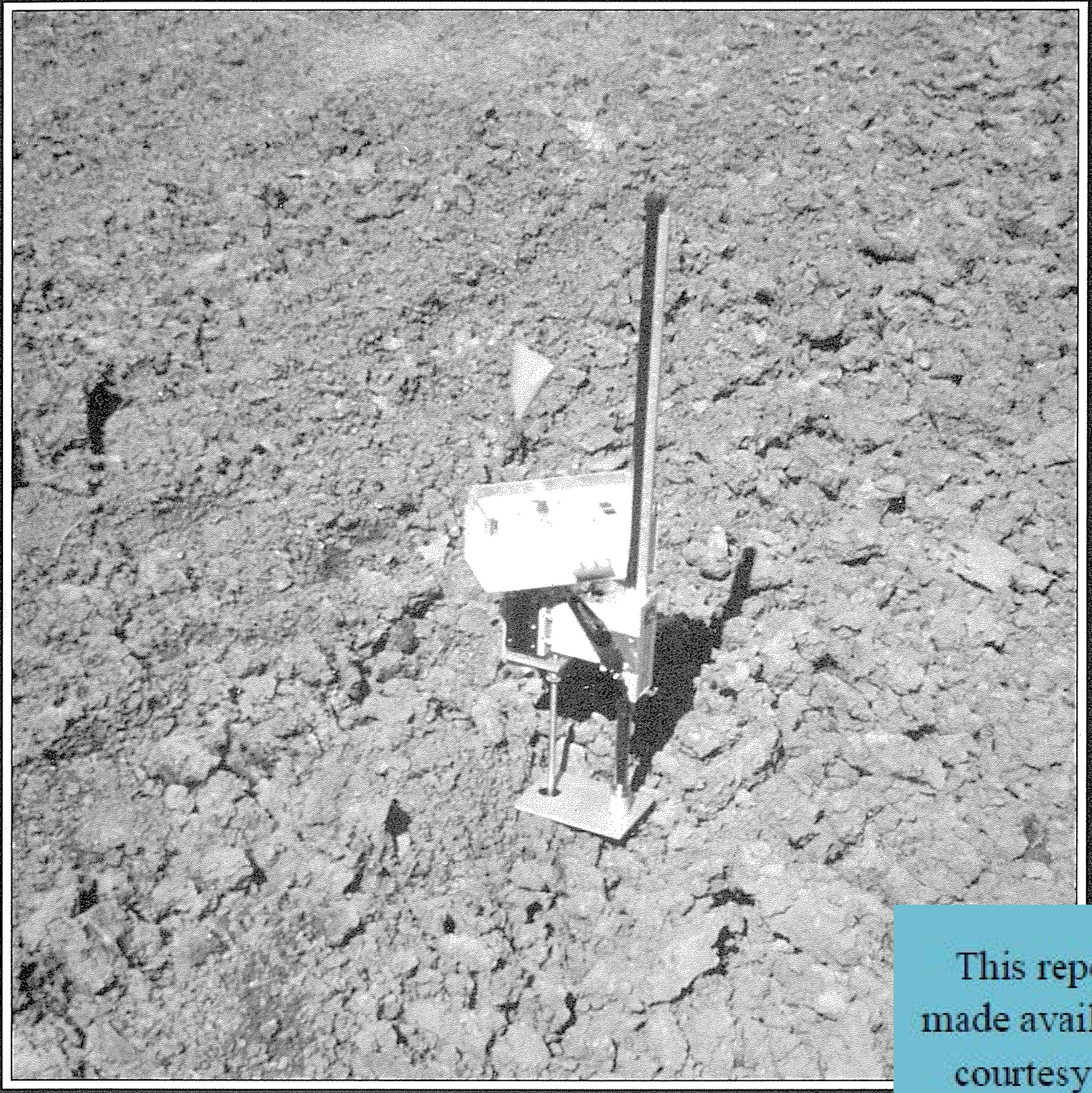
# Effect of Pipeline Construction on Soil Compaction in Alberta





NOVA Gas Transmission

# EFFECT OF PIPELINE CONSTRUCTION ON SOIL COMPACTION IN ALBERTA

by

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## FOREWORD

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This study was commissioned to evaluate the effects of pipeline construction on soil compaction using soil strength measurements on selected pipelines within Alberta. This report was prepared by Sandra Landsburg, M.Sc., P.Ag., NOVA Gas Transmission Ltd. and, Karen R. Cannon and Nancy M. Finlayson, Land Resources Network Ltd (a private consulting company).

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ABSTRACT

A study was initiated in 1988 to evaluate the effects of pipeline construction on soil compaction in the province of Alberta. The pipelines were located throughout Alberta on a number of different soils and were constructed using various techniques. Cone penetration resistance of soils (soil strength) was monitored to a depth of 31.5 cm at 14 study areas. Soil strength measurements were taken from right-of-way locations as well as from an adjacent undisturbed control. Soils were also analyzed to determine percent organic matter, moisture and clay.

Soil strength information from the 14 study areas suggests that pipeline construction procedures can cause changes in soil strength on pipeline rights-of-way in Alberta. However, decreases in soil strength on the RoW compared to adjacent controls are more common than increases. These differences in soil strength appear to be short lived in the majority of cases; most differences, both increases and decreases, had disappeared one year after construction or were less than 2 bars.

Although pipelines constructed through a number of different soils types were monitored, no clear relationships emerged between soil Orders, zones, or soil parent materials and the effect of pipeline construction on soil compaction. Soil moisture conditions appear to be more important. Pipelines constructed under moist to wet soil conditions were more likely to be compacted than if construction took place under dry soil conditions. Gleysolic soils for example were no more likely to be compacted during construction than soils of any other Order, provided construction took place under dry soil conditions.

ACKNOWLEDGEMENTS

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## 1.0 INTRODUCTION

Concerns about soil compaction on pipeline rights-of-way (RsoW) have increased with the introduction of heavier, more powerful construction equipment. RsoW are susceptible to compaction because of the repeated high traffic associated with construction procedures. Soil compaction can lead to poor root penetration, difficult cultivation, poor seedbed preparation, increased soil strength, reduced water infiltration, increased surface water runoff and decreased soil porosity (Lull 1959; Swan et al. 1987). Root and crop growth can be affected because of limited root elongation and distribution due to restricted movement of gases, water and nutrients. Where pipeline RsoW cross agricultural land, there is the potential for landowner concerns resulting from reduced crop production caused by soil compaction.

Limited data are available on the effect of pipeline construction on soil compaction. Such knowledge is important because each soil can respond differently to various construction procedures. The degree of compaction depends mainly on variables such as soil type and soil conditions at the time of pipeline construction, as well as on vehicle type and traffic density. Studies are needed to understand the problem of soil compaction so that it can be minimized or ameliorated. The ability to predict which soil may be more susceptible to compaction would enable the implementation of preventative measures during pipeline construction.

### 1.1 OBJECTIVE

The objective of this study was to evaluate the effect of pipeline construction on soil compaction in Alberta. In order to achieve the objective, a study was initiated to monitor penetrometer cone resistance on a number of NOVA Gas Transmission Ltd. (NGTL) pipeline RsoW immediately after construction and one year after construction.

## 2.0 REVIEW OF RELATED LITERATURE

## 2.1 CONVERSIONS

Both SI and non-SI Units were encountered in papers read for the literature review. For consistency, non-SI Units were converted to SI Units and the SI conversions were reported first, followed in brackets by the non-SI Units. Note that 1 Mg is equivalent to 1 tonne (1 t), 1.1 tons, or 2,200 pounds. One bar is equivalent to 100 kPa.

## 2.2 SOIL STRENGTH AND SOIL COMPACTION

Soil compaction is the increase in density of a soil that results from an externally applied force or pressure. The degree of compaction resulting from an applied force is affected by the texture, structure, organic matter content and moisture content of the soil at the time of compression. The permanence of the compaction is determined by the capacity of the soil to return to its original condition after the occurrence of a compactive event.

Soil strength is determined by measuring the resistance of a soil to the penetration of a probing instrument. As a result, it is "an integrated index of soil compaction, moisture content, texture, and type of clay mineral" (Baver et al. 1972). Consequently, soil strength is a dynamic property that defines the soil based upon conditions existing at the time of measurement. Soil moisture content, in particular, "appears to be the dominant factor influencing the penetrometer readings, although there is no simple relationship between these readings and the amount of water present" (Baver et al. 1972).

Linear regression techniques have been used to determine the effect of various soil properties on soil strength (Gerard et al. 1982; Stitt et al. 1982). Both of these studies found soil moisture content to be an important variable affecting soil strength. They found that decreases in soil strength occurred as water content increased. Increases in soil organic matter levels also resulted in decreases in soil strength (Ohu et al. 1986). In contrast, soil strength increased with increased clay content (Gerard et al. 1982), as soil particle surface roughness increased (Stitt et al. 1982) and with increased bulk density (Gerard et al. 1982; Stitt et al. 1982). However, none of these studies was able to clearly quantify the relationship between soil strength and soil properties.

Given equal moisture contents, percent organic matter and similar parent material, the higher soil strength reading of two adjacent tests will indicate the more compacted soil. However, the variable nature of soil, even over short distances, limits the reliability of this test to a qualitative or at best semi-quantitative measure of compaction.

## 2.3 SOIL STRENGTH AND PIPELINE CONSTRUCTION

Information in the literature on the impact of pipeline installation on soil compaction is generally conflicting. Some studies have shown that pipeline construction can lead to soil compaction, whereas other studies have demonstrated that little or no compaction results from installation procedures. In some studies, reduction in soil bulk densities as a result of pipeline construction have been reported. Reductions in bulk density can occur when a compacted horizon is broken up during the trenching operation. Increased bulk density can result during pipeline construction because of repeated passage of equipment on the surface of a right-of-way (RoW), because of denser subsoil being mixed with topsoil, because of loss of less dense topsoil or because the soil was too wet during construction. The amount of soil compaction due to pipeline construction depends on soil moisture content, soil texture, organic matter content, original soil structure and the force of compaction.

Results from earlier studies by de Jong and Button (1973) indicated that pipeline installation neither harmed nor improved the physical properties of Chernozemic soils. However, in Solonetzic soils, lower bulk densities resulted in improved permeability and aeration of the Bnt horizon. Saturated permeability and air-filled porosity of the Solonetzic Bnt horizon prior to trenching were considered undesirable. Trenching on Solonetzic soils tended to decrease the bulk density at depth, whereas trenching on Chernozemic soils occasionally resulted in increased bulk densities at depth. The occasional increases in bulk density were thought to have occurred because of compaction by heavy machinery or by puddling of the exposed subsoil.

A study to evaluate the effect of pipeline construction on agricultural land was conducted for two seasons on the Sarnia-Montreal oil pipeline (Stewart and MacKenzie 1979). The soils studied included a clay loam developed on lacustrine sediment, a clay loam developed on glacial till and a sandy soil developed on fluvio-aeolian materials. Pipeline construction occurred in both fall and winter. Topsoil was salvaged during fall construction but not during winter construction. The researchers found that surface (0 to 15 cm) bulk densities were higher on the RsoW than off, with the trench tending to have the highest bulk density. Bulk densities were similar for the two years studied, indicating little or no change over that time. Bulk densities at depths of 15 to 30 cm were less affected by construction, but again there were higher bulk densities over the trench. Lower saturation water content in the surface of the RsoW indicated that total pore space was reduced compared to control sites, and was consistent with soils of higher bulk density. This effect was not noticeable over the trench. At lower depths, reduced saturation water content was found only in the trench. Season of construction appeared to have little influence on levels of compaction.

Considerable soil compaction was also measured across the entire RoW on the same Sarnia-Montreal oil pipeline by Culley et al. (1982). Compaction was especially predominant on medium- to fine-textured soils. However, compaction did not appear to be a problem on coarse-textured soils. Bulk densities were 10% greater on the RoW than on adjacent undisturbed fields for the medium- to fine-textured soils. The work side of the RoW was found to have the highest bulk density, unlike results reported by Stewart and MacKenzie (1979). Culley et al. (1982) found hydraulic conductivity to be 38% lower on average in the trench and work side portions of the RoW as compared to the control. Culley et al. (1982) also found that surface layers of the RoW had lower available water-holding capacities than surface layers of control sites, similar to results reported by Stewart and MacKenzie (1979). This decrease in available water-holding capacity was attributed to lowered total porosity. Soil strength, as measured by penetrometer resistance, was greater on the RoW than off, averaging 67% and 50% more over trench and work areas respectively (Culley et al. 1982). This increase in soil strength was believed to be due to greater clay content and reduced organic matter in the soil after the trenching operation.

The potential severity of soil compaction on a RoW in southwestern Ontario was presented in a study by Moncrieff (1984). Eight kilometres of a RoW had been turned into a homogenous saturated mixture of topsoil and subsoil after having been exposed to deteriorating weather conditions and heavy equipment movement. Crop yields on the RoW were approximately 40% lower than those on the adjacent field, even after five years. These yield reductions were attributed to the conversion of the original structure of the B horizon into a massive structure. The result was reduced air and water movement, which limited root penetration. Subsoiling procedures were necessary to break up the subsoil and provide surface drainage. This amelioration of the site led to improved yields that approached and in some cases even exceeded those on the adjacent undisturbed control.

Research was conducted in eastern Oklahoma on a fine sandy loam to determine the extent to which physical characteristics of a soil were altered by a single ditch pipeline construction project (Zellmer et al. 1985). No attempt was made to separate or remove the topsoil during trenching and backfilling. This study concluded that the surface (0 to 15 cm) bulk density was not increased by pipeline installation in this semi-arid environment. Bulk densities were not increased by construction traffic on the RoW. There were also no significant differences between the soil bulk densities from the work side transect and those in the adjacent control transect. Bulk densities were lower in the trench than on the adjacent undisturbed control site in 16 of 20 control sets of observations. Similar trends were observed for subsurface (to a depth of 50 cm) bulk densities. In cultivated soil, bulk densities averaged approximately 1.56 Mg $m^{-3}$ for the control site and 1.46 Mg $m^{-3}$ in the trench. Similar trends occurred for pasture land, with bulk densities averaging approximately 1.46 and 1.27 Mg $m^{-3}$ for the control and trench locations respectively. Lower bulk densities for the pasture land compared to the cultivated soil were attributed to the extensive root system of the vegetation.

A study was conducted in southern Alberta on Solonetzic native rangelands to evaluate the persistence of physical and chemical changes along a pipeline corridor. The corridor contained five adjacent natural gas pipelines that were constructed in 1957, 1963, 1968, 1972 and 1981 (Naeth 1985). Measurements were taken in 1983, two years after construction of the 1981 pipeline. Surface bulk densities (0 to 7.6 cm) were found to be greater by 51 to 82% for all disturbed transects compared to the undisturbed transects, where bulk densities were 0.90 to 1.00 Mg $m^{-3}$. The highest increases were reported for the 1981 transect. Greater bulk densities, to a depth of 55 cm, occurred on all 1981 transects except on the trench, where subsurface densities were lower than on the undisturbed transect. Lower bulk densities on the trench were attributed to the breaking up of the Bnt horizon during the trenching procedure. Older RsoW showed lower surface bulk densities on native Solonetzic rangelands compared to more recent RsoW, indicating that ameliorative effects occurred within 10 years of pipeline construction. Even after 24 years, however, trench bulk densities were still significantly lower than those in adjacent control prairie soil.

A study to evaluate soil handling during winter pipeline construction on Orthic Gray Luvisols and Gleyed Dark Gray Luvisols in northern Alberta on the Heart River Pipeline was conducted by Cloutier (1988). Results indicated that bulk densities in the trenches were as much as 0.79 Mg $m^3$ lower than on adjacent controls. Generally, topsoil bulk density of the trench was similar or even lower than on the control soils. Lower topsoil bulk density was attributed to the formation of a thick sod layer on the RoW, which was not present on the control soil, and lower subsoil bulk densities in the trench were attributed to the breaking up of the dense Bt horizon during pipeline installation.

Research in central Alberta on cultivated and pastured Orthic Dark Brown Chernozems and on cultivated Dark Brown Solonetz soils was conducted to study the effects of pipeline construction on agricultural soil quality ratings (Landsburg 1989). Bulk densities of the Ap horizons were similar between the work side and control for each of the three soils, indicating that there was no compaction due to heavy equipment. Construction had little effect on the work side because optimum weather conditions resulted in minimal soil rutting. There were also no significant differences between Ap horizons of the trench and control for each of the three soils studied. The cultivated Dark Brown Solonetz had a significantly greater bulk density on the spoil side compared to the control (1.22 versus 1.09 Mg $m^{-3}$ respectively). This trend was also observed for the Orthic Dark Brown Chernozem on pasture land, with bulk densities of 0.82 and 1.16 Mg $m^{-3}$ for the control and spoil sides respectively. Greater bulk density on the Solonetz soil was attributed to the presence of spoil material on the B horizon before topsoil replacement, whereas greater bulk density for the Chernozem on pasture land was thought to be due to the impact of construction equipment during backfill. Results indicated, however, that the greater bulk densities posed no limitation to crop growth.

## 2.4 SOIL STRENGTH AND PLANT GROWTH

Cassel et al. (1978) and Cassel (1982; 1983) noted a number of difficulties in relating soil strength data to plant growth because of the following factors:

- Soil strength is a dynamic characteristic that is dependent on soil physical and chemical properties.

- The cone penetrometer is much larger and penetrates the soil much faster than a root tip. Roots are capable of weaving in and out between soil particles and through cracks and fissures. Plant root growth can occur through cracks even when the soil near the crack is strong enough to inhibit root growth.

- Soil conditions vary temporally and spatially. For example, soil conditions vary spatially by position and depth, and vary temporally as a result of changing traffic patterns or weather conditions.

- The use of different equipment and techniques makes it difficult to compare soil strength data for a particular soil to data for another soil, and makes it difficult to compare results of laboratory and field studies. Shape of tip (blunt or cone shaped), angle and diameter of the penetrometer will affect soil strength measurements. An ideal constant penetration rate of 3 cm/sec is difficult to obtain in field research, especially if there is considerable soil strength variation occurring with depth. Soil physical and chemical properties at one site can differ from those of another site.

Various studies have shown soil strength to affect plant growth. For example, Taylor and Gardner (1963), in a laboratory study, reported that 70% of plants penetrated soils with strengths of 1000 kPa (10 bars), but only 30% penetrated soils with strengths of 2000 kPa (20 bars). There was no root growth in soils with strengths over 2960 kPa (29.6 bars). Taylor et al. (1966) found that root penetration was drastically reduced with greater soil strength, to 2500 kPa (25 bars); there was no root growth over 2500 kPa (25 bars). Both of these studies monitored cotton taproots in sandy loam soils with soil moisture at or close to field capacity, using a penetrometer with a 0.48 cm diameter cylindrical tip pushed into the soil surface.

A given increase in soil strength caused a greater reduction in root elongation for cotton plants than for peanuts in a loamy sand (Taylor and Ratliff 1969). An increase in soil strength from 0 to 10 bars reduced root elongation by 62% for cotton plants, but reduced peanut plant growth by only 29%. This study used a 60 degree cone-shaped penetrometer with a diameter of 0.318 cm. Gerard et al. (1982) found that the critical strength that prevented root elongation of cotton seedlings ranged from 25 bars in clay soils to 60 to 70 bars in coarse-textured soils. The penetrometer that was used had a 60 degree cone-shaped tip with a diameter of 3.5 mm. Moisture of the soils varied within the range of available moisture.

Differences in soil moisture can influence the ability of plant roots to overcome soil strengths. For example, Mirreh and Ketcheson (1973) found that maximum elongation of corn roots occurred at low soil resistance and high soil water content. With negligible soil resistance, good elongation was independent of soil water. However, with high soil resistance, root elongation was only found to occur with high soil water content. Similar results for cotton and peanuts were observed by Taylor and Ratliff (1969). Increased soil strength reduced plant top weights and root lengths only with low soil water content.

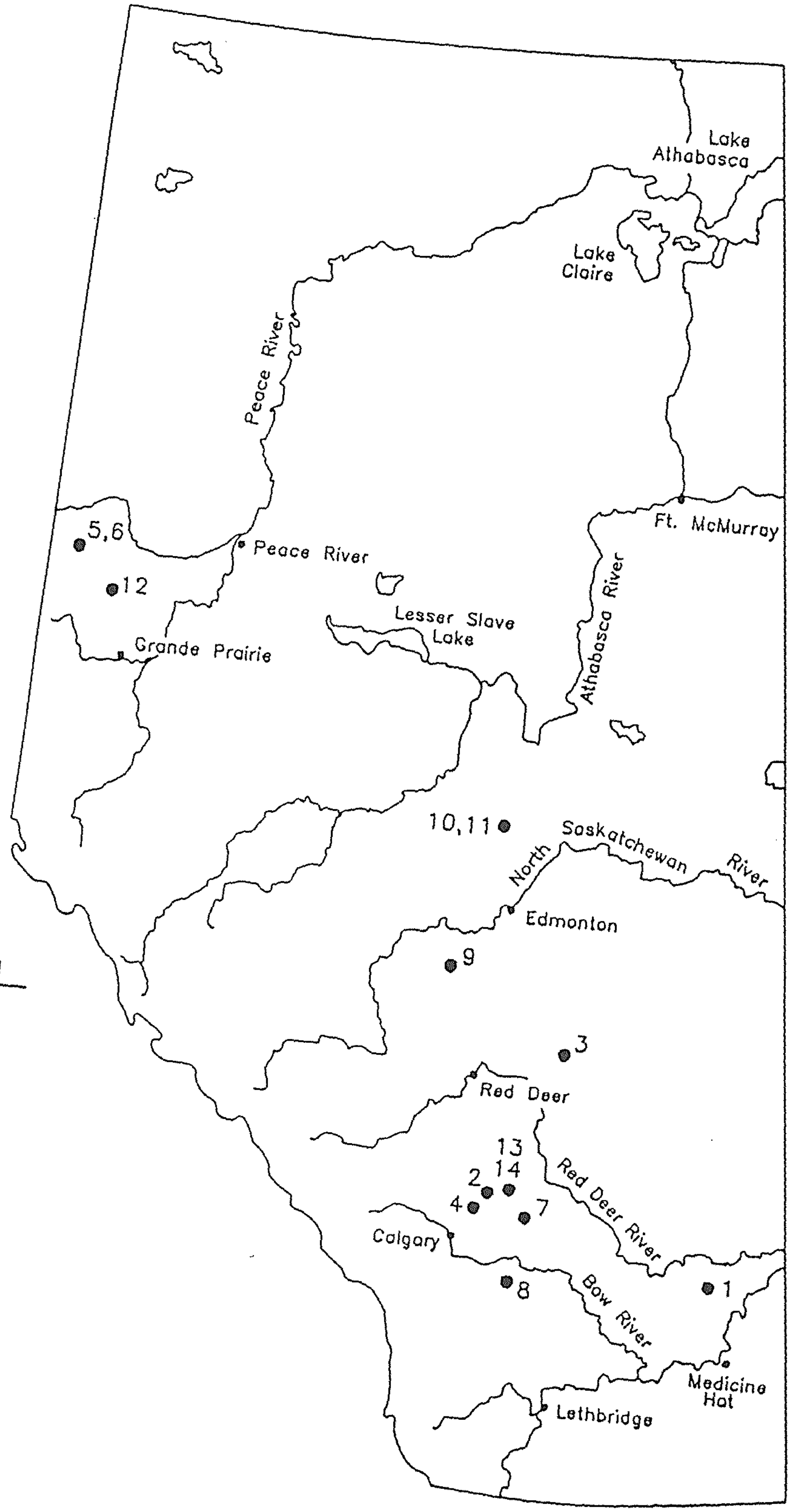
Wheat grain yields were lower when soils were compacted to 1.6 Mg $m^{-3}$ from 1.2 $Mg^{-3}$. Surface compaction reduced wheat yields for the first year but not as much in the second year. This effect was attributed to reduced bulk density through freezing and thawing and soil moisture changes (Wittsell and Hobbs 1965). In another study, the distribution of alfalfa roots grown on plots that had been packed to bulk densities of 1.7 Mg $m^{-3}$ from 1.5 Mg $m^{-3}$ was assessed. There was a greater distribution of fine roots at all depths, and more taproot branching in the top 30 cm in the unpacked plots compared to the packed plots (Blake et al. 1976).

# 3.0 MATERIALS AND METHODS

## 3.1 EXPERIMENTAL DESIGN

Fourteen study areas were monitored for soil strength on NGTL pipeline RsoW immediately following pipeline construction. In 1988, six study areas were initially monitored for soil compaction, and, in 1989, eight additional study areas on newly constructed pipeline RsoW were also monitored (Figure 1). At the time of monitoring, seedbed preparation had taken place on all study areas. One year after initial construction was completed, all 14 study sites (six sites in 1989 and eight sites in 1990) were again monitored for soil strength. Soils at the 14 study areas were described and classified and are presented in the Appendix. A summary of study area information at the time of pipeline construction is shown in Table 1.

Study areas along a RoW were selected with a view towards choosing average conditions. Criteria used were:




STUDY AREAS

| Site No. | Site Name | Year Initiated |
|---|---|---|
| 1 | Atlee-Buffalo | 1989 |
| 2 | Craigmyule | 1988 |
| 3 | Ferintosh | 1989 |
| 4 | Ghostpine | 1988 |
| 5 | Henderson 1 | 1989 |
| 6 | Henderson 2 | 1989 |
| 7 | Michichi | 1988 |
| 8 | Milo | 1988 |
| 9 | Pigeon Lake | 1989 |
| 10 | Redwater 1 | 1989 |
| 11 | Redwater 2 | 1989 |
| 12 | Valhalla | 1989 |
| 13 | Victor 1 | 1988 |
| 14 | Victor 2 | 1988 |

Figure 1. Study Area Locations

- Soils should be uniform within an area that is long enough to accommodate three adjacent monitoring plots.

- Soils should be representative of the major soil type(s) occurring along the pipeline route.

- Pipeline construction techniques and conditions should be representative of those occurring throughout the length of the line.

As wide a range of soil subgroups and parent materials as possible were monitored. Once a suitable site was chosen, three replicates were laid out, each 2 m wide and running across the RoW 5 m into an adjacent undisturbed control. Each replicate was separated by a distance of 15 m (Figure 2).

Table 1. Study Areas Information Summary

| Site # | Site Name | Soil Classification | Parent Material | Soil Conditions[1] | Topsoil Stripped[2] | Land Use |
|---|---|---|---|---|---|---|
| 1 | Atlee-Buffalo | Orthic Humic Gleysol | lacustrine overlying till | dry | 10 cm | native pasture |
| 2 | Craigmyle | Dark Brown Solodized Solonetz | residual | wet | 15 cm | cultivated |
| 3 | Ferintosh | Orthic Black Chernozem | fluvial overlying till | dry to moist | 30 cm | cultivated |
| 4 | Ghostpine | Orthic Dark Brown Chernozem | till | wet | 15 cm | cultivated |
| 5 | Henderson 1 | Solonetzic Dark Gray Luvisol | till | dry | 15 cm | cultivated |
| 6 | Henderson 2 | Dark Gray Luvisol | till | dry | 15 cm | cultivated |
| 7 | Michichi | Dark Brown Solodized Solonetz | glaciolacustrine blanket | dry | 15 cm | cultivated |
| 8 | Milo | Solonetzic Brown Chernozem | glaciofluvial | dry | 20 cm | cultivated |
| 9 | Pigeon Lake | Orthic Dark Gray Chernozem | till | moist | 15 cm | hay |
| 10 | Redwater 1 | Gleyed Black Chernozem | glaciofluvial | moist to wet | 40 cm | cultivated |
| 11 | Redwater 2 | Orthic Dark Gray Chernozem | glaciofluvial overlying till | moist to wet | 15 cm | hay |
| 12 | Valhalla | Gleyed Dark Gray Luvisol | till | dry | 10 cm | cultivated |
| 13 | Victor 1 | Orthic Humic Gleysol | lacustrine | dry | 15 cm | cultivated |
| 14 | Victor 2 | Orthic Dark Brown Chernozem | lacustrine | dry | 15 cm | cultivated |

[1]Soil conditions during pipeline construction.

[2]Topsoil stripped on trench and spoil side for all sites except Atlee-Buffalo, which was only stripped over the ditchline.

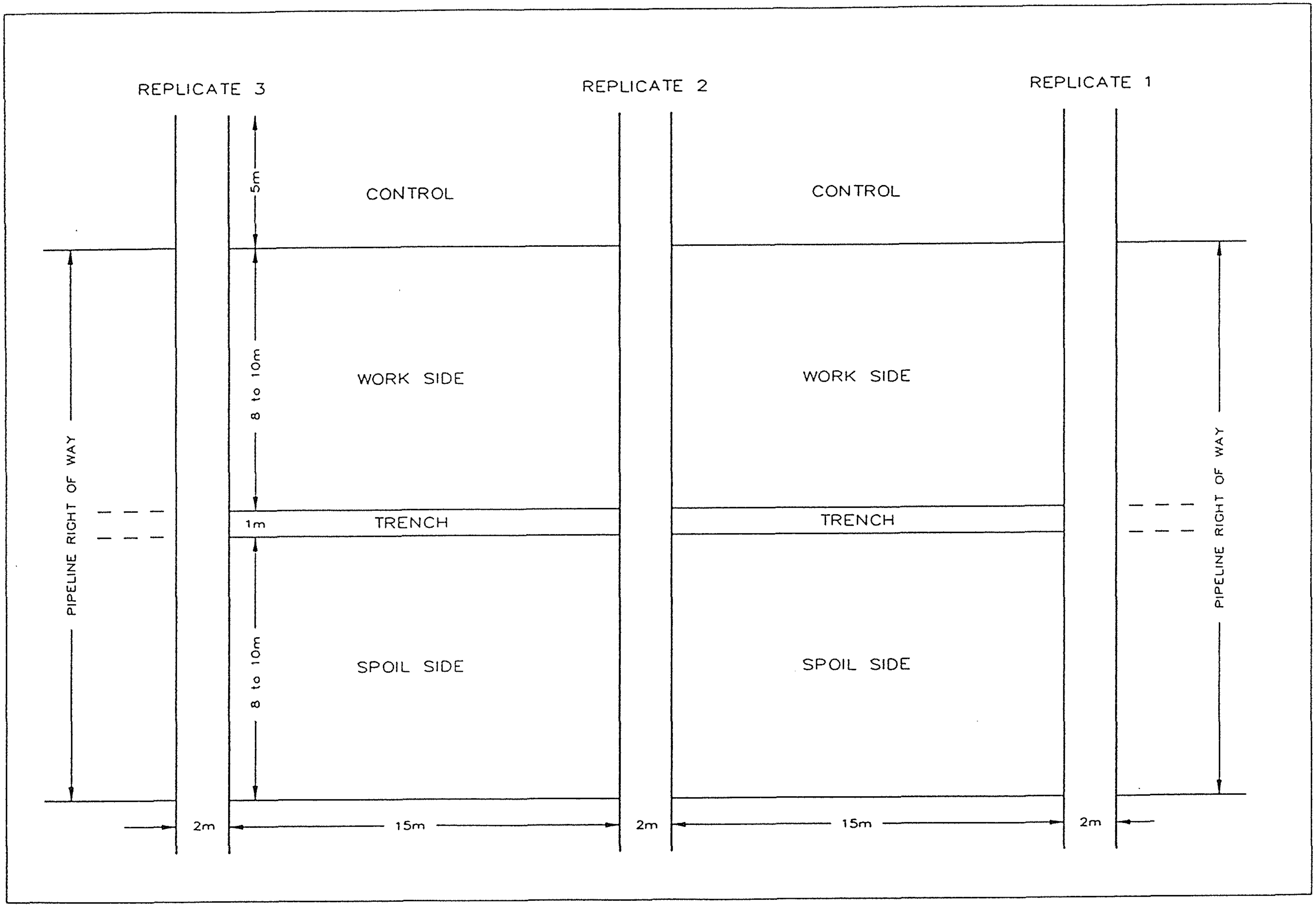



Figure 2. Experimental design of the plots monitored at each study area

## 3.2 FIELD ANALYSES

A Bush Recording Soil Penetrometer (Mark I Model) with a 12.9 mm diameter $30^0$ cone was used to measure cone resistance 'in situ' (Findlay, Irvine Ltd. 1979). Soil strength was measured by determining the cone resistance as the penetrometer was pushed into the ground at a rate of approximately 3 cm $s^{-1}$. The property measured is termed cone resistance and is recorded in units of bars. An overload protection was provided by an audible beeper at 38 bars (3800 kPa), allowing readings from 0 to 38 bars (0 to 3800 kPa). The penetrometer was unable to record strengths of soils greater than 38 bars.

Because of the considerable variation in cone resistance measurements of soil that have been reported, both in the literature (Cassel 1982) and for Alberta soils (D. Thacker, pers. comm.), composite measurements were taken within each replicate. Ten measurements were obtained at each sampling depth and averaged to obtain a mean value for each depth for each replicate. The locations of the ten soil strength measurements were evenly spaced within each replicate, running across the RoW for the work side, spoil side and control, and running parallel to the RoW for the trench. At every study area, three replicates were obtained for each of the trench, work side and spoil side portions of the RoW, as well as for an adjacent control area. If the cone penetrometer hit a stone, a new penetration was conducted. In 1988, the spoil sides of the RsoW were not monitored. In 1989, however, a decision was made to monitor the spoil sides of the RsoW of all future study areas because of the potential effects of traffic during backfilling operations on compaction. Within each replicate, soil strength measurements were taken at five sampling depths (3.5, 10.5, 17.5, 24.5 and 31.5 cm).

Soil samples were collected from the trench, spoil side, work side and control locations from each of the three replicates from each study area. Samples were taken by horizon from the soil surface down to 50 cm. Soils were described and classified at each control sampling location using the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey 1987).

## 3.3 LABORATORY ANALYSES

Samples were analyzed using procedures outlined by McKeague (1978). Soil moisture was analyzed on a dry weight basis, organic matter by Leco induction furnace, and particle size by the hydrometer method. Soil moisture and soil organic matter contents were determined for each sampling event. Particle size analysis was only done for the first sampling event immediately following pipeline construction.

## 3.4 STATISTICAL EVALUATION

For each depth increment monitored for soil strength, and for each soil horizon sampled for soil moisture, clay content and soil organic matter, treatments were compared using the Students' 't' test for unpaired data to determine whether the difference between composite means was significant at $p < 0.05$ (Webster 1977). At each study area, the trench, work and spoil sides of the RoW were compared to the control. When maximum penetration resistance of the penetrometer (3800 kPa, 38 bars) was exceeded for any sampling depth, statistical comparisons could not be carried out.

Soil strength measurements are influenced by moisture content, density (Frietag 1971), and organic matter (Ohu et al. 1986). Consequently, linear regression techniques were used to analyze the relationship between these parameters and soil strength as measured by the cone penetrometer.

## 3.5 LIMITATIONS OF THE CONE PENETROMETER

The cone penetrometer was used to determine soil strength as an indirect measure of soil compaction. Soil strength was determined by measuring the resistance of soil to the penetrating cone-shaped tip of the cone penetrometer. The penetrometer was pushed into the soil at a steady rate and the applied force versus depth was measured. The applied force is indicative of the shear resistance of the soil. The advantages of the cone penetrometer include the relative simplicity, rapidity and cost-effectiveness of data collection (James 1988). The cone penetrometer used to determine on- and off-RoW soil strength is easy to carry, easy to set up in the field, and results can be quickly and easily determined.

Penetration resistance reflects the state of compaction, and is influenced by moisture content and density as well as by the size, shape and surface texture of the penetrating element (Frietag 1971). This method, like many indirect methods used to determine the extent of compactive forces, requires a separate analysis before and after the compactive action. Some limitations to the use of the cone penetrometer were noticed during the course of this study:

- Multiple replications are required in order to determine a single soil strength reading, resulting in large amounts of data to be handled.

- Soil strength measurements are influenced by moisture content, density and organic matter content. Therefore soil samples must be collected and analyzed to determine these factors as well. However, the relationships between soil strength and soil moisture, and between soil organic matter and soil texture are not clearly defined. This makes interpretation of soil strength data difficult in some situations.

- The cone penetrometer used for this study cannot penetrate soils with strengths greater than 38 bars (3800 kPa), the upper limit of the equipment used. This limits cone penetrometer use in dry areas or in dry years, making comparisons between wet versus dry years and between cropped versus uncropped soil difficult.

- The cone penetrometer cannot be used on stony or gravelly soils, or in soils with gravelly or compact lenses or horizons.

## 4.0 RESULTS

Soil strength values for 1988, 1989 and 1990 sampling years were compiled for each study site and sampling depth, and are presented in tables in this section. Statistical significance at $p < 0.05$ is indicated in these tables; 'mp' (maximum penetration) recorded at a sampling depth indicates that the cone penetrometer could not penetrate that depth, meaning that soil strengths were greater than 38 bars (3800 kPa).

The 1988, 1989 and 1990 data for soil moisture, soil organic matter and clay are also presented in table form in this section, with statistical significance at $p < 0.05$. Increased soil strengths would be expected for soils with decreased soil moisture and organic matter contents or with increased clay content. Decreased soil strengths would be expected with increased soil moisture and organic matter contents or with decreased clay content.

Detailed soil profile and landscape descriptions for each study site are presented in table form in the Appendix.

No statistically significant relationships between soil moisture content, organic matter content, clay content and soil strength were found using linear regression analysis. The results of these tests are not reported here.

## 4.1 CHERNOZEMIC ORDER

### 4.1.1 Ghostpine

The 28.5 km pipeline runs from the Ghostpine Meter Station (NE2-32-21-W4M) to the Rumsey Meter Station (SE31-33-20-W4M) (Figure 1; Finlayson 1988a). The pipeline was constructed in the summer of 1988 under wet soil conditions. The study plots were located in NW7-33-20-W4M. The soil monitored for soil strength was a cultivated Orthic Dark Brown Chernozem developed on undulating to rolling, medium- to moderately fine-textured till (Appendix, Table A4). Topsoil (15 cm) was stripped from the trench and spoil side and was placed on the far side of the spoil side on the RoW. Subsoil removed from the trench was placed on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1988, soil strengths of the work side at depths of 10.5, 17.5 and 24.5 cm were greater than control soil strengths for the same depths (Table 2). At 17.5 cm, trench soil strength was greater than the control. However, at 31.5 cm, trench soil strength was lower than that of the control. Work side soil moisture and clay at 0 to 15 cm were lower than the control values. Trench soil moisture, soil organic matter and clay at 0 to 15 cm were also lower than the control values.

In 1989, there were no significant differences in soil strength between the control and either the trench or the work side (Table 2). Work side soil moisture and organic matter at 0 to 15 cm were lower than the control values.

Table 2. Cone Resistance and Physical and Chemical Characteristics, Ghostpine[1]

| | Depth | 1988 | | | | | | 1989 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Control | | Work | | Trench | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.1 | 0.38 | 1.8 | 0.23 | 1.3 | 0.31 | 1.5 | 0.84 | 1.1 | 0.65 | 1.8 | 1.03 |
| | 10.5 | 6.3 | 1.57 | *11.6 | 1.26 | 5.6 | 1.28 | 11.3 | 1.70 | 17.9 | 8.46 | 14.8 | 6.51 |
| | 17.5 | 15.4 | 6.06 | *26.1 | 1.68 | *27.5 | 2.11 | 22.3 | 2.16 | 26.1 | 2.96 | 25.9 | 4.91 |
| | 24.5 | 20.6 | 0.81 | *24.1 | 1.41 | 18.2 | 2.06 | 22.7 | 0.42 | 23.0 | 1.60 | 25.0 | 4.00 |
| | 31.5 | 21.2 | 1.67 | 23.3 | 0.08 | *16.3 | 0.99 | 23.0 | 1.14 | 23.6 | 1.65 | 23.6 | 2.44 |
| % Clay | 0-15 | 22.9 | 0.93 | *26.9 | 1.00 | *30.2 | 0.06 | - | - | - | - | - | - |
| | 15-25 | 32.2 | 0.32 | 38.4 | 4.21 | 32.2 | 0.75 | - | - | - | - | - | - |
| | 25-50 | 35.9 | 1.93 | 35.8 | 3.97 | 33.2 | 1.88 | - | - | - | - | - | - |
| % Organic Matter | 0-15 | 6.3 | 1.08 | 6.0 | 0.41 | *3.8 | 0.29 | 6.1 | 0.72 | *4.6 | 0.95 | *5.1 | 0.37 |
| | 15-25 | 1.6 | 0.36 | 1.5 | 0.58 | 2.1 | 0.68 | - | - | - | - | - | - |
| | 25-50 | 0.6 | 0.32 | 0.9 | 0.06 | 2.9 | 2.36 | - | - | - | - | - | - |
| % Moisture | 0-15 | 25.5 | 1.15 | 18.0 | 3.74 | *17.2 | 1.10 | 21.7 | 1.50 | *17.6 | 0.67 | 19.0 | 2.48 |
| | 15-25 | 19.1 | 1.63 | 19.9 | 1.89 | 21.1 | 1.76 | 16.1 | 0.65 | 17.7 | 6.52 | 17.4 | 0.82 |
| | 25-50 | 18.9 | 3.77 | 15.5 | 1.59 | 21.1 | 2.36 | 16.9 | 1.56 | 17.7 | 2.63 | 17.1 | 0.49 |

1 Values shown are an average of 3 replicates.

* Mean is significantly different from control mean at $p < 0.05$.

mp Maximum penetration. Cone resistance > 38 bars.

\- No data collected.

### 4.1.2 Victor 2

The pipeline runs north 8.5 km from the Delia Meter Station (SE15-32-18-W4M) to the Victor Meter Station (SW11-33-18-W4M) (Figure 1; Finlayson 1988b). The pipeline was constructed in the summer of 1988 under dry soil conditions. The legal location of the study plots was NE22-32-18-W4M. The soil was a cultivated Orthic Dark Brown Chernozem developed on moderately fine textured lacustrine material (Appendix, Table A14). Topsoil (15 cm) was stripped from the trench and spoil side of the RoW and stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW. Wet weather conditions prevailed prior to final cleanup, but topsoil was not replaced until it was dry.

In 1988, the work side soil strengths at depths of 10.5 and 17.5 cm were higher than those of the control at the same depths (Table 3). There were no significant differences in soil strengths between the control and the trench, nor were there significant differences in soil moisture, soil organic matter and clay between RoW locations and the control.

In 1989, there were no significant differences between soil strengths for the control soil and those on the work side or the trench (Table 3). Work side soil moisture at 0 to 15 cm was lower than the control soil moisture at the same depth. There were no significant differences in soil organic matter between RoW locations and the control.

Table 3. Cone Resistance and Physical and Chemical Characteristics, Victor 2[1]

| | Depth | 1988 | | | | | | 1989 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Control | | Work | | Trench | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.1 | 0.55 | 1.5 | 0.51 | 1.7 | 0.42 | 0.3 | 0.20 | 0.7 | 0.19 | 0.4 | 0.24 |
| | 10.5 | 3.6 | 1.87 | *16.9 | 3.05 | 6.9 | 1.35 | 7.0 | 1.59 | 5.2 | 1.54 | 8.0 | 2.03 |
| | 17.5 | 14.6 | 0.76 | *22.3 | 1.27 | 15.4 | 2.36 | 19.4 | 6.26 | 19.7 | 5.65 | 18.1 | 3.41 |
| | 24.5 | 18.4 | 0.58 | 21.6 | 2.41 | 17.6 | 2.71 | 26.3 | 2.20 | 28.4 | 0.70 | 20.4 | 3.85 |
| | 31.5 | 20.5 | 1.23 | 25.6 | 3.36 | 21.4 | 4.52 | mp | - | mp | - | 26.1 | 3.26 |
| % Clay | 0-15 | 43.8 | 2.56 | 44.2 | 0.91 | 45.4 | 1.85 | - | - | - | - | - | - |
| | 15+ | 47.7 | 3.37 | 47.6 | 4.87 | 48.7 | 5.71 | - | - | - | - | - | - |
| % Organic Matter | 0-15 | 3.8 | 0.77 | 3.9 | 0.88 | 2.7 | 2.2 | 4.5 | 0.50 | 4.3 | 1.30 | 3.5 | 0.49 |
| % Moisture | 0-15 | 29.5 | 1.15 | 27.7 | 1.82 | 27.2 | 4.58 | 15.5 | 1.62 | *21.9 | 3.09 | 15.1 | 3.95 |
| | 15+ | 30.4 | 3.54 | 31.9 | 0.55 | 30.6 | 1.11 | 22.7 | 1.60 | 21.2 | 3.53 | 23.1 | 0.81 |

1 Values shown are an average of 3 replicates.

* Mean is significantly different from control mean at $p < 0.05$.

mp Maximum penetration. Cone resistance > 38 bars.

\- No data collected.

### 4.1.3 Ferintosh

The 13.6 km pipeline is located near Ferintosh, Alberta (Figure 1). The pipeline runs from SE29-45-21-W4M to SE17-44-21-W4M (Twardy 1989b). The pipeline was constructed in the summer and fall of 1989 under dry to moist soil conditions. The study plots were located in SE5-45-21-W4M. The soil monitored for soil strength was a cultivated Orthic Black Chernozem developed on fluvial material overlying till (Appendix, Table A3). Topsoil (30 cm) was stripped from the trench and spoil side of the RoW and stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1989, trench soil strengths at depths of 17.5 and 24.5 cm were lower than those of the control at the same depths (Table 4). There were no significant differences between soil strengths for the control and those for the work side or spoil side. Trench soil moisture at depths of 0 to 15 and 15 to 32 cm was lower than for the control. In addition, spoil side soil moisture at 0 to 15 cm was lower than the control value. Trench clay at 15 to 32 cm was greater than for the control. There were no significant differences in soil organic matter between RoW locations and the control.

In 1990, there were no differences in soil strength between soils of the spoil side and the control (Table 4). Work side soil strength at 3.5 cm was lower than that of the control. Trench soil strengths were significantly lower than those of the control at depths of 17.5 and 24.5 cm. Work side organic matter at 0 to 15 cm was lower than that of the control. There were no significant differences in soil moisture between RoW locations and the control.

Table 4. Cone Resistance and Physical and Chemical Characteristics, Ferintosh[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 0.7 | 0.39 | 0.6 | 0.26 | 0.7 | 0.57 | 0.7 | 0.44 | 0.5 | 0.08 | *0.3 | 0.04 | 0.3 | 0.09 | 0.4 | 0.16 |
| | 10.5 | 5.4 | 1.82 | 4.1 | 1.63 | 2.8 | 0.90 | 4.2 | 1.16 | 1.6 | 0.19 | 1.4 | 0.31 | 2.3 | 0.45 | 1.7 | 0.65 |
| | 17.5 | 14.2 | 3.12 | 9.8 | 2.86 | *3.2 | 1.57 | 16.0 | 2.29 | 16.5 | 1.85 | 13.8 | 4.42 | *10.8 | 2.40 | 19.3 | 3.56 |
| | 24.5 | 22.3 | 3.09 | 25.2 | 1.22 | *11.3 | 5.56 | 23.9 | 1.65 | 27.4 | 2.33 | 30.3 | 2.32 | *20.3 | 1.64 | 26.2 | 2.55 |
| | 31.5 | 24.2 | 4.25 | 29.4 | 1.24 | 21.8 | 7.69 | 24.5 | 0.94 | 30.5 | 3.71 | mp | - | 25.6 | 2.24 | 26.1 | 1.83 |
| % Clay | 0-15 | 19.5 | 0.58 | 18.8 | 1.00 | 19.1 | 1.53 | 16.1 | 3.79 | - | - | - | - | - | - | - | - |
| | 15-32 | 14.5 | 2.31 | 18.8 | 2.65 | *19.8 | 2.00 | 17.1 | 4.73 | - | - | - | - | - | - | - | - |
| | 32-50 | 22.8 | 5.29 | 17.5 | 2.52 | 28.1 | 6.03 | 26.5 | 5.03 | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-15 | 9.2 | 0.19 | 9.3 | 0.23 | 8.4 | 0.91 | 8.9 | 0.50 | 9.3 | 0.21 | *8.4 | 0.06 | 8.0 | 0.24 | 9.1 | 0.85 |
| % Moisture | 0-15 | 34.2 | 1.76 | 30.7 | 2.63 | *28.1 | 0.76 | *27.1 | 2.09 | 22.8 | 4.84 | 20.0 | 1.59 | 21.0 | 2.37 | 19.7 | 1.95 |
| | 15-32 | 30.2 | 0.75 | 21.6 | 7.70 | *23.7 | 3.00 | 25.7 | 3.35 | 23.5 | 4.49 | 21.3 | 3.68 | 21.0 | 1.71 | 21.4 | 2.28 |
| | 32-50 | 14.3 | 3.44 | 12.9 | 1.15 | 19.7 | 1.54 | 18.7 | 1.80 | 14.8 | 3.36 | - | - | 17.5 | 0.28 | - | - |

1 Values shown are an average of 3 replicates.
* Mean is significantly different from control mean at $p < 0.05$.
mp Maximum penetration. Cone resistance > 38 bars.
\- No data collected.

### 4.1.4 Redwater 2

The 21.7 km pipeline is located north of Clyde, Alberta (Figure 1) and runs from SE7-62-25-W4M to NE26-60-24-W4M (Twardy 1988). The pipeline was constructed in the summer of 1989 under moist to wet soil conditions. The legal location of the plots was NW26-61-25-W4M. The soil was an Orthic Dark Gray Chernozem developed on glaciofluvial material overlying till (Appendix, Table A12). The plots were located on pasture land. Topsoil (15 cm) was stripped from the trench and spoil side of the RoW and stored on the far side of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation and harrowing of the RoW. Topsoil replacement occurred during dry soil moisture conditions.

In 1989, at 10.5 cm, work side soil strength was lower than the control (Table 5). Trench and spoil soil strengths were lower than those on the control at 3.5 and 10.5 cm. Maximum penetration was reached at all locations, especially the control. Soil moisture for the top 20 cm was higher on the trench than on the control area. There were no significant differences in soil organic matter or clay between the RoW locations and the control.

In 1990, work side and spoil side soil strengths at 3.5 cm were greater than those on the control (Table 5). Spoil side soil strength at 10.5 cm was also lower than the control soil strength. Maximum penetration was reached at all locations. There were no significant differences in soil moisture and soil organic matter between RoW locations and the control.

Table 5. Cone Resistance and Physical and Chemical Characteristics, Redwater 2[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 3.4 | 1.13 | 2.1 | 0.20 | *1.3 | 0.43 | *1.4 | 0.48 | 0.6 | 0.13 | *1.7 | 0.40 | 1.4 | 0.579 | *1.4 | 0.24 |
| | 10.5 | 28.1 | 3.23 | *11.7 | 2.30 | *10.9 | 5.43 | *6.4 | 2.49 | 24.4 | 0.38 | 19.8 | 4.70 | 19.5 | .48 | 18.1 | 1.16 |
| | 17.5 | mp | - | 19.3 | 3.14 | 26.5 | 8.11 | 11.8 | 2.79 | mp | - | mp | - | mp | - | 24.9 | 3.99 |
| | 24.5 | | | mp | - | 30.0 | 0.16 | 26.1 | 2.50 | | | | | | | mp | - |
| | 31.5 | | | | | mp | - | mp | - | | | | | | | | |
| % Clay | 0-20 | 15.9 | 0.58 | 14.9 | 1.53 | 16.5 | 0.58 | 15.9 | 0.58 | - | - | - | - | - | - | - | - |
| | 20-35 | 18.2 | 3.46 | 19.5 | 5.77 | 19.2 | 2.64 | 19.9 | 3.06 | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-20 | 3.5 | 1.05 | 4.3 | 0.17 | 3.6 | 0.06 | 3.4 | 0.47 | 3.8 | 0.43 | 3.5 | 0.23 | 3.4 | 0.13 | 3.6 | 0.20 |
| % Moisture | 0-20 | 12.1 | 1.82 | 14.1 | 1.85 | *16.4 | 1.28 | 13.8 | 2.31 | 8.3 | 1.26 | 10.0 | 2.27 | 11.6 | 1.04 | 8.3 | 2.06 |
| | 20-35 | 8.8 | 1.04 | 10.8 | 4.05 | 9.8 | 0.70 | 11.3 | 3.44 | - | - | - | - | - | - | - | - |

1 Values shown are an average of 3 replicates.

* Mean is significantly different from control mean at $p < 0.05$.

mp Maximum penetration. Cone resistance > 38 bars.

\- No data collected.

### 4.1.5 Pigeon Lake

The 5.9 km pipeline is located southwest of Edmonton, Alberta (Figure 1) and runs south from Pigeon Lake Meter Station (SW35-45-27-W4M) to the Falun Meter Station (NW11-45-27-W4M) (Monenco Consultants Limited 1989). The pipeline was constructed in the summer of 1989 under moist soil conditions. The location of the study plots was NW23-45-27-W4M. The soil monitored was a cultivated Orthic Dark Gray Chernozem developed on till (Appendix, Table A9). Topsoil (15 cm) was stripped from the trench and spoil side of the RoW and stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1989, soil strength was greater for the work side than for the control at 3.5 cm (Table 6). At depths of 3.5 and 10.5 cm, trench and spoil side soil strengths were lower than those of the control. Maximum penetration was reached in the pipeline transects, especially for the work side, in spite of higher soil moisture. Greater soil moisture was recorded in the top 18 cm of the RoW locations when compared to the control soil. There were no significant differences in soil organic matter and clay between the RoW locations and the control.

In 1990, there were no differences in soil strength between soils on the RoW and the control (Table 6). Maximum penetration was only reached within the spoil side location. There were no significant differences in soil moisture and soil organic matter between RoW locations and the control.

Table 6. Cone Resistance and Physical and Chemical Characteristics, Pigeon Lake[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 3.0 | 1.18 | *11.6 | 2.84 | *0.7 | 0.15 | *0.7 | 0.36 | 0.8 | 0.46 | 0.3 | 0.13 | 0.6 | 0.19 | 0.9 | 0.52 |
| | 10.5 | 25.7 | 2.98 | mp | - | *3.8 | 1.37 | *7.5 | 0.64 | 3.3 | 0.57 | 2.9 | 0.71 | 5.7 | 1.59 | 5.6 | 1.65 |
| | 17.5 | 26.7 | 4.06 | | | 15.0 | 7.30 | 22.4 | 1.25 | 5.5 | 2.40 | 6.2 | 2.07 | 7.7 | 0.66 | 9.3 | 0.56 |
| | 24.5 | 32.1 | 0.70 | | | *26.6 | 1.99 | *25.0 | 0.59 | 10.0 | 4.51 | 14.2 | 7.04 | 17.9 | 6.20 | 18.8 | 6.18 |
| | 31.5 | 32.7 | 0.35 | | | mp | - | mp | - | 23.3 | 6.98 | 29.8 | 4.61 | 27.1 | 2.16 | mp | - |
| % Clay | 0-18 | 21.9 | 0.58 | 22.2 | 0.00 | 22.9 | 1.15 | 23.5 | 1.15 | - | - | - | - | - | - | - | - |
| | 18-35 | 26.9 | 5.51 | - | - | 25.2 | 2.65 | 25.5 | 1.15 | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-18 | 5.4 | 1.29 | 6.0 | 0.29 | 6.7 | 0.34 | 5.0 | 0.96 | 4.9 | 0.56 | 4.3 | 0.55 | 4.6 | 1.70 | 5.8 | 0.68 |
| % Moisture | 0-18 | 14.4 | 0.90 | *17.7 | 1.12 | *22.1 | 0.44 | *18.4 | 0.76 | 20.8 | 1.22 | 20.5 | 0.89 | 18.2 | 0.40 | 20.3 | 2.10 |
| | 18-35 | 13.6 | 1.31 | - | - | 14.0 | 1.50 | 13.9 | 1.83 | 17.0 | 6.48 | 16.4 | 1.71 | 15.5 | 0.95 | 15.1 | 1.84 |

1 Values shown are an average of 3 replicates.

* Mean is significantly different from control mean at $p < 0.05$.

mp Maximum penetration. Cone resistance > 38 bars.

- No data collected.

### 4.1.6 Milo

The pipeline is located near Brooks, Alberta (Figure 1), mainly on native rangeland. The 38.5 km pipeline runs from the Muskateer Energy Limited gas plant (4-31-18-19-W4M) to NOVA's South Lateral (9-13-16-17-W4M) (NOVA, An Alberta Corporation 1985). The pipeline was constructed in the summer and fall of 1988 under very dry soil conditions. The study plots were located in SW17-17-17-W4M. The soil monitored for soil strength was a cultivated Solonetzic Brown Chernozem developed on glaciofluvial material (Appendix, Table A8). One of the three replicates was classified as a Solonetzic Brown Chernozem, calcareous phase, developed on medium glaciofluvial parent materials, overlying moderately fine textured till material. Topsoil (20 cm) was stripped from the trench and spoil side of the RoW and placed on the far edge of the spoil side of the RoW. Subsoil removed from the trench was placed on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1988, soil strength of the trench at depths of 3.5 and 10.5 cm was lower than that of the control at the same depths (Table 7). Trench and work side soil organic matter at 0 to 15 cm was lower than for the control. Maximum penetration occurred at all locations. There were no significant differences in soil moisture or clay at 0 to 15 cm.

In 1989, there were no significant differences between soil strengths for the control soil and those on the work side or trench (Table 7). As in 1988, maximum penetration was reached at all locations. There were no significant differences in soil moisture and soil organic matter between RoW locations and the control.

Table 7. Cone Resistance and Physical and Chemical Characteristics, Milo[1]

| | Depth | 1988 | | | | | | 1989 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Control | | Work | | Trench | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.2 | 0.12 | 1.4 | 0.08 | *1.0 | 0.08 | 0.8 | 0.28 | 0.9 | 0.21 | 0.5 | 0.12 |
| | 10.5 | 18.7 | 2.41 | 8.8 | 6.15 | *5.7 | 1.36 | 9.2 | 2.65 | 17.8 | 3.20 | 15.1 | 9.06 |
| | 17.5 | mp | - | mp | - | 21.5 | 3.70 | mp | - | mp | - | 27.4 | 0.77 |
| | 24.5 | | | | | mp | - | | | | | mp | - |
| | 31.5 | | | | | | | | | | | | |
| % Clay | 0-15 | 16.3 | 3.83 | 15.5 | 0.92 | 16.6 | 1.70 | - | - | - | - | - | - |
| | 15-30 | 30.6 | 10.5 | 16.7 | 2.19 | 16.8 | 1.92 | - | - | - | - | - | - |
| | 30-50 | 28.1 | 5.07 | *18.4 | 2.42 | *16.8 | 1.99 | - | - | - | - | - | - |
| % Organic Matter | 0-15 | 2.5 | 0.90 | *2.0 | 0.12 | *1.4 | 0.13 | 1.9 | 0.69 | 1.2 | 0.08 | 2.2 | 0.30 |
| | 15-30 | 1.8 | 0.37 | 1.8 | 0.40 | *0.8 | 0.13 | - | - | - | - | - | - |
| | 30-50 | 2.2 | 1.18 | 1.5 | 0.18 | 0.8 | 0.28 | - | - | - | - | - | - |
| % Moisture | 0-15 | 6.6 | 1.44 | 6.0 | 0.11 | 6.1 | 0.44 | 6.4 | 2.00 | 5.5 | 0.38 | 8.4 | 1.34 |
| | 15-30 | 10.3 | 2.48 | *5.8 | 0.57 | *5.5 | 1.21 | 10.2 | 2.63 | - | - | 8.5 | 0.45 |
| | 30-50 | 8.4 | 0.62 | *4.3 | 2.24 | *5.7 | 1.14 | - | - | - | - | - | - |

1 Values shown are an average of 3 replicates.
* Mean is significantly different from control mean at $p < 0.05$.
mp Maximum penetration. Cone resistance > 38 bars.
\- No data collected.

### 4.1.7 Redwater 1

The 21.7 km pipeline is located north of Clyde, Alberta (Figure 1), and runs from SE7-62-25-W4M to NE26-60-24-W4M (Twardy 1988). The pipeline was constructed in the summer of 1989 under moist to wet soil conditions. The legal location of the plots was SE18-61-24-W4M. The soil was a cultivated Gleyed Black Chernozem developed on glaciofluvial material (Appendix, Table A10). Topsoil (40 cm) was stripped from the trench and spoil side of the RoW and stored on the far side of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation and harrowing of the RoW. Topsoil replacement occurred during dry soil moisture conditions.

In 1989, soil strengths of the work side at depths of 3.5, 10.5, 17.5 and 24.5 cm were lower than those of the control for the same depths (Table 8). Trench soil strengths at depths of 10.5, 17.5 and 24.5 cm were also lower than those of the control at the same depths. Spoil side soil strengths at depths of 10.5 and 17.5 cm were lower than for the control at the same depths as well. Maximum penetration occurred only at the control location. RoW soil moisture at 20 to 40 cm was greater than that of the control. There were no significant differences in soil organic matter and clay between RoW locations and the control.

In 1990, there were no differences in soil strength between soils of the spoil side and the control (Table 8). Trench soil strengths at depths of 10.5 and 31.5 cm were greater than those of the control at the same depths, whereas work side soil strength at 31.5 cm was greater than the control soil strength of 23.0 bars at this depth. Maximum penetration was reached only at the spoil side location. There were no significant differences in soil moisture and soil organic matter between RoW locations and the control.

Table 8. Cone Resistance and Physical and Chemical Characteristics, Redwater 1[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.7 | 0.12 | *0.9 | 0.00 | 1.8 | 0.68 | 1.8 | 0.13 | 0.4 | 0.20 | 0.3 | 0.04 | 0.5 | 0.33 | 0.5 | 0.30 |
| | 10.5 | 12.0 | 2.13 | *3.4 | 1.00 | *2.3 | 0.42 | *2.1 | 0.31 | 1.7 | 0.31 | 1.9 | 0.36 | *3.5 | 0.38 | 2.4 | 0.69 |
| | 17.5 | 21.0 | 2.00 | *12.0 | 2.06 | *2.5 | 0.20 | *13.1 | 1.11 | 7.0 | 5.23 | 10.5 | 5.75 | 8.6 | 2.34 | 8.0 | 4.11 |
| | 24.5 | 29.9 | 3.77 | *20.3 | 1.51 | *16.9 | 3.70 | 19.9 | 4.24 | 15.0 | 12.3 | 22.9 | 4.33 | 23.3 | 1.53 | 25.0 | 1.68 |
| | 31.5 | mp | - | 25.0 | 2.01 | 21.1 | 1.02 | 22.2 | 2.97 | 23.0 | 1.35 | *30.4 | 1.02 | *32.0 | 0.22 | mp | - |
| % Clay | 0-20 | 14.5 | 2.00 | 16.1 | 0.90 | 16.1 | 1.62 | 16.8 | 2.25 | - | - | - | - | - | - | - | - |
| | 20-40 | 13.1 | 3.41 | 15.8 | 1.97 | 16.8 | 1.97 | 19.1 | 4.00 | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-20 | 3.7 | 0.80 | 3.7 | 0.08 | 3.2 | 0.19 | 3.1 | 0.36 | 4.5 | 1.69 | 4.3 | 1.04 | 4.0 | 0.92 | 4.2 | 1.44 |
| % Moisture | 0-20 | 11.6 | 1.87 | 14.5 | 1.65 | 12.0 | 1.13 | 15.3 | 2.36 | 14.0 | 5.68 | 13.4 | 2.46 | 11.8 | 2.34 | 13.2 | 4.63 |
| | 20-40 | 5.7 | 1.76 | *12.4 | 0.96 | *13.0 | 0.87 | *15.3 | 1.21 | 14.2 | 6.67 | 14.4 | 3.95 | 13.3 | 1.70 | 14.9 | 2.56 |

1 Values shown are an average of 3 replicates.

* Mean is significantly different from control mean at $p < 0.05$.

mp Maximum penetration. Cone resistance > 38 bars.

\- No data collected.

## 4.2 LUVISOLIC ORDER

### 4.2.1 Valhalla

The 6.4 km pipeline is located northwest of Grande Prairie, Alberta (Figure 1) and runs east-west from SW9-75-9-W6M to SE12-75-9-W6M (Can-Ag Enterprises Ltd. 1989). The pipeline was constructed in the spring of 1989 under dry soil conditions. The location of the study plots was SW10-75-9-W6M. The soils monitored for soil strength were cultivated Gleyed Dark Gray Luvisols and Dark Gray Luvisols developed on till (Appendix, Table A12). Topsoil (10 cm) was stripped from the trench and spoil side of the RoW and was stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1989, there were no significant differences in soil strength between the control and work side (Table 9). Trench soil strengths at depths of 10.5 and 17.5 cm were lower than for the control for the same depths. At a depth of 17.5 cm, spoil side soil strength (12.5 b) was lower than the control soil strength of 17.2 bars. Maximum penetration was reached at the work side location. There were no significant differences in soil moisture, soil organic matter and clay between RoW locations and the control.

In 1990, at a depth of 3.5 cm, work side, trench and spoil side soil strengths were all lower than the control soil strength of 1.8 bars (Table 9). Work side soil strength at 10.5 cm was greater than the control soil strength. It was difficult to speculate why the differences in RoW soil strength for the top 10.5 cm occurred, because in the previous year there had been no significant differences except for the trench. Maximum penetration occurred in the pipeline transects, but not at the control location. There were no significant differences in soil moisture and soil organic matter between RoW locations and the control.

Table 9. Cone Resistance and Physical and Chemical Characteristics, Valhalla[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.6 | 0.50 | 2.8 | 0.69 | 1.2 | 0.04 | 1.1 | 0.18 | 1.8 | 0.19 | *0.9 | 0.24 | *1.3 | 0.18 | *0.6 | 0.13 |
| | 10.5 | 9.2 | 1.81 | 11.2 | 1.04 | *4.4 | 0.34 | 7.5 | 1.40 | 9.8 | 1.07 | *10.9 | 1.09 | 10.3 | 1.01 | 8.6 | 2.22 |
| | 17.5 | 17.2 | 2.41 | 18.4 | 2.95 | *6.4 | 1.38 | *12.5 | 0.34 | 17.1 | 1.57 | 21.0 | 2.26 | 16.2 | 3.02 | 20.9 | 2.85 |
| | 24.5 | 21.3 | 6.15 | 22.4 | 1.42 | 14.9 | 0.51 | 22.3 | 3.89 | 25.0 | 1.01 | mp | - | 30.4 | 4.06 | mp | - |
| | 31.5 | 25.3 | 4.08 | mp | - | 21.0 | 1.15 | 24.2 | 3.82 | 29.4 | 2.63 | | | mp | - | | |
| % Clay | 0-17 | 26.7 | 2.52 | 25.0 | 1.41 | 26.7 | 3.06 | 27.0 | 1.73 | - | - | - | - | - | - | - | - |
| | 17-33 | 30.7 | 7.09 | 28.3 | 6.36 | 30.3 | 1.53 | 33.3 | 8.08 | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-17 | 2.6 | 0.37 | 3.1 | 0.38 | 2.4 | 0.74 | 2.3 | 0.32 | 2.6 | 0.29 | 2.4 | 0.42 | 2.3 | 0.14 | 2.6 | 0.60 |
| % Moisture | 0-17 | 20.4 | 2.14 | 18.6 | 0.97 | 18.9 | 1.85 | 19.2 | 0.87 | 24.4 | 2.30 | 20.1 | 1.68 | 22.7 | 2.29 | 21.3 | 2.48 |
| | 17-33 | 16.7 | 1.37 | 19.0 | 1.85 | 14.9 | 1.42 | 18.0 | 0.26 | 16.0 | 2.33 | - | - | - | - | - | - |

1 Values shown are an average of 3 replicates.

* Mean is significantly different from control mean at $p < 0.05$.

mp Maximum penetration. Cone resistance > 38 bars.

\- No data collected.

### 4.2.2 Henderson 1

The 8.5 km pipeline is located near Gordondale, Alberta (Figure 1) and runs in a northwesterly direction from the Gordondale Sales Meter Station (SE12-79-12-W6M) to the Henderson Creek Meter Station (NW34-79-12-W6M) (Can-Ag Enterprises Ltd. 1988). The pipeline was constructed in the spring of 1989 under dry soil conditions. The study plots were located in SW34-79-12-W6M. The soil was a cultivated Solonetzic Dark Gray Luvisol developed on till (Appendix, Table A5). Topsoil (15 cm) was stripped from the trench and spoil side of the RoW and stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1989, at depths of 10.5 and 17.5 cm, soil strengths for the work side, trench and spoil side were all lower than for the control at the same depths (Table 10). Maximum penetration occurred for all locations except the trench. RoW soil moisture at 0 to 21 cm was greater than that of the control. Trench clay at 21 to 35 cm was lower than that of the control, whereas spoil side clay at 0 to 21 cm was greater than that of the control (Table 10). There were no significant differences in soil organic matter between RoW locations and the control.

In 1990, there were no significant differences in soil strength between soils of the trench or spoil side and the control soil (Table 10). Work side soil strength at 3.5 cm was greater than that of the control. Maximum penetration was reached for all locations. There were no significant differences in soil moisture and soil organic matter between RoW locations and the control.

Table 10. Cone Resistance and Physical and Chemical Characteristics, Henderson 1[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 2.9 | 1.43 | 1.0 | 0.19 | 1.3 | 0.65 | 0.9 | 0.43 | 0.6 | 0.27 | *1.5 | 0.48 | 0.7 | 0.39 | 2.0 | 0.84 |
| | 10.5 | 23.9 | 4.13 | *4.6 | 1.00 | *4.4 | 0.92 | *2.6 | 0.58 | 11.2 | 2.83 | 12.9 | 4.94 | 13.8 | 4.34 | 11.9 | 1.28 |
| | 17.5 | 31.0 | 5.50 | *8.0 | 2.74 | *9.7 | 2.76 | *7.6 | 4.08 | 23.0 | 5.50 | 24.2 | 6.19 | 23.6 | 2.62 | 21.1 | 4.79 |
| | 24.5 | mp | - | 16.8 | 1.5 | 29.0 | 2.75 | 21.6 | 3.61 | mp | - | mp | - | 30.7 | 3.29 | mp | - |
| | 31.5 | | | mp | - | 34.1 | 1.19 | mp | - | | | | | mp | - | | |
| % Clay | 0-21 | 20.9 | 1.15 | 23.3 | 1.53 | 23.6 | 1.73 | *24.9 | 2.08 | - | - | - | - | - | - | - | - |
| | 21-35 | 49.6 | 5.29 | 45.9 | 9.81 | *33.3 | 3.79 | 57.9 | 3.21 | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-21 | 4.0 | 0.48 | 4.5 | 1.03 | 3.7 | 0.93 | 3.4 | 0.86 | 3.4 | 0.61 | 3.9 | 0.74 | 3.9 | 0.26 | 4.3 | 0.34 |
| % Moisture | 0-21 | 11.0 | 0.85 | *15.1 | 1.16 | *15.8 | 1.61 | *14.3 | 1.15 | 25.3 | 1.22 | 24.4 | 8.84 | 23.4 | 1.36 | 27.0 | 1.57 |
| | 21-35 | 17.7 | 4.01 | 19.3 | 4.76 | 16.5 | 1.00 | 24.2 | 3.59 | 15.0 | 4.10 | - | - | - | - | - | - |

1 Values shown are an average of 3 replicates.
* Mean is significantly different from control mean at $p < 0.05$.
mp Maximum penetration. Cone resistance > 38 bars.
\- No data collected.

### 4.2.3 Henderson 2

This site is located on the same pipeline as Henderson 1. The legal location of these plots was SE14-79-12-W6M. The soil was a cultivated Dark Gray Luvisol developed on till (Appendix, Table A6). Topsoil (15 cm) was stripped from the trench and spoil side of the RoW and stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1989, soil strengths of the trench, spoil and work sides were lower than control soil strengths at depths of 10.5 and 17.5 cm (Table 11). Maximum penetration was reached only for the trench location. There were no differences in soil moisture, soil organic matter or clay between RoW locations and the control.

In 1990, there were no significant differences in soil strength between soils on and off the RoW, nor were there significant differences in soil moisture and soil organic matter between RoW locations and the control (Table 11). Maximum penetration occurred for all locations.

Table 11. Cone Resistance and Physical and Chemical Characteristics, Henderson 2[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 3.9 | 1.47 | 2.1 | 0.68 | 1.8 | 0.26 | 2.5 | 0.71 | 2.0 | 1.16 | 1.5 | 0.16 | 1.9 | 0.60 | 1.1 | 0.23 |
| | 10.5 | 26.8 | 4.42 | *4.3 | 1.44 | *5.7 | 0.50 | *5.2 | 1.01 | 17.8 | 2.94 | 13.1 | 1.07 | 14.0 | 0.78 | 11.8 | 2.34 |
| | 17.5 | 25.4 | 3.16 | *6.0 | 2.37 | *6.9 | 2.59 | *8.5 | 3.60 | 21.7 | 3.92 | 22.2 | 1.02 | 24.6 | 0.73 | 21.3 | 2.20 |
| | 24.5 | 25.8 | 6.76 | 14.6 | 4.96 | 19.6 | 4.41 | 15.6 | 2.07 | mp | - | mp | - | 22.3 | 10.2 | mp | - |
| | 31.5 | 30.5 | 3.19 | 26.2 | 2.73 | mp | - | 26.7 | 1.04 | | | | | mp | - | | |
| % Clay | 0-18 | 19.3 | 3.21 | 25.0 | 8.19 | 21.7 | 3.21 | 19.7 | 0.58 | - | - | - | - | - | - | - | - |
| | 18-34 | 33.2 | 11.3 | 32.3 | 12.0 | 40.3 | 7.77 | 28.7 | 12.7 | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-18 | 2.2 | 1.00 | 1.7 | 0.25 | 1.8 | 0.19 | 1.7 | 0.85 | 3.8 | 4.16 | 1.8 | 0.45 | 1.7 | 0.18 | 1.9 | 0.34 |
| % Moisture | 0-18 | 15.5 | 2.95 | 14.0 | 0.10 | 15.5 | 1.45 | 15.5 | 1.21 | 18.0 | 2.45 | 14.5 | 2.48 | 16.3 | 1.57 | 15.3 | 3.28 |
| | 18-34 | 14.6 | 3.99 | 16.1 | 1.50 | 16.2 | 3.93 | 14.3 | 2.17 | 17.0 | 3.07 | 14.4 | 2.97 | 15.0 | 3.25 | 11.3 | 7.34 |

1 Values shown are an average of 3 replicates.
* Mean is significantly different from control mean at $p < 0.05$.
mp Maximum penetration. Cone resistance > 38 bars.
\- No data collected.

## 4.3 SOLONETZIC ORDER

### 4.3.1 Craigmyle

The 6.3 km pipeline is located west of Hanna, Alberta (Figure 1), and runs from the Rowley Meter Station (SE13-32-19-W4M) to the Delia Meter Station (SE15-32-18-W4M) (NOVA, An Alberta Corporation 1983). The pipeline was constructed in the summer of 1988 under wet soil conditions. The study plots were located in SW17-32-18-W4M. The soil monitored for soil strength was a cultivated Dark Brown Solonetz developed on moderately fine textured weathered bedrock (Appendix, Table A2). Topsoil (15 cm) was stripped from the trench and spoil storage area and placed on the far edge of the spoil side of the RoW. Subsoil removed from the trench was placed on the spoil side of the RoW at least one meter from the topsoil. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1988, soil strength on the work side of the RoW was greater than the control at a depth of 10.5 cm (Table 12). However, at 10.5 cm, soil strength of the trench was lower than that of the control. Maximum penetration was reached only for the trench location. Work side organic matter at 0 to 13 cm was lower than that of the control. There were no significant differences in soil moisture and clay between the RoW locations and the control.

In 1989, there were no significant differences in soil strength between the control and work side (Table 12). Trench soil strength at a depth of 24.5 cm was greater than that of the control. Trench soil moisture at 15-40 cm was lower than the control value. There were no significant differences in soil organic matter between RoW locations and the control.

Table 12. Cone Resistance and Physical and Chemical Characteristics, Craigmyle[1]

| | Depth | 1988 | | | | | | 1989 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Control | | Work | | Trench | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.8 | 0.50 | 3.1 | 2.32 | 2.1 | 0.36 | 0.5 | 0.14 | 0.8 | 0.34 | 0.6 | 0.27 |
| | 10.5 | 12.7 | 1.11 | *25.4 | 4.57 | *9.3 | 1.12 | 5.8 | 5.36 | 2.9 | 2.69 | 3.8 | 1.67 |
| | 17.5 | 21.9 | 3.11 | 26.4 | 1.08 | 20.8 | 5.66 | 18.4 | 2.57 | 19.2 | 3.02 | 18.5 | 3.09 |
| | 24.5 | 25.2 | 3.31 | 25.4 | 1.05 | mp | - | 20.2 | 1.01 | 22.6 | 1.70 | *24.9 | 0.92 |
| | 31.5 | 24.1 | 3.58 | 29.9 | 2.16 | | | 21.2 | 1.70 | 24.0 | 2.36 | 25.9 | 2.87 |
| % Clay | 0-13 | 48.3 | 0.65 | 43.9 | 3.82 | 51.9 | 2.17 | - | - | - | - | - | - |
| | 13+ | 59.1 | 3.72 | 53.6 | 3.21 | 49.3 | 11.0 | - | - | - | - | - | - |
| % Organic Matter | 0-13 | 5.5 | 0.44 | *2.4 | 1.09 | 2.9 | 1.99 | 5.1 | 1.03 | 4.2 | 0.44 | 5.5 | 0.15 |
| % Moisture | 0-13 | 27.1 | 5.89 | 27.6 | 1.80 | 23.0 | 7.60 | 19.9 | 6.15 | 21.0 | 1.55 | 22.7 | 7.02 |
| | 13+ | 27.2 | 6.22 | 31.8 | 3.76 | 20.5 | 4.63 | 33.3 | 3.34 | 32.3 | 7.13 | *25.0 | 2.93 |

1 Values shown are an average of 3 replicates.
* Mean is significantly different from control mean at $p < 0.05$.
mp Maximum penetration. Cone resistance > 38 bars.
\- No data collected.

### 4.3.2 Michichi

The pipeline is located north of Drumheller, Alberta (Figure 1), running southwest for 7.4 km from the Michichi Meter Station (SW8-31-18-W4M) to the Morrin Meter Station (SW33-30-19-W4M) (Twardy and Dowgray 1988). The pipeline was constructed in the summer of 1988 under dry soil conditions. The location of the study plots was SE7-31-18-W4M. The soil monitored for strength was a cultivated Dark Brown Solonetz developed on a moderately fine to fine textured glaciolacustrine blanket (Appendix, Table A7). Topsoil (15 cm) was stripped from the trench and spoil side of the RoW and stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side. Subsoil and topsoil replacement were followed by cultivation of the RoW.

In 1988, there were no significant differences in soil strength between the control, work side and trench, nor were there significant differences in soil moisture, soil organic matter and clay between RoW locations and the control (Table 13). Maximum penetration occurred only for the trench location.

In 1989, work side soil strength at 3.5 cm was higher than that of the control (Table 13). Trench soil strength at 10.5 cm was higher than control soil strength at the same depth. Both differences were less than 2 bars. Maximum penetration occurred at all locations. Work side and trench soil moisture at 15 to 40 cm was lower than that of the control. In addition, work side soil organic matter at 0 to 15 cm was lower than the control value.

Table 13. Cone Resistance and Physical and Chemical Characteristics, Michichi[1]

| | Depth | 1988 | | | | | | 1989 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Control | | Work | | Trench | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.1 | 0.31 | 0.8 | 0.24 | 1.3 | 0.71 | 0.4 | 0.14 | *0.7 | 0.09 | 1.0 | 0.52 |
| | 10.5 | 10.4 | 2.45 | 12.4 | 2.48 | 7.5 | 3.13 | 2.4 | 0.89 | 4.7 | 1.96 | *4.9 | 0.55 |
| | 17.5 | 18.9 | 2.65 | 22.8 | 1.73 | mp | - | 10.7 | 5.55 | 12.6 | 8.10 | 13.8 | 1.97 |
| | 24.5 | 27.6 | 1.67 | mp | - | | | 27.2 | 1.04 | mp | - | 26.5 | 2.36 |
| | 31.5 | mp | - | | | | | mp | - | | | mp | - |
| % Clay | 0-15 | 35.4 | 1.80 | 37.6 | 6.63 | 39.8 | 3.25 | - | - | - | - | - | - |
| | 15-40 | 46.4 | 7.26 | 46.5 | 3.49 | 49.2 | 5.11 | - | - | - | - | - | - |
| | 40-60 | 47.5 | 4.16 | 47.1 | 0.74 | 54.8 | 3.36 | - | - | - | - | - | - |
| % Organic Matter | 0-15 | 5.2 | 0.93 | 5.2 | 0.95 | 4.4 | 0.70 | 5.0 | 0.63 | *2.7 | 0.65 | 4.5 | 0.53 |
| | 15-40 | 2.6 | 0.52 | - | - | - | - | - | - | - | - | - | - |
| % Moisture | 0-15 | 31.7 | 2.59 | 27.9 | 9.40 | 33.2 | 9.86 | 14.0 | 3.61 | 14.2 | 1.57 | 14.2 | 1.51 |
| | 15-40 | 29.6 | 11.9 | 31.0 | 3.89 | 32.7 | 6.35 | 19.2 | 1.93 | *14.2 | 0.06 | *14.1 | 0.92 |

1 Values shown are an average of 3 replicates.
* Mean is significantly different from control mean at $p < 0.05$.
mp Maximum penetration. Cone resistance > 38 bars.
\- No data collected.

## 4.4 GLEYSOLIC ORDER

### 4.4.1 Victor 1

The pipeline runs north 8.5 km from the Delia Meter Station (SE15-32-18-W4M) to the Victor Meter Station (SW11-33-18-W4M) (Finlayson 1988b). The pipeline was constructed in the summer of 1988 under dry soil conditions. The legal location of the study plots was NE22-32-18-W4M. The soil was a cultivated Orthic Humic Gleysol developed on moderately fine to fine textured lacustrine material (Appendix, Table A13). Topsoil (15 cm) was stripped from the trench and spoil side of the RoW and stored on the far edge of the spoil side. Subsoil removed from the trench was also stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by cultivation of the RoW. Wet weather conditions prevailed prior to final cleanup, but topsoil was not replaced until dry.

In 1988, there were no significant differences in soil strength for the control soil versus the work side and trench at any of the depths monitored (Table 14). Work side soil moisture at depths greater than 15 cm was greater than the control. Trench soil organic matter at 0 to 15 cm was lower than the control. There were no significant differences in clay between the RoW locations and the control.

As in 1988, there were no significant differences in soil strength for the control soil versus the work side or trench for the 1989 sampling year (Table 14). Similarly,there were no significant differences in soil moisture or soil organic matter between RoW locations and the control.

Table 14. Cone Resistance and Physical and Chemical Characteristics, Victor 1[1]

| | Depth | 1988 | | | | | | 1989 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Control | | Work | | Trench | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.6 | 0.78 | 2.0 | 0.69 | 2.0 | 0.95 | 0.6 | 0.15 | 0.6 | 0.11 | 0.7 | 0.08 |
| | 10.5 | 5.1 | 1.33 | 9.6 | 3.14 | 5.8 | 0.59 | 4.5 | 2.46 | 5.8 | 5.23 | 8.5 | 4.72 |
| | 17.5 | 9.7 | 3.20 | 13.1 | 4.04 | 9.5 | 1.58 | 10.4 | 3.41 | 12.5 | 4.11 | 14.0 | 0.32 |
| | 24.5 | 14.7 | 6.43 | 16.1 | 6.01 | 11.3 | 0.53 | 17.6 | 3.92 | 19.8 | 6.47 | 18.0 | 2.54 |
| | 31.5 | 18.8 | 8.50 | 21.1 | 6.59 | 14.9 | 1.92 | 25.7 | 4.62 | 22.6 | 4.93 | 25.2 | 6.13 |
| % Clay | 0-15 | 51.3 | 3.21 | 53.6 | 4.47 | 52.6 | 2.57 | - | - | - | - | - | - |
| | 15+ | 59.1 | 4.90 | 54.4 | 8.76 | 56.7 | 4.09 | - | - | - | - | - | - |
| % Organic Matter | 0-15 | 4.1 | 0.40 | 3.6 | 0.70 | *3.1 | 0.11 | 3.5 | 0.22 | 2.8 | 0.20 | 3.5 | 0.64 |
| % Moisture | 0-15 | 38.5 | 3.00 | 34.2 | 5.44 | 33.2 | 2.08 | 23.0 | 5.62 | 29.1 | 6.00 | 27.7 | 1.94 |
| | 15+ | 35.1 | 1.03 | *38.6 | 0.68 | 38.0 | 3.48 | 30.6 | 4.20 | 31.8 | 3.41 | 26.3 | 1.89 |

1 Values shown are an average of 3 replicates.

* Mean is significantly different from control mean at $p < 0.05$.

mp Maximum penetration. Cone resistance > 38 bars.

\- No data collected.

### 4.4.2 Atlee-Buffalo

The 8.7 km pipeline is located north of the Suffield Military Reserve in southeastern Alberta (Figure 1) and runs south from Atlee-Buffalo Meter Station (SE13-21-7-W4M) to an existing pipeline (SE24-20-7-W4M) (Twardy 1989a). The pipeline was constructed in the summer of 1989 under very dry soil moisture conditions. The study plots were located in SW12-21-7-W4M on native pasture land. The soil was an Orthic Humic Gleysol developed on lacustrine material overlying till (Appendix, Table A1). Topsoil (10 cm) was stripped from the ditchline with a step blade and stored on the work side. Subsoil removed from the trench was stored on the spoil side of the RoW. Subsoil and topsoil replacement were followed by levelling of the RoW and harrowing of the spoil and trench areas.

In 1989, there were no significant differences in soil strength for the control, work side, trench and spoil side (Table 15). Maximum penetration was reached for all locations. Trench soil moisture at 0 to 11 cm was lower than that of the control, whereas spoil side soil moisture was greater than that of the control. Work side organic matter at 0 to 11 cm was greater than the control value. There were no significant differences in clay between RoW locations and the control.

In 1990, there were no significant differences in soil strength between soils on and off the RoW (Table 15). As in 1989, maximum penetration occurred for all locations. Work side soil moisture at 0 to 10 cm was lower than the control. There were no significant differences in soil organic matter between RoW locations and the control.

Table 15. Cone Resistance and Physical and Chemical Characteristics, Atlee-Buffalo[1]

| | Depth | 1989 | | | | | | | | 1990 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | Work | | Trench | | Spoil | | Control | | Work | | Trench | | Spoil | |
| | cm | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| Cone Resistance (bars) | 3.5 | 1.9 | 0.16 | 3.4 | 1.33 | 1.7 | 0.70 | 1.5 | 0.35 | 1.1 | 0.35 | 0.9 | 0.20 | 0.7 | 0.12 | 2.4 | 2.55 |
| | 10.5 | 30.3 | 2.78 | mp | - | 30.0 | 4.67 | 26.6 | 4.29 | 22.8 | 1.91 | 23.2 | 2.53 | mp | - | 25.7 | 4.66 |
| | 17.5 | 31.8 | 0.09 | | | mp | - | mp | - | mp | - | mp | - | | | mp | - |
| | 24.5 | mp | - | | | | | | | | | | | | | | |
| | 31.5 | | | | | | | | | | | | | | | | |
| % Clay | 0-11 | 21.7 | 5.03 | 20.4 | 5.29 | 23.7 | 2.31 | 21.7 | 5.77 | - | - | - | - | - | - | - | - |
| | 11-20 | 35.1 | 1.15 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| % Organic Matter | 0-11 | 6.8 | 0.41 | *8.1 | 0.44 | 3.8 | 2.39 | 9.7 | 6.44 | 6.6 | 1.97 | 5.3 | 3.36 | 8.4 | 2.06 | 8.4 | 3.72 |
| % Moisture | 0-11 | 17.7 | 5.71 | 26.8 | 23.2 | *10.3 | 1.55 | *28.4 | 5.20 | 14.2 | 1.74 | *9.3 | 1.46 | 14.9 | 0.64 | 14.4 | 5.00 |
| | 11-20 | 14.2 | 4.23 | 22.1 | 0.00 | 9.6 | 0.00 | 26.0 | 0.00 | 14.6 | 1.73 | - | - | 16.8 | 0.00 | 15.8 | 1.48 |
| | 20-35 | - | - | - | - | - | - | - | - | - | - | - | - | - | | - | - |

1 Values shown are an average of 3 replicates.
* Mean is significantly different from control mean at $p < 0.05$.
mp Maximum penetration. Cone resistance > 38 bars.
\- No data collected.

## 5.0 DISCUSSION

### 5.1 SOIL STRENGTH MEASUREMENTS

When interpreting results, it must be kept in mind that very small differences in soil strength, sometimes of 1 bar or less, may not be significant to a growing plant, even if differences are statistically significant. This consideration is particularly important when interpreting soil strength data for the upper 3.5 cm depth. At this depth soil strength values tend to be low, and variability relatively high. For example, for the Redwater 2 Study Area, the 1990 spoil strength was statistically significantly higher than the control strength at the 3.5 cm depth. However, the actual difference was only 0.8 bar, with a standard deviation of 0.24. We do not consider a difference this small to be of any importance to plant growth.

### 5.2 PLANT GROWTH

Soil strengths over the 25 bar level, which have been suggested by Taylor et al. (1966) and Taylor and Ratliff (1969) to prevent root elongation, were recorded at most of the study sites, on both the RsoW and controls. However, roots were visible in all soils with strengths greater than 25 bars. Most of the soil strength measurements were taken when soil water was considerably below field capacity and reflected root-zone moisture deficit situations. At other times of the year, or in years of higher rainfall, higher soil moisture levels can be found, likely with corresponding lower soil strengths. Roots in soils with strengths considerably higher than 25 bars may have penetrated at higher moisture contents and lower soil strengths. No data are available at present on the effect of soil strengths on crops grown in Alberta. Plant growth was not monitored for this study.

## 5.3 SOILS

In this study, no consistent relationship was found between soil strength and parent material or land use. Soil strength changes were found to occur in pipeline RsoW constructed across a variety of soils, parent materials, land use and soil moisture conditions. Most of the study areas were under cultivation, except for the two Orthic Gray Chernozems, which were in hay, and Atlee-Buffalo, which was a native pasture site.

### 5.3.1 Chernozemic Order

Increased work side soil strengths measured in the topsoil and subsoil immediately after construction on Orthic Dark Brown Chernozems at Ghostpine and Victor 2 were attributed to construction traffic, and were not evident one year later, suggesting that soil strengths were equal to pre-disturbed conditions. Construction at Ghostpine occurred under wet soil conditions, whereas construction at Victor 2 occurred in dry soil conditions. Differences (increase at 17.5 cm and decrease at 31.5 cm) between trench and control soil strengths monitored in the subsoil at Ghostpine were present immediately following construction only. Increased soil strength can be attributed to packing during backfill operations; decreased soil strength can be attributed to breaking up of the subsoil during trenching.

There were no significant differences in work side or spoil side soil strengths compared to the control for the Orthic Black Chernozem at Ferintosh immediately following construction in 1989. Decreased trench soil strengths were monitored in the subsoil. Construction occurred in dry to moist soil conditions. One year later, a minor (0.2 bar) decrease in work side soil strength was observed in the topsoil. Decreased subsoil trench soil strengths persisted from the previous year. The decreases in trench soil strength were attributed to breaking up of subsoil material during the trenching procedure. Results at this study area are similar to those of Zellmer et al. (1985), in which bulk densities were found to be lower in the trench than on an adjacent control soil in 16 of

20 sets of observations in a fine sandy loam in Oklahoma. These researchers also found no significant differences in soil strength between soils of the control and soils of either the work side or spoil side.

Immediately following pipeline construction in moist to wet soil conditions, decreased soil strengths occurred across the RoW within the topsoil of the two Orthic Dark Gray Chernozems (Redwater 2 and Pigeon Lake). The only exception was an increase in work side soil strength at 3.5 cm for Pigeon Lake. The decreased soil strengths most likely resulted from cultivation of the RoW after construction. Decreased soil strengths also occurred at Pigeon Lake at 24.5 cm for the spoil side and the trench. It was difficult to speculate why soil strengths on the spoil side would decrease; the decreased trench soil strength was believed to be the result of breaking up of subsoil material during the trenching procedure.

One year later, there were no significant differences in soil strength between RoW locations and control at Pigeon Lake. At Redwater 2, increases in spoil side and work side soil strengths were noted in the topsoil at 3.5 cm, but these differences were only 0.8 to 1.1 bars greater than the control, and are not considered to be a limiting factor to plant growth. Reasons for the decreased spoil side soil strength at 10.5 cm were unknown, but may be a function of natural soil variability.

Soil strength comparisons between RoW locations and control soils could not be made below 10.5 cm at Redwater 2. The inability of the penetrometer to penetrate was most likely due to the dryness of the soil, which was due in part to the high root proliferation of hay, enhancing greater extraction of water within the root zone.

Decreased topsoil soil strengths compared to the control soil occurred for the Solonetzic Brown Chernozem at Milo immediately following construction. Decreases in soil strengths were attributed to the breaking up of subsoil material during trenching or to cultivation of the RoW after construction. One year later, there were no significantly different soil strengths for the RoW locations compared to the control, indicating soil strengths were similar to predisturbed conditions. Soil strength comparisons could only be made to 10.5 cm for both sampling years because of penetrometer limitations. Pipeline construction had occurred in dry soil conditions.

Immediately following pipeline construction in moist to wet soil conditions, decreased soil strengths across the RoW were observed to a depth of 24.5 cm for the Gleyed Black Chernozem at Redwater 1. These decreases in soil strength most likely reflected the return of topsoil (which had been stripped to depth of 40 cm) to the RoW and its subsequent cultivation or harrowing after construction was completed. The cone penetrometer could not penetrate the control soils past 24.5 cm at Redwater 1, which was most likely due to the greater extraction of water by the crop within the root zone.

One year following construction at Redwater 1, isolated increased trench soil strengths occurred at 10.5 and 31.5 cm. The increased trench soil strengths compared to the control in 1990 may indicate that settling of the trench was likely occurring.

### 5.3.2 Luvisolic Order

All three Luvisolic soils were developed on till, and soil conditions at the time of pipeline construction were dry. Decreased soil strengths across the entire RoW within the top 17.5 cm were observed for two of the three Luvisolic soils (Henderson 1 and Henderson 2) immediately following construction. These decreased soil strengths were attributed to cultivation of the RsoW after construction.

Decreases in soil strengths occurred only within the trench portion of the RoW within the top 17.5 cm for the Valhalla study area immediately following construction. These soil strength decreases were most likely a result of the cultivation of the RoW after construction was completed.

One year later, there were no significant differences in soil strength for the subsoils for all three Luvisolic soils or for the topsoil at Henderson 2, suggesting soil strengths were similar to predisturbed conditions. The soil strength differences in the topsoil at Valhalla and Henderson 1 varied from 0.5 to 1.2 bars, and are not considered to be a limiting factor to plant growth.

### 5.3.3 Solonetzic Order

Both increases and decreases in soil strength were observed for the Craigmyle study area immediately following pipeline construction. Increased work side soil strength was found only in the topsoil. Results of Naeth (1985), on the other hand, indicated that bulk densities of work side soils were increased to a depth of 55 cm on Solonetzic rangelands. In this study, decreased trench soil strength was observed at 10.5 cm; however, the cone penetrometer could not penetrate the trench past 17.5 cm. One year later, increased trench soil strength for the subsoil compared to the control was observed. These results contrast the findings of Naeth (1985), which indicated that bulk densities of subsurface trench soil were decreased compared to control soils for Solonetzic rangelands in southern Alberta. There were no differences between the work side and control soils, suggesting that soil strengths were similar to predisturbed conditions. Lower work side topsoil organic matter compared to the control in 1988 may help explain the increased work side soil strengths at the 10.5 cm depth. Differences in both % organic matter and soil strength disappeared one year after construction. Pipeline construction occurred on dry soil conditions.

Immediately following pipeline construction, there were no significant soil strength differences for the Michichi study area. Pipeline construction took place in wet soil conditions. One year later, increased work side soil strengths of 0.3 bars were reported within the topsoil, a difference which is not considered limiting to plant growth. The cone penetrometer was unable to penetrate the control soil past 24.5 to 31.5 cm in any of the monitoring years, reflecting the high inherent strength of Solonetzic soils.

### 5.3.4 Gleysolic Order

No significant soil strength differences occurred immediately following construction or one year later for either the Victor 1 or the Atlee-Buffalo study areas, suggesting pipeline construction had no effect on soil strength. Soil strength comparisons for Atlee-Buffalo could not be made past the topsoil for either sampling year because of penetrometer limitations. The cone penetrometer was unable to penetrate the control soil at Atlee-Buffalo past 17.5 cm for any of the monitoring years, reflecting the high inherent soil strengths of the dry rangelands. For both study areas, soil had developed on lacustrine materials and pipeline construction took place in dry soil conditions.

## 6.0 CONCLUSIONS

Based on the results of this study, the following conclusions about the effects of pipeline construction on soil compaction may be made:

1. As a result of pipeline construction, decreases in soil strength were more common than increases in soil strength on RsoW. These changes in soil strength had disappeared one year after construction.

   Immediately following pipeline construction, decreases in strength of RoW soils compared to control soils, were more common than increases, although both occurred. Increases and decreases in soil strength that occurred immediately after construction at many of the study areas had disappeared one year after construction (e.g. Ghostpine, Victor 2, Pigeon Lake, Milo and Henderson 2). Only minor differences of less than 2 bars remained at several additional sites (e.g. Redwater 2, Valhalla and Henderson 1). Two additional sites had no differences in soil strength between the RoW and controls, either immediately after construction or after one year (e.g. Victor 1 and Atlee-Buffalo).

2. No clear relationships emerged between soil Orders or soil parent materials and the effect on soil compaction of pipeline construction. However, several observations can made:

   - Solonetzic soils or Solonetzic intergrades are decompacted during construction of the trench. These soils often show reduced soil strength compared to a control shortly after construction is completed. However, they either show no significant difference from a control soil, or show slightly higher soil strength than a control after one year (e.g. Craigmyle).

   - Soils with parent materials high in sand tend to have lower soil strengths after construction and frequently, but not always, return to pre-construction conditions in one year (e.g. Milo).

   - Gleysolic soils are no more prone to soil compaction during pipeline construction than soils of other Orders, provided construction is carried out under dry conditions (e.g. Victor 1 and Atlee-Buffalo).

3. There is a lower chance of compacting soil when pipelines are constructed under dry soil conditions than when pipelines are constructed under moist to wet soil conditions.

Construction under wet conditions results in compaction on the work side. As well, large aggregates are produced that cannot be returned to the trench without producing either increased large pore space at depth, if backfilling takes place when dry, or compaction, if backfilling takes place when wet (e.g. Ghostpine).

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# 8.0 APPENDIX: SOIL DESCRIPTIONS FOR EACH STUDY AREA

Representative profiles for soils in each of the 14 study areas are presented in Tables A1 to A14.

Table A1. Soil Profile Descriptions of Controls, Atlee-Buffalo Study Area, Replicates 1, 2 and 3

## LANDSCAPE

| | |
|---|---|
| Classification: | Orthic Humic Gleysol |
| Parent Material: | Lacustrine overlying till |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Poorly |
| Stoniness Class: | Slightly (S1) |

REPLICATE

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Of | 1.5-0 | | | | |
| Ahk | 0-11 | L | weak granular | friable | 10YR 4/1 |
| Bgk | 11-17 | CL | moderate, fine, subangular blocky | friable | 5Y 7/1 & 5Y 5/1 |
| Cgk | 17+ | CL | weak, subangular blocky to massive | friable | 5Y 6/1 & 5Y 6/2 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Of | 1-0 | | | | |
| Ahk | 0-11 | C | weak granular | friable | 10YR 3/1 |
| Bgk | 11-20 | CL | moderate, fine, subangular blocky | friable | 5Y 5/2 |
| Cgk | 20+ | CL | weak, subangular blocky to massive | friable | 5Y 7/1 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ahk | 0-14 | L | weak granular | friable | 10YR 4/2 |
| Bgk | 14-25 | CL | moderate, fine, subangular blocky | friable | 10YR 5/1 |
| Cgk | 25+ | CL | weak, subangular blocky to massive | friable | 10YR 6/2 |

Table A2. Soil Profile Descriptions of Controls, Craigmyle Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Dark Brown Solodized Solonetz |
| Parent Material: | Weathered Bedrock |
| Topography: | Level to undulating (0 to 0.5% slopes) |
| Drainage: | Moderately well |
| Stoniness Class: | Stone-free (S0) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | SiCL | fine medium coarse granular | loose | 10YR 3/2 |
| Bnt1 | 15+ | CL | coarse column flat top breaking to medium angular blocky | very firm | 10YR 3/2 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-13 | SiCL | fine medium coarse granular | loose | 10YR 3/2 |
| Bnt1 | 15-61 | CL | coarse column flat top breaking to medium angular blocky | very firm | 10YR 3/2 |
| Bnt2 | 61+ | CL | | | |
| Csk | 48+ | SiCL-CL | - | firm | 10YR 3/2 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | SiCL | fine medium course granular | loose | 10YR 3/2 |
| Bnt1 | 15+ | CL | coarse column flat top breaking to medium angular blocky | very firm | 10YR 3/2 |

Table A3. Soil Profile Descriptions of Controls, Ferintosh Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Orthic Black Chernozem |
| Parent Material: | Fluvial overlying till |
| Topography: | Undulating (0.5 to 2% slopes) |
| Drainage: | Moderately well |
| Stoniness Class: | Slightly (S1) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | granular | friable | 10YR 2/1 |
| Ah | 15-30 | L | granular | friable | 10YR 2/1 |
| Bm | 30-50 | SL | weak, subangular blocky | friable | 10YR 5/4 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | granular | friable | 10YR 2/1 |
| Ah | 15-35 | L | weak, subangular blocky to granular | friable | 10YR 2/1 |
| AB | 35-45 | CL | weak, subangular blocky to granular | friable | 10YR 4/2 |
| Bm | 45-50+ | CL | weak, subangular blocky | friable | 10YR 5/4 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | granular | friable | 10YR 2/1 |
| Ah | 15-35 | L | granular | friable | 10YR 2/1 |
| Bm | 35-50 | SL | weak, subangular blocky | friable | 10YR 5/4 |

Table A4. Soil Profile Descriptions of Controls, Ghostpine Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Orthic Dark Brown Chernozem |
| Parent Material: | Morainal |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Well |
| Stoniness Class: | Slightly stony (S1) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | weak fine granular | friable | - |
| Bm | 15-25 | CL | weak medium subangular blocky | friable | - |
| Ck | 25+ | CL | weak subangular blocky to massive | friable | - |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | weak fine granular | friable | - |
| Bm | 15-26 | CL | weak subangular blocky | friable | - |
| Ck | 26+ | CL | massive | friable | - |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-18 | L | weak granular | friable | - |
| Bm | 18-27 | CL | weak subangular blocky | friable | - |
| Ck | 27+ | CL | massive | friable | - |

Table A5. Soil Profile Descriptions of Controls, Henderson 1 Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Solonetzic Dark Grey Luvisol |
| Parent Material: | Glacial till |
| Topography: | Undulating (0.5 to 2% slopes) |
| Drainage: | Moderately well |
| Stoniness Class: | Stone-free (S0) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | SiL | weak granular | friable | 10YR 4/2 |
| Ae | 15-20 | SiL | weak platy | friable | 10YR 6/3 |
| Btnj | 20-35 | C | strong, subangular blocky | very friable | 10YR 4/1 & 10YR 4/4 |
| Bt2 | 35-50 | C | weak, subangular blocky | very friable | 10YR 4/1 & 10YR 4/4 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-16 | SiL | weak granular | friable | 10YR 4/2 |
| Ae | 16-23 | SiL | weak platy | friable | 10YR 7/2 |
| Btnj | 23-35 | C | columnar breaking to strong, subangular blocky | very friable | 10YR 4/1 & 10YR 4/3 |
| Bt2 | 35-50 | C | weak, subangular blocky | very friable | 10YR 4/1 & 10YR 4/3 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | SiL | weak granular | friable | 10YR 4/2 |
| Ae | 15-20 | SiL | weak platy | friable | 10YR 6/3 |
| Btnj | 20-35 | C | strong, subangular blocky | very friable | 10YR 4/1 & 10YR 4/4 |
| Bt2 | 35-50 | C | weak, subangular blocky | very friable | 10YR 4/1 & 10YR 4/4 |

Table A6. Soil Profile Descriptions of Controls, Henderson 2 Study Area, Replicates 1, 2 and 3

LANDSCAPE
Classification: Dark Grey Luvisol
Parent Material: Glacial till
Topography: Undulating (0.5 to 2% slopes)
Drainage: Moderately well
Stoniness Class: Slightly (S1)

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | very weak granular | very friable | 10YR 5/3 |
| Ae | 15-18 | L | weak platy | very friable | 10YR 7/3 |
| AB | 18-30 | L | weak, subangular blocky | friable | 10YR 6/3 &10YR5/3 |
| Bt | 30-50 | CL | strong, subangular blocky | friable | 10YR 5/2 &10YR5/4 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | very weak granular | very friable | 10YR 5/3 |
| Ae | 15-19 | L | weak platy | very friable | 10YR 7/3 |
| AB | 19-22 | L | weak, subangular blocky | friable | 10YR 6/3 &10YR5/3 |
| Bt1 | 22-35 | CL | strong, subangular blocky | friable | 10YR 5/2 &10YR5/4 |
| Bt2 | 35-50 | C | strong, subangular blocky | friable | 10YR 5/2 &10YR5/4 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | weak granular | friable | 10YR 5/2 |
| Bt1 | 15-35 | C | strong, subangular blocky | friable | 10YR 5/6 &10YR5/1 |
| Bt2 | 35-50 | C | weak, subangular blocky | friable | 10YR 5/6 &10YR5/1 |

Table A7. Soil Profile Descriptions of Controls, Michichi Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Dark Brown Solodized Solonetz |
| Parent Material: | Glaciolacustrine blanket |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Imperfectly |
| Stoniness Class: | Stone-free (S0) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap/Ah | 0-15 | CL | fine granular | friable | 10YR 3/2 |
| Bm | 15-25 | CL | weak fine subangular blocky | friable | 10YR 4/2 |
| Bnt | 25-43 | CL-C | moderate medium subangular blocky | friable | 10YR 4/3 |
| BC | 43-45 | C | weak subangular blocky to massive | friable | 10YR 4/2 |
| Ck | 45+ | C | weak subangular blocky to massive | friable | 10YR 4/2 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | CL | moderately fine granular | very friable | 10YR 3/2 |
| Ah | 15-23 | C | weak very fine subangular blocky | friable | 10YR 3/2 |
| Bnt | 23-40 | C | moderate medium subangular blocky | hard | 10YR 3/2 |
| Ck | 40+ | C | - | - | - |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap/Ah | 0-15 | CL | fine granular | friable | 10YR 3/2 |
| Bnt | 15-40 | CL | very fine weak subangular blocky | friable | 10YR 3/2 |
| Ck | 40 + | C | very weak fine subangular blocky | friable | 10YR 3/2 |

Table A8. Soil Profile Descriptions of Controls, Milo Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Solonetzic Brown Chernozem |
| Parent Material: | Glaciofluvial |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Moderately well |
| Stoniness Class: | Slightly to moderately stony (S1 to S2) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | weak fine granular | slightly friable | 2.5Y 5/4 |
| Bnj | 15-30 | CL | medium subangular blocky | hard | 10YR 4/3 |
| Ck | 30+ | C | weak subangular blocky to massive | hard | 10YR 5/3 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Apk | 0-15 | SCL | weak granular | slightly friable | 2.5Y 5/4 |
| Bnjk | 15-30 | L | fine medium subangular blocky | hard | 10YR 4/3 |
| Ck | 30+ | L | weak subangular blocky | hard | 10YR 5/3 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | weak fine granular | slightly friable | 2.5Y 5/4 |
| Bnj | 15-30 | CL | medium subangular blocky | hard | 10YR 4/3 |
| Ck | 30+ | C | weak subangular blocky to massive | hard | 10YR 5/3 |

Table A9. Soil Profile Descriptions of Controls, Pigeon Lake Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Orthic Dark Grey Chernozem |
| Parent Material: | Glacial till |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Moderately well |
| Stoniness Class: | Stone-free (S0) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ah | 0-17 | L | weak granular | friable | 10YR 3/2 |
| Ae | 17-18 | CL | weak platy | friable | 10YR 5/3 |
| Bt | 18-50+ | CL | moderate, fine, subangular blocky | friable | 10YR 4/3 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap/Ah | 0-32 | L | weak granular | friable | 10YR 3/2 |
| Ae | 32-36 | L | weak platy | friable | 10YR 5/3 |
| Bt | 36-50+ | CL | moderate, fine, subangular blocky | friable | 10YR 4/3 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap/Ah | 0-32 | SCL | weak granular | friable | 10YR 3/2 |
| Ae | 32-36 | L | weak platy | friable | 10YR 5/3 |
| Bt | 36-50+ | L | moderate, fine , subangular blocky | friable | 10YR 4/3 |

Table A10. Soil Profile Descriptions of Controls, Redwater 1 Study Area, Replicates 1, 2 and 3

| LANDSCAPE | |
|---|---|
| Classification: | Gleyed Black Chernozem |
| Parent Material: | Glaciofluvial |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Imperfectly |
| Stoniness Class: | Slightly (S1) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ah | 0-20 | SL | weak granular | very friable | 10YR 3/1 |
| AB/Bm | 20-40 | LS | strong granular | very friable | 10YR 3/2 |
| Bgj | 40-50 | SL | strong granular | very friable | 10YR 4/2 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-20 | SL | weak granular | very friable | 10YR 3/1 |
| Bm | 20-40 | SL | strong granular | very friable | 10YR 3/2 |
| Bgj | 40-50 | SL | strong granular | very friable | 10YR 6/3 &10YR5/2 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-20 | SL | weak granular | very friable | 10YR 3/1 |
| Bm | 20-40 | SL | strong granular | very friable | 10YR 3/2 |
| Bgj | 40-50 | SL | strong granular | very friable | 10YR 6/3 &10YR5/2 |

Table A11. Soil Profile Descriptions of Controls, Redwater 2 Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Dark Grey Luvisol |
| Parent Material: | Glaciofluvial overlying till |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Moderately well |
| Stoniness Class: | Slightly (S1) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-16 | SL | weak, fine granular | friable | 10YR 4/2 |
| Ae | 16-20 | SL | weak, medium platy | friable | 10YR 6/4 |
| Bt1 | 20-35 | SCL | moderate, fine, subangular blocky | friable | 10YR 5/3 |
| BC | 35-50 | SCL | weak, fine, subangular blocky | friable | 10YR 5/3 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-20 | L | weak granular | friable | 10YR 4/2 |
| Ae | 20-35 | L | weak platy | friable | 10YR 5/3 |
| Bt1 | 35-50 | L | weak, subangular blocky | friable | 10YR 5/4 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-20 | L | weak granular | friable | 10YR 4/2 |
| Ahe | 20-28 | L | moderate, fine platy | friable | 10YR 4/2 |
| Ae | 28-35 | L | weak, medium platy | friable | 10YR 5/3 |
| Bt1 | 35-50+ | L | moderate, fine, subangular blocky | friable | 10YR 5/4 |

Table A12. Soil Profile Descriptions of Controls, Valhalla Study Area, Replicates 1, 2 and 3

LANDSCAPE

| | |
|---|---|
| Classification: | Gleyed Dark Grey Luvisol |
| Parent Material: | Glacial till |
| Topography: | Undulating (2 to 5% slopes) |
| Drainage: | Imperfectly |
| Stoniness Class: | Slightly to moderately (S1 to S2) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | CL | moderate granular | friable | 10YR 4/2 |
| Btgj | 15-30 | CL | moderate, fine, subangular blocky | friable | 10YR 4/1 & 10YR 4/6 |
| BC | 30-50 | CL | weak, subangula r blocky | friable | 10YR 4/3 & 10YR 4/1 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | granular | friable | 10YR 4/2 |
| Ah | 15-20 | L | granular | friable | 10YR 4/2 |
| Ae | 20-30 | L | weak platy | friable | 10YR 6/4 |
| Bt | 30-40 | L | subangular blocky | friable | 10YR 4/2 |
| BC | 40-50 | SCL | subangular blocky | friable | 10YR 4/2 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 | L | granular | friable | 10YR 3/2 |
| Ah | 15-20 | L | granular to weak, subangular blocky | friable | 10YR 3/2 |
| Ae/ABgj | 20-30 | L | weak, subangular blocky | friable | 10YR 5/1 & 10YR 5/3 |
| Btgj | 30-40 | L | weak, subangular blocky | friable | 10YR 4/1 & 10YR 5/4 |
| BCgj | 40-50 | SCL | weak, subangular blocky | friable | 10YR 4/1 & 10YR 5/4 |

Table A13. Soil Profile Descriptions of Controls, Victor 1 Study Area, Replicates 1, 2 and 3

LANDSCAPE
Classification: Orthic Humic Gleysol
Parent Material: Lacustrine
Topography: Undulating (2 to 5% slopes)
Drainage: Poor
Stoniness Class: Stone-free (S0)

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ahgk | 0-18 | CL-C | massive | firm, sticky plastic | 10YR 3/2 |
| Bgk | 18+ | CL-C | coarse, moderate fine sub-angular blocky | firm, sticky plastic | 10YR 3/2 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ahgk | 0-18 cm | CL-C | massive | firm, sticky plastic | 10YR 3/2 |
| Bgk | 18-41 cm | CL-C | coarse, moderate fine sub-angular blocky | firm, sticky plastic | 10YR 3/2 |
| Cgk | 41+ cm | CL-C | - | firm, sticky plastic | 10YR 3/2 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ahgk | 0-15 | CL-C | massive | firm, sticky plastic | 10YR 3/2 |
| Bgk | 15+ | CL-C | coarse, moderate fine sub-angular blocky | firm, sticky plastic | 10YR 3/2 |

Table A14. Soil Profile Descriptions of Controls, Victor 2 Study Area, Replicates 1, 2 and 3

| | |
|---|---|
| LANDSCAPE | |
| Classification: | Orthic Dark Brown Chernozem |
| Parent Material: | Lacustrine |
| Topography: | Undulating (0 to 2% slopes) |
| Drainage: | Well |
| Stoniness Class: | Stone-free (S0) |

REPLICATE 1

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-13 | CL | moderate fine granular | loose | 10YR 3/3 |
| Bm | 13+ | CL | coarse, medium fine sub-angular blocky | friable to firm | 10YR 3/3 |

REPLICATE 2

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-15 cm | CL | moderate fine granular | loose | 10YR 3/3 |
| Bm | 15-36 cm | CL | coarse, medium fine sub-angular blocky | friable to firm | 10YR 3/3 |
| Ck | 36+ cm | CL | - | firm | 10YR 3/3 |

REPLICATE 3

| HORIZON | DEPTH (cm) | TEXTURE | STRUCTURE | CONSISTENCE | COLOUR |
|---|---|---|---|---|---|
| Ap | 0-20 | CL | moderate fine granular | loose | 10YR 3/3 |
| Bm | 20+ | CL | coarse, medium fine sub-angular blocky | friable to firm | 10YR 3/3 |