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Pipeline right-of-way construction activities impact on deep soil compaction

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Abstract

A 762-mm-diameter pipe 1,886 km long was installed to transfer crude oil in the USA from North Dakota to Illinois. To investigate the impact of construction and restoration practices on long-term soil productivity and crop yield, vertical soil stresses induced by a Caterpillar (CAT) pipe liner PL 87 (475 kN vehicle load) and semi-trailer truck (8.9 kN axle load) were studied in a farm field. Soil properties (bulk density and cone penetration resistance) were measured on field zones within the right-of-way (ROW) classified according to construction machine trafficking and subsoil tillage (300-mm-depth tillage and 450-mm-depth tillage in two repeated passes) treatments. At 200 mm depth from the subsoiled surface, the magnitude of peak vertical soil stress from trafficking by the semi-truck trailer and CAT pipe liner PL 87 was 133 kPa. The peak vertical soil stress at 400 mm soil depth appeared to be influenced by vehicle weight, where the Caterpillar pipe liner PL 87 created soil compaction a magnitude of 1.5 greater than from the semi-trailer truck. Results from the soil bulk density and soil cone penetration resistance measurements also showed the ROW zones had significantly higher soil compaction than adjacent unaffected corn planted fields. Tillage to 450 mm depth alleviated the deep soil compaction better than the 300-mm-depth tillage as measured by soil cone penetration resistance within the ROW zones and the unaffected zone. These results could be incorporated into agricultural mitigation plans in ROW construction utilities to minimize soil and crop damage.

KEYWORDS

deep tillage, soil bulk density, soil compaction, soil cone penetration resistance, vertical soil stress

1 | INTRODUCTION

Soil compaction is a process of soil particle rearrangement that reduces the air-filled fraction of soil pores and has been recognized as a major problem associated with crop production (Hamza & Anderson, 2005; Soane & Van Ouwerkerk, 1994). Compaction of soils often results in decreased soil aeration and hydraulic conductivity and increased soil bulk density and soil strength (Al-Adawi & Reeder, 1994; Hillel, 1998). Excessive soil compaction negatively affects crop yield and accelerates soil erosion (Al-Adawi & Reeder, 1994; Hillel, 1998; Soane & Van Ouwerkerk, 1994). Reviews on how soil compaction is created and management practices to minimize its negative effects on crop yield and the environment have been published by Hamza and Anderson (2005), Raper and Kirby (2006), and Batey (2009).

Numerous studies conducted in Europe and North America during the 1980s have shown that heavy vehicles with an axle load of 10 t or higher can create subsoil compaction to a depth of 500 to 600 mm (Etana &

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Hakansson, 1994; Hakansson & Reeder, 1994; Lowery & Schuler, 1991; Schjonning & Rasmussen, 1994). Schjonning and Rasmussen (1994) measured soil physical properties (i.e., bulk density and penetration resistance) and small grain yields after field traffic by a heavy vehicle (Volvo BM 860 Dump Truck). The vehicle with two front tyres of 18.0R25 XRA*TL and four rear tyres of 20.5R 25XA*TL were loaded to 10 t per front axle and 22 t per rear tandem axle. Four wheel passes by the truck on the exposed plough bottom (200 mm from the soil surface) created severe subsoil compaction (soil cone penetration resistance of 4.2 MPa) which was nearly a fourfold magnitude greater than the soil cone penetration resistance measured on the control treatment (no compaction). Hakansson and Reeder (1994) suggested limiting vehicle load to 10 t per axle in order to reduce the incidence of subsoil compaction and minimize long-term negative impacts on crop yields.

Soil compaction also occurs in cropland during utility construction activities within right-of-way (ROW) areas from heavy equipment traffic, trenching and backfilling, having adverse potential impacts on crop yields and soil quality. Batey (2015) reported bulk densities of 1.7 t m^{-3} (undisturbed) and 1.9 t m^{-3} (running track) at a depth of 350 mm, and restricted crop root growth 15 years after a pipeline was installed in the 1970s in Murthly, Perthshire, UK. On excessively deep compacted soils (bulk density values of 1.9 to 2.0 t m^{-3}) such as in pipeline sites, Spoor (2006) recommended 5 to 6 repeated passes of tillage (up to 750 mm depth) to loosen the soils. The restoration of soil productivity and crop yield post construction depends on the vulnerability of the loosened soil conditions to re-compaction, crop type, climate and proper drainage (Batey, 2015; Spoor, 2006). Limited information was available on measurement of soil compaction and crop yield in the subsequent years after the pipeline installations (Batey, 2015).

Dakota Access, LLC (DAPL) (2016) installed a 762-mm-diameter pipe over 1,886 km to transfer crude oil in the USA from North Dakota to Illinois. The Iowa pipeline section was buried at a minimum depth of 1.2 m in all agricultural lands. DAPL developed an agricultural mitigation plan that implemented measures for minimizing impacts to cropland during the pipeline construction (e.g., land clearing, separation of top soil, pipeline trenching and backfilling of the subsoil materials) and restoration phases after compaction by heavy construction equipment on all impacted agricultural cropland (Dakota Access, LLC (DAPL) 2016). The DAPL mitigation plan includes three repeated passes of deep tillage to a depth of 450 mm on exposed subsoil, restoring the topsoil condition, and soil levelling to its preconstruction conditions in compliance with Chapter 9 “Restoration of Agricultural Lands During and After Pipeline Construction” of the State of Iowa Administration Code, Section 199: Utilities Division.

Limited field-based research studies are available to support the development of the agricultural farm and crop damage compensation plan from utility construction activities on croplands. Studies evaluating the impacts of heavy construction vehicles and restoration activities on subsoil compaction and long-term crop yields may benefit industry, researchers, extension and government institutions in developing data-driven decision support and restoration of agricultural soil and crop productivity to preconstruction conditions. The overall goal of this research was to quantify the impacts of utility construction equipment, heavy vehicle traffic management, and deep tillage on soil compaction and long-term crop yields. The objectives of this study were to (a) investigate the effects of construction equipment trafficking and deep tillage within the ROW on deep soil (subsoil) compaction, and (b) investigate the effects of deep tillage treatments on soil compaction.

2 | MATERIALS AND METHODS

2.1 | Experiment description

The experimental test was established along the pipeline ROW at the Iowa State University (ISU) farm in Washington Township of Story County, Iowa. A five year long-term corn–soybean (*Zea mays L. - Glycine max*) crop rotation study was established on an experimental plot of a 2 ha area consisting of a ROW section (46 m wide and 244 m long) and adjacent unaffected crop fields (39 m wide and 244 m long). The study began in fall 2016, and corn was planted in spring 2017. Clarion loam (*fine-loamy, mixed, superactive, mesic Typic Hapludolls*) and Canisteo clay loam (*fine-loamy, mixed, superactive, calcareous mesic Typic Endoqualls*) are the dominant soil series at the site according to the USDA soil survey (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). The ROW was set at a bearing of 123° to accommodate the pipeline direction and was approximately 46 m wide. According to the DAPL agricultural mitigation plan, topsoil with an approximate depth of 525 mm below the original cropland topsoil surface was scraped from the ROW construction zone and stockpiled. Subsoil excavated from the pipeline trench was also stockpiled separately from the topsoil and returned to the excavated trench. Preceding the replacement of topsoil, the subsoil within the ROW which had been trafficked by heavy construction equipment was tilled to a depth of 450 mm from the top surface of the exposed subsoil using a subsoiler implement with 7-shanks at 760 mm spacing. The 450-mm-depth tillage was done in three repeated passes. After the topsoil was replaced, the land was levelled and tilled using a field cultivator at a tool depth of 100 mm.

Figure 1 shows the heavy vehicles frequently used for soil separation and pipeline installation. The ground contact

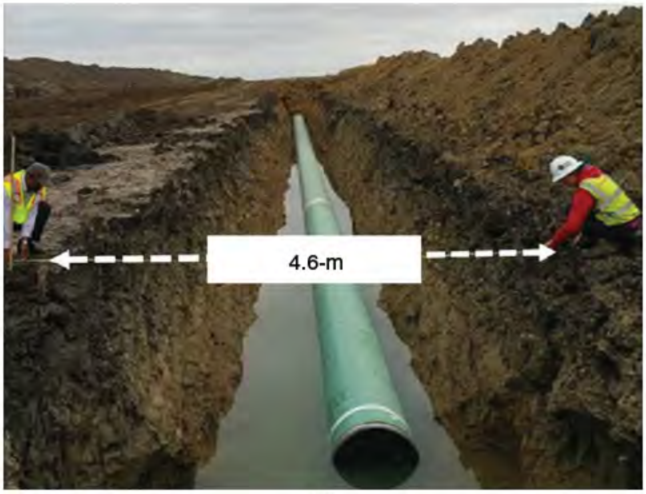
Caterpillar pipe liner PL 87. Fully loaded weight = 475 kN. Each track dimension had a nominal track contact length, which is the length of track in contact with a flat, unyielding surface (ISTVS, 1977), of 3.71 m and a width of 0.76 m.

Caterpillar 349F hydraulic excavator. Fully loaded weight = 522 kN. Each track had a nominal track contact length of 5.36 m long and a width of a 0.76 m.

Caterpillar D7E bulldozer. Fully loaded weight = 256 kN. Each track had a nominal track contact length of 3.02 m and a width of 0.76 m.

Semi-trailer truck with three pipes (each pipe was 24.4 m long, 0.76 m outer diameter, and 9.5 mm wall thickness).

(a)



(b)

FIGURE 1 Right-of-way pipeline construction heavy equipment—Caterpillar pipe liner PL 87, Caterpillar 349F hydraulic excavator, Caterpillar D7E bulldozer and semi-trailer truck with three pipes (a). The excavated trench for the pipe and the stockpiled subsoil adjacent to the pipe (b). At the experimental site, the pipe trench width was approximately 4.6 m [Colour figure can be viewed at wileyonlinelibrary.com]

pressure estimated from the vehicle weight and track contact area for the Caterpillar pipe liner PL 87, Caterpillar D7E bulldozer and Caterpillar 349F hydraulic excavator were 168, 111 and 128 kPa, respectively. The semi-trailer truck had single tyres on the front axle, dual tyres on each of two rear axles of the road tractor and dual tyres on each of two rear axles of the trailer. The tyre size was 275/80R-24.5 (Michelin). According to the U.S. Department of Transportation (DOT), the front axle load of the semi-trailer truck carrying a full load should not exceed 8.9 kN on highway roads.

After observing the field operations and vehicle traffic management within the ROW, four zones were delineated depending on traffic intensity during land clearing, topsoil separation and pipe trenching and stockpiling subsoil materials. A 7.6 m wide zone with the pipe at centreline (CL) was classified as Zone-1 (Z-1). Zone-2 (Z-2) was classified as a zone adjacent to Z-1 and opposite to the stockpiled subsoil. Relative to all the zones within the ROW, Z-2 received the highest traffic intensity. Zone-3 (Z-3) received heavy equipment traffic less frequently and was located between Z-2 and the stockpiled topsoil. Between one of the unaffected crop field zones (located at the southern side of the pipe) and the stockpiled subsoil, a separate zone was classified as Zone-x (Z-x). Relative to Z-1, Z-2 and Z-3, Z-x was observed to receive the lowest traffic intensity. The four zones (Z-1, Z-2, Z-3 and Z-x) within the ROW and the two unaffected crop field zones (Control-N and Control-S) to the northern and southern side of the pipe were defined as experimental blocks in our experimental design (Figure 2). The unaffected crop zones were outside the ROW area and parallel to the pipeline.

2.2 | Peak vertical soil stress measurement

Soil stresses were measured prior to the topsoil replacement to quantify the impact of loading from the high axle vehicle trafficking on deep induced soil stresses. Within Z-x, vehicle induced peak vertical soil stresses were measured at three soil depths using a GEOKON model 3500, 1 MPa capacity, piezoelectric earth pressure sensor (GEOKON [Lebanon, NH, USA]) as a vehicle passed over the sensors. The Caterpillar pipe liner PL 87 (with bender) and semi-trailer truck (with three pipes) were tested passing over the buried sensors. The pressure sensor was 100 mm in diameter and 10 mm in thickness. Each pressure sensor was installed at one of three soil depths (200 mm, 400 mm and 600 mm) from the top surface of the exposed subsoil. The centre-to-centre distance between the adjacent sensors along the vehicle travel direction was 300 mm. A trench with a width approximately three times the diameter of the pressure sensor was excavated. Before the trench was covered with the spoil material, an approximate 50-mm-thick layer of clean Ottawa #10 sand was placed above and below the sensor, according to the pressure sensor calibration procedure explained in White, Vennapusa, and Gieselman (2009) for studies on roller compactor-induced soil stress measurement. The vertical soil stress data were acquired using a USB-1408FS data acquisition (DAQ) device (Measurement Computing Corp., Norton, MA, USA) and sampled at 100 Hz. The soil during the soil stress measurement was moist and its consistency was close to the lower plastic limit. During the one-week heavy vehicle trafficking, mean precipitation measured at the nearest weather station in Boone, Iowa was 8.5 mm.

FIGURE 2 Map of experimental research plot showing the designated construction zones (Zone-1, Zone-2, Zone-3 and Zone-x) and unaffected crop field zones (Control-S and Control-N) aligned in reference to the pipeline. Zone-P refers to where the topsoil was piled Colour figure can be viewed at wileyonlinelibrary.com]

2.3 | Soil sampling for bulk density measurement

After the pipe was installed and prior to topsoil placement, soil core samples were taken for dry soil bulk density and soil moisture content measurement within Z-1, Z-2, Z-3 and Z-x starting from the top surface of the exposed subsoil. A Gidding hydraulic driven sampling probe (Giddings Machine Co., Windsor, CO) was used to collect 76-mm-diameter and 916-mm-long soil cores at each sampling position. Nine soil core sampling locations were selected along the centre of each zone within the ROW. Similarly, nine soil core tube samples were taken from the unaffected crop field zone (Control-S). Each tube sample was cut into 50 mm increments. The soil core samples were oven-dried at 105°C for 48-hr to determine dry soil bulk density and dry basis soil moisture content.

2.4 | Deep tillage experimental design

A Randomized Complete Block Design (RCBD) subsoiling tillage experiment was established with two subsoil tillage depths (300 mm and 450 mm from the top surface of the exposed soil) within the zones (Z-1, Z-2 and Z-3; Figure 3). Each zone was considered as an experimental block, where the tillage treatments were applied in four replicates. Two repeated subsoil tillage passes were applied in parallel to the pipeline. A John Deere 8320R MFWD tractor (196 kW [263 hp] PTO power) tractor pulling a John Deere V-Ripper (5-shanks at

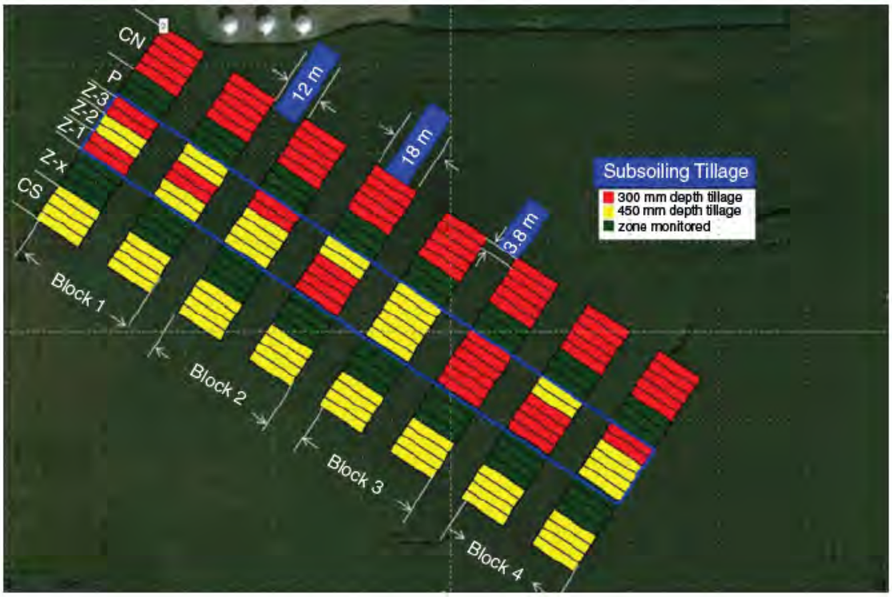


FIGURE 3 Based on the randomized complete block design (RCBD), the 300-mm- and 450-mm-deep tillage treatments were applied within Zone-1, Zone-2 and Zone-3 prior to topsoil replacement ("blue" rectangle). Each subsoil tillage plot size was 7.6 m width by 18 m long. Within the right-of-way (ROW), Zone-x and Zone-P (topsoil pile zone) were not part of the RCBD tillage experiment design. Crop field zones (Control-N, CN (north) and Control-S, CS (south)) were outside the ROW and unaffected by the pipeline construction [Colour figure can be viewed at wileyonlinelibrary.com]

760 mm spacing with DMI ripper points, 63.5-mm-wing width) was used to apply the subsoil tillage operation.

After the topsoil was replaced, the two unaffected zones designated as Control-N and Control-S (Figure 2) were added to the long-term (5-years) experimental plots to represent the soil and crop conditions outside the ROW that receive normal farm cultivation practices. Note that Control-N and Control-S had corn planted in the field adjacent to the ROW. At the unaffected zones, after the fall 2016 corn harvest and the pipeline construction were completed, including replacing the topsoil, Control-N received 300-mm-depth tillage using a Case 690 disk ripper pulled by a John Deere 8260R WFWD tractor (161 kW [216 hp] PTO power) which was followed by a second pass of 300-mm-depth tillage using the aforementioned John Deere 8320R MFWD tractor and the John Deere V-Ripper. In the Control-S zone, first pass tillage was completed at 300 mm depth using the Case 690 disk ripper pulled by the John Deere 8260R MFWD tractor and followed by a second pass of 450-mm-depth tillage using the John Deere V-Ripper pulled by the John Deere 8320R MFWD tractor. The disk ripper implement was the preferred tool to manage corn residue before applying the tillage using the V-Ripper without disc.

2.5 | Soil cone penetration resistance measurement

After the first year crop harvest in fall 2017, soil cone penetration resistance was measured according to the ASABE standards (ASAE Standards, 2004a,b). A tractor-mounted three-probe cone penetrometer designed and built at ISU (Figure 4) was used to measure the soil cone penetration resistance. Cone penetration resistance force was measured using a Transducer Techniques model LPU-500 load cell transducer with 2224-N capacity (Transducer Techniques, LLC (Temecula, CA)) and a Metromatics USB DEWE-43 DAQ System (Metromatics (North Lakes, Brisbane, QLD, Australia)) acquiring data at 100 Hz. Soil cone penetration resistance (kPa) was calculated by dividing the cone penetration resistance force by 285 mm^2 ASABE cone base area (ASAE Standards, 2004a).

FIGURE 4 Three-probe cone penetrometer mounted on the three-point hitch of a tractor. The lateral spacing between the penetrometer probes was 150 mm during field measurements. An ASABE 30-degree conical tip with 285 mm^2 cone base area was attached to each of the probes. The probe insertion rate was 30 mm s^{-1} [Colour figure can be viewed at wileyonlinelibrary.com]

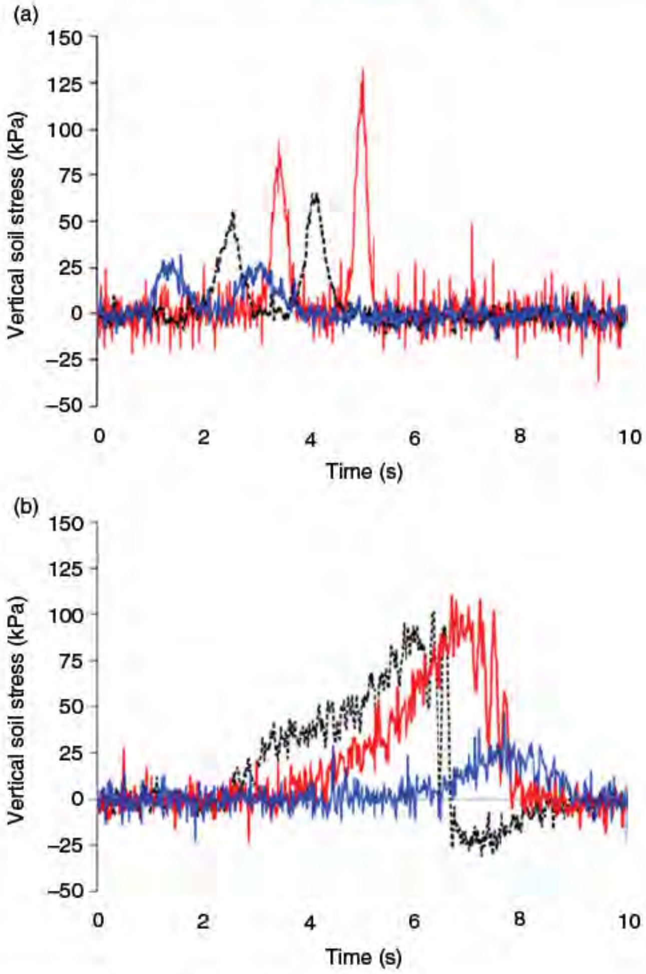


FIGURE 5 Soil vertical stress measured using the buried piezoelectric earth pressure cell at three depths ("red"—soil depth of 200-mm; "black"—soil depth of 400 mm; and "blue"—soil depth of 600 mm) as the semi-truck trailer hauling three pipes (24.4 m long, 0.76 m outer diameter, and 9.5 mm wall thickness); (a) and the Caterpillar Pipe Liner PL 87 (with bender) passes (b). Note that the comparison was made on the peak induced vertical soil stress (maximum soil vertical stress) from the front axle pass of the semi truck trailer and track pass of the Caterpillar Pipe Liner PL 87 [Colour figure can be viewed at wileyonlinelibrary.com]

2.6 | Data analysis

Data analysis to compare the vertical soil stresses from the vehicles was performed on the first pass peak vertical soil stress. In order to not hinder pipeline construction field operations, the construction equipment for loading the pressure sensors was available for only one week. Thus, the measurement with the pressure sensor buried at the three depths was limited to one replicate. The field machine productivity was approximately 0.2 km h^{-1} (personal communication with field superintendent).

Data from soil bulk density and soil cone penetration resistance were analysed using the GLM procedure in SAS JMP Ver. 14. (JMP, 2013). Means were compared using a *p*-value of 0.05 as a significance level. From the unaffected zone, the soil cores sampled from the top surface of the exposed subsoil to the end core length of the Gidding cylinder were used to compare with the soil bulk density at the corresponding soil depth from the ROW zones.

TABLE 1 Peak vertical soil stress induced from first pass of the heavy vehicle Caterpillar pipe liner PL 87 (with bender) and semi-truck trailer (with three pipes) on soil within the ROW

	Peak vertical soil stress (kPa)	
Soil depth (mm)[a]	**Vehicle-A**[b]	**Vehicle-B**[c]
200	133	133
400	115	78
600	63	49

[a]Soil depth was measured from the top surface of the exposed subsoiled soil to the top surface of the sensor. [b]Vehicle-A: Caterpillar pipe liner PL 87 (with bender). [c]Vehicle-B: Semi-truck trailer (three pipes).

3 | RESULTS AND DISCUSSION

3.1 | Peak vertical soil stress

Multiple peak values of vertical soil stresses were observed as the tyres of the semi-trailer truck passed over the buried pressure sensors (Figure 5). From a single pass of the Caterpillar Pipe Liner PL 87 (with bender) travelling at 0.45 m sec^{-1}, the peak vertical soil stress occurred towards the end of the track contact length. Table 1 shows the peak vertical soil stress measured from the first pass of the two heavy vehicles. At the shallow depth (200 mm), there was small difference in the peak vertical soil stress between the front axle (DOT highway limit of 8.9 kN) pass of the semi-trailer truck (275/80R-24.5 tyre) and the single pass of the Caterpillar pipe liner PL 87 (contact area of each track 2.82 m^2). At the depth of 400 mm, the peak vertical soil stress appeared to be influenced more by the vehicle weight, whereby the peak vertical soil stress from the Caterpillar liner PL87 was 1.5 times higher than from the semi-trailer truck. At 600 mm depth, the magnitude of peak vertical soil stress from the Caterpillar pipe liner PL 87 was 1.3 times the stress induced by the semi-trailer truck. Having one replicate measurement statistically limited the comparison of impacts from heavy vehicles of the semi-trailer truck versus the Caterpillar pipe liner PL87. The narrow contact ground area and tyre inflation pressure from the semi-trailer truck had a strong effect on shallow vertical soil stress, while the deep (400 mm and 600 mm) vertical soil stresses was affected more by the magnitude of vehicle load. The effect of vehicle type with high tyre inflation pressure and axle load on shallow and deep soil compaction was similar to previous studies (Bailey, Raper, Way, Burt, & Johnson, 1996; Hakansson & Reeder, 1994). Measurement of soil stress from the other heavy vehicle (Caterpillar 349F and Caterpillar D7E) passes showed similar trends as the effects from the Caterpillar pipe liner PL 87. The soil pressure measurements from the Caterpillar 349F and Caterpillar D7E passes had

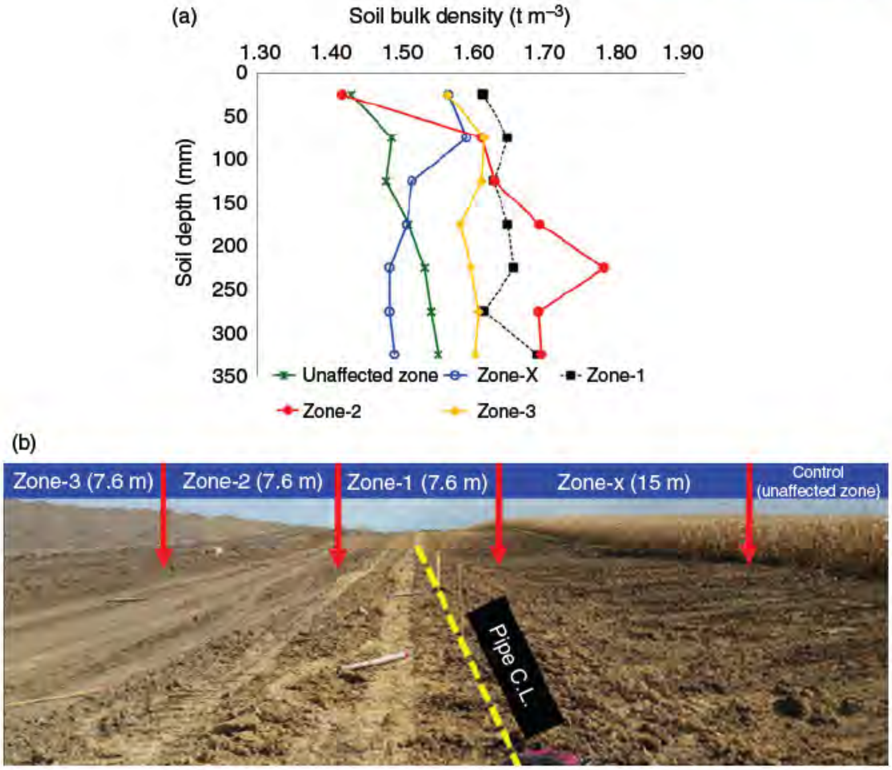


FIGURE 6 Soil bulk density with depth from the construction ROW zones (Zone-1, Zone-2, Zone-3 and Zone-x) and the unaffected zone (Control-S). The reported soil depth refers to the top surface of the exposed subsoil (b) within the ROW. "C.L." is the pipe centreline. Each data point is a mean of nine replicates [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Mean soil bulk density ($t\ m^{-3}$) by soil depth class

Soil bulk density ($t\ m^{-3}$)					
Soil depth class[b] (mm)	**Zone-1**	**Zone-2**	**Zone-3**	**Unaffected zone**	**Zone-x**
0–50	1.62 (A)[a]	1.42 (B)	1.57 (A B)	1.46 (B C)	1.57(B)
50–100	1.65 (A)	1.62 (A)	1.62 (A)	1.52 (B)	1.59 (A B)
100–150	1.63 (A)	1.63 (A)	1.62 (A)	1.51 (B)	1.52 (B)
150–200	1.65 (A)	1.70 (A)	1.58 (A B)	1.54 (B)	1.51 (B)
200–250	1.66 (A)	1.79 (A)	1.60 (B)	1.55 (B)	1.49 (B)
250–300	1.62 (A)	1.70 (A)	1.61 (A)	1.59 (A B)	1.49 (B)
300–350	1.69 (A)	1.70 (A)	1.61 (A B)	1.57 (B)	1.49 (B C)

[a] The same letter within each depth indicates there is no significant difference at $p \leq 0.05$. [b] The zero soil depth is in reference to the top surface of the exposed subsoil. The difference between soil depth (mm) relative to undisturbed topsoil surface on the unaffected zone "Control-S" outside of the ROW and soil depth (mm) relative to the top surface of exposed subsoil was the topsoil removed from the ROW.

relatively high data variability, partly because there was substantial precipitation prior to data collection.

3.2 | Soil bulk density

The soil bulk density trend at different soil depth (Figure 6) shows the higher magnitude of soil compaction from the soil disturbance and vehicle trafficking in the construction ROW zones compared to the unaffected zone. The soil bulk density values in Figure 6 were all relative to the top surface of the exposed subsoil.

Comparing the soil bulk density values among zones (Z-1, Z-2 and Z-3) within the ROW and the unaffected area (Table 2), the soil compaction effect from the construction activity was statistically significant ($p < 0.05$) to a depth of 300 mm below the top surface of the exposed subsoil. The differences in soil bulk density between the unaffected zone and Z-x that received relatively light traffic were minimum, except in the top 50 mm. The deep compaction in Z-1 and Z-2 had soil bulk density close to a Proctor compaction test (ASTM D698) of maximum bulk density (1.72 t m^{-3}) at an optimal soil moisture content (21.5%, d.b.) of a loam soil (33.29% sand; 45.21% silt; 21.5% clay). The Proctor compaction test was conducted on loam soil (Clarion loam series) sampled at a nearby ISU farm location. The control (unaffected) area and the least trafficked zone in the ROW (Z-x) had wetter soil conditions (Figure 7), indicating that the compaction from the construction activities, especially on Z-2 and Z-3, seemed to restrict water infiltration prior to the bulk density measurement. The backfilled subsoil to the pipe trench in Z-1 was compacted by DAPL to reduce soil settlement.

Within the ROW (below 300 mm from the top surface of the exposed subsoil), soil compaction was found with higher bulk density in Z-1 (1.67 t m^{-3}), Z-2 (1.70 t m^{-3}) Z-3 (1.58 t m^{-3}) than the less trafficked zone (Z-x) (1.52 t m^{-3}). Soil core samples from the unaffected zone below 300 mm from the top surface of the exposed subsoil were not available due to the limit of the maximum Giddings cylinder stroke length.

3.3 | Deep tillage effect on soil cone index

Table 3 shows means and standard deviations of soil cone penetration resistance values within Z-1, Z-2 and an unaffected area (Control-N) for two soil depth layers of 0 to 300 mm and 300 to 750 mm. Taking cone penetration readings on all zones within the ROW (Z-1, Z-2, and Z-3) and adjacent zones (Control-N and Control-S) was not practically feasible without introducing wide soil moisture variations during the sampling period. To minimize undesired soil moisture effects on cone penetration resistance, we focused on Z-1, Z-2 and Control-N for comparison of the tillage remediation effects within the ROW and the adjacent unaffected area. The soil moisture contents during the cone penetration reading from the topsoil (0–150 mm) within Z-1, Z-2 and Control-N were 16.28% d.b. ($SD = 1.72\%$), 15.98% d.b. ($SD = 1.11\%$), and 17.78% d.b. ($SD = 1.72\%$), respectively. The soil moisture content was not significantly different across the various sampling zones ($p = 0.09$).

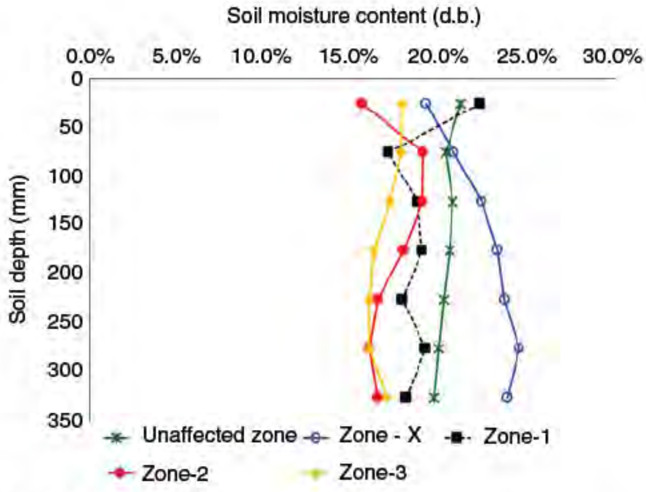


FIGURE 7 Soil moisture content of soil depth from four construction zones Zone-1, Zone-2, Zone-3, Zone-x and an unaffected zone (Control-S). The reported soil depth refers to the top surface of the exposed subsoil within the ROW. Each data point is a mean of nine replicates [Colour figure can be viewed at wileyonlinelibrary.com]

Within Z-1 and Z-2, the 300-mm-depth tillage and 450-mm-depth tillage applied prior to topsoil replacement did not have a significant effect on the soil cone penetration resistance within the 0 to 300 mm soil depth ($p > 0.05$). Comparing the zones within ROW (Z-1 and Z-2) to the unaffected area, Z-1 had statistically the highest soil cone penetration resistance ($p < 0.01$) in the topsoil profile (0–300 mm).

Deeper than 300 mm soil depth, the effect of the utility construction equipment on deep soil compaction was noticeable, even though the ROW zones received subsoiling from the tillage treatments (300-mm-depth tillage and 450-mm-depth tillage; Figure 8). Similar to the soil bulk density, deep soil compaction in Z-2 was higher than in Z-1 and in the adjacent unaffected crop field. Overall, the 450-mm-depth tillage alleviated the deep soil compaction created by the pipeline construction equipment better than the shallow tillage (300-mm-depth tillage). No significant differences ($p > 0.05$) in the mean soil cone penetration resistance (300 to 750 mm) were observed comparing the compaction from each of the ROW zones (Z-1 and Z-2) to the unaffected zone after Z-1 and Z-2 received the 450-mm-depth tillage. In the deeper soil profile (below 600 mm; Figure 8), Z-1 and Z-2 which received the 450-mm-depth tillage had soil cone penetration resistance values close to those of the unaffected area.

After subsoiling at the 300-mm-depth tillage in Z-1 and Z-2, the deep soil compaction (300 mm to 750 mm) was not fully removed (Figure 8) and soil compaction was significantly ($p < 0.05$) higher than in the unaffected area.

The pipeline construction equipment trafficking created deep soil compaction (a hardpan) as shown by an abrupt increase in soil cone penetration resistance as the cone penetrometer was inserted into the subsoiled layer (Figure 8). Tekeste, Raper, Schwab, and Seymour (2008) and Raper, Reaves, Shaw, van Santen, and Mask (2005) detected crop-limiting soil hardpan layers on Coastal Plains soils in the southeastern United States by analysing the soil cone penetration resistance profile for a soil depth range. Raper et al. (2005) applied site-specific tillage at a depth that had a maximum soil cone index approximating the depth of soil hardpan and reported soil compaction alleviation. Schjonning and Rasmussen (1994) also reported deep soil compaction on loam soils that persisted even after 5 years traffic with four passes of a vehicle with high axle load (32t) on the bottom of a 200 mm exposed soil layer.

The deep soil compaction created on the Clarion loam and Canisteo clay loam from the pipeline construction will require depth-specific subsoiling management in the future

TABLE 3 Mean soil cone index (MPa) for 0 to 300-mm and 300 to 750-mm soil depth range for the Zone-1, Zone-2 and the unaffected zone

Zone	Tillage remediation	Depth range (mm)[b]	Replicate	Soil cone index (MPa)	
				Mean	*SD*
Unaffected zone	Control-N[a]	0–300	4	1.7	0.19
		300–750	4	1.9	0.17
Z-1	300 mm depth tillage	0–300	4	2.1	0.3
		300–750	4	2.6	0.5
	450 mm depth tillage	0–300	4	2.0	0.2
		300–750	4	2.0	0.4
Z-2	300 mm depth tillage	0–300	4	1.4	0.4
		300–750	4	2.6	1.0
	450 mm depth tillage	0–300	4	1.3	0.1
		300–750	4	1.7	0.6

[a]The tillage practice in the unaffected area was similar to the tillage in control-N. [b]The top depth for the soil cone index reporting refers to the top surface of the unaffected zone.

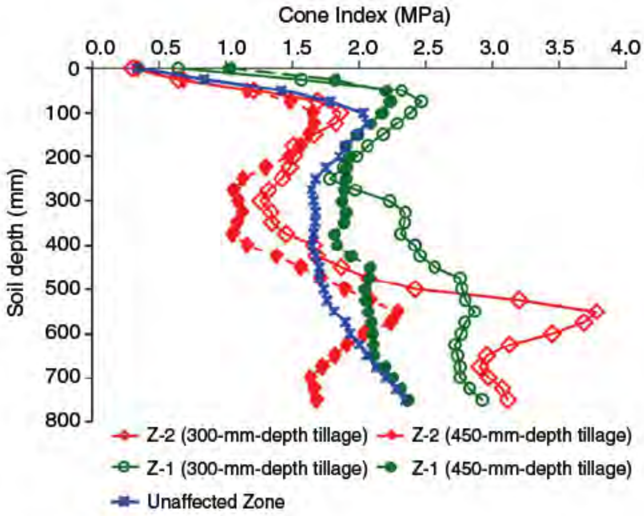


FIGURE 8 Soil cone index profile measured from the right-of-way (ROW) zones (Zone-1 and Zone-2) subsoiled at 300-mm- and 450-mm-depth tillage treatments prior to the topsoil replacement and the unaffected zone outside the ROW. The topsoil depth refers to the topsoil surface from the unaffected zone. Each data point is a mean of four replicates of the three-point cone penetrometer readings [Colour figure can be viewed at wileyonlinelibrary.com]

to remove the root-limiting hardpan layers and prevent the persistent problem of deep compaction. Excessive compaction deeper than 500 mm soil depth is relatively deeper than typical fall tillage practices (200-mm-depth tillage) in the area (Karlen, Kovar, Cambardella, & Colvin, 2013).

4 | CONCLUSIONS

A five-year long-term corn–soybean field experiment was established to assess impacts of utility construction activities and deep tillage remediation treatments (300-mm-depth tillage and 450-mm-depth tillage applied at the exposed subsoil) within the ROW.

Using a pressure sensor, the peak vertical soil stresses measured at three soil depths (200, 400, and 600 mm) successfully identified the machine configuration (size and tractive element) that created excessive soil compaction below the exposed subsoil.

The impact on soil compaction from pipeline installation on exposed subsoil was also evaluated comparing soil bulk density within ROW and adjacent unaffected crop field area. First-year soil responses to deep tillage were also investigated using cone penetration resistance measurement. Heavy vehicle and high traffic intensity within the ROW created deep soil compaction with significantly higher soil bulk density in the pipeline zone (Z-1) and adjacent heavily trafficked zone (Z-2) to a depth of 300 mm. Comparing the soil cone penetration profile from the ROW deep tilled zones and the unaffected zone, deep tillage applied using a 450 mm depth alleviated the deep compaction created during the pipeline construction. Subsoiling using 300-mm-depth tillage, however, did not significantly reduce the deep soil compaction.

Delineating the pipeline construction zones on the basis of vehicle trafficking, the techniques to quantify machine induced peak vertical soil stress and subsoil tillage management may be used to develop soil compaction management plans for pipeline construction activities in cropland.

Future studies will include deep tillage management effects on soil compaction (bulk density and cone penetration resistance) and corn–soybean crop yields.

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