Attachment No. 8

Every Dollar Spent on This Climate Technology Is a Waste

Credit... Josh Haner / The New York Times

By Charles Harvey and Kurt House *New York Times* Aug. 16, 2022
https://bit.ly/3Qw1xvU

[Dr. Harvey is a professor of environmental engineering at the Massachusetts Institute of Technology. Dr. House is the chief executive officer of KoBold Metals, a metals exploration company.]

The technology called carbon capture and storage is aptly named. It is supposed to capture carbon dioxide emissions from industrial sources and pump them deep underground. It was a big winner in the climate provisions of the Inflation Reduction Act passed by Congress last week and signed into law by President Biden on Tuesday.

What the technology, known as C.C.S., also does is allow for the continued production of oil and natural gas at a time when the world should be ending its dependence on fossil fuels.

The Inflation Reduction Act does more to cut fossil fuel use and fight climate change than any previous legislation by expanding renewable energy, electric cars, heat pumps and more. But the law also contains a counterproductive waste of money, backed by the fossil fuel industry, to subsidize C.C.S.

Fifteen years ago, before the cost of renewable energy plummeted, carbon capture seemed like a good idea. We should know: When we began a start-up 14 years ago — the first privately funded company to make use of C.C.S. in the United States — the idea was that the technology could compete as a way to produce carbon-free electricity by capturing the carbon dioxide emissions emitted from power plants and burying them. But now it's clear that we were wrong, and that every dollar invested in renewable energy — instead of C.C.S. power — will eliminate far more carbon emissions.

Even so, this technology has broad political support, including from Senator Joe Manchin of West Virginia, an ally of the coal industry, because it enables the continued extraction and burning of fossil fuels while also preventing the resulting carbon dioxide from entering the atmosphere. Industry campaigns such as "Clean Coal" have also promoted the technology as something that could ramp up quickly to bridge the gap to the deployment of large-scale renewable energy. But by promoting C.C.S., the fossil fuel industry is slowing the transition away from fossil fuels.

Under the Inflation Reduction Act, facilities using this technology will be eligible for generous tax credits provided they break ground by the end of 2032 — an extension of the current deadline of 2025. Those benefits come on top of $12 billion in government investments in C.C.S., as well as in technology that would pull carbon dioxide directly from the air, which were included in the infrastructure bill signed by President Biden last fall.

C.C.S. is seen as a solution to the emissions problem for a range of industries, from electricity generating plants powered by fossil fuel to industrial facilities that produce cement, steel, iron, chemicals and fertilizer.

Where C.C.S. has been most widely used in the United States and elsewhere, however, is in the production of oil and natural gas. Here's how: Natural gas processing facilities separate carbon dioxide from methane to purify the methane for sale. These facilities then sometimes pipe the "captured" carbon dioxide to what are known as enhanced oil recovery projects, where it is injected into oil fields to extract additional oil that would otherwise be trapped underground.

Of the 12 commercial C.C.S. projects in operation in 2021, more than 90 percent were engaged in enhanced oil recovery, using carbon dioxide emitted from natural gas processing facilities or from fertilizer, hydrogen or ethanol plants, according to an industry report. That is why we consider these ventures oil or natural gas projects, or both, masquerading as climate change solutions.

The projects are responsible for most of the carbon dioxide now sequestered underground in the United States. Four projects that do both enhanced oil recovery and natural gas processing account for two-thirds to three-quarters of all estimated carbon sequestered in the United States, with two plants storing the most. But the net effect is hardly climate friendly. This process produces more natural gas and oil, increases carbon dioxide emissions and transfers carbon dioxide that was naturally locked away underground in one place to another one elsewhere.

In an effort to capture and store carbon dioxide from fossil-fuel-burning power plants, the Department of Energy has allocated billions of dollars for failed C.C.S. demonstration projects. The bankruptcy of many of these hugely subsidized undertakings makes plain the failure of C.C.S. to reduce emissions economically.

The Kemper Power Project in Mississippi spent $7.5 billion on a coal C.C.S. plant before giving up on C.C.S. in 2017 and shifting to a gas-powered plant without C.C.S. The plant was partially demolished in October 2021, less than six weeks before President Biden signed the infrastructure bill with its billions of taxpayer money for C.C.S.: good money thrown after bad. The FutureGen project in Illinois started as a low-emission coal-fired power plant in 2003 with federal funds, but ultimately failed as a result of rising costs.

The Texas Clean Energy and Hydrogen Energy California C.C.S. projects were allocated over a half- billion dollars collectively, then dissolved. The list goes on, with at least 15 projects burning billions of dollars of public money without sequestering any meaningful amount of carbon dioxide. Petro Nova, apparently the only recent commercial-scale power project to inject carbon dioxide underground in the United States (for enhanced oil recovery), shut down in 2020 despite hundreds of millions of dollars in tax credits.

These projects failed because renewable electricity generation outcompetes C.C.S. Renewable power now is cheaper than coal-fired power without C.C.S. Add the cost of the energy required to couple C.C.S. with fossil fuel power and it becomes hopelessly uncompetitive. We can only guess how much more the full costs of

C.C.S. would exceed renewable power because, after decades of promotion and many billions of dollars spent, we still have next to no real-world data about the costs of running, maintaining and monitoring large C.C.S. projects.

These C.C.S. projects are subsidized by Section 45Q of the federal tax code, which now offers companies a tax credit for each metric ton of carbon dioxide injected into the ground. Those enhanced oil recovery subsidies would rise under the new law, to $60 per ton from $35. The legislation also significantly broadens the number of facilities eligible for tax credits. And they will be able to claim the tax credit through a tax refund. The 45Q program is nominally a program to fight climate change. But since nearly all carbon dioxide injections subsidized by 45Q are for enhanced oil recovery, the 45Q program is actually an oil production subsidy.

The Internal Revenue Service does not provide information about who gets the credits. But we do know that it issued more than $1 billion of these credits as of 2020.

These subsidies create a perverse incentive, because for companies to qualify for the subsidies, carbon dioxide must be produced, then captured and buried. This incentive handicaps technologies that reduce carbon dioxide production in the first place, tilting the playing field against promising innovations that avoid fossil fuels in the steel, fertilizer and cement industries while locking in long-term oil and gas use.

Industry campaigns for C.C.S. also have shifted their decades-long disinformation fight: Instead of spreading doubt about climate science, the industry now spreads false confidence about how we can continue to burn fossil fuels while efficiently cutting emissions. For example, Exxon Mobil advertises that it has “cumulatively captured more carbon dioxide than any other company — 120 million metric tons.”

What Exxon Mobil doesn’t say is that this carbon dioxide was already sequestered underground before it “captured” it while producing natural gas and then injected it back into the ground to produce more oil. These advertising campaigns lend support to government programs to directly subsidize C.C.S.

Solving climate change requires resources; misappropriating these resources makes solving the problem harder. We have no time to waste. We need to stop subsidizing oil extraction and carbon dioxide production in the name of fighting climate change and stop burning billions in taxpayer money on white elephant projects. Clean power from carbon capture and sequestration died with the success of renewable energy; it’s time to bury this technology deep underground.

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Attachment No. 9

IOWA STATE UNIVERSITY
College of Agriculture and Life Sciences

https://www.cals.iastate.edu/news/releases/pipeline-study-shows-soil-compaction-and-crop-yield-impacts-construction-right-way

Pipeline study shows soil compaction and crop yield impacts in construction right-of-way

Iowa State University College of Agriculture and Life Sciences
November 11th, 2021

AMES, Iowa — An Iowa State University study looking at the impacts of soil disturbance and early remediation practices from construction of the Dakota Access Pipeline finds significant soil compaction and gradual recovery of crop yield in the right-of-way over five years.

The research funded by Dakota Access Pipeline (DAPL) aimed to investigate construction influences of the underground pipeline on farmland. The pipeline transports crude oil over 1,172 miles from North Dakota to Patoka, Illinois, passing through South Dakota and about 347 miles in Iowa. The study's primary goal was to assess the extent of soil and cropping disturbances in the approximately 150-foot right-of-way caused by land clearing, topsoil removal and soil mixing, pipeline trenching and backfilling during the construction process.

Researchers also wanted to evaluate the effectiveness of state-mandated remediation requirements and a DAPL agricultural mitigation plan designed to minimize impacts to cropland. The Iowa Utility Code requires pipeline projects to remove topsoil and apply deep tillage to exposed subsoil before replacing the topsoil. The researchers are continuing to study the benefits of these practices, which can be costly.

Such field-based research quantifying soil properties and recovery in the years after a pipeline installation on farmlands is limited across the corn-soybean regions of the United States.

"Our findings show extensive soil disturbance from construction activities had adverse effects on soil physical properties, which come from mixing of topsoil and subsoil, as well as soil compaction from heavy machinery," said Mehari Tekeste, assistant professor of agricultural and biosystems engineering, director of the Soil Machine Dynamics Laboratory at Iowa State, and leader of the project.

Tekeste worked with a team that included: Mark Hanna, retired Iowa State Extension agricultural engineer; Robert Horton, who holds the Charles F. Curtiss Distinguished Professorship in Agriculture and Life Sciences in agronomy; and Elnaz Ebrahimi, research scientist in agricultural and biosystems engineering.

After the local pipeline construction was completed in 2016, the researchers began studying the impacts of construction and reclamation on a short stretch where the pipeline crossed an Iowa State research farm near Ames, Iowa. They monitored soil characteristics like bulk density and chemical properties at different depths across three zones within the right-of-way and adjacent undisturbed crop fields. In 2017 and 2018, they analyzed yield data for corn and soybean plots planted on the reclaimed land in the pipeline right-of-way under two tillage systems (no-till and conventional tillage) and compared the yields to crops in the undisturbed fields with similar soils. A peer-reviewed article in the journal “Soil Use and Management” summarizes their early results.

“Overall, in the first two years, we found the construction caused severe subsoil compaction, impaired soil physical structure that can discourage root growth and reduce water infiltration in the right-of-way,” said Horton, the lead soil physicist on the project. They also found changes in available soil water and nutrients.

Though the heavy equipment-induced compaction was still evident two years after construction, a deep subsoil tillage treatment showed some benefit for alleviating the compaction.

The team found crop yields in the right-of-way were reduced by an average of 25% for soybeans and 15% for corn during the first and second crop seasons, compared to undisturbed fields.

“However, we have already started to see gradual recovery in yields from the soybean-corn rotation re-established in the right-of-way,” Ebrahimi said. “Also, results from our tillage comparisons suggest that use of no-till slightly improved corn production in the right-of-way zones, especially under the unfavorable weather conditions of 2020.”

The researchers are finalizing analyses from the subsequent years of the project. What they can say at this point is the compaction and yields are very slowly starting to recover. Ebrahimi has simulated the impacts of the soil compaction on crop yields over time using the Agricultural Production Systems sIMulator (APSIM). A publication on her results is in the process of review.

“We would like to continue this research -- and especially collect more years of data on corn – and use it to provide recommendations for best management practices that can more effectively mitigate the impacts of future pipeline installation on crop yields,” Tekeste said.

Received: 14 September 2019 | Revised: 8 June 2020 | Accepted: 26 June 2020
DOI: 10.1111/sum.12623

RESEARCH PAPER

Soil Use and Management
WILEY

Effect of subsoil tillage during pipeline construction activities on near-term soil physical properties and crop yields in the right-of-way

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Abstract

Persistence of subsoil compaction in construction right-of-way (ROW) areas is a major cropland concern following installation of underground pipelines. Soil physical disturbance and remediation practices including removal of topsoil, subsoil tillage and replacement of topsoil were investigated in a soybean–corn rotation field, which was located within a pipeline ROW. The objectives of the study were to investigate the effectiveness of subsoil tillage (300 and 450 mm) applied shortly after the pipeline installation used to help restore soil physical properties and to recover crop yields. Soil bulk density, soil cone index and crop yields (soybean and corn) from three ROW trafficked zones (Z1, Z2 and Z3) and adjacent unaffected zones were compared at one year and two years after pipeline installation. Compared to 300 mm of subsoil tillage in the ROW zones, 450 mm of subsoil tillage did not significantly improve the soil bulk density and crop (soybean and corn) yields. Compared to 300 mm of subsoil tillage, 450 mm of subsoil tillage created significantly lower soil cone index values within the treated soil layer. Compared to yield data from the adjacent unaffected zones, the ROW zones (Z1, Z2 and Z3) had statistically significant ($p < .05$) crop yield declines of 25% in soybean (2017) and 15% in corn (2018). The near-term soil physical properties and crop yield have been improved from the subsoil tillage applied in the affected zones; however, their recovery to normal conditions as in the unaffected areas has not been achieved within the 2-year period.

KEYWORDS

corn, soil bulk density, soil cone penetration resistance, soybean, subsoil tillage, tillage systems

1 | INTRODUCTION

Natural gas and oil consumption are projected (U.S. Energy Information Administration, 2019) to increase globally and domestically through 2040. According to the report released by the Interstate Natural Gas Association of America (INGAA, 2015), extraction and transportation of natural resources will require establishment of thousands of kilometres of new pipeline infrastructures. As an inevitable consequence, installation of underground pipelines implicates extensive soil disturbance with adverse effects on soil physical properties through soil compaction and mixing of topsoil and subsoil because of construction right-of-way (ROW) activities (Naeth, McGill, & Bailey, 1987; Shi, Xiao, Wang, & Chen, 2014; Yu et al., 2010). Machinery-induced excessive soil compaction reduces crop yield (Bell, 2010; Lowery & Schuler, 1991;

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Raper, Reaves, Shaw, van Santen, & Mask, 2005; Soon, Rice, Arshad, & Mills, 2000) through increases in soil bulk density and soil strength (Cambi et al., 2015; Kumar, Chen, Sadek, & Rahman, 2012; Lepilin, Laurén, Uusitalo, & Tuittila, 2019; Raper et al., 2005).

Restoration of soil productivity after disturbance depends on the severity of soil compaction, vulnerability of the loosened soil conditions to re-compaction, crop type and climate (Batey, 2015; Batey & McKenzie, 1999; Shi et al., 2014; Spoor, 2006). However, there are still knowledge gaps in understanding soil structural deterioration, effectiveness of tillage reclamation methods and revegetation strategies in disturbed ROW areas during the post-construction phase (Batey, 2015; Brown, 2012; Noble, 2006). Field-based research studies are rare that quantify soil compaction and recovery time in the subsequent years after installation of underground pipelines. Some studies have indicated the negative impacts of ROW construction activities on soil structure (Li, Deng, Cao, Lei, & Xia, 2013; Soon et al., 2000; Tekeste, Hanna, Neideigh, & Guillemette, 2019; Turney & Fthenakis, 2011) and crop yield in highly productive farmlands of the US-Midwest (Olson & Doherty, 2012). Soil structural recovery can be measured by spatial and temporal comparisons of soil characteristics, such as soil bulk density and cone penetration resistance in disturbed and non-disturbed areas.

Developing effective reclamation methods for disturbed croplands requires an accurate determination of the soil disturbance, the soil compaction and the restoration cycle of specific soil types after ROW activities. Different strategies such as application of subsoil tillage, alternative tillage systems and crop rotations can be applied during the post-construction phase. The decision on proper soil recovery management varies based on site-specific conditions, where the level of soil disturbance and environmental factors correlate with the intensity of site management necessary to promote soil restoration in cropland (Antille et al., 2016; Bolling & Walker, 2000; Li et al., 2013).

Determination of proper subsoil tillage depth, number of repeated tillage passes and traffic management to avoid unnecessary trafficking is important factors to consider in developing a best management strategy (Spoor, Tijink, & Weisskopf, 2003). The no-tillage (NT) system has been promoted to conserve soil, water and crop yields (Blanco-Canqui, Claassen, & Stone, 2010; Yadav, Lal, & Meena, 2019) and can potentially restore soil structure and productivity by increasing aggregate stability and soil organic matter (Kumar et al., 2012; Vepraskas, Busscher, & Edwards, 1995; Woodward, 1996).

Measurements made on an exposed subsoil after pipeline installation but prior to topsoil replacement at a pipeline site (Tekeste et al., 2019) indicated extremely high peak vertical soil stresses (up to 133 kPa) and bulk density (1.72 Mg m^{-3}) equal to the Proctor compaction test maximum bulk density value. Such extreme soil compaction created during the pipeline construction phase and at a depth below the conventional deep tillage practices raised the need to investigate post-construction soil recovery management practices. Our current study investigates the effects of subsoil tillage and surface tillage on soil compaction and crop yields in pipeline installation ROW zones of a field in the Midwest region of the U.S.A.

The specific objectives of this paper are to (a) investigate the near-term effects of subsoil tillage treatments and surface applied tillage systems on soil compaction (soil bulk density and soil cone index) within the ROW zones and (b) quantify soybean and corn yield variations related to soil disturbance intensity within ROW disturbed zones relative to the adjacent unaffected areas.

2 | MATERIALS AND METHODS

2.1 | Description of the field site

Field plots were established on a crop farm along the Dakota Access Pipeline (DAPL) ROW area, which was located on an Iowa State University (ISU) farm in Story County, Iowa. A soybean (*Glycine max*)—corn (*Zea mays* L.) rotation was established on a 2 ha area after subsoil tillage reclamation practices, and topsoil replacement was completed in the ROW. As explained in the DAPL agricultural mitigation plan, the main construction activities in the ROW included removing and stockpiling topsoil (approximately depth of 525 mm), trenching and burying the pipeline, performing subsoil tillage to loosen the compaction created from the heavy machine trafficking and finally replacing the topsoil. Clarion loam (fine-loamy, mixed, super-active, mesic Typic *Hapludolls*) and Canisteo clay loam (fine-loamy, mixed, super-active, calcareous mesic Typic *Endoqualls*) were the two dominant soil series at the site (Web Soil Survey, 2018). Tekeste et al. (2019) provided further details on the heavy machinery equipment deployed during the pipeline construction phase and tillage equipment used for the subsoil tillage applications. The current study focuses on near-term soil physical properties and crop yield after the topsoil restoration practices of the DAPL agricultural mitigation plan were completed.

The field site was classified into ROW trafficked (disturbed) zones and adjacent unaffected (non-disturbed) areas. The ROW traffic area was divided into three zones based on the intensity of vehicular trafficking during the pipeline construction phase. Zone 1 (trench, Z1) was an area where the pipeline was buried, Zone 2 (Z2) was categorized as a heavy traffic area, and Zone 3 (Z3) was the area that received a relatively light traffic intensity. Each of the zones in the ROW was considered as a measurement zone. Classifying the zones as measurement zones was essential because the variations in traffic intensity among the zones were created according to the DAPL field operation protocol.

Prior to replacing the topsoil to the ROW area, subsoil tillage treatments including two levels (300 and 450 mm) were established using a Randomized Complete Block Design (RCBD). The subsoil tillage treatment levels of 300 and 450 mm were randomly assigned on the experimental units within each of the zones in four replications. The subsoil tillage was applied directly to the exposed subsoil shortly after completion of the ROW construction activities and before topsoil was replaced. Each subsoil tillage plot was 7.6 m wide by 18.0 m long. The field plot setup also included two undisturbed (unaffected) zones, named control-north (CN) and control-south (CS), which were located on the north and south sides of the pipeline.

As part of the DAPL mitigation plan, the topsoil was replaced to the ROW zones and levelled by a Caterpillar D7E bulldozer (fully loaded weight was 256 kN with a track that had a nominal track contact length of 3.02 m and a width of 0.76 m, Figure 1). Following the site-levelling, surface tillage was performed using a field cultivator with a tool depth of 100 mm.

Post-construction phase cropping system surface soil conventional tillage operations were applied perpendicular to the pipeline on the field plots. The conventional tillage refers to operation of fall disc ripping, which was applied after the corn cropping season. Spring seed-bed tillage was applied using a field cultivator prior to planting both during the corn and soybean cropping seasons. No-till planting plots designated as 'no-till' (NT) were added during the second crop season (2018) adjacent to the conventional tillage (CT) plots.

2.2 | Soil bulk density and soil cone index measurements

During the post-construction phase, soil bulk density (BD) and soil cone index (CI) were measured in fall 2017 and fall 2018. In 2017, because of the limited number of field working days, soil cone index measurements were taken from the relatively high traffic zones in the ROW zone (Z1 and Z2) and in one unaffected zone (CN). Both in 2017 and 2018, soil core samples for BD measurements were sampled from Z1, Z2, Z3 and the unaffected zones (CN and CS). A Giddings hydraulic-driven sampling probe (Giddings Machine Co.) was used to collect a 76 mm diameter and 1,200 mm long soil core at each sampling position. Twelve soil core sampling locations were taken along the centre of each zone within the ROW and in the unaffected crop field zones (CN and CS). Within each zone, three samples in two replicates were taken within each subsoiling depth treatment. Each tube sample was cut into 50 mm increments starting from the topsoil surface. The soil core samples were oven-dried at 105°C for 48 hr to determine dry soil bulk density and soil moisture content on a dry mass basis (%, d.b.).

A tractor-mounted three-probe cone penetrometer designed and built at ISU (Tekeste et al., 2019) was used to measure the soil cone index according to ASABE standards (ASAE Standards, 2004a and ASAE Standards, 2004b). Within each top surface tillage measurement zone (9 m × 7 m), the three-probe cone penetrometer was inserted at 30 mm s^{-1} (ASAE Standard, 2004b) on six sampling points. A total of 288 soil cone index measurements were taken within each zone. Cone penetration resistance force was measured using a Transducer Techniques model LPU-500 load cell transducer with 2224-N capacity (Transducer Techniques, LLC) and a Metromatics USB DEWE-43 DAQ System (Metromatics) acquiring data at 100Hz. Soil cone index (kPa) was calculated by dividing the cone penetration resistance force by the 285 mm^2 ASABE cone base area (ASAE Standard, 2004a).

2.3 | Crop planting and harvesting

Soybean (2017) and corn (2018) were planted on 760 mm row-spacing using an 8-row John Deere Max Emerge 5 Planter model pulled by a John Deere 6170R MFWD. Planting was performed parallel to the pipeline. Yield from the centre four rows of each plot, conventional and no-till sections, was combine harvested using the on-board Harvestmaster system

FIGURE 1 (a) Topsoil pile adjacent to the ROW zones. (b) The top soil was replaced by a Caterpillar D7E bulldozer after the exposed subsoil was tilled. The Caterpillar D7E fully loaded weight was 256 kN. Each track had a nominal track contact length of 3.02 m and a width of 0.76 m (Tekeste et al., 2019) [Colour figure can be viewed at wileyonlinelibrary.com]

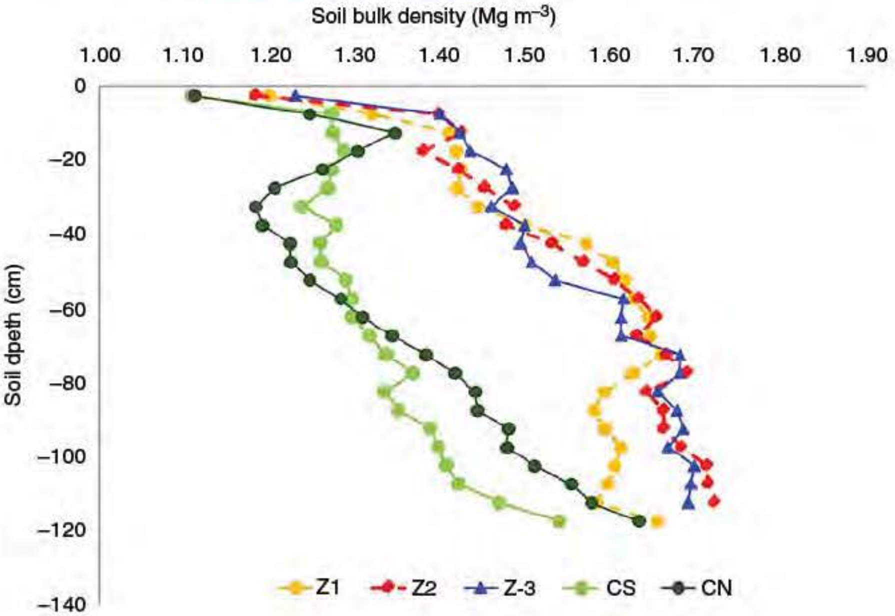

FIGURE 2 Soil bulk density profiles from fall 2017 within the ROW zones (Z1, Z2 and Z3) and the unaffected zones (CN and CS) [Colour figure can be viewed at wileyonlinelibrary.com]

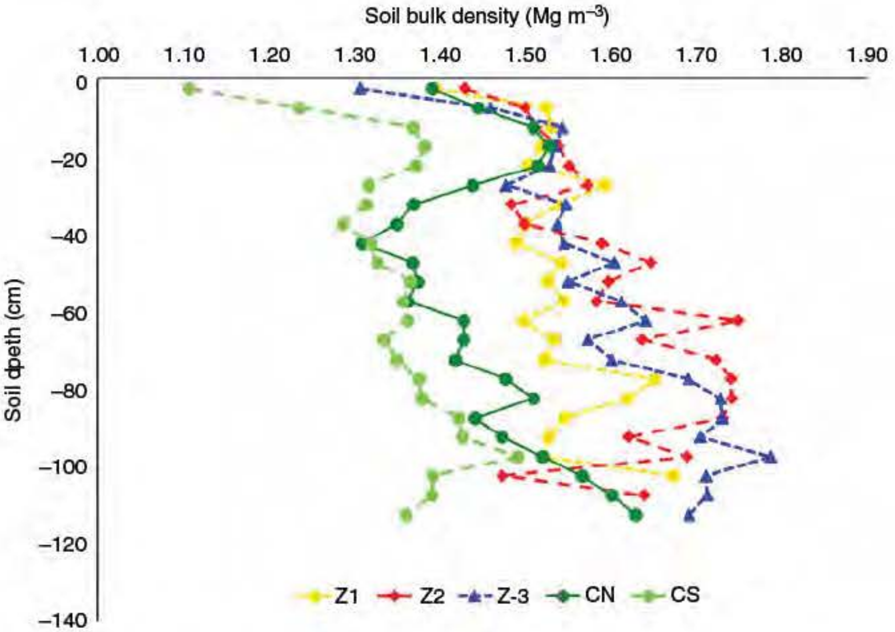

FIGURE 3 Soil bulk density profiles from fall 2018 within the ROW zones (Z1, Z2 and Z3) and the unaffected zones (CN and CS) [Colour figure can be viewed at wileyonlinelibrary.com]

HM800 grain gauge (Logan, UT) on a John Deere 9450 combine harvester. Within the smallest experiment unit (post-construction tillage system) of the ROW zones, there were a total of 16 samples of crop yield (two four centre crop rows for the two subsoil tillage treatments (300 and 450 mm) at four replicates). The harvesting pattern for the CN and CS zones was similar to the harvesting pattern within the ROW zones.

2.4 | Data analysis

All measured data for BD, CI and crop yield were subjected to analyses of variance using the GLM procedure (SAS JMP Ver. 14.JMP, 2013) and compared using Fisher's least significant difference (LSD) method with 95% confidence (*p*-value .05). Analyses of variance were also performed to compare the soil physical properties and crop yields from the individual zones within ROW zones and compared with the data from the adjacent unaffected zones (control). Improvement indices were calculated as relative changes in BD and CI from 2017 to 2018 for the top soil layer (top layer soil restoration, TSR) and the subsoil layer (subsoil layer soil restoration, SSR). The conventional tillage operations perpendicular to the pipeline precluded the ability to randomize conventional and no-till plots with respect to each other within the two levels of post-construction subsoiling (300 and 450 mm) that were previously established. Statistical comparison between the two post-construction tillage systems (NT and CT) from the near-term study was not feasible because of the inability to randomly assign the no-till and the tilled plots within each of the ROW trafficked zones. In order to avoid experimental bias because of the placement of the no-till adjacent to the tilled plots, statistical comparisons of subsoil tillage impacts on the measured soil properties and crop yields were done within each of the tillage systems.

3 | RESULTS AND DISCUSSION

3.1 | Soil bulk density

Soil bulk density profiles from the ROW zones (Z1, Z2 and Z3) (Figure 2, fall 2017; and Figure 3, fall 2018) indicated that soil compaction still persisted two years after the heavy equipment traffic and subsoil tillage. Differences in BD between the ROW and the unaffected zones were obvious in the top (0–500 mm) and deep (500–1,200 mm) soil layers. A summary of BD for the top soil layer (0–500 mm) and the deep soil layer (500–1,200 mm) is provided in Table 1.

In fall 2018, Z2 had the lowest BD in the top soil layer (0–500 mm) within the ROW. The mean BD of the top layer (fall 2018) within the ROW was 1.52 Mg m^{-3}, which was significantly larger than the BD in the unaffected zones of CN (1.44 Mg m^{-3}) and CS (1.29 Mg m^{-3}). For the deep soil layer (below 500 mm deep) from the fall 2018, no statistical differences ($LSD_{0.05}$ = 0.045 Mg m^{-3}) of BD were found among the ROW zones (Z1, Z2 and Z3) with 300 and 450 mm subsoil tillage. Within the deep soil layer, the BD averaged over both years among the ROW zones and the two subsoil tillage treatments were 1.60 Mg m^{-3}, a value estimated to be at 93% of the maximum Proctor compaction test value (Tekeste et al., 2019). The BD in the deep layer (500–1,200 mm) within the ROW was statistically larger ($LSD_{0.05}$ = 0.0040 Mg m^{-3}) than the BD in the adjacent unaffected zones (CN = 1.48 Mg m^{-3} and CS = 1.39 Mg m^{-3}).

The BD restoration (improvement index) calculated as percentage changes of 2018 BD data relative to the 2017 BD data is shown in Table 1. The BD restoration for the 0 to 500 mm soil layer was not significant because of subsoil tillage applied on the ROW zones (p = .196) or because of interaction effects of the ROW zones and subsoil tillage (p = .11). In the subsoil layer (500 to 1,200 mm), the BD showed significant improvements on Z1 (SSR = 9.2) (p < .05), which was better than the improvements in Z2 (SSR = 1.25%) and in Z3 (SSR = −0.60%). Within the ROW zones, the BD in the subsoil layer decreased from 1.65 Mg m^{-3} (fall 2017) to 1.60 Mg m^{-3} (fall 2018). No statistical differences in BD recovery were observed in the subsoil tillage treatments within each ROW zone (p > .05).

3.2 | Soil cone index

Figure 4 illustrates soil cone index (CI) profiles in fall 2017 and fall 2018 in ROW zones that received 300 and 450 mm subsoil tillage (Figure 4a–d). The subsoil tillage treatments in Figure 4 refer to the subsoil tillage treatments applied on the exposed subsoil prior to the topsoil replacement in fall 2016 (Tekeste et al., 2019). Within the ROW zones (Z1 and Z2), two peak soil cone penetration values occurred. One peak was at an approximate depth of 100 mm with the mean maximum values averaged by ROW and subsoil tillage depth of 2.06 MPa in 2017 and 1.73 MPa in 2018 (Figure 4a–d). The second peak in the soil cone penetration values occurred in the heavy equipment trafficked subsoil layer (300–600 mm soil layer) with mean maximum values averaged by ROW of

TABLE 1 Soil bulk density measured in fall 2017 and fall 2018 in a surface soil layer (0–500 mm) and a subsoil layer (500–1,200 mm) in post-pipeline construction right-of-way (ROW) zones (Z1, Z2 and Z3) and in unaffected zones (CN and CS)

		Soil bulk density (Mg m^{-3})				
		Fall 2017		Fall 2018		
Zone	Soil depth class (mm)	Mean[a]	*SD*	Mean	*SD*	Soil bulk density restoration[b] (%)
Z-1	0–500	1.46 (C)	0.06	1.53 (B)	0.14	−4.6 (TSR)
Z-1	500–1,200	1.67 (A)	0.04	1.53 (B)	0.14	9.2 (SSR)
Z-2	0–500	1.42 (DC)	0.04	1.49 (C)	0.11	−4.7 (TSR)
Z-2	500–1,200	1.62 (AB)	0.08	1.60 (A)	0.11	1.3 (SSR)
Z-3	0–500	1.42 (C)	0.08	1.55 (B)	0.09	−8.4 (TSR)
Z-3	500–1,200	1.66 (A)	0.03	1.67 (A)	0.05	−0.6 (SSR)
CN	0–500	1.23 (E)	0.08	1.44 (D)	0.12	
CN	500–1,200	1.41 (D)	0.03	1.48 (C)	0.06	
CS	0–500	1.25 (E)	0.03	1.29 (E)	0.05	
CS	500–1,200	1.31 (E)	0.05	1.39 (D)	0.04	

[a] Mean soil bulk density values followed by the same letter are not significantly different at $\alpha = 0.05$.

[b] TSR and SSR were calculated as relative changes in BD from 2017 to 2018.

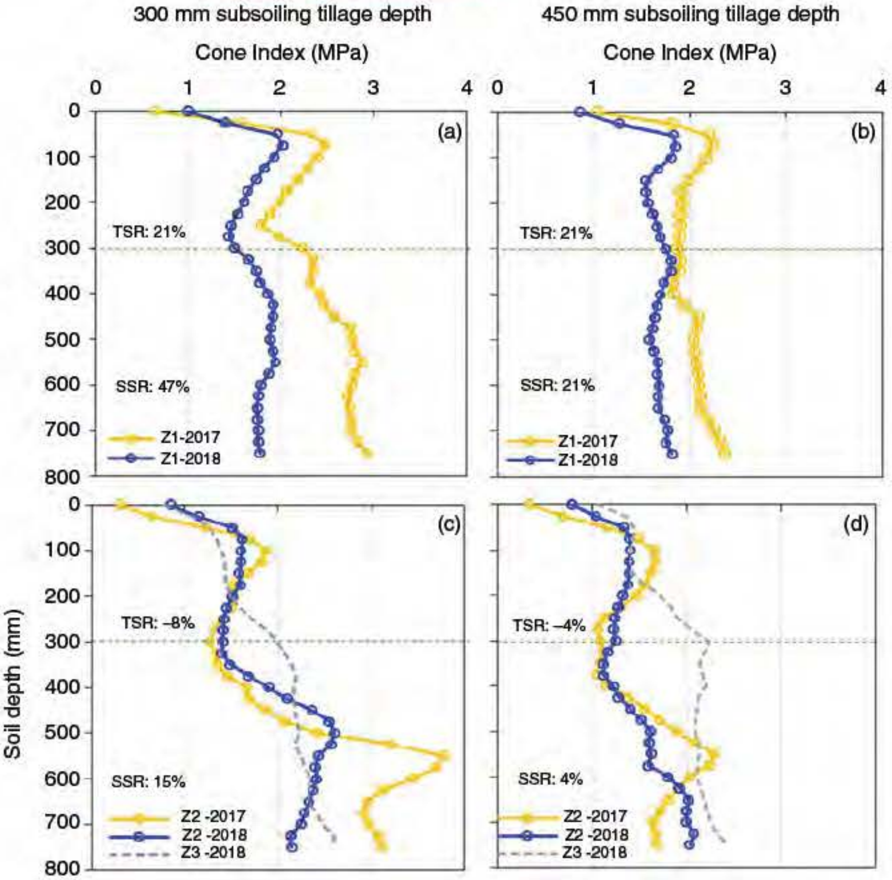

FIGURE 4 Soil cone penetration resistance profile for soils within trafficked ROW zones and unaffected zone from the fall 2017 and fall 2018 data. Within the ROW trafficked zones, subsoil tillage treatments of 300 mm (a, c) and 450 mm (b, d) were applied. Dashed lines (at 300 mm) separate the top soil layers from the subsoil layers. TSR and SSR (%) represent soil strength improvement within the affected zones (i.e. Z1, Z2) comparing data from fall 2017 and fall 2018. In Z3, TSR and SSR were not calculated because data were not collected in fall 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

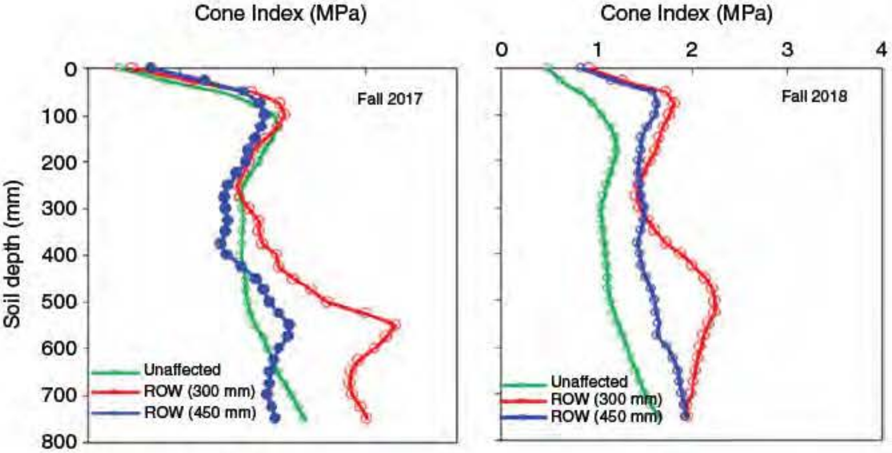

FIGURE 5 Mean soil cone penetration resistance profiles within ROW and unaffected zones from fall 2017 and fall 2018 data. Within the ROW trafficked zones, subsoil tillage treatments of 300 and 450 mm were applied [Colour figure can be viewed at wileyonlinelibrary.com]

2.76 MPa in 2017 and 1.99 MPa in 2018. Even though subsoil tillage was used, subsoil (below 300 mm) within Z1 and Z2 (Figure 4a–d) had significantly larger CI values ($p < .01$) compared to subsoil (below 300 mm) in the unaffected zones (Figure 5). The excessive soil compaction (CI greater than 2 MPa) in Z3 (fall 2018) occurred at a shallower depth than in Z1 and Z2. As part of the DAPL construction activities, the exposed subsoil surface in Z3 was at a higher elevation than the other ROW zones. Thus, the maximum CI occurred at a shallower depth in Z3 than in Z1 and Z2, because less topsoil was replaced on Z3 than on Z1 and Z2.

The TSR and SSR percent improvements from fall 2017 data (Figure 4) were found only in Z1 and Z2. The amount of soil strength improvement from 2017 to 2018 (Figure 4a–d; TSR vs. SSR) varied by zone and depth. Among both top- and subsoil layers, Z1 showed a higher recovery rate than Z2 (Figure 4). Within the ROW (affected), the mean CI profile values in fall 2018 were less than those in fall 2017, indicating a temporal reduction of soil strength (ROW mean TSR and SSR of 7.5% and 22%, respectively).

The heavy equipment-induced subsoil compaction was still evident for 2 years after subsoil tillage (300 mm or

450 mm) (Figure 5), because the ROW CI values were significantly larger ($p < .01$) than those in the unaffected zones. Significant impacts ($p < .01$) in reducing the mean CI were observed in the 300–600 mm soil layer of the subsoil tillage treatments. The 2017 and 2018 soil cone penetration measurements (Figure 5) indicated that the 450 mm subsoil tillage loosened the traffick-induced deep compaction better than the 300 mm subsoil tillage. Relative per cent changes in CI from the disturbed (ROW) zones and the unaffected (undisturbed) zones increased by 46.2% (CT) and 54.3% (NT) in the 300 mm, and by 31.5% (CT) and 48.3% (NT) in the 450 mm subsoil tilled fields, respectively (Table 2). Shi et al. (2014) found the values of soil properties (alkali hydrolyzable nitrogen (AN), available phosphorous (AP), total nitrogen (NT) and soil organic matter (SOM)) in the ROW areas (trench, piling and working areas, which are equivalent to Z1, Z2 and Z3) were lower compared to the values outside the working areas (20 and 50 m from the pipeline line). According to Håkansson (1994), subsoiling can only partially loosen compaction in deep subsoil layers, and in regions with high precipitation, it may not be practical. Lowery and Schuler (1991) reported that deep compaction was not removed completely by subsoil tillage even four years after heavy axle load traffic. The excessive subsoil compaction within the ROW in particular at the deeper soil layer (300–600 mm) could remain for many years (300–450 mm) (Raper et al., 2005). The presence of soil compaction in the topsoil layers two years after pipeline operations might be because of the heavy vehicle (Caterpillar D7E) used to bulldoze the stockpiled soil back to the ROW. The topsoil compaction was not entirely removed by the shallow tillage (100 mm field cultivation).

The per cent changes in CI between the ROW zones and the unaffected area by the subsoil tillage treatments are shown in Tables 2 and 3. No-till plots had higher CI than the CT plots by 4% within the ROW and 2% in the unaffected areas, possibly contributing to the lack of statistical significance. Other studies (Bueno, Amiama, Hernanz, & Pereira, 2006; Kumar et al., 2012; Roth, Mayer, Frede, & Derpsch, 1988) reported that changing a tillage system from conventional tillage (CT) to no-tillage (NT) could result in higher soil BD and CI values especially in topsoil. Lower CI values are associated with the tilled layer near the soil surface. Cavalaris and Gemtos (2002) reported a linear increase of CI in their 0–200 mm soil layer, where the increase was steeper in the no-tillage system compared to the conventionally tilled soils. Radford, Yule, McGarry, and Playford (2007) reported that positive impacts of no-tillage (NT) were because of improvements in soil structure and soil resilience capacity after a disturbance, because soil organic matter increased, especially in the surface layer.

3.3 | Crop yields

The ROW working zones (Z1, Z2 and Z3) had statistically significant ($p < .05$) crop yield declines of 25% in soybean (2017) and 15% in corn (2018) in contrast to the crop yields from the adjacent unaffected zones (Figure 6). Yield reduction within zones ($p < .01$) followed the damage from soil compaction as the highest soybean yield was measured in the unaffected zones (mean from CN and CS of 4.2 Mg ha^{-1}), which had less soil compacted zones, followed by Z1 (3.2 Mg ha^{-1}), Z3 (3.1 Mg ha^{-1}) and Z2 (2.9 Mg ha^{-1}). The highest mean corn yield in the CT tilled zone (fall 2018) was observed in the unaffected zones (14.4 Mg ha^{-1}) followed by the corn yield from Z1 (12.5 Mg ha^{-1}), Z3 (11.9 Mg ha^{-1})

TABLE 2 Mean soil cone index (MPa) values from each zone in the ROW as influenced by subsoil tillage (300 and 450 mm) in conventional tillage (CT) and compared with the mean soil cone index (MPa) values from the unaffected zones in fall 2018. *SD* represents averaged standard deviation of means ($n = 8$)

Zones	Subsoil tillage (mm)	Soil Cone index (Mpa) Mean	*SD*	Relative change[a] (%)
Zone 1	300	1.73	0.52	33
Zone 1	450	1.63	0.26	25
Zone 2	300	1.89	0.56	45
Zone 2	450	1.47	0.42	13
Zone 3	300	2.08	0.75	60
Zone 3	450	2.03	0.63	56
Unaffected		1.3	0.4	

[a] Relative change (%) was calculated from differences of mean soil cone index in each zone and subsoil depth relative to the unaffected zone.

TABLE 3 Mean soil cone index (MPa) values from each zone in the ROW as influenced by subsoil tillage (300 and 450 mm) in no-tillage (NT) system and compared with the mean soil cone index (MPa) values from the unaffected zones in fall 2018. *SD* represents averaged standard deviation of means ($n = 8$)

Zones	Subsoil tillage (mm)	Soil Cone index (Mpa) Mean	*SD*	Relative change[a] (%)
Zone 1	300	1.89	0.46	47
Zone 1	450	1.82	0.29	41
Zone 2	300	2.05	0.92	59
Zone 2	450	1.83	1.29	42
Zone 3	300	2.03	0.65	57
Zone 3	450	2.09	0.46	62
Unaffected		1.29	0.37	

[a] Relative change (%) was calculated from differences of mean soil cone index in each zone and subsoil depth relative to the unaffected zone.

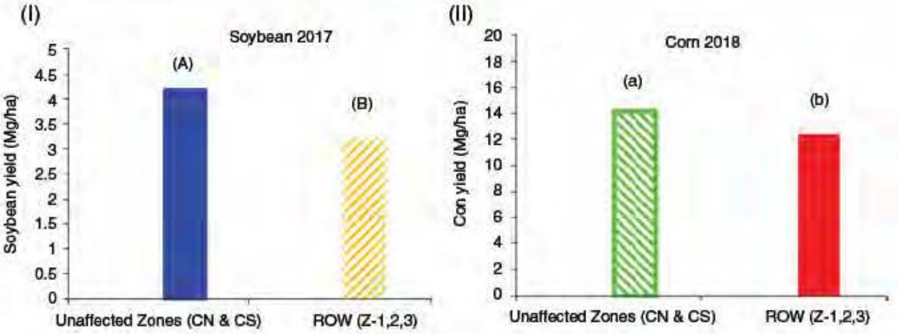

FIGURE 6 Soybean (I) and corn (II) crop yields (Mg ha^{-1}) from ROW affected (Z1, Z2 and Z3) and unaffected zones (CN and CS). Same letters assigned to the bars are not significantly different at the *p*-value of .05 [Colour figure can be viewed at wileyonlinelibrary.com]

and Z2 (11.5 Mg ha^{-1}). In the no-tilled (NT) zones (fall 2018), the highest mean corn yield was also observed in the unaffected zones (14.6 Mg ha^{-1}) followed by the corn yield from Z1 (13.3 Mg ha^{-1}), Z2 (12.6 Mg ha^{-1}) and Z3 (12.4 Mg ha^{-1}). Soybean and corn yields from the highest trafficked zone (Z2) were statistically lower compared to Z1 (Table 4). No statistical differences in crop yields were observed for the subsoil tillage treatments within each ROW zone ($p > .05$).

For corn from the ROW, the yield from the NT system in the ROW was 7% larger than that for the conventionally tilled soil. The difference in corn yield in the unaffected areas between the CT and NT system was minimum (−1%). As shown in previous studies (Gaultney, Krutz, Steinhardt, & Liljedahl, 1982; Lowery & Schuler, 1991; Raghavan, McKyes, Taylor, Richard, & Watson, 1979; Schjonning & Rasmussen, 1994), heavy axle load-induced soil compaction showed significant crop yield declines (9%–50%) compared to the control. Our study indicated that the yield depressions on soybean (fall 2017) and corn (fall 2018) could be attributed to heavy equipment traffic-induced increases in soil bulk density and soil cone penetration resistance, which caused mechanical impedance to root growth. Raper et al. (2005) reported negative impacts of soil compaction on crop yield occurred as soil cone index exceeded 2–2.5 MPa. Another potential reason for crop yield depressions in the ROW might be because of the mixing of top- and subsoil layers during construction activities and replacement of topsoil (data are not presented in this paper). Adjacent to the experiment site (approximately 1.6 km) along the pipeline, visual observations (Figure 7) were made in a soil trench cut perpendicular to the pipeline and across the ROW. The visual assessment showed that soil profiles in Z1 and Z2 had relatively poor soil structure and stubby (thicker) roots compared to the soil profile in the adjacent unaffected zone. Such a visual assessment could potentially be integrated into a post-construction feasibility assessment to minimize top- and subsoil mixing, especially during the topsoil replacement phase.

For short-term post-construction soil compaction management, application of subsoiling may be beneficial in the top- and subsoil layers to loosen the compacted layers that had soil cone index exceeding 2 MPa, a root limiting threshold value (Raper et al., 2005; Taylor & Gardner, 1963). The improved trend on crop yield in the short-term introduction of the NT system might be attributed to the benefits of reduced tillage practices (Sommer & Zach, 1992). Sommer and Zach (1992) reported the benefits of non-inverting soil loosening conservation tillage in reducing soil erosion, which implied that reduced tillage practices might have potential benefits as a long-term reclamation management strategy at pipeline construction sites.

TABLE 4 Soybean (fall 2017) and corn (fall 2018) yields (Mg ha^{-1}) from the ROW (Z1, Z2 and Z3) and the unaffected zones (average of CN and CS) in conventional tillage (CT) system, and no-tillage (NT) system (fall 2018). The no-till plots were added during the second crop season (2018)

	Crop Yield (Mg ha^{-1})					
	Soybean[a]		**Corn**[b]			
	CT		**CT**		**NT**	
Zone	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***
Z-1	3.2 (B)	0.57	12.5 (B)	1.50	13.3 (AB)	1.21
Z-2	2.9 (B)	0.43	11.5 (B)	2.01	12.6 (B)	1.49
Z-3	3.1 (BC)	0.32	11.9 (B)	1.57	12.4 (B)	1.88
Unaffected	4.2 (A)	0.59	14.4 (A)	1.12	14.6 (A)	0.81

[a] Soybean yield values followed by the same letter are not significantly different at α = .05.

[b] Corn yield values followed by the same letter are not significantly different at α = .05.

FIGURE 7 Visual observation of the soil structure from Zone 1, Zone 2 and the unaffected zone. A trench approximately 1 m wide by 2 m deep was excavated. Soil structure and root distribution were observed on the exposed trench face. The trench was on the DAPL pipeline, and it was located approximately 1.6 km east of the experimental plots [Colour figure can be viewed at wileyonlinelibrary.com]

4 | CONCLUSIONS

Pipeline construction activities and subsoil tillage remediation impacts on soil properties resulted in significantly ($p < .05$) larger CI and BD within the ROW zones compared to the adjacent unaffected zones. There were statistically significant ($p < .05$) crop yield declines of 25% in soybean (2017) and 15% in corn (2018) in the ROW zones relative to the crop yields in the adjacent unaffected zones. Subsoil tillage of 450 mm created statistically smaller soil cone index values in the 300–600 mm soil layer in the ROW, compared to the subsoil tillage of 300 mm ($p < .05$). BD and crop yield (soybean and corn), however, did not statistically differ for subsoil of 300 mm and 450 mm ($p > .05$). Within the near-term period, introducing no-till resulted 7% increase in corn yield (2018).

ACKNOWLEDGEMENTS

We acknowledge DAPL for providing funding to conduct this study. We also acknowledge field support from Kent Berns, Supervisor Agricultural Station, Carl Pederson, Agricultural Specialist at the Department of Agricultural and Biosystems Engineering at Iowa State University in Ames, Iowa, and Kent Heikens, Agricultural Science Research Technician (Soils) at the National Laboratory for Agriculture and the Environment, USDA-ARS in Ames, Iowa.

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How to cite this article: Tekeste MZ, Ebrahimi E, Hanna MH, Neideigh ER, Horton R. Effect of subsoil tillage during pipeline construction activities on near-term soil physical properties and crop yields in the right-of-way. *Soil Use Manage*. 2021;37:545–555. https://doi.org/10.1111/sum.12623