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North Dakota landowners sue over pipeline easement payments

By Timothy Mclaughlin

(Reuters) - Over a dozen landowners in North Dakota have filed a lawsuit against a company involved in the development of the Dakota Access Pipeline, charging they were misled into accepting unfair compensation for allowing the pipeline to cross their land, according to court documents.

Dakota Access LLC used false statements to get some landowners in Morton County, North Dakota, to accept less money than others for the necessary easements, according to the lawsuit, filed Jan. 6 in U.S. District Court of North Dakota in Bismarck.

The landowners are seeking $4 million in damages from Dakota Access, court documents said.

"We feel the allegations are without merit," Vicki Granado, a spokeswoman for Texas-based Energy Transfer Partners, parent company of Dakota Access, said by email.

The company secured easements from 800 landowners in North Dakota for the project, she said.

EXHIBIT
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The $3.8 billion pipeline has faced months of protests from Native Americans and environmental activists who say it threatens water resources and sacred lands.

An attorney representing the landowners was not immediately available for comment.

Most landowners named in the suit were offered $216 per rod, a unit of measurement used in land surveying that is equal to 16.5 feet(5 m), in August 2014 for land easements.

Dakota Access, the court documents said, told the landowners that if they did not agree to the amount offered they faced losing money, having their land taken by eminent domain or that the pipeline would be rerouted. The landowners agreed to the payments.

However, other landowners in Morton County, through which 71 miles of the pipeline runs, were paid has much as $2,000 per rod, the suit said.

On Wednesday, the U.S. Army began the process of launching an environmental study of the pipeline's path under Lake Oahe, a reservoir formed by a dam on the Missouri River.

A December denial of the easement under the lake was a major victory for those opposed to the project, and members of the Standing Rock Sioux tribe called on protesters to disband.

However, some have remained and clashed again with law enforcement this week, and dozens have been arrested.

Reporting by Timothy Mclaughlin in Chicago; Editing by Leslie Adler


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Effects of pipeline installation on soil and plant properties: A literature review and quantitative synthesis

Core Ideas:

- Pipelines cause sustained soil degradation for years following installation.
- Soil compaction and mixing detrimentally impact other soil functionalities.
- 21 of 34 studies reported decreased plant biomass following installation.

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 ecosystems has been challenging. Here, we performed a systematic literature review to compile studies which have evaluated impacts of pipeline installation on soil and plant properties. We found 34 studies reporting pipeline impacts on agricultural and natural ecosystems from eight countries. We quantified and synthesized the magnitude of responses and found that the majority of studies found areas over pipelines had increased compaction (17 out of 26) and soil mixing (24 out of 28) and decreased aggregate stability (12 out of 12) and soil carbon (17 out of 21) relative to adjacent, undisturbed areas. Aggregate stability decreased an average of 43.6% along ROW areas, water infiltration capacity reduced an average of 85.6%, and compaction via penetration resistance increased an average of 51.6%. This soil degradation led to general declines in plant productivity, with 15 out of 25 studies documenting declines in crop yields and 6 out of 9 studies reporting decreased biomass from natural ecosystems like wetlands, grasslands, and forests. Reductions in crop yields ranged from 10.6 to 45.6%, and reductions in biomass from natural ecosystems ranged from 14.7 to 43.2%. We conclude from our quantitative synthesis that pipeline installation typically results in degraded soil and vegetation resources, and this can persist for many years after installation.

Abbreviations:

- CEC: Cation Exchange Capacity
- EC: Electrical Conductivity
- MBC: Microbial Biomass Carbon
- ROW: Right-of-Way
- SIC: Soil Inorganic Carbon
- SOC: Soil Organic Carbon
- SOM: Soil Organic Matter
- TSN: Total Soil Nitrogen

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). 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, 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, and 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.

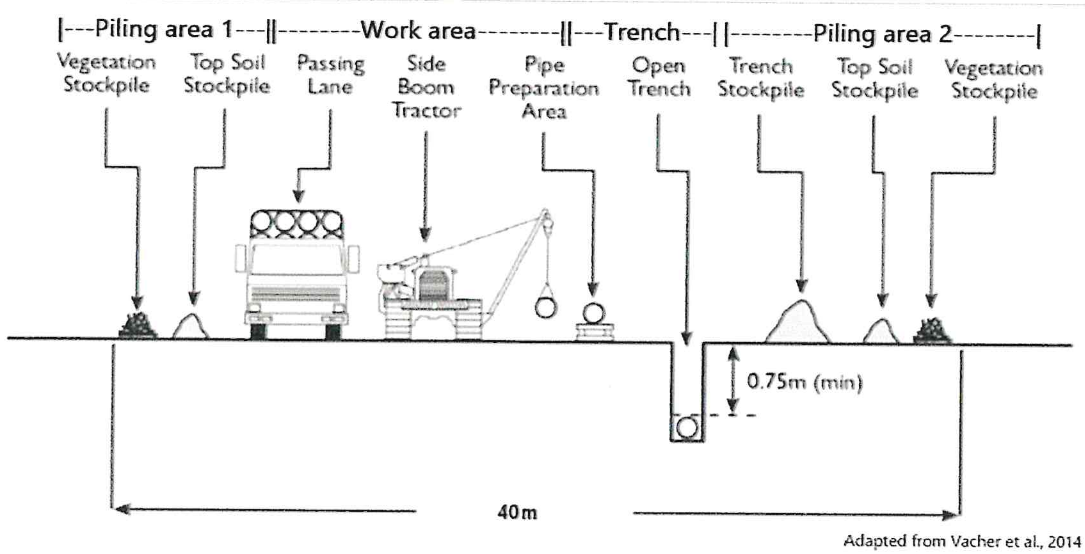

Figure 1: A schematic of the pipeline installation process, detailing multiple piling storage areas utilizing a double lift method for soil extraction, the work area or road, and the pipeline trench. Figure adapted from Vacher et al., 2014.

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 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 & Cannon (1995) reviewed 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. 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 any 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):

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

Percent difference was used as a way to standardize values and 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). The first pivotal study of the effects of pipeline system installation on agricultural areas was written in 1973 by de Jong & 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 after 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 separation of topsoil and subsoil.

Table 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 (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
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 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 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 2). Culley, Dow, Presant, & MacLean (1981) found that compaction and penetration resistance were more prevalent on fine or medium textured soils compared to 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, McGill, & Bailey (1987) reported 51-82% increases in bulk density in disturbed ROW, with greater subsurface compaction in the work area relative to the trench area where deeper soils had been removed and replaced.

Soon, Arshad, Rice, & Mills (2000b) 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, Antille, Huth & Raine (2016), where subsurface compaction increased by 15-20 percent.

Tekeste, Hanna, Neideigh, & Guillemette (2019) conducted compaction studies during the installation of the Dakota Access Pipeline 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 increasing 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, Taylor, & Carter (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 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 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.

		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
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 ranged from 22.2 to 84.5% (Table 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 & 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, Xiao, Wang, & Chen (2014) in soils from western China and by Duncan and DeJoia (2011) in midwestern United States. Landsburg & Cannon (1995) stated that wind erosion potential increased on pipeline areas if revegetation was not successful, particularly in soils with clayey surfaces. Additionally, Winning & 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 & 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 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 & 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 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, McGill, & Bailey, 1993). Halmova, Polakova, Koncekova, & Feher (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 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, Dow, Presant, & MacLean, 1982; Culley & Dow, 1988; Soon, Rice, Arshad, & Mills, 2000a). Culley et al. (1982) found that hydraulic conductivity in 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 et al. (2000a) 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 three studies which analyzed water infiltration capacity, there was an average decrease of 85.6% across all 3 studies (Table 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 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 2). De Jong & Button reported surface pH generally increased 0.5 for soils but increased up to 1.0 in Chernozemic soils. Additionally, Landsburg & 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 et al. (2000b) 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 tree species.

Organic matter and soil carbon

An average decrease of 24.4% in soil organic matter or soil organic carbon occurred in 17 of 21 studies (Table 2). Increases in either organic matter or soil carbon were not found in any study. In general, most studies found the soil organic carbon (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 & 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 et al. (2000a) reported a SOC decrease of 12% in a work area three years after pipeline installation. In a continuous study for 10 years after a pipeline installation in Ontario, Canada, Culley & Dow (1988) reported that there were still lower soil organic matter (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 & 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, MacKensie, & Stewart (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 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 & Dow

(1988) reported ROW soils still contained 23.9% less TSN than undisturbed fields. Landsburg & Cannon (1995), Soon et al. (2000a), Kowaljow & Rostagno (2008), Shi et al. (2014), and Shi et al. (2015) reported similar decreases in TSN with pipeline installation. Schindelbeck & 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 not consistently 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 2). Culley et al. (1982) reported a decrease in CEC within ROW agricultural soils compared to undisturbed fields. This finding was confirmed by a later study by Culley & Dow (1988), which found that CEC was still 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 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 & 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 & Button found that EC increased with depth, particularly in Solonetzic soils with newly installed pipelines. Similarly, Soon et al. (2000b) reported that EC levels were appreciably higher at deeper levels, from 50-100 cm, but the decrease after installation time Landsburg & 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 2). On average, alterations to phosphorus, potassium, and magnesium nutrient levels were not significantly different from adjacent areas. De Jong & 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 et al. (2000b) 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 et al., 2000b). In a 10-year study performed by Culley & 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 et al., 2000b).

Soil Biological Properties

Little research has been conducted regarding impacts of pipelines on biological soil properties. Soon et al. (2000a) 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, Huzurbazar, & Stahl (2016) also reported variable microbial abundance in ROW areas crossing a native sagebrush steppe in Wyoming, USA. Comparatively, Schindelbeck & van Es (2012) found 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. Root health ratings taken during this study were not significant.

Crop and Plant Yield Responses

Decreases in plant biomass accumulation were common between 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 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 after pipeline installation (Culley et al., 1981).

Table 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.

			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 & 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 et al. (2000a) 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 nutrient contents even when maturity was delayed, particularly in silage corn.

De Jong & 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 & 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 & 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, Gates, Adams, & Revel (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, Wang, Shi, Yang, & Chen (2014); Low (2016); and Xiao, Shi, Wang, Yi, & Yang (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 & 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.

CONCLUSIONS

Pipeline installations have occurred through the world and accordingly, research studies documenting the impacts of installation vary greatly in time and space. 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.

Data Availability Statement:

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

Conflict of Interest Statement:

The authors declare no conflict of interest.

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