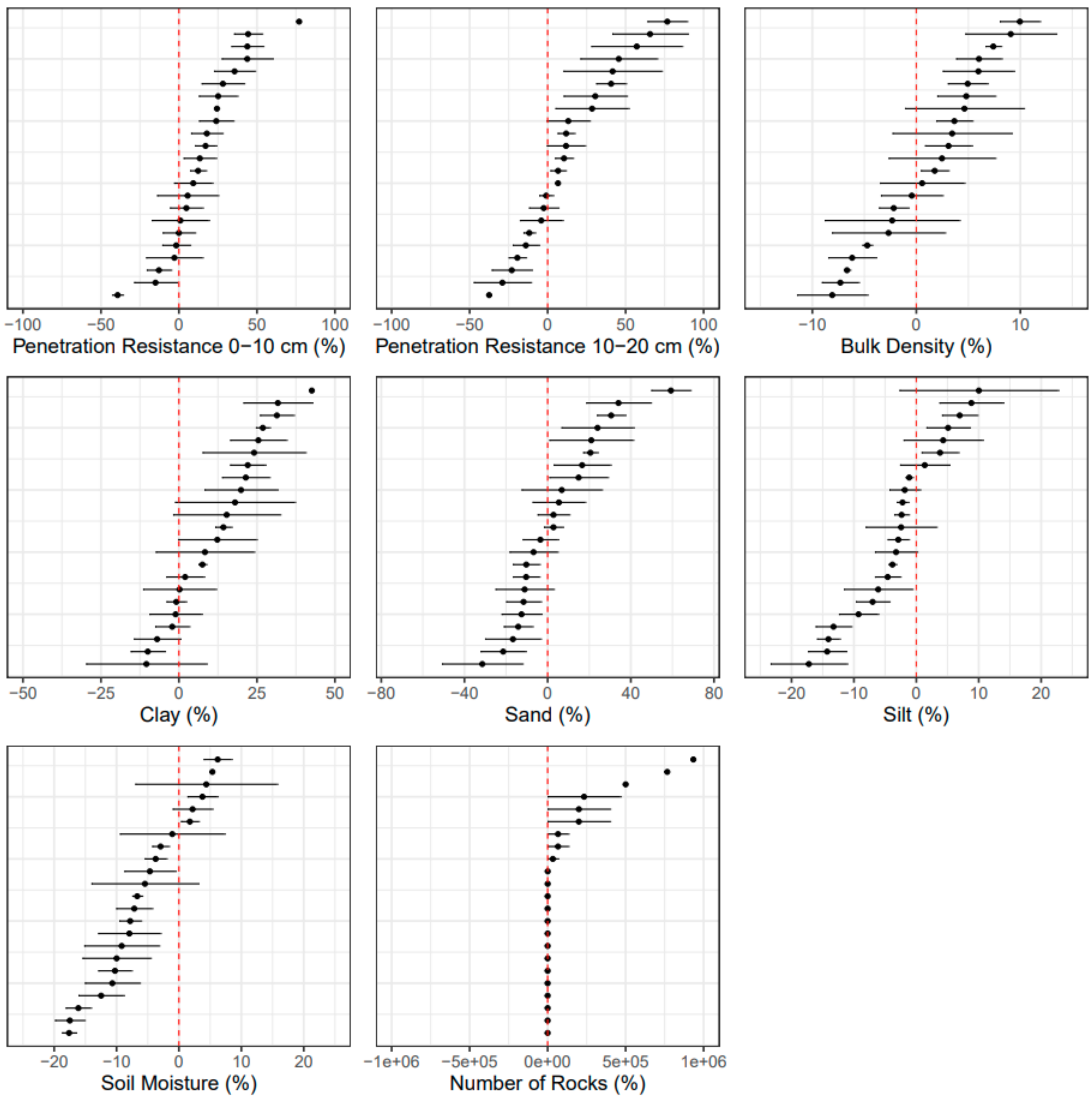
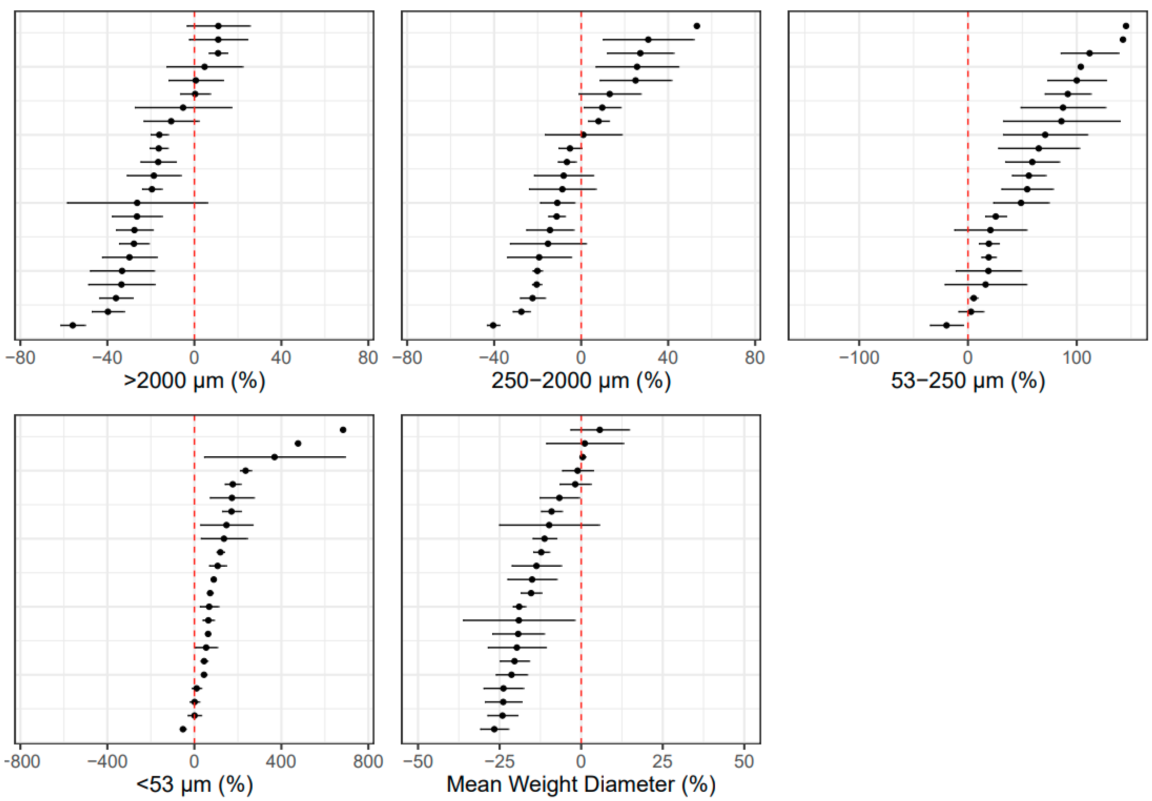
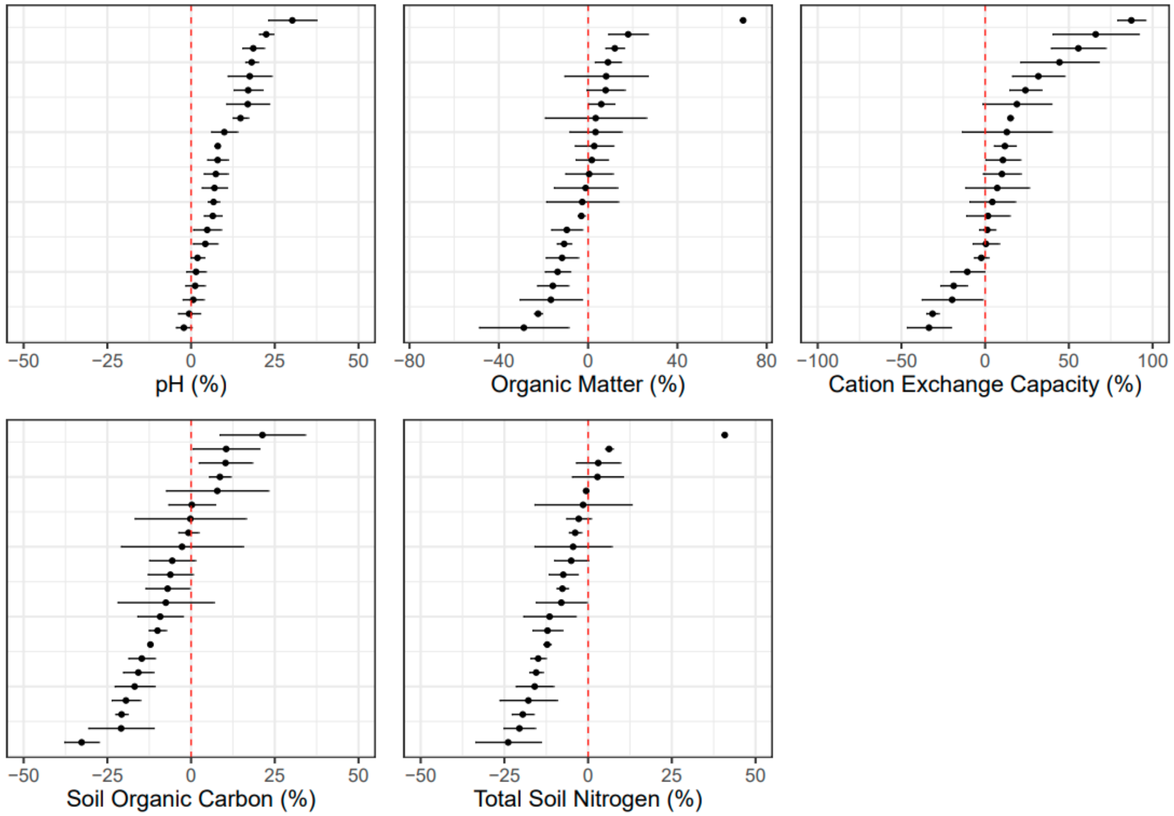
Appendix A. Supplemental Figures



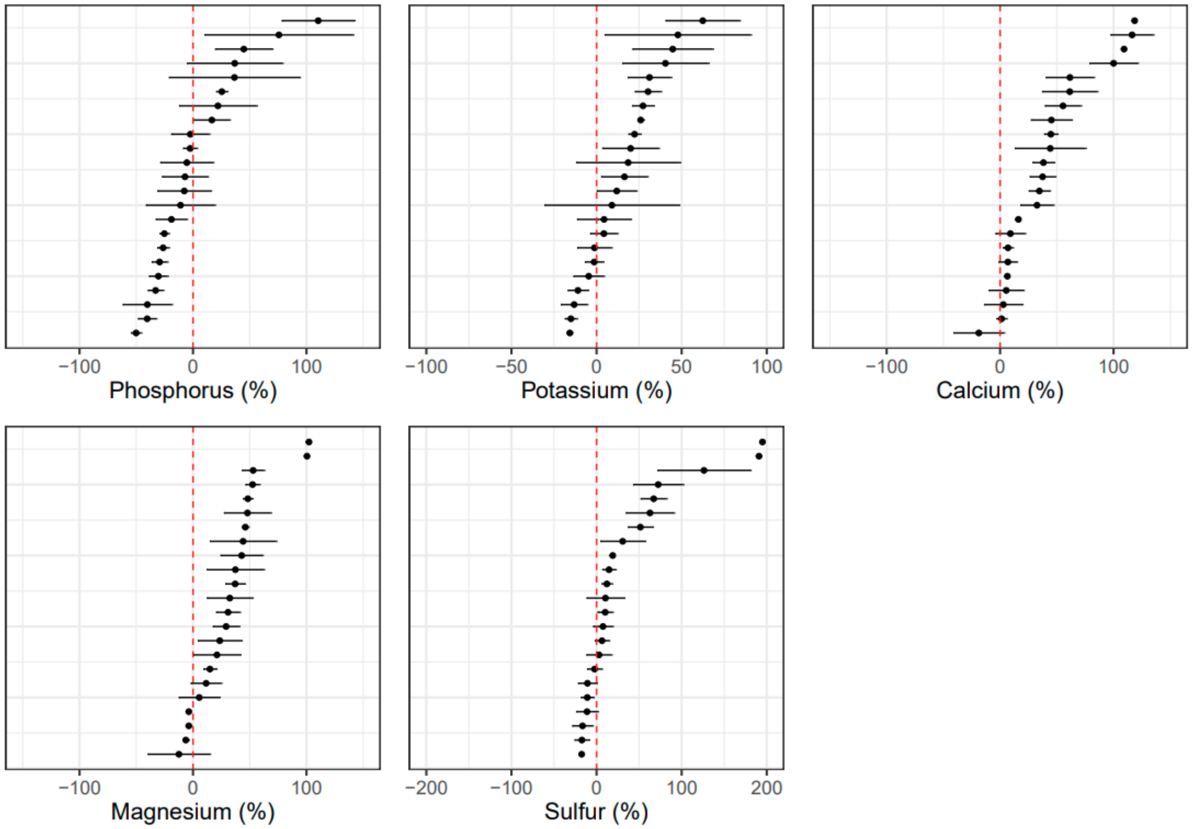
Supplemental Figure S1: Average percent difference values for select soil physical properties between right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites. Percent differences were calculated with each paired replicate with the point representing the mean of each site and error 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.



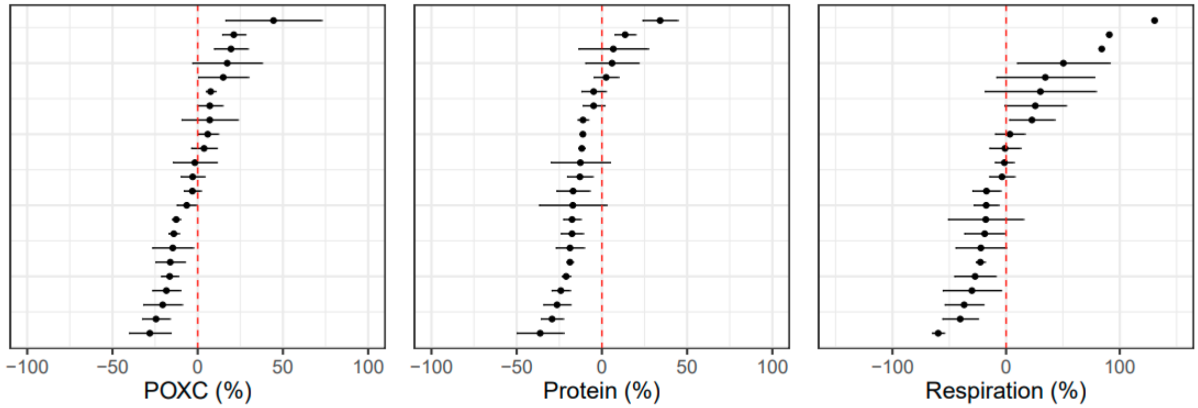
Supplemental Figure S2: Average percent difference values for aggregate stability size classes between right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites. Percent differences were calculated with each paired replicate with the point representing the mean of each site and error 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 select size classes when compared with adjacent values, while values on the right side indicate an increase in select size classes.



Supplemental Figure S3: Average percent difference values for select soil chemical properties between right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites. Percent differences were calculated with 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.



Supplemental Figure S4: Average percent difference values for select Mehlich-3 extractable nutrients between right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites. Percent differences were calculated with 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 nutrient values when compared with adjacent values, while values on the right side indicate an increase in nutrient values.



Supplemental Figure S5: Average percent difference values for select soil biological and biochemical properties between right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across 23 sites. Percent differences were calculated with 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.

Appendix B. Supplemental Tables

Supplemental Table S1: Mean (standard error) of select soil physical characteristics in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across all 23 sites.

	Mean (Standard Error) of Select Soil Physical Characteristics									
							Penetration Resistance (MPa)			
	Soil Moisture (g kg^{-1})		Number of Rocks		Bulk Density (g cm^{-3})		0-10 cm		10-20 cm	
Site ID	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**
1	197.7 (7.83)	220.3 (3.3)	23.0 (3.6)^{a}	1.0 (0.6)^{b}	1.3 (0.0)	1.3 (0.0)	4.2 (0.3)	4.4 (0.5)	5.2 (0.1)	4.7 (0.3)
2	186.3 (3.8)^{b}	222.2 (2.6)^{a}	9.0 (2.6)	7.3 (1.9)	1.4 (0.0)	1.3 (0.0)	2.9 (0.4)	2.0 (0.2)	4.2 (0.5)	2.9 (0.2)
3	146.1 (1.2)^{b}	177.4 (2.9)^{a}	12.0 (1.2)	12.0 (4.7)	1.3 (0.0)	1.3 (0.0)	4.2 (0.4)	3.4 (0.2)	4.6 (0.4)	3.6 (0.4)
4	164.4 (2.0)	170.9 (4.6)	15.0 (1.2)	11.0 (2.1)	1.2 (0.0)	1.2 (0.0)	2.5 (0.3)	2.7 (0.3)	3.5 (0.2)	4.1 (0.3)
5	184.1 (9.3)	203.5 (8.9)	24.0 (9.5)	14.0 (7.8)	1.2 (0.0)	1.2 (0.0)	3.1 (0.3)	2.7 (0.2)	2.8 (0.3)	3.4 (0.2)
6	150.7 (2.5)	164.6 (8.3)	7.7 (0.3)	9.0 (4.6)	1.2 (0.0)^{b}	1.3 (0.0)^{a}	3.6 (0.4)	4.4 (0.3)	4.7 (0.2)	4.5 (0.3)
7	169.4 (1.9)^{b}	181.5 (1.0)^{a}	3.0 (1.0)	1.0 (0.6)	1.0 (0.0)	1.1 (0.1)	2.7 (0.2)^{a}	2.2 (0.1)^{b}	3.2 (0.1)	3.2 (0.4)
8	145.3 (5.1)^{b}	176.2 (5.1)^{a}	51.3 (9.1)^{a}	18.3 (7.7)^{b}	1.1 (0.1)	1.2 (0.1)	4.2 (0.2)	3.6 (0.1)	4.5 (0.1)^{a}	4.0 (0.1)^{b}
9	201.8 (14.5)	195.0 (9.3)	8.7 (4.2)	6.7 (2.3)	1.2 (0.0)^{b}	1.3 (0.0)^{a}	2.5 (0.2)	2.7 (0.5)	3.1 (0.1)	3.2 (0.3)
10	177.0 (12.4)	191.9 (27.2)	7.7 (3.5)	7.3 (5.9)	1.3 (0.1)^{a}	1.2 (0.0)^{b}	2.5 (0.5)	1.8 (0.3)	2.7 (0.5)	3.1 (0.5)
11	203.1 (7.8)	232.3 (6.2)	4.0 (1.2)	2.7 (0.9)	1.3 (0.0)	1.2 (0.0)	1.8 (0.1)	1.5 (0.2)	3.2 (0.4)^{a}	2.0 (0.1)^{b}
12	224.6 (1.4)^{a}	211.6 (3.1)^{b}	3.0 (0.6)	1.3 (1.3)	1.1 (0.0)	1.2 (0.0)	1.2 (0.2)	1.3 (0.3)	1.6 (0.3)	2.1 (0.1)
13	227.5 (3.5)	223.7 (2.1)	5.3 (1.5)	7.3 (1.9)	1.2 (0.0)	1.2 (0.1)	1.4 (0.1)	1.6 (0.1)	1.4 (0.0)^{b}	2.3 (0.1)^{a}
14	227.6 (15.9)	218.9 (10.4)	2.7 (1.8)	1.0 (0.6)	1.0 (0.0)	1.0 (0.0)	2.6 (0.4)	2.5 (0.4)	3.6 (0.4)	3.7 (0.1)

Supplemental Table S1, Continued

15	203.8 (8.8)	220.0 (11.9)	10.7 (2.3)	9.7 (9.2)	1.3 (0.0)	1.2 (0.0)	2.5 (0.2)[a]	1.8 (0.1)[b]	2.4 (0.1)	2.0 (0.3)
16	216.4 (2.5)	243.2 (10.6)	14.3 (1.2)	8.3 (2.3)	1.2 (0.0)	1.1 (0.0)	2.5 (0.3)	1.9 (0.1)	2.9 (0.2)	2.0 (0.1)
17	134.3 (3.9)	141.1 (3.9)	2.0 (1.0)	4.7 (0.7)	1.2 (0.0)	1.3 (0.0)	3.0 (0.3)	2.8 (0.2)	3.2 (0.4)	3.0 (0.1)
18	186.4 (7.6)[b]	202.0 (4.5)[a]	14.3 (4.1)	8.3 (2.4)	1.4 (0.1)	1.3 (0.0)	3.2 (0.4)	2.8 (0.3)	3.1 (0.7)	2.2 (0.0)
19	220.1 (1.5)[a]	208.9 (1.4)[b]	2.0 (0.6)	1.0 (0.6)	1.1 (0.1)	1.1 (0.0)	0.8 (0.0)[b]	1.4 (0.1)[a]	1.1 (0.1)	1.7 (0.3)
20	263.6 (4.7)	271.6 (1.1)	0.0 (0.0)	0.0 (0.0)	1.1 (0.0)[a]	1.0 (0.0)[b]	2.0 (0.2)	1.2 (0.2)	2.0 (0.1)	1.9 (0.2)
21	241.0 (2.4)	236.3 (7.6)	23.0 (1.5)[a]	3.3 (2.4)[b]	1.3 (0.0)[a]	1.2 (0.0)[b]	4.2 (0.2)	1.7 (0.1)	5.2 (0.6)	1.9 (0.1)
22	150.7 (9.6)	169.3 (18.9)	30.0 (7.0)[a]	4.3 (2.3)[b]	1.2 (0.0)	1.2 (0.0)	3.0 (0.5)	2.3 (0.1)	4.1 (0.4)	2.3 (0.1)
23	183.7 (6.9)	187.3 (10.4)	10.0 (3.5)	4.3 (2.8)	1.1 (0.0)[a]	1.0 (0.0)[b]	1.5 (0.1)	1.5 (0.2)	2.4 (0.2)	2.2 (0.1)

Supplemental Table S2: Number of significant ($p < 0.05$) increases or decreases in right-of-way (ROW) soil physical, chemical, and biological/biochemical characteristics, as compared with adjacent, unaffected areas, out of 23 possible observations.

Physical			**Chemical**			**Biological and Biochemical**		
Variable	**Increases**	**Decreases**	**Variable**	**Increases**	**Decreases**	**Variable**	**Increases**	**Decreases**
Penetration Resistance (MPa)			pH	8	1	POXC	0	3
0-10 cm	2	1	OM	0	1	Protein	0	7
10-20 cm	2	1	CEC	3	1	Respiration	0	2
Bulk Density (g cm^{-3})	4	2	Total C	0	3			
Texture (g kg^{-1})			TSN	2	7			
Clay	6	0	P	1	5			
Sand	2	0	K	6	0			
Silt	1	4	Ca	11	1			
Aggregate Stability (%)			Mg	5	1			
>2000 µm	1	5	S	3	0			
250-2000 µm	0	5						
53-250 µm	7	0						
<53 µm	8	0						
Mean Weight Diameter (µm)	7	2						
Soil Moisture (g kg^{-1})	2	5						
Number of Rocks	4	0						

Supplemental Table S3: Mean (standard error) of soil textural characteristics (g kg^{-1}) in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across all 23 sites.

	Mean (Standard Error) of Soil Textural Characteristics (g kg^{-1})					
	Clay		Sand		Silt	
Site ID	ROW	ADJ	ROW	ADJ	ROW	ADJ
1	137.3 (13.8)	114.1 (79.4)	193.7 (30.4)	229.7 (10.2)	669.0 (23.6)	637.3 (8.7)
2	138.0 (6.6)	72.3 (77.7)	182.0 (7.7)	164.0 (18.0)	680.3 (4.8)	660.7 (13.1)
3	159.3 (20.7)[a]	89.4 (49.1)[b]	222.3 (6.0)	227.7 (11.3)	618.3 (18.2)	606.0 (6.6)
4	124.3 (9.3)[a]	114.3 (70.9)[b]	246.7 (28.9)	214.3 (15.1)	628.7 (19.6)[b]	659.7 (15.8)[a]
5	147.3 (7.4)[a]	121.3 (121.7)[b]	220.7 (18.5)	288.3 (28.8)	632.0 (13.1)	543.0 (17.0)
6	151.0 (3.5)	103.0 (36.7)	172.3 (2.3)	177.3 (10.0)	676.3 (1.5)[b]	660.3 (6.5)[a]
7	345.7 (20.9)	178.7 (178.4)	230.3 (25.3)	150.3 (28.6)	424.0 (5.5)	440.0 (11.9)
8	153.0 (11.9)	98.6 (114.6)	166.7 (14.4)	265.3 (28.3)	680.3 (16.7)[a]	562.3 (38.5)[b]
9	139.3 (19.9)	119.7 (20.3)	202.3 (7.2)	190.0 (29.0)	658.3 (25.1)	644.0 (28.0)
10	151.7 (32.9)	108.8 (224.1)	378.3 (75.5)	352.3 (40.1)	470.3 (44.1)	485.3 (19.8)
11	224.3 (9.5)	141.7 (83.3)	192.7 (22.3)	198.3 (10.8)	583.3 (14.5)	529.0 (19.1)
12	208.3 (11.6)[a]	104.7 (49.1)[b]	207.3 (19.3)	234.0 (20.6)	584.3 (7.9)	506.7 (16.3)
13	196.0 (11.0)	111.3 (101.7)	237.7 (15.4)	194.0 (20.5)	566.0 (23.6)	549.7 (11.7)
14	246.3 (19.2)	263.7 (405.0)	294.3 (23.8)	256.0 (42.5)	459.7 (5.0)	442.0 (2.1)
15	170.7 (33.4)	108.6 (51.3)	211.7 (38.8)[a]	188.7 (34.0)[b]	617.7 (10.2)	672.0 (31.6)
16	165.3 (3.2)	121.3 (95.6)	163.7 (18.7)	168.0 (16.5)	670.7 (15.8)	678.7 (16.1)
17	90.7 (3.5)	77.2 (158.6)	560.3 (15.9)	488.3 (49.1)	349.7 (12.2)	382.7 (35.5)
18	151.0 (6.1)	97.4 (116.8)	253.0 (27.1)	295.0 (47.1)	596.3 (31.9)	555.3 (39.1)
19	195.7 (12.6)[a]	173.3 (219.6)[b]	197.0 (9.6)	172.7 (21.0)	607.7 (8.4)[b]	600.7 (7.5)[a]
20	245.3 (10.2)[a]	132.3 (52.4)[b]	173.0 (5.7)	135.0 (15.0)	582.0 (13.3)	622.0 (13.8)
21	189.7 (27.0)	148.3 (164.8)	179.0 (2.5)	215.7 (4.5)	631.3 (28.1)	539.7 (13.7)
22	164.3 (13.5)	100.5 (453.5)	666.0 (12.1)[a]	625.0 (35.7)[b]	562.3 (38.5)[b]	680.3 (16.7)[a]
23	167.0 (22.3)	122.0 (144.5)	645.7 (21.7)	623.3 (7.9)	644.0 (28.0)	658.3 (25.1)

Supplemental Table S4: Mean (standard error) of soil aggregate stability (%) in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across all 23 sites.

	Mean (Standard Error) of Aggregate Stability (%)									
	>2000 µm		250-2000 µm		53-250 µm		<53 µm		Mean Weight Diameter (µm)	
Site ID	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**
1	197.7 (7.83)	220.3 (3.3)	23.0 (3.6)[a]	1.0 (0.6)[b]	114.1 (79.4)	1373 (13.8)	229.7 (10.2)	193.7 (30.4)	637.3 (8.7)	669.0 (23.6)
2	186.3 (3.8)[b]	222.2 (2.6)[a]	9.0 (2.6)	7.3 (1.9)	72.3 (77.7)	138.0 (6.6)	164.0 (18.0)	182.0 (7.7)	660.7 (13.1)	680.3 (4.8)
3	146.1 (1.2)[b]	177.4 (2.9)[a]	12.0 (1.2)	12.0 (4.7)	89.4 (49.1)[b]	159.3 (20.7)[a]	227.7 (11.3)	222.3 (6.0)	606.0 (6.6)	618.3 (18.2)
4	164.4 (2.0)	170.9 (4.6)	15.0 (1.2)	11.0 (2.1)	114.3 (70.9)[b]	124.3 (9.3)[a]	214.3 (15.1)	246.7 (28.9)	659.7 (15.8)[a]	628.7 (19.6)[b]
5	184.1 (9.3)	203.5 (8.9)	24.0 (9.5)	14.0 (7.8)	121.3 (121.7)[b]	147.3 (7.4)[a]	288.3 (28.8)	220.7 (18.5)	543.0 (17.0)	632.0 (13.1)
6	150.7 (2.5)	164.6 (8.3)	7.7 (0.3)	9.0 (4.6)	103.0 (36.7)	151.0 (3.5)	177.3 (10.0)	172.3 (2.3)	660.3 (6.5)[a]	676.3 (1.5)[b]
7	169.4 (1.9)[b]	181.5 (1.0)[a]	3.0 (1.0)	1.0 (0.6)	178.7 (178.4)	345.7 (20.9)	150.3 (28.6)	230.3 (25.3)	440.0 (11.9)	424.0 (5.5)
8	145.3 (5.1)[b]	176.2 (5.1)[a]	51.3 (9.1)[a]	18.3 (7.7)[b]	98.6 (114.6)	153.0 (11.9)	265.3 (28.3)	166.7 (14.4)	562.3 (38.5)[b]	680.3 (16.7)[a]
9	201.8 (14.5)	195.0 (9.3)	8.7 (4.2)	6.7 (2.3)	119.7 (20.3)	139.3 (19.9)	190.0 (29.0)	202.3 (7.2)	644.0 (28.0)	658.3 (25.1)
10	177.0 (12.4)	191.9 (27.2)	7.7 (3.5)	7.3 (5.9)	108.8 (224.1)	151.7 (32.9)	352.3 (40.1)	378.3 (75.5)	485.3 (19.8)	470.3 (44.1)
11	203.1 (7.8)	232.3 (6.2)	4.0 (1.2)	2.7 (0.9)	141.7 (83.3)	224.3 (9.5)	198.3 (10.8)	192.7 (22.3)	529.0 (19.1)	583.3 (14.5)
12	224.6 (1.4)[a]	211.6 (3.1)[b]	3.0 (0.6)	1.3 (1.3)	104.7 (49.1)[b]	208.3 (11.6)[a]	234.0 (20.6)	207.3 (19.3)	506.7 (16.3)	584.3 (7.9)
13	227.5 (3.5)	223.7 (2.1)	5.3 (1.5)	7.3 (1.9)	111.3 (101.7)	196.0 (11.0)	194.0 (20.5)	237.7 (15.4)	549.7 (11.7)	566.0 (23.6)
14	227.6 (15.9)	218.9 (10.4)	2.7 (1.8)	1.0 (0.6)	263.7 (405.0)	246.3 (19.2)	256.0 (42.5)	294.3 (23.8)	442.0 (2.1)	459.7 (5.0)
15	203.8 (8.8)	220.0 (11.9)	10.7 (2.3)	9.7 (9.2)	108.6 (51.3)	170.7 (33.4)	188.7 (34.0)[b]	211.7 (38.8)[a]	672.0 (31.6)	617.7 (10.2)
16	216.4 (2.5)	243.2 (10.6)	14.3 (1.2)	8.3 (2.3)	121.3 (95.6)	165.3 (3.2)	168.0 (16.5)	163.7 (18.7)	678.7 (16.1)	670.7 (15.8)
17	134.3 (3.9)	141.1 (3.9)	2.0 (1.0)	4.7 (0.7)	77.2 (158.6)	90.7 (3.5)	488.3 (49.1)	560.3 (15.9)	382.7 (35.5)	349.7 (12.2)
18	186.4 (7.6)[b]	202.0 (4.5)[a]	14.3 (4.1)	8.3 (2.4)	97.4 (116.8)	151.0 (6.1)	295.0 (47.1)	253.0 (27.1)	555.3 (39.1)	596.3 (31.9)
19	220.1 (1.5)[a]	208.9 (1.4)[b]	2.0 (0.6)	1.0 (0.6)	173.3 (219.6)[b]	195.7 (12.6)[a]	172.7 (21.0)	197.0 (9.6)	600.7 (7.5)[a]	607.7 (8.4)[b]
20	263.6 (4.7)	271.6 (1.1)	0.0 (0.0)	0.0 (0.0)	132.3 (52.4)[b]	245.3 (10.2)[a]	135.0 (15.0)	173.0 (5.7)	622.0 (13.8)	582.0 (13.3)
21	241.0 (2.4)	236.3 (7.6)	23.0 (1.5)[a]	3.3 (2.4)[b]	148.3 (164.8)	189.7 (27.0)	215.7 (4.5)	179.0 (2.5)	539.7 (13.7)	631.3 (28.1)
22	150.7 (9.6)	169.3 (18.9)	30.0 (7.0)[a]	4.3 (2.3)[b]	100.5 (453.5)	164.3 (13.5)	625.0 (35.7)[b]	666.0 (12.1)[a]	680.3 (16.7)[a]	562.3 (38.5)[b]
23	183.7 (6.9)	187.3 (10.4)	10.0 (3.5)	4.3 (2.8)	122.0 (144.5)	167.0 (22.3)	623.3 (7.9)	645.7 (21.7)	658.3 (25.1)	644.0 (28.0)

Supplemental Table S5: Mean (standard error) of soil chemical characteristics in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across all 23 sites.

Mean (Standard Error) of Select Soil Chemical Properties

	Soil pH		OM (g kg^{-1})		CEC (cmol$_c$ kg^{-1})		Total C (g kg^{-1})		Total Soil N (g kg^{-1})	
Site ID	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**
1	7.3 (0.2)^{a}	6.4 (0.3)^{b}	190.00 (20.00)	120.00 (17.32)	11.3 (0.5)^{a}	7.0 (0.7)^{b}	114.10 (12.65)	103.33 (7.13)	11.47 (0.63)	11.53 (0.62)
2	6.3 (0.0)	6.2 (0.2)	140.00 (10.00)	166.67 (3.33)	8.2 (0.5)	8.1 (0.9)	72.33 (4.63)^{b}	107.67 (2.19)^{a}	9.60 (0.44)^{b}	12.10 (0.26)^{a}
3	7.1 (0.1)^{a}	5.8 (0.1)^{b}	150.00 (25.17)	180.00 (0.00)	12.2 (0.6)	9.7 (1.8)	89.37 (11.60)	106.83 (9.05)	11.13 (1.44)	12.50 (0.78)
4	7.2 (0.1)^{a}	6.7 (0.1)^{b}	166.67 (8.82)	163.33 (8.82)	11.8 (0.3)	10.9 (1.0)	114.33 (5.24)	122.67 (6.89)	11.70 (0.20)^{b}	13.37 (0.55)^{a}
5	6.9 (0.1)	6.6 (0.2)	176.67 (14.53)	200.00 (0.00)	9.9 (0.5)	8.8 (0.2)	121.33 (4.91)^{b}	153.00 (3.06)^{a}	13.57 (0.27)^{a}	16.07 (0.32)^{b}
6	6.3 (0.1)	5.9 (0.1)	163.33 (8.82)	150.00 (0.00)	7.8 (0.3)	7.7 (0.4)	103.00 (0.00)	104.00 (3.21)	12.53 (0.15)^{b}	11.80 (0.25)^{a}
7	7.3 (0.0)	7.2 (0.1)	230.00 (5.77)^{b}	296.67 (8.82)^{a}	17.0 (0.3)	17.5 (0.8)	178.67 (6.06)^{b}	203.33 (6.39)^{a}	19.73 (0.55)^{b}	21.37 (0.20)^{a}
8	6.0 (0.1)	6.2 (0.0)	193.33 (13.33)	173.33 (14.53)	8.3 (0.4)	8.3 (0.3)	98.57 (24.23)	99.40 (5.93)	11.23 (1.69)	11.70 (0.47)
9	7.3 (0.0)	7.3 (0.1)	190.00 (20.82)	200.00 (15.28)	12.1 (2.5)	11.7 (1.1)	119.67 (10.97)	99.80 (9.60)	13.27 (0.84)	14.47 (0.35)
10	6.0 (0.1)^{b}	6.4 (0.0)^{a}	173.33 (14.53)	173.33 (26.67)	10.5 (1.1)^{a}	9.1 (0.9)^{b}	108.83 (10.71)	124.53 (23.31)	18.47 (1.60)	13.70 (2.42)
11	7.4 (0.2)	6.5 (0.2)	180.00 (26.46)	186.67 (31.80)	16.9 (1.0)	12.2 (1.5)	141.67 (7.88)	141.67 (2.60)	11.80 (1.46)	15.53 (0.38)
12	6.9 (0.1)	6.7 (0.1)	190.00 (10.00)	180.00 (10.00)	16.9 (0.7)^{a}	9.0 (0.3)^{b}	104.67 (3.93)	112.33 (10.84)	10.53 (0.38)	11.13 (0.49)
13	6.7 (0.2)^{a}	5.2 (0.2)^{b}	196.67 (3.33)	200.00 (20.00)	11.8 (1.7)	15.5 (1.8)	111.33 (4.81)	120.33 (5.17)	12.33 (0.30)	13.37 (0.55)
14	6.7 (0.1)	6.3 (0.2)	406.67 (21.86)	350.00 (37.86)	23.0 (1.4)	18.8 (2.1)	263.67 (23.02)	243.33 (23.75)	22.33 (1.33)	23.30 (1.82)
15	6.0 (0.1)	6.0 (0.1)	166.67 (24.04)	253.33 (43.33)	9.0 (1.1)	13.3 (2.0)	108.63 (11.32)	143.33 (29.42)	12.03 (0.93)	15.07 (2.39)
16	6.6 (0.2)	6.3 (0.1)	200.00 (11.55)	206.67 (14.53)	9.5 (0.5)	8.4 (1.2)	121.33 (6.39)	134.67 (3.28)	12.27 (0.61)^{a}	14.40 (0.36)^{b}
17	6.0 (0.1)	5.5 (0.1)	150.00 (5.77)	140.00 (5.77)	5.0 (0.5)	4.8 (0.7)	77.17 (5.05)	73.00 (5.10)	8.73 (0.38)	8.53 (0.27)
18	6.4 (0.1)^{a}	5.5 (0.2)^{b}	166.67 (8.82)	186.67 (6.67)	7.3 (0.5)	8.3 (0.7)	97.43 (4.40)	114.33 (2.60)	10.80 (0.25)^{b}	12.30 (0.15)^{a}
19	6.6 (0.1)^{a}	5.6 (0.1)^{b}	213.33 (16.67)	246.67 (3.33)	11.4 (0.6)	10.4 (0.6)	173.33 (21.33)	189.67 (8.74)	14.47 (0.37)	14.90 (0.21)
20	6.2 (0.2)	6.2 (0.1)	220.00 (17.32)	226.67 (14.53)	10.3 (1.1)	12.6 (0.5)	132.33 (7.88)	157.00 (1.53)	13.80 (0.45)^{b}	16.50 (0.61)^{a}
21	7.3 (0.1)^{a}	6.0 (0.0)^{b}	263.33 (12.02)	260.00 (51.32)	8.8 (1.6)^{b}	10.0 (2.0)^{a}	148.33 (9.68)	136.00 (14.19)	14.87 (0.78)	14.53 (1.14)
22	5.8 (0.3)	5.0 (0.1)	173.33 (14.53)	196.67 (32.83)	8.8 (0.2)	14.1 (2.2)	100.53 (9.48)	125.67 (14.45)	11.60 (1.05)^{b}	14.43 (1.33)^{a}
23	6.8 (0.4)^{a}	5.8 (0.4)^{b}	196.67 (16.67)	193.33 (6.67)	9.6 (0.8)	9.4 (1.5)	122.00 (13.75)	124.33 (7.22)	13.43 (1.41)	13.80 (0.64)

Supplemental Table S6: Mean (standard error) of select Mehlich-3 extractable nutrients (mg kg^{-1}) in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across all 23 sites.

Mean (Standard Error) of Select Mehlich-3 Extractable Nutrients (mg kg^{-1})

	P		**K**		**Ca**		**Mg**		**S**	
Site ID	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**	**ROW**	**ADJ**
1	35.7 (3.2)	31.3 (3.8)	129.3 (7.4)	131.3 (4.7)	2391.7 (260.1)[a]	1104.0 (61.1)[b]	213.0 (12.8)	196.0 (23.3)	22.3 (2.9)	14.7 (0.9)
2	11.0 (0.6)[b]	19.0 (2.1)[a]	79.0 (4.2)	78.3 (9.0)	1454.3 (19.1)	1365.7 (69.0)	242.3 (15.2)[a]	165.7 (8.1)[b]	12.3 (0.7)	12.0 (2.1)
3	21.3 (3.2)	24.7 (6.2)	128.7 (5.9)	150.0 (11.0)	2188.0 (70.1)[a]	1402.3 (192.8)[b]	365.0 (15.7)	284.3 (35.5)	12.7 (0.9)	10.7 (0.9)
4	27.0 (2.1)	34.7 (4.2)	99.3 (3.4)	117.7 (8.8)	2462.3 (140.9)	1899.0 (218.7)	245.0 (6.4)	211.7 (27.4)	22.7 (4.4)	17.7 (2.3)
5	27.0 (4.7)	29.7 (2.7)	95.3 (5.5)	75.0 (12.1)	1602.3 (85.9)	1505.7 (41.8)	288.0 (19.7)	250.7 (12.2)	12.0 (0.0)	13.7 (1.2)
6	45.0 (1.7)[b]	60.3 (1.8)[a]	169.0 (3.5)[a]	134.3 (4.7)[b]	1468.3 (57.5)[a]	1075.3 (43.8)[b]	258.7 (8.6)[a]	190.0 (13.1)[b]	9.3 (0.3)	10.7 (0.9)
7	64.3 (15.2)	71.0 (24.0)	251.0 (23.4)	227.3 (25.1)	3211.7 (74.5)[a]	3017.3 (44.3)[b]	605.7 (15.2)	629.0 (5.0)	11.7 (0.9)	11.0 (0.6)
8	27.3 (8.9)	12.7 (2.6)	124.7 (7.9)[a]	78.3 (6.2)[b]	1434.7 (103.9)	1332.7 (75.0)	8.0 (26.7)	209.0 (18.3)	14.0 (1.7)	8.3 (0.3)
9	64.3 (6.2)	30.3 (2.6)	105.0 (20.4)	77.7 (13.7)	2964.7 (862.0)	2703.3 (375.4)	157.7 (32.2)	110.0 (6.7)	11.3 (1.3)	13.7 (0.3)
10	27.3 (5.8)	38.3 (7.8)	126.7 (5.8)	122.7 (9.6)	1897.7 (256.3)[a]	1632.7 (216.9)[b]	222.3 (39.3)[a]	149.0 (23.1)[b]	12.7 (1.2)	12.7 (1.5)
11	43.0 (5.6)	27.0 (3.5)	114.3 (12.1)[a]	93.3 (9.1)[b]	4756.7 (845.4)[a]	2233.0 (161.3)[b]	381.3 (49.8)	269.0 (28.5)	32.0 (11.0)	11.0 (0.0)
12	46.7 (3.9)	26.0 (5.0)	139.0 (3.1)	100.7 (14.7)	3928.0 (722.6)	1936.0 (160.4)	378.0 (15.4)	213.7 (49.5)	26.3 (10.3)	10.0 (1.5)
13	16.7 (0.7)	17.3 (1.9)	109.7 (7.9)	95.3 (6.1)	1856.0 (283.4)	926.0 (145.0)	341.7 (62.9)	189.0 (49.8)	26.3 (2.8)[a]	16.7 (1.7)[b]
14	53.3 (8.7)	77.0 (9.8)	165.0 (4.0)	176.0 (16.7)	4105.7 (336.7)[a]	3028.7 (443.7)[b]	562.7 (60.6)[a]	373.3 (54.2)[b]	23.7 (4.7)	27.0 (4.0)
15	27.3 (2.3)[a]	22.0 (2.6)[b]	85.7 (4.4)	95.0 (22.6)	1326.0 (119.3)	1859.0 (454.3)	255.3 (10.3)	346.0 (87.2)	14.0 (1.7)	13.0 (0.6)
16	34.7 (6.6)	31.7 (6.1)	109.0 (9.7)	101.7 (21.7)	1351.7 (185.5)	1337.7 (120.1)	279.7 (33.8)	275.0 (39.4)	12.3 (0.3)	11.3 (0.9)
17	50.7 (10.5)	32.3 (4.7)	115.7 (13.0)	84.3 (5.5)	927.0 (42.6)[a]	640.3 (3.5)[b]	124.3 (5.7)	132.7 (3.2)	12.3 (0.7)	11.0 (0.0)
18	61.3 (2.7)[b]	88.0 (5.6)[a]	107.0 (3.5)	110.3 (10.4)	1179.7 (15.3)[a]	834.3 (89.2)[b]	236.0 (3.0)	186.7 (28.5)	11.3 (0.3)	14.0 (1.5)
19	40.0 (1.0)[b]	54.7 (2.8)[a]	122.3 (5.3)[a]	96.3 (3.8)[b]	1556.3 (59.0)[a]	1014.3 (63.7)[b]	418.7 (18.4)[a]	327.0 (17.5)[b]	14.3 (1.7)	14.7 (1.2)
20	31.3 (3.3)[b]	63.0 (4.7)[a]	156.3 (5.0)[a]	185.7 (7.8)[b]	1512.7 (88.7)	1492.3 (48.4)	400.3 (17.6)	415.3 (13.3)	13.3 (0.7)	11.7 (0.3)
21	31.0 (0.6)	30.7 (4.2)	109.3 (13.1)	133.7 (15.9)	1528.7 (156.7)[b]	1851.0 (230.9)[a]	223.7 (28.5)[b]	265.7 (37.2)[a]	34.0 (3.2)[a]	12.7 (0.3)[b]
22	31.0 (3.5)	47.3 (18.3)	109.3 (3.0)	123.7 (7.2)	1528.7 (127.5)	1116.3 (133.1)	223.7 (15.9)	169.0 (16.8)	34.0 (6.7)[a]	15.3 (0.9)[b]
23	66.7 (5.8)	62.3 (16.5)	144.0 (5.0)[a]	111.7 (9.9)[b]	1868.7 (134.6)[a]	1228.7 (234.2)[b]	265.0 (9.5)	187.3 (29.7)	14.3 (1.3)	17.3 (1.3)

Supplemental Table S7: Mean (standard error) of soil biological and biochemical characteristics in right-of-way (ROW) versus adjacent, unaffected areas (ADJ) across all 23 sites.

	Mean (Standard Error) of Soil Biological Characteristics					
	POXC (mg kg^{-1})		Protein (g kg^{-1})		Respiration (mg kg^{-1})	
Site ID	ROW	ADJ	ROW	ADJ	ROW	ADJ
1	35.7 (3.2)	31.3 (3.8)	129.3 (7.4)	131.3 (4.7)	2391.7 (260.1)[a]	1104.0 (61.1)[b]
2	11.0 (0.6)[b]	19.0 (2.1)[a]	79.0 (4.2)	78.3 (9.0)	1454.3 (19.1)	1365.7 (69.0)
3	21.3 (3.2)	24.7 (6.2)	128.7 (5.9)	150.0 (11.0)	2188.0 (70.1)[a]	1402.3 (192.8)[b]
4	27.0 (2.1)	34.7 (4.2)	99.3 (3.4)	117.7 (8.8)	2462.3 (140.9)	1899.0 (218.7)
5	27.0 (4.7)	29.7 (2.7)	95.3 (5.5)	75.0 (12.1)	1602.3 (85.9)	1505.7 (41.8)
6	45.0 (1.7)[b]	60.3 (1.8)[a]	169.0 (3.5)[a]	134.3 (4.7)[b]	1468.3 (57.5)[a]	1075.3 (43.8)[b]
7	64.3 (15.2)	71.0 (24.0)	251.0 (23.4)	227.3 (25.1)	3211.7 (74.5)[a]	3017.3 (44.3)[b]
8	27.3 (8.9)	12.7 (2.6)	124.7 (7.9)[a]	78.3 (6.2)[b]	1434.7 (103.9)	1332.7 (75.0)
9	64.3 (6.2)	30.3 (2.6)	105.0 (20.4)	77.7 (13.7)	2964.7 (862.0)	2703.3 (375.4)
10	27.3 (5.8)	38.3 (7.8)	126.7 (5.8)	122.7 (9.6)	1897.7 (256.3)[a]	1632.7 (216.9)[b]
11	43.0 (5.6)	27.0 (3.5)	114.3 (12.1)[a]	93.3 (9.1)[b]	4756.7 (845.4)[a]	2233.0 (161.3)[b]
12	46.7 (3.9)	26.0 (5.0)	139.0 (3.1)	100.7 (14.7)	3928.0 (722.6)	1936.0 (160.4)
13	16.7 (0.7)	17.3 (1.9)	109.7 (7.9)	95.3 (6.1)	1856.0 (283.4)	926.0 (145.0)
14	53.3 (8.7)	77.0 (9.8)	165.0 (4.0)	176.0 (16.7)	4105.7 (336.7)[a]	3028.7 (443.7)[b]
15	27.3 (2.3)[a]	22.0 (2.6)[b]	85.7 (4.4)	95.0 (22.6)	1326.0 (119.3)	1859.0 (454.3)
16	34.7 (6.6)	31.7 (6.1)	109.0 (9.7)	101.7 (21.7)	1351.7 (185.5)	1337.7 (120.1)
17	50.7 (10.5)	32.3 (4.7)	115.7 (13.0)	84.3 (5.5)	927.0 (42.6)[a]	640.3 (3.5)[b]
18	61.3 (2.7)[b]	88.0 (5.6)[a]	107.0 (3.5)	110.3 (10.4)	1179.7 (15.3)[a]	834.3 (89.2)[b]
19	40.0 (1.0)[b]	54.7 (2.8)[a]	122.3 (5.3)[a]	96.3 (3.8)[b]	1556.3 (59.0)[a]	1014.3 (63.7)[b]
20	31.3 (3.3)[b]	63.0 (4.7)[a]	156.3 (5.0)[a]	185.7 (7.8)[b]	1512.7 (88.7)	1492.3 (48.4)
21	31.0 (0.6)	30.7 (4.2)	109.3 (13.1)	133.7 (15.9)	1528.7 (156.7)[b]	1851.0 (230.9)[a]
22	31.0 (3.5)	47.3 (18.3)	109.3 (3.0)	123.7 (7.2)	1528.7 (127.5)	1116.3 (133.1)
23	66.7 (5.8)	62.3 (16.5)	144.0 (5.0)[a]	111.7 (9.9)[b]	1868.7 (134.6)[a]	1228.7 (234.2)[b]

Supplemental Table S8: Mean (standard error) of yield in Mg ha^{-1} and harvested stand count for corn grain crops during 2020 and 2021.

			Mean (Standard Error)			
			Yield in Mg ha^{-1}		Harvested Stand Count	
Crop	**Year**	**Site ID**	**ROW**	**ADJ**	**ROW**	**ADJ**
Corn	2020	2	7.86 (0.31)[b]	12.17 (0.51)[a]	78.0 (2.5)	81.3 (0.7)
		3	9.10 (1.16)[b]	14.53 (0.47)[a]	86.3 (11.3)	73.7 (1.2)
		4	9.85 (0.13)[b]	12.09 (0.43)[a]	70.3 (3.8)	66.7 (3.9)
		6	10.53 (0.74)	11.24 (0.45)	77.0 (1.0)[b]	61.0 (2.1)[a]
		9	6.37 (0.65)	6.07 (0.89)	64.0 (1.0)	64.3 (4.1)
		10	11.02 (0.22)[b]	12.40 (0.42)[a]	60.0 (3.2)	63.0 (1.5)
		14	8.70 (1.74)[b]	14.16 (0.67)	55.3 (6.9)	72.3 (2.7)
		15	11.87 (0.50)[b]	14.21 (0.50)[a]	65.7 (3.8)	66.0 (5.1)
		18	3.67 (0.86)	4.15 (0.13)	38.3 (2.0)	98.0 (18)
		21	12.37 (0.41)[b]	15.83 (0.63)[a]	63.7 (1.3)[b]	73.7 (3.3)[a]
		22	5.15 (1.00)[b]	11.69 (0.57)[a]	44.0 (7.5)[b]	73.0 (3.8)[a]
		23	3.52 (1.24)[b]	11.69 (0.88)[a]	35.0 (5.6)[b]	65.7 (3.3)[a]
		24	12.88 (0.31)[b]	15.079 (0.52)[a]	69.0 (6.0)	69.7 (5.0)
	2021	8	7.76 (0.98)	7.56 (0.32)	41.3 (1.2)	43.7 (3.4)
		12	5.55 (0.71)[b]	7.24 (0.44)[a]	34.7 (1.2)	39.3 (0.9)
		14	4.60 (0.25)[b]	6.24 (0.36)[a]	38.3 (0.9)	36.3 (1.2)
		25	8.79 (0.45)[b]	9.83.8 (0.30)[a]	40.7 (0.3)	39.3 (0.7)
		27	5.38 (0.74)[b]	8.40 (0.40)[a]	36.0 (1.2)	36.0 (1.7)
		28	6.18 (0.24)	5.90 (0.16)	36.3 (1.2)[a]	30.7 (1.7)[b]
		30	7.36 (0.27)[b]	9.53 (0.39)[a]	40.3 (1.8)	44.0 (2.1)

Supplemental Table S9: Mean (standard error) of yield in Mg ha^{-1} and harvested stand count for corn silage crops during 2020.

			Mean (Standard Error)			
			Yield in kt ha^{-1}		Harvested Stand Count	
Crop	**Year**	**Site ID**	**ROW**	**ADJ**	**ROW**	**ADJ**
Corn Silage	2020	1	51.97 (1.64)[b]	94.41 (3.02)[a]	20.3 (1.9)	25.7 (1.2)
		5	52.55 (3.59)	61.18 (4.31)	25.0 (3.2)	20.7 (0.3)

Supplemental Table S10: Mean (standard error) of yield in Mg ha^{-1} and harvested stand count for soybean crops during 2020 and 2021.

			Mean (Standard Error)			
			Yield in Mg ha^{-1}		Harvested Stand Count	
Crop	**Year**	**Site ID**	**ROW**	**ADJ**	**ROW**	**ADJ**
Soybean	2020	7	5.77 (0.51)	6.69 (0.86)	72.7 (10.7)	62.0 (3.5)
		8	2.56 (0.16)	2.91 (0.22)	44.7 (2.6)	46.0 (1.7)
		12	4.28 (0.08)	4.46 (0.07)	56.0 (2.5)	69.3 (4.3)
		13	4.26 (0.20)	4.48 (0.15)	69.0 (7.1)	73.3 (3.8)
		17	4.90 (0.13)	5.35 (0.72)	59.3 (2.2)	51.0 (6.0)
	2021	1	3.98 (0.55)	5.10 (0.63)	36.7 (4.2)	43.3 (1.2)
		2	3.67 (0.23)	4.02 (0.26)	61.3 (4.7)	60.0 (4.0)
		3	4.11 (0.08)[b]	6.36 (0.55)[a]	73.0 (4.7)	72.7 (1.2)
		4	6.62 (0.28)	5.74 (0.24)	53.0 (8.1)	53.7 (2.6)
		6	6.62 (0.28)	5.74 (0.24)	68.7 (1.2)[b]	74.3 (0.9)[a]
		10	4.75 (0.51)	4.08 (0.49)	81.7 (0.3)	84.7 (1.9)
		11	3.23 (0.13)[b]	4.73 (0.29)[a]	41.0 (1.7)[b]	52.7 (3.3)[a]
		15	4.50 (0.25)	4.39 (0.06)	59.3 (3.7)	65.7 (2.8)
		22	2.19 (0.173)[b]	4.61 (0.18)[a]	74.3 (4.4)	77.7 (2.7)
		23	2.52 (0.42)[b]	4.68 (0.18)[a]	67.0 (6.5)	76.7 (1.9)
		24	4.13 (0.16)	4.44 (0.26)	58.0 (1.2)	60.3 (1.2)
		26	8.84 (0.92)	9.25 (0.53)	68.7 (5.7)	58.0 (7.6)
		29	1.79 (0.13)	1.97 (0.09)	78.5 (2.5)	58.0 (NA)

Supplemental Table S11: Mean (standard error) and significance of normalized difference vegetation index (NDVI) for all sites where on-farm yield was sampled in either 2020 or 2021.

Site ID	Mean (Standard Error) of NDVI 2020		2021	
	ROW	ADJ	ROW	ADJ
1	0.44 (0.01)[b]	0.64 (0.01)	0.62 (0.06)[b]	0.76 (0.04)
2	0.54 (0.00)[b]	0.62 (0.01)	0.71 (0.00)[b]	0.75 (0.00)
3	0.39 (0.02)[b]	0.55 (0.01)	0.73 (0.00)[b]	0.75 (0.00)
4	0.54 (0.01)[b]	0.59 (0.00)	0.79 (0.01)	0.81 (0.00)
5	0.60 (0.00)[b]	0.67 (0.01)		
6	0.37 (0.00)[b]	0.52 (0.01)	0.48 (0.01)[b]	0.76 (0.00)
7	0.49 (0.01)	0.49 (0.02)		
8	0.60 (0.02)	0.63 (0.02)	0.65 (0.03)	0.69 (0.02)
9	0.35 (0.01)[b]	0.39 (0.02)		
10	0.51 (0.03)	0.49 (0.01)	0.78 (0.00)	0.76 (0.00) [b]
11			0.48 (0.04)	0.52 (0.01)
12	0.55 (0.01)	0.56 (0.00)	0.71 (0.01)	0.71 (0.01)
13	0.43 (0.02)[b]	0.49 (0.02)		
14	0.45 (0.01)	0.50 (0.00)	0.66 (0.02)	0.74 (0.00)
15	0.62 (0.01)	0.61 (0.00)	0.69 (0.04)	0.71 (0.03)
16	0.51 (0.01)[b]	0.54 (0.00)		
17	0.31 (0.01)[b]	0.50 (0.01)		
20	0.40 (0.05)[b]	0.50 (0.04)		
21	0.39 (0.00)[b]	0.49 (0.01)	0.56 (0.03)[b]	0.71 (0.01)
22	0.58 (0.01)[b]	0.60 (0.01)	0.53 (0.04)	0.66 (0.00)
23	0.43 (0.02)[b]	0.53 (0.02)	0.63 (0.00)[b]	0.68 (0.00)
24			0.57 (0.00)	0.57 (0.01)
25			0.58 (0.00)[b]	0.59 (0.00)
26			0.56 (0.01)[b]	0.63 (0.00)
27			0.60 (0.00)[b]	0.62 (0.00)
28			0.48 (0.03)	0.51 (0.02)
29			0.66 (0.00)	0.65 (0.00)