Agrosystems, Geosciences & Environment / Volume 5, Issue 4 / e20312

REVIEW | Open Access

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

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First published: 07 December 2022
https://doi.org/10.1002/agg2.20312

Assigned to Associate Editor Joshua McGrath.

Abstract

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

Exhibit I.11.a

ecosystems (1.7–56.8%). We conclude from our quantitative synthesis that pipeline installation typically results in degraded soil and vegetation resources, and this can persist for many years following installation.

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

1 INTRODUCTION

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

Pipeline installation occurs within a right-of-way (ROW) or easement area, containing three major components: a trench where the pipe is laid, a work area where pipe-laying machinery traffic occurs, and a pile area where topsoil and subsoil are staged while the pipe is laid which is often adjacent to the trench. The total area of each pipeline's ROW can differ per pipeline installation, pipe size, and installation depth. Historically, pipeline trenches were excavated with little to no attention paid to separating topsoil from subsoil, a practice known as a "single lift" (de Jong & Button, 1973; Harper & Kershaw, 1997; Landsburg & Cannon, 1995; Zellmer et al., 1985). Current best practices now ensure topsoil and subsoil are lifted from the trench area individually, known as a "double lift," to maintain proper separation during the installation process (Neilsen et al., 1990; Soon, Arshad, et al., 2000; Soon, Rice, et al., 2000; Tekeste et al., 2019). Double lifts are thought to decrease the rates of soil mixing between horizon layers, which often differ in texture, porosity, organic matter content, soil chemistry, and overall soil function (Desserud et al., 2010; Landsburg & Cannon, 1995; Olson & Doherty, 2012; Shi et al., 2014). Additionally, current best management practices suggest surface and deep subsoil ripping near impacted areas after pipelines have been laid to decrease long-term effects of compaction on agricultural or natural landscapes (Nexus Staff, 2022; Rover Staff, 2022).

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

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

Core Ideas

A literature review uncovered 34 studies reporting on pipeline installation impacts to soils and plants.

Pipelines cause sustained soil degradation for years or decades following installation.

Soil compaction and soil horizon mixing detrimentally impact soil function.

The 21 of 34 studies reported decreased plant biomass following installation.

2 MATERIALS AND METHODS

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

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

After examining the reported studies, our ability to conduct a meta-analysis was compromised by a (a) limited number of total studies, (b) lack of key information regarding pipeline installation processes (e.g., single vs. double lift), (c) lack of reported estimates of variability, and (d) inconsistencies across studies regarding soil and plant properties reported. As such, we opted for a quantitative synthesis which standardized responses across studies for comparative purposes. Data were compiled from all relevant papers regarding soil physical, chemical, and biological properties as well as vegetative response to pipeline installation. First, all soil and plant variables reported from each study were classified into one of three categories: increase, no significant change, or decrease. These classifications reflected what authors reported in the respective studies of how areas over pipeline ROW were impacted relative to nondisturbed adjacent areas, with statistical significance used from the original studies at $p < .05$ or $p < .1$ levels. From each study, a percentage difference was calculated to assess the impact of pipeline installation on the reported variable. For studies that reported multiple areas over the ROW (e.g., over the trench, from work areas, etc.), all values were combined into one average “ROW” value for the study, while all measurements reported from adjacent areas were combined into one average “ADJ” value, used as a control to understand implications of pipeline installation on a study-by-study basis. Then a percentage difference for each variable within each study was calculated using Equation 1:

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

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

3 RESULTS AND DISCUSSION

Characteristics of pipelines studied

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

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

Study reference no.	Country	State/province	Citation	No. of pipelines studied	Years since pipeline installed	Soil properties reported	Plant propertie reported
1	Canada	Saskatoon	de Jong and Button (1973)	13	1–13	physical, chemical	grain yielc
2		Ontario	Culley et al. (1981)	1	3	physical, chemical	grain yielc midsumm plant heig nutrient content

Study reference no.	Country	State/province	Citation	No. of pipelines studied	Years since pipeline installed	Soil properties reported	Plant propertie reported
3		Ontario	Culley et al. (1982)	1	5	physical, chemical	grain yielc biomass productio

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

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

Soil physical properties

3.2.1 Compaction

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

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

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

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

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

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

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

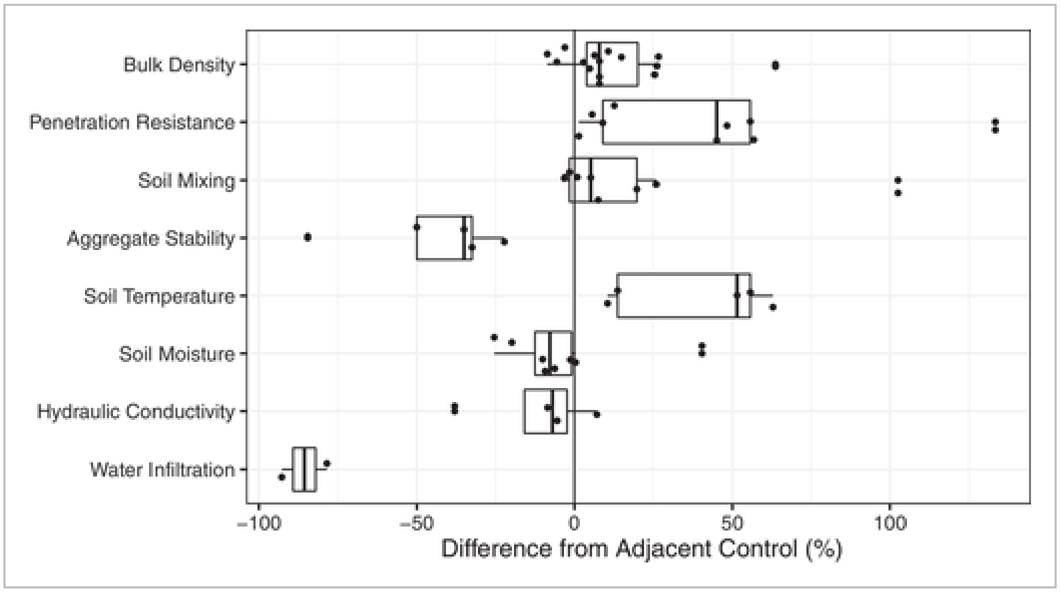

FIGURE 1

Open in figure viewer

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

Soon, Arshad, et al. (2000) measured bulk density in Alberta, Canada, and found that bulk density was significantly higher in the trench zone than in undisturbed fields. Additionally, penetration resistance in these fields was found to increase with disturbance, with trench = pile area > work area > undisturbed field. In a wetland study in Wisconsin, ROW soil had bulk densities 63% higher than adjacent areas (Olson & Doherty, 2012). Antille et al. (2015) found that soil compaction within lease areas increased by approximately 10% compared with undisturbed fields ($p < .05$). Additionally, surface compaction from 0 to 40 cm and subsurface compaction were significantly higher in all lease areas as well. In the United Kingdom, Batey (2015) observed that severe subsoil compaction was a factor in poor crop growth and drainage, particularly in work areas around the country. However, surface compaction in these soils was rarely detected. A similar conclusion was found by Vacher et al. (2016), where subsurface compaction increased by 15–20% in disturbed areas.

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

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

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

3.2.2 Soil mixing

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

Hartshorn et al., 2006; Sandor & Homburg, 2017). However, remediation measures such as erosion control blankets, chemical amendments like humic acids, and biological amendments such as cover cropping can alleviate some detrimental effects of soil mixing in some ecological stands given proper rates of amendments (Wester et al., 2019).

3.2.3 Aggregate stability and erodibility potential

All 12 studies that measured pipeline installation impacts on aggregate stability found significant decreases, with an average reduction of 44.8% and ranging from 22.2 to 84.5% (Table 2, Figure 1). Evidence of subsidence, or the gradual settling or sinking of soil, in ROW areas has been documented by Vacher et al. (2016), which states that depressions in disturbed fields after pipeline installation measured between 10 and 20 cm below the average slope of the adjacent study area. Introduced depressions like this can create instances of new hydric soils or vernal pools. In this study, aerial imagery was used to demonstrate alterations in elevation within the ROW, and erosion potential in these subsided areas was three to four times higher than unaffected areas. This study was conducted on vertic (vertisol) soils, which have a high shrink-swell capacity due to high clay content, paired with high water infiltration capacity, making them generally difficult to erode under normal circumstances. Ivey and McBride (1999) documented eroded areas with ROWs as well, noting that these areas contained lower percentage organic C than uneroded areas of the ROW, and similar findings were reported by Shi et al. (2014) in soils from western China and by Duncan and DeJoia (2011) in the midwestern United States. Landsburg and Cannon (1995) stated that wind erosion potential increased on pipeline areas if revegetation was not successful, particularly in soils with clayey surfaces. Additionally, Winning and Hann (2014) note that erosion potential also increased near rivers and in areas of high seismic activity. Schindelbeck and van Es (2012) found evidence of significant reduction in aggregate stability in all land types studied (agricultural areas, wetlands, and fallow lands) following pipeline installation, resulting in an average of 32% reduction in aggregate stability following construction activities. Fallow lands showed the most intensive decrease in aggregate stability (60%), while agricultural lands decreased an average of 27%.

3.2.4 Soil temperature

Increased soil temperature was documented by five studies, with an average increase in temperature of 38.9% along ROW compared with adjacent areas, ranging from 10.5 to 62.9% higher in ROW areas compared with ADJ (Table 2). Pipelines are often internally heated to ensure proper fluidity of materials being transported, and great effort is made to reduce heat loss from pipelines into the surrounding environment. Yet, some heat can escape from pipelined areas, resulting in elevated soil temperature, decreased soil moisture, and potential alteration to soil microbial communities (Naeth et al., 1993). Halmova et al. (2017) in the Slovak

Republic reported the temperature of a transported gas pipeline increased soil temperature above the pipeline 2.1–3.4 °C higher than soils farther away from the pipeline. Comparatively, Shi et al. (2015) reported a 1.0–2.0 °C increase in temperature along ROW areas in western China. However, it is essential to note that changes in albedo due to surface color change from bare soil or introduction of a new type of vegetation can also impact soil temperatures. Nonetheless, pipeline-impacted areas which do experience alterations in vegetation as well as potential pipeline-derived temperature leakages may be subject to increased soil temperatures near the pipeline trench.

3.2.5 Soil moisture, hydraulic conductivity, and water infiltration capacity

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

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

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

3.2.6 Exposed coarse rock fragments

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

Soil chemical properties

3.3.1 pH

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

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

Property	No. of studies				Mean percentage change (range)	Citations
	Total	Increase	No change	Decrease		
pH	19	9	10	0	6.81 (0.57 to 41.0)	1, 2, 3, 4, 5, 6, 9, 10, 11, 15, 16, 17, 19, 20, 21, 25,

Property	No. of studies				Mean percentage change (range)	Citations
	Total	Increase	No change	Decrease		
						26, 29, 31
Soil organic carbon (C) [a]	21	0	4	17	−20.8 (−49.7 to 2.4)	2, 3, 4, 5, 6, 7, 9, 10, 12, 15, 16, 17, 19, 20, 24, 25, 26, 28, 29, 31, 33
Total soil nitrogen (N)	11	2	0	9	97.3 (−49.5 to 1,166.7)	2, 3, 5, 7, 12, 15, 20, 21, 24, 26, 31
Cation exchange capacity	7	1	4	2	−1.0 (−26.8 to 42.5)	1, 3, 5, 15, 16, 17, 29
Electrical conductivity	9	7	2	0	109.4 (5.2 to 267.0)	1, 4, 6, 11, 16, 20, 21, 29, 31

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

[a] Soil organic carbon is calculated from both soil organic matter and soil C.

[b] NO_3–N extractants used by de Jong and Button (1973) and Schindelbeck and van Es (2012) were $CuSO_4$ and KCl, respectively.

[c] Extractable P, K, Ca, Mg, Na, S.

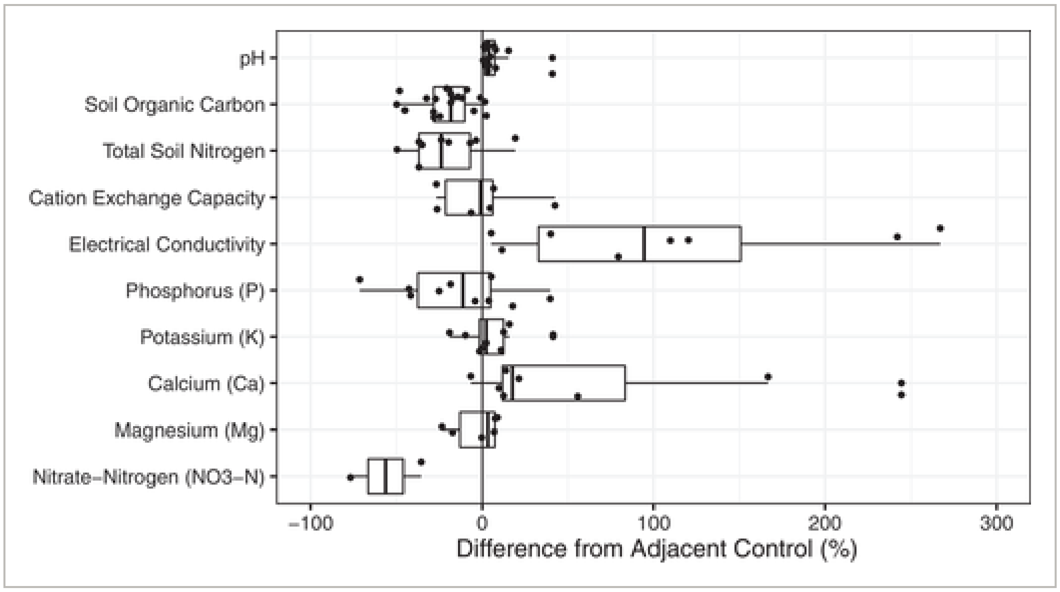

FIGURE 2

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

3.3.2 Soil organic C

An average decrease of 20.8% in soil organic C, measured by a combination of soil organic matter (SOM) and soil organic carbon (SOC), occurred in ROW areas compared with ADJ, throughout 21 studies (Table 3). Increases in either organic matter or soil C were not found in any study (Figure 2). In general, most studies found the SOC levels decreased in proximity to the trench, with highest SOC levels found in undisturbed fields > work areas > trenches.

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

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

3.3.3 Nitrogen

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

3.3.4 Cation exchange capacity

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

3.3.5 Electrical conductivity

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

3.3.6 Available nutrients

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

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

Soil biological and biochemical properties

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

Crop yield and plant productivity responses

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

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

Ecosystem type	Plant community	No. of studies				Mean percentage change (range)	Citations
		Total	Increase	No change	Decrease		
Agricultural crops	corn (grain)	5	0	1	4	−10.5 (−30.7 to 23.7)	2, 3, 5, 7, 26
	corn (silage)	2	0	0	2	−33.2 (−40.3 to −26.2)	3, 5
	soybean	3	0	0	3	−23.6 (−27.6 to −18.3)	2, 3, 5
	alfalfa	3	0	2	1	−6.2 (−22.2 to 1.91)	2, 3, 5

Ecosystem type	Plant community	No. of studies Total	Increase	No change	Decrease	Mean percentage change (range)	Citations
	small grains (barley	11	2	3	4	−10.8 (−67.6 to 32.0)	1, 2, 3, 5, 12, 16, 29

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

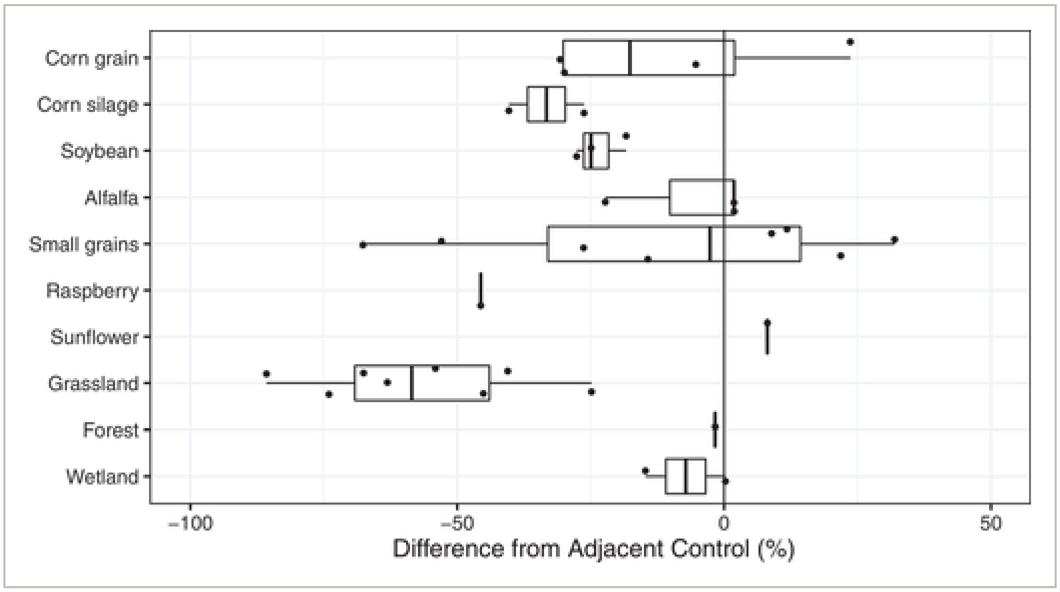

FIGURE 3

Open in figure viewer

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

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

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

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

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

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

4 CONCLUSIONS

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

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

AUTHOR CONTRIBUTIONS

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

CONFLICT OF INTEREST

The authors declare no conflict of interest.

Open Research

DATA AVAILABILITY STATEMENT

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

REFERENCES

Antille, D. L., Eberhard, J., Huth, N. I., Marinoni, O., Cocks, B., & Schmidt, E. J. (2015). *The effects of coal seam gas infrastructure development on arable land. Final Report Project 5: Without a trace*. Gas Industry Social and Environmental Research Alliance (GISERA). CSIRO.

Batey, T. (2015). The installation of underground pipelines: Effects on soil properties. *Soil Use and Management*, **31**(1), 60– 66. https://doi.org/10.1111/sum.12163

CIA World Factbook Staff. (2021). *Pipelines - The world factbook*. Central Intelligence Agency. https://www.cia.gov/the-world-factbook/field/pipelines/

Culley, J. L., & Dow, B. K. (1988). Long-term effects of an oil pipeline installation on soil productivity. *Canadian Journal of Soil Science*, **68**(1), 177– 181. https://doi.org/10.4141/cjss88-018

Culley, J. L., Dow, B. K., Presant, E. W., & Maclean, A. J. (1981). *Impacts of installation of an oil pipeline on the productivity of Ontario cropland*. Research Branch, Agriculture Canada.

Culley, J. L., Dow, B. K., Presant, E. W., & MacLean, A. J. (1982). Recovery of productivity of Ontario soils disturbed by an oil pipeline installation. *Canadian Journal of Soil Science*, **62**(2), 267– 279. https://doi.org/10.4141/cjss82-031 de Jong, E., & Button, R. G. (1973). Effects of pipeline installation on soil properties and productivity. *Canadian Journal of Soil Science*, **53**(1), 37– 47. https://doi.org/10.4141/cjss73-005

Desserud, P., Gates, C. C., Adams, B., & Revel, R. D. (2010). Restoration of foothills rough fescue grassland following pipeline disturbance in southwestern Alberta. *Journal of Environmental Management*, **91**(12), 2763– 2770. https://doi.org/10.1016/j.jenvman.2010.08.006

Dror, I., Yaron, B., & Berkowitz, B. (2021). The human impact on all soil-forming factors during the anthropocene. *ACS Environmental Au*, **2**(1), 11– 19. https://doi.org/10.1021/acsenvironau.1c00010

Duncan, M. M., & Dejoia, A. (2011). Topsoil loss: Evaluating agronomic characteristics of surface soils on a pipeline right-of-way. *Journal American Society of Mining and Reclamation*, **2011**(1), 185– 201. https://doi.org/10.21000/jasmr11010185

Federal Energy Regulatory Commission. (2016). *Final environmental impact statement: Rover Pipeline Project, Panhandle Backhaul, and Trunkline Backhaul Projects*. Federal Energy Regulatory Commission. https://cms.ferc.gov/sites/default/files/2020-05/impact-statement.pdf

Gasch, C. K., Huzurbazar, S. V., & Stahl, P. D. (2016). Description of vegetation and soil properties in sagebrush steppe following pipeline burial, reclamation, and recovery time. *Geoderma*, **265**, 19– 26. https://doi.org/10.1016/j.geoderma.2015.11.013

Halmova, D., Polánkova, Z., Končekova, L., & Fehér, A. (2017). Impact of operating temperature of gas transit pipeline on soil quality and production potential of crops. *Agriculture (Pol'nohospodárstvo)*, **63**(3), 120– 127. https://doi.org/10.1515/agri-2017-0012

Harper, K. A., & Kershaw, G. P. (1997). Soil characteristics of 48-year-old borrow pits and vehicle tracks in shrub tundra along the CANOL No. 1 Pipeline Corridor, Northwest Territories, Canada. *Arctic and Alpine Research*, **29**(1), 105– 111. https://doi.org/10.2307/1551840

Hartshorn, A. S., Chadwick, O. A., Vitousek, P. M., &, & Kirch, P. V. (2006). Prehistoric agricultural depletion of soil nutrients in Hawaii. *Proceedings of the National Academy of Sciences*, **103**(29), 11092–11097. https://doi.org/10.1073/pnas.0604594103

Ivey, J. L., & Mcbride, R. A. (1999). Delineating the zone of topsoil disturbance around buried utilities on agricultural land. *Land Degradation & Development*, **10**(6), 531– 544. https://doi.org/10.1002/(sici)1099-145x(199911/12)10:6<531::aid-ldr353>3.0.co;2-7

Jones, I. L., Bull, J. W., Milner-Gulland, E. J., Esipov, A. V., & Suttle, K. B. (2014). Quantifying habitat impacts of natural gas infrastructure to facilitate biodiversity offsetting. *Ecology and Evolution*, **4**(1), 79–90.

Kowaljow, E., & Rostagno, C. M. (2008). Efectos de la instalacio'n de un gasoducto sobre algunas propiedades del suelo superficial y la cobertura vegetal en el ne de Chebut. *Ciencia del Suelo*, **26**(1), 51–62.

Landsburg, S. (1989). Effects of pipeline construction on Cheronzemic and Solonetzic A and B horizons in central Alberta. *Canadian Journal of Soil Science*, **69**(2), 327– 336. https://doi.org/10.4141/cjss89-033

Landsburg, S., & Cannon, K. R. (1995). *Impacts of overstripping topsoil on native rangelands in Southeastern Alberta: A literature review (NGTL Environmental Research Monographs. 1995-1)*. NOVA Gas Transmission.

Langlois, L. A., Drohan, P. J., & Brittingham, M. C. (2017). Linear infrastructure drives habitat conversion and forest fragmentation associated with Marcellus shale gas development in a forested landscape. *Journal of Environmental Management*, **197**, 167– 176.

Low, C. H. (2016). *Impacts of a six-year-old pipeline right of way on Halimolobos Virgata (Nutt.) O.E. Schulz (slender mouse ear cress), native dry mixedgrass prairie uplands, and wetlands*. University of Alberta.

McClung, M. R., & Moran, M. D. (2018). Understanding and mitigating impacts of unconventional oil and gas development on land-use and ecosystem services in the US. *Current Opinion in Environmental Science & Health*, **3**, 19– 26.

Naeth, M. A., Bailey, A. W., & McGill, W. B. (1987). Persistence of changes in selected soil chemical and physical properties after pipeline installation in Solonetzic native rangeland. *Canadian Journal of Soil Science*, **67**(4), 747– 763. https://doi.org/10.4141/cjss87-073

Naeth, M. A., Chanasyk, D. S., McGill, W. B., & Bailey, A. W. (1993). Soil temperature regime in mixed prairie rangeland after pipeline construction and operation. *Canadian Agricultural Engineering*, **35**(2), 89–95.

Neilsen, D., MacKenzie, A. F., & Stewart, A. (1990). The effects of buried pipeline installation and fertilizer treatments on corn productivity on three eastern Canadian soils. *Canadian Journal of Soil Science*, **70**(2), 169– 179. https://doi.org/10.4141/cjss90-019

NEXUS Staff (2022). *Final environmental impact statement: NEXUS gas transmission project and Texas eastern Appalachian lease project (2016)*. NEXUS Gas Transmission, LLC. https://cms.ferc.gov/sites/default/files/2020-05/FEIS.pdf

Olson, E., & Doherty, J. (2012). The legacy of pipeline installation on the soil and vegetation of southeast Wisconsin wetlands. *Ecological Engineering*, **39**, 53– 62. https://doi.org/10.1016/j.ecoleng.2011.11.005

Sandor, J. A., & Homburg, J. A. (2017). Anthropogenic soil change in ancient and traditional agricultural fields in arid to semiarid regions of the Americas. *Journal of Ethnobiology*, **37**(2), 196. https://doi.org/10.2993/0278-0771-37.2.196

Schindelbeck, R. R., & van Es, H. M. (2012). Using soil health indicators to follow carbon dynamics in disturbed urban environments – A case study of gas pipeline right-of-way construction. In R. Lal & B. Augustin (Eds.), *Carbon sequestration in urban ecosystems*. Springer. https://doi.org/10.1007/978-94-007-2366-5_

Shi, P., Huang, Y., Chen, H., Wang, Y., Xiao, J., & Chen, L. (2015). Quantifying the effects of pipeline installation on agricultural productivity in west China. *Agronomy Journal*, **107**(2), 524– 531. https://doi.org/10.2134/agronj14.0023

Shi, P., Xiao, J., Wang, Y.-F., & Chen, L. D. (2014). The effects of pipeline construction disturbance on soil properties and restoration cycle. *Environmental Monitoring and Assessment*, **186**(3), 1825– 1835. https://doi.org/10.1007/s10661-013-3496-5

Soon, Y. K., Arshad, M. A., Rice, W. A., & Mills, P. (2000). Recovery of chemical and physical properties of boreal plain soils impacted by pipeline burial. *Canadian Journal of Soil Science*, **80**(3), 489– 497. https://doi.org/10.4141/s99-097

Soon, Y. K., Rice, W. A., Arshad, M. A., & Mills, P. (2000). Effect of pipeline installation on crop yield and some biological properties of boreal soils. *Canadian Journal of Soil Science*, **80**(3), 483– 488. https://doi.org/10.4141/s99-096

Tekeste, M. Z., Ebrahimi, E., Hanna, M. H., Neideigh, E. R., & Horton, R. (2020). Effect of subsoil tillage during pipeline construction activities on near-term soil physical properties and crop yields in the right-of-way. *Soil Use and Management*, **2020**, 1– 11. https://doi.org/10.1111/sum.12623

Tekeste, M. Z., Hanna, H. M., Neideigh, E. R., & Guillemette, A. (2019). Pipeline right-of-way construction activities impact on deep soil compaction. *Soil Use and Management*, **35**(2), 293– 302. https://doi.org/10.1111/sum.12489

Turner, T. (2016). *Edaphic and crop production changes resulting from pipeline installation in semiarid agricultural ecosystems*. University of Northern British Columbia. https://core.ac.uk/download/pdf/84874737.pdf

U.S. Bureau of Transportation Statistics Staff. (2021). *U.S. oil and gas pipeline mileage*. U.S. Bureau of Transportation. https://www.bts.gov/content/us-oil-and-gas-pipeline-mileage

U.S. PHMSA Staff. (2018). *General pipeline FAQs*. U.S. Bureau of Transportation. https://www.phmsa.dot.gov/faqs/general-pipeline-faqs

U.S. PHMSA Staff. (2020). *By-decade inventory*. U.S. Bureau of Transportation. https://www.phmsa.dot.gov/data-and-statistics/pipeline-replacement/decade-inventory

Vacher, C., Antille, D., Huth, N., & Raine, S. (2016). *Assessing erosion processes associated with establishment of coal seam gas pipeline infrastructure in Queensland, Australia* (American Society of Agricultural and Biological Engineers, 2016 ASABE International Meeting, pp. 1–13). https://doi.org/10.13031/aim.20162461210

Vacher, C. A., White, S., Eberhard, J., Schmidt, E., Huth, N. I., & Antille, D. L. (2014). *Quantifying the impacts of coal seam gas (CSG) activities on the soil resource of agricultural lands in Queensland, Australia*. (Paper presented at the 2014 ASABE Annual International Meeting (pp. 1–11). American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/aim.20141898868

Wester, D. B., Hoffman, J. B., Rideout-Hanzak, S., Ruppert, D. E., Acosta-Martinéz, V., Smith, F. S., & Stumberg, P. M. (2019). Restoration of mixed soils along pipelines in the western Rio Grande Plains, Texas, USA. *Journal of Arid Environments*, **161**, 25– 34. https://doi.org/10.1016/j.jaridenv.2018.10.002

Winning, H. K., & Hann, M. J. (2014). Modelling soil erosion risk for pipelines using remote sensed data. *Biosystems Engineering*, **127**, 135– 143. https://doi.org/10.1016/j.biosystemseng.2014.08.020

Xiao, J., Shi, P., Wang, Y.-F., Yu, Y., & Yang, L. (2017). A framework for quantifying the extent of impact to plants from linear construction. *Scientific Reports*, **7**(2488), 1– 13. https://doi.org/10.1038/s41598-017-02443-3

Xiao, J., Wang, Y.-F., Shi, P., Yang, L., & Chen, L.-D. (2014). Potential effects of large linear pipeline construction on soil and vegetation in ecologically fragile regions. *Environmental Monitoring and Assessment*, **186**(11), 8037– 8048. https://doi.org/10.1007/s10661-014-3986-0

Zellmer, S. D., Taylor, J. D., & Carter, R. P. (1985). Edaphic and crop production changes resulting from pipeline installation in semiarid agricultural ecosystems. *Journal American Society of Mining and Reclamation*, **1985**(1), 181– 189. https://doi.org/10.21000/JASMR85010181