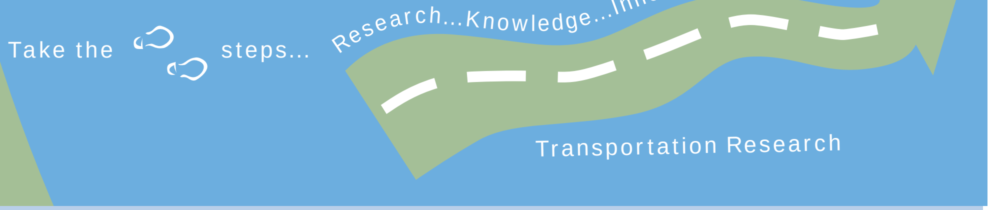
MINNESOTA DEPARTMENT OF TRANSPORTATION

# RESEARCH

2008-01

# Compaction Remediation for Construction Sites



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The goal of this project is to develop a sub-soiling regimen that will enhance and be compatible with existing erosion control measures. This project is important in minimizing the effect of construction-induced compaction on the urban and rural landscape. This activity, if successful, will become a building block for use in Best Management Practices (BMPs) that will ensure full vegetative growth post construction, and save on the cost of reapplication of erosion control measures. For a good comparative study, several sites were selected for typical slope and soil type.

The study shows that there are low cost benefits to deep tillage of ROW. Heavy clay soils are problematic in that improvements in infiltration could not be detected after a single tillage operation. In lighter sandy soils, the benefits of tillage are such that significant increases in infiltration can be gained following a single pass tillage operation. The differences in tillage implement used could not be detected.

The post-tillage aesthetic appeal when using a non-inverting plow (Kongskilde Paraplow) was apparent in this study. The vegetation was largely undisturbed following tillage, and this would be beneficial in preventing erosion on slopes. The ripper and the DMI inverted more soil, and therefore the tillage operation was less appealing to motorists.

The relatively low cost of ownership and operation for the tillage is overshadowed by the high land cost when new roads are constructed. Tillage would be beneficial on lighter soils, however the "utility congestion" that is likely in such a scenario would make machinery management difficult.

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# Compaction Remediation for Construction Sites

## Final Report

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## Executive Summary

The goal of this project is to develop a sub-soiling regimen that will enhance and be compatible with existing erosion control measures. This project is important in minimizing the effect of construction-induced compaction on the urban and rural landscape. This activity, if successful, will become a building block for use in Best Management Practices (BMPs) that will ensure full vegetative growth post construction, and save on the cost of reapplication of erosion control measures. For a good comparative study, several sites were selected for typical slope and soil type.

The study shows that there are low cost benefits to deep tillage of ROW. Heavy clay soils are problematic in that improvements in infiltration could not be detected after a single tillage operation. In lighter sandy soils, the benefits of tillage are such that significant increases in infiltration can be gained following a single pass tillage operation. The differences in tillage implement used could not be detected.

The post-tillage aesthetic appeal when using a non-inverting plow (Kongskilde Paraplow) was apparent in this study. The vegetation was largely undisturbed following tillage, and this would be beneficial in preventing erosion on slopes. The ripper and the DMI inverted more soil, and therefore the tillage operation was less appealing to motorists.

The relatively low cost of ownership and operation for the tillage is overshadowed by the high land cost when new roads are constructed. Tillage would be beneficial on lighter soils, however the “utility congestion” that is likely in such a scenario would make machinery management difficult.

In this study only one pass of the tillage implement was used. It is likely that multiple passes and time will begin to improve a compacted topsoil structure. This is highlighted in McKyes (1985) discussion of “Tillage of Compacted Soils”.

## Introduction and Premise for the Study

The goal of this project is to develop a sub-soiling regimen that will enhance and be compatible with existing erosion control measures. This project is important in minimizing the effect of construction-induced compaction on the urban and rural landscape. This activity, if successful, will become a building block for use in Best Management Practices (BMPs) that will ensure full vegetative growth post construction, and save on the cost of reapplication of erosion control measures. For a good comparative study, several sites were selected for typical slope and soil type.

## Objectives

The specific research objectives are:

1. To assess the degree of compaction using a tractor-mounted soil cone penetrometer.

2. To establish test plots of approximately one acre in size, which will be sub-soiled before topsoil is replaced, before application of erosion blankets, and after vegetation is established on different plots. Plots will be located on sites that represent the major groups of sand, silt and clay. Early screening will be used to examine the soil profile to determine the tillage needed. Test plots will not be uniform in dimension due to width restraints that may be imposed at the site.

3. To measure soil cone index and infiltration rate for each test plot and quantify vegetative growth as an index of tillage benefit.

## Methodology

The research work comprised of locating exemplary sites large enough to make meaningful comparisons between tillage equipment, including sloped and flat topography on which to conduct the tillage, and be representative of a wide range of soil types encountered by MnDOT.
The research team worked with MnDOT personnel to identify areas of Right of Way (ROW) that exhibited poor infiltration. The sites were selected where traffic density was low to minimize risk to the research team. The sites used in the study were:

- HWY 169-TH 19 Belle Plaine (clayey soil, established vegetation) Aug04
- HWY 319 Crow Wing Park entrance and visitor center (sandy soil, established vegetation) May05
- HWY 14-County 3 Janesville (clayey soil, newly constructed) Aug05
- MnROAD facility, Albertville (Silty Loam) Jun06

The research sites were first mapped using a DGPS instrument fitted to a JD 6400 tractor used which was as an instrument platform. The machine was equipped with a Giddings auger. The unit was modified to take Cone Index (CI) measurements and the auger was modified so that torque could be determined from the pressure differential across the driving hydraulic motor. The rationale for the added measure of soil compaction was a result of initial discussion with MnDOT personnel; indicating that in some instances the soil was so compact that a CI measurement could not be taken. What they failed to convey is that their methods used manual penetrometers whereas we were using the force from a hydraulic ram to make the measurement. In this report cone index, (CI) and soil strength will be used synonymously.

Infiltration measurements were made using the Philip-Dunne method (Munoz-Carpena et al 2001). Initially tension infiltrometers were used, however the time required for set-up and their unreliable performance led us to the simpler method. Measurements were taken on the slope, on the flat, in furrow, and in between the furrow.

The tillage treatments applied in this study consisted of:

- DMI Ecolotill 5 tines 30” spacing 12” operational depth (DMI)
- Kongskilde Paraplow 4 tines 36” spacing 18” operational depth (KSK)
- Caterpillar Subsoiler 2 tines 36” spacing 24” operational depth (RIP)
- Control no tillage

## Field Work

All vehicles were equipped with MARS hazard beacons and personnel were equipped with fluorescent work vests and hard hats which were worn when working on site. Each site was mapped using Gopher One Service to ensure that all known underground services were identified and flagged before site operations commenced.

Mathowitz Construction provided the tillage equipment and transportation with two exceptions; The Paraplow was managed by the University of Minnesota team, and the MnROAD site tested only the Paraplow. A 250 HP tractor was rented for tillage activities at each site. This size tractor was determined by the size of the available equipment. For the Caterpillar Subsoiler (Ripper), a contractor's machine was used.

Prior to tillage, the site was mapped using the DGPS on the instrumented tractor. This map was used to define the perimeter of the tillage areas. The next operation was to collect soil strength and soil moisture data. The soil strength measurements were made to a depth of 30 inches, whereas the surface moisture was measured (0-8"). Soil strength measurements were taken using a cone penetrometer and a short flight hydraulically powered auger. The rationale behind developing an alternate means of determining soil strength was brought during initial discussions with MnDOT personnel who had previously been unable to use a cone penetrometer due to the levels of compaction found on some ROW.

Samples were taken at random intervals across the site, the path roughly describing a "W" pattern on the site. Additional measurements were taken to fill out the data set. All samples were taken over a one-or two-day period.

After the baseline soil parameters were collected, the site was divided into sub plots and the tillage performed. Tillage activities were limited to conditions that suited the activity; the application occurred when the soil was in a friable condition. The distribution of the tillage was randomized. Replicate plots were made in most cases in order to minimize local effects and provide statistical model leverage.

## **Data Collection**

Data was collected from each site during the two summers that followed the application of the tillage treatment. The procedure for post tillage data collection was the same as that of the pre-tillage activity, except that soil strength and saturated hydraulic conductivity measurements were taken. Each plot was re-surveyed by Gopher One before collecting additional penetrometer data to make sure that all services were identified.

## **Statistical Analysis**

A statistical analysis was performed using JMP, a software package from SAS. The analysis comprised of investigating the difference in means between groups of data. Compaction data includes measurements of the Cone Index kPa (CI), Auger Torque N.m (torque), and soil moisture content (MC) dry mass basis. Soil strength measurements were grouped by depth from the soil surface to 30 inches deep in 6 inch increments. Soil types were:

- Clay Loam (Janesville and Belle Plaine)
- Sandy Loam (Brainerd)
- Silty Loam (MnROAD)

## Soil Strength Measurements

A comparative analysis was made between pre- and post-tilled soil strength data. The analysis showed that no significant differences could be detected between soil strength using either the CI or auger methods. During the tests, the CI exceeded 3000 kPa in the depth range of 12-18” for silty loam soil. This value is well above the 2000-2500 kPa level reported by Voorhees (1975) which inhibits root development.

An inverse relationship was detected between the auger torque and cone index values. This could be due to the complexity of the shearing activity at the tip of the auger, or to interaction between the oil pressure to the cylinder and the motor used to drive the auger in the hydraulic system of the instrumentation tractor. For this reason, the results of the auger-based study have been set aside from this report.

A comparison between control and tilled soil strength for the three soil types is shown in Figures 1-3. The CI observed for the sites shows that the silty loam has the highest level of compaction at 30”. Significant differences in soil strength due to tillage activities could not be detected in any soil type.

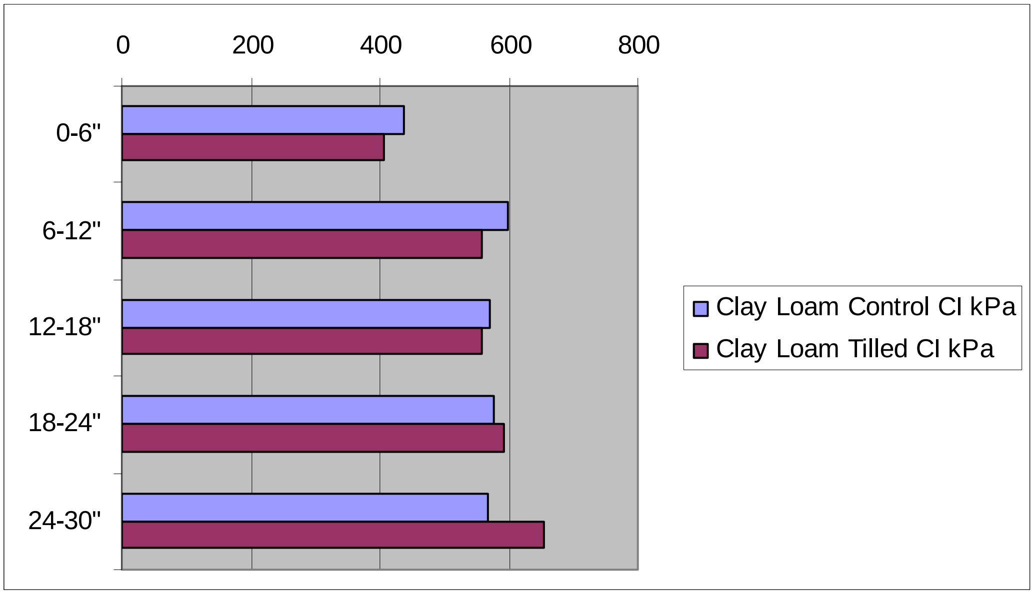


**Figure 1. Comparison between Control and Tillage (All) Clay Loam CI kPa**

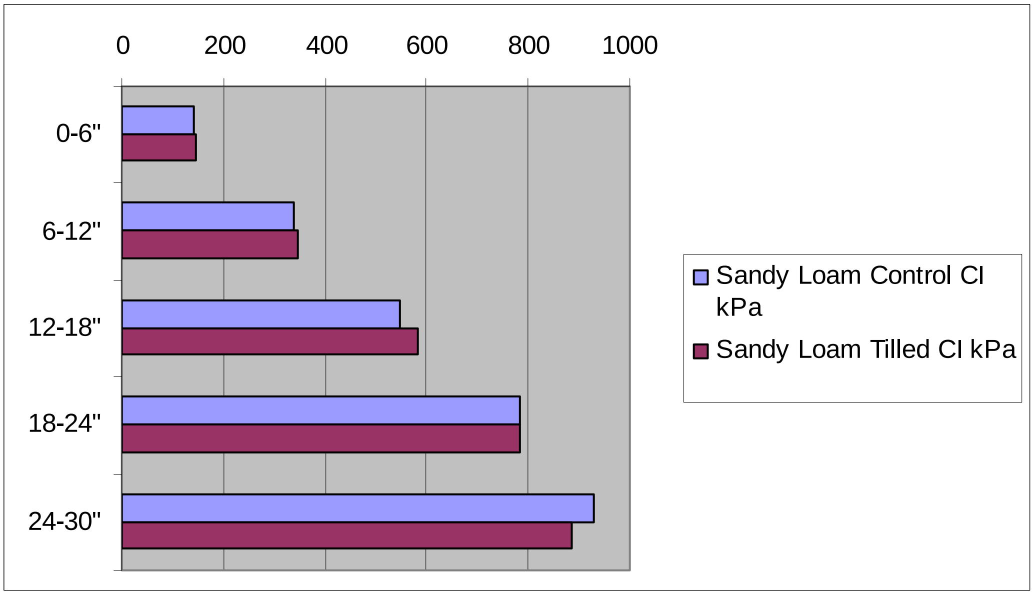


**Figure 2. Comparison between Control and Tillage (All) Sandy Loam CI kPa**

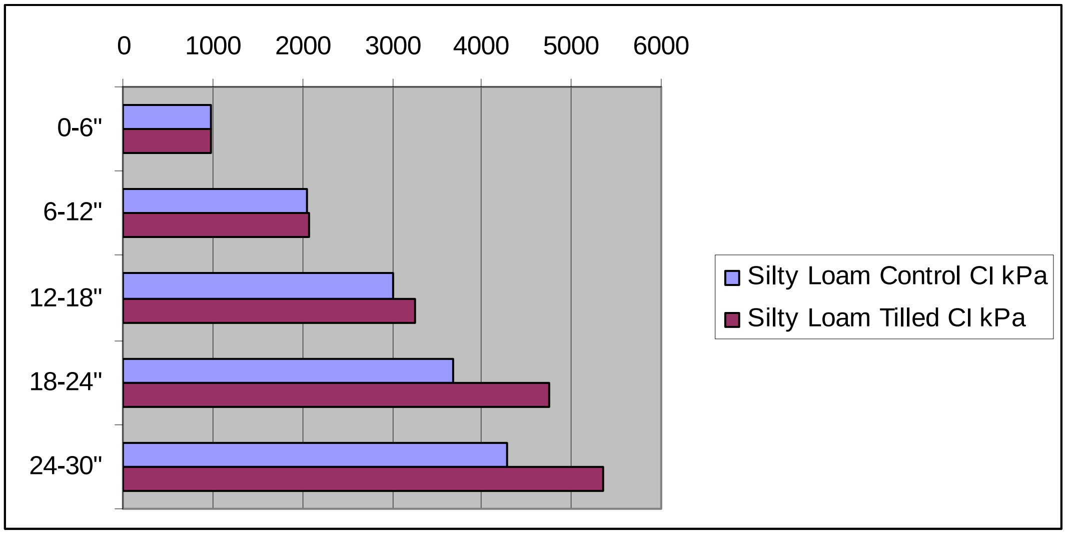
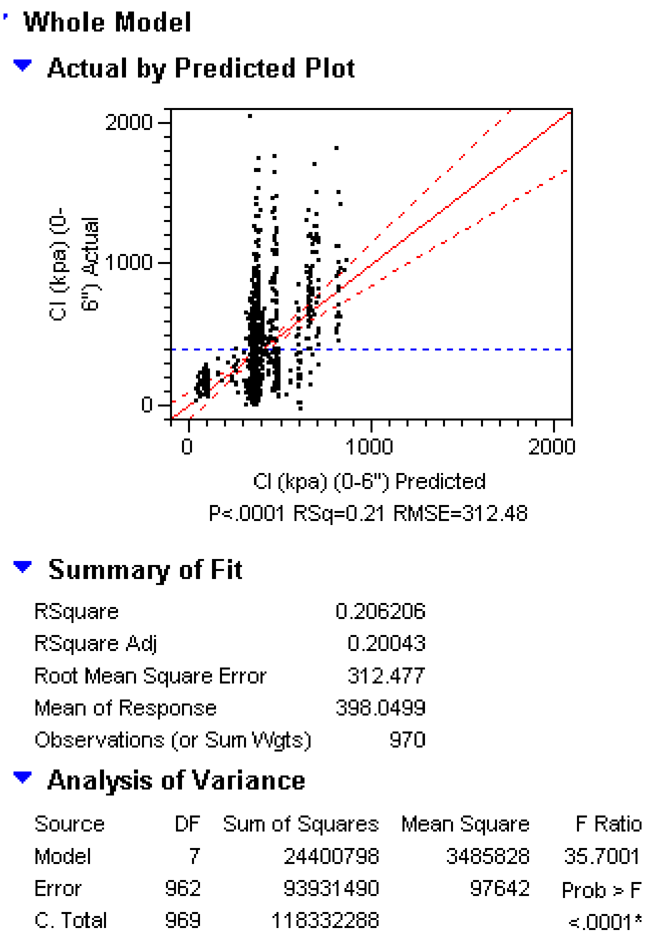


**Figure 3. Comparison between Control and Paraplow Silty Loam CI kPa**

Several statistical models were used to explain the variability in the CI readings in terms of measured parameters. The models were fitted using JMP, a statistical modeling software package. The following model (Model 1) describes the surface (0-6”) CI variability as a linear function of soil type, surface moisture content, number of years after tillage, and tillage treatment used.

Model 1. CI (0-6”) = [soil type, tillage, year after tillage, moisture content] * $\beta + \varepsilon$



**Whole Model**

**Actual by Predicted Plot**

**Summary of Fit**

| | |
|---|---|
| RSquare | 0.206206 |
| RSquare Adj | 0.20043 |
| Root Mean Square Error | 312.477 |
| Mean of Response | 398.0499 |
| Observations (or Sum Wgts) | 970 |

**Analysis of Variance**

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 7 | 24400798 | 3485828 | 35.7001 |
| Error | 962 | 93931490 | 97642 | Prob > F |
| C. Total | 969 | 118332288 | | <.0001* |

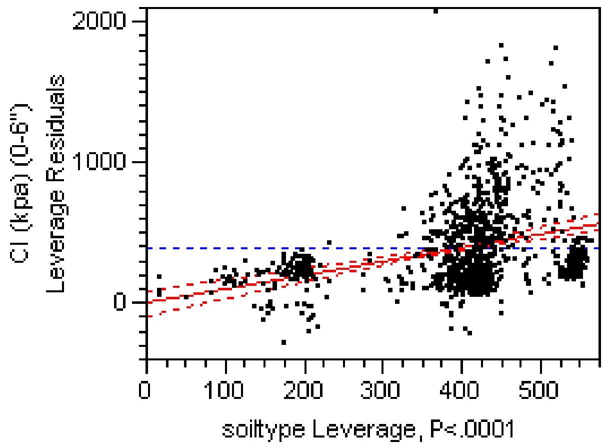
**Figure 4. Whole model (0-6")**

Analysis showed that tillage is significant in explaining some variability in cone index measured in the 0-6" layer. Large differences could be detected, which could be due to the overall variability of conditions in the site or to the random error in the measurements. A lack of sensitivity of the instrumentation may also lead to small changes in soil strength going undetected.

A difference between compaction in the soil types was evident in the data. Plots of leveraged residuals show that the ranking of the average soil strength was sandy loam<clay loam<sandyy loam for the surface (0-6") layer.

**soiltype**

**Leverage Plot**



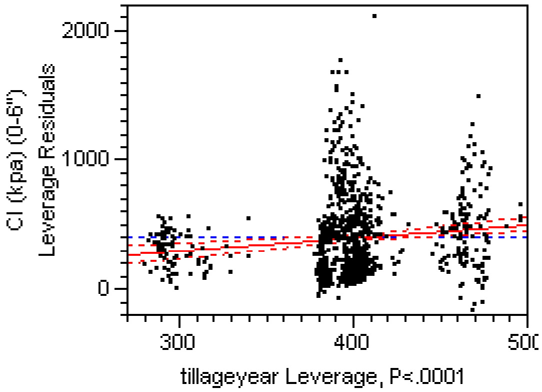
**Least Squares Means Table**

```
Level           Least Sq Mean                    Std Error      Mean
Clay loam                   .   NonEstimable             .   417.248
loam                        .   NonEstimable             .   514.224
Sandy loam                  .   NonEstimable             .   140.990
```

Figure 5. Residuals and Least Squares Means for Soil Type (0-6")

**tillageyear**

**Leverage Plot**



**Least Squares Means Table**

```
Level   Least Sq Mean                   Std Error      Mean
1                   .   NonEstimable            .   648.161
2                   .   NonEstimable            .   407.369
n/a                 .   NonEstimable            .   346.013
```

Figure 6.  Leverage plot for Years after Tillage (0-6")

There was some indication that as the number of years following tillage increased, there was an overall increase in CI as shown by Figure 6. CI is slightly inversely related to surface moisture content (0-6”), as shown in Figure 7; that is, as the surface moisture increases the average soil strength decreases. Figure 8 shows that tillage also had some effect on CI.

**MC (nearest neighbor)**

**Leverage Plot**

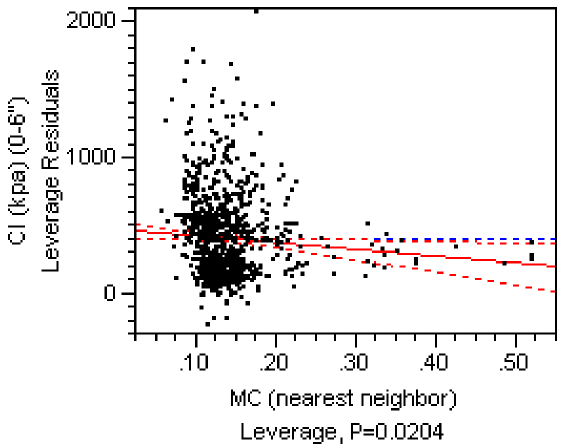
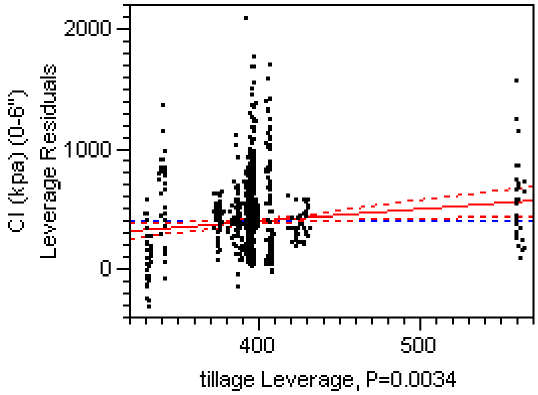


**Figure 7. Residuals Moisture Content (0-6”)**

**tillage**

**Leverage Plot**



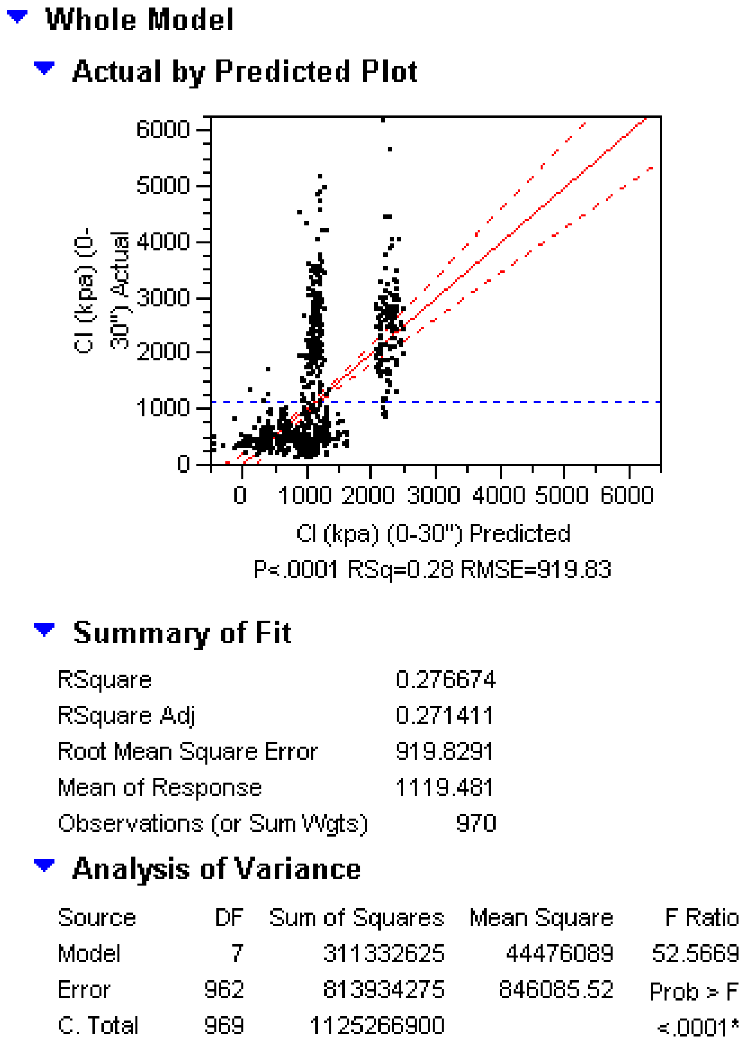
**Least Squares Means Table**

| Level | Least Sq Mean | | Std Error | Mean |
|---|---|---|---|---|
| control | . | NonEstimable | . | 346.013 |
| DMI | . | NonEstimable | . | 539.246 |
| KSK | . | NonEstimable | . | 522.066 |
| RIP | . | NonEstimable | . | 788.147 |

**Figure 8. Leverage plot for Tillage (0-6”)**

Another analysis was conducted investigating the average cone index over the 0-30” soil depth for each site. The model fitted in this case was:

Model 2. CI (0-30”) = [soil type, tillage, year after tillage, moisture content] * $\beta + \varepsilon$

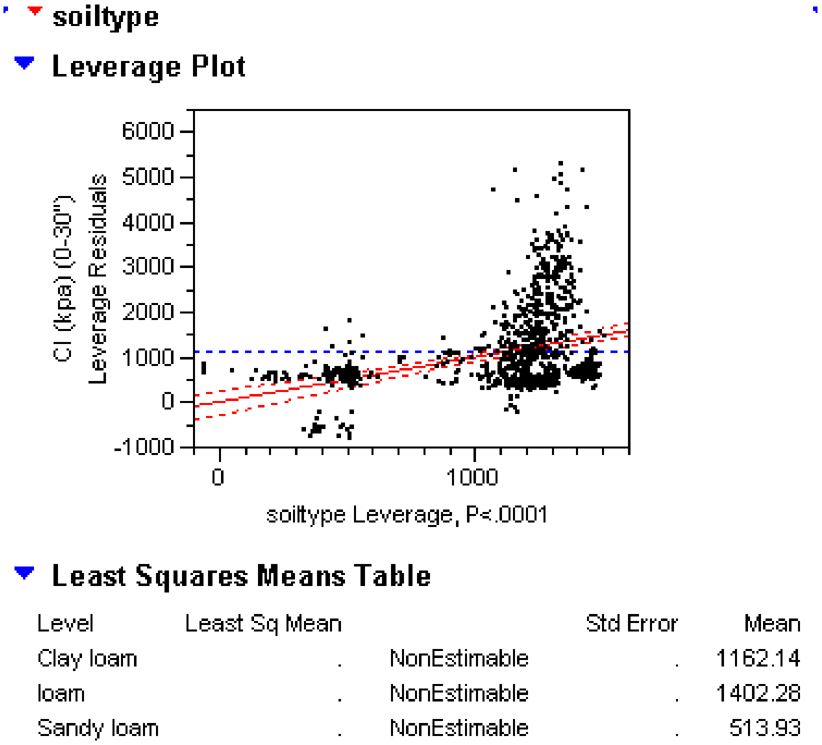


```
RSquare                          0.276674
RSquare Adj                      0.271411
Root Mean Square Error           919.8291
Mean of Response                 1119.481
Observations (or Sum Wgts)            970
```

```
Source       DF   Sum of Squares   Mean Square    F Ratio
Model         7        311332625      44476089    52.5669
Error       962        813934275     846085.52   Prob > F
C. Total    969       1125266900                  <.0001*
```

**Figure 9. Whole Model 0-30”**

Inspection of Figures 9 and 10 shows that soil strength, based on the 0-30” average CI is silty loam<clay loam<sandy loam, reflecting the cumulative effects of compacted strata in the heavy soils. The differences between tillage types were again not significant, however the time after tillage does explain some of the variability in cone index over the 0-30” depth range.



soiltype

Leverage Plot

Least Squares Means Table

```
Level        Least Sq Mean              Std Error     Mean
Clay loam                .  NonEstimable         .  1162.14
loam                     .  NonEstimable         .  1402.28
Sandy loam               .  NonEstimable         .   513.93
```

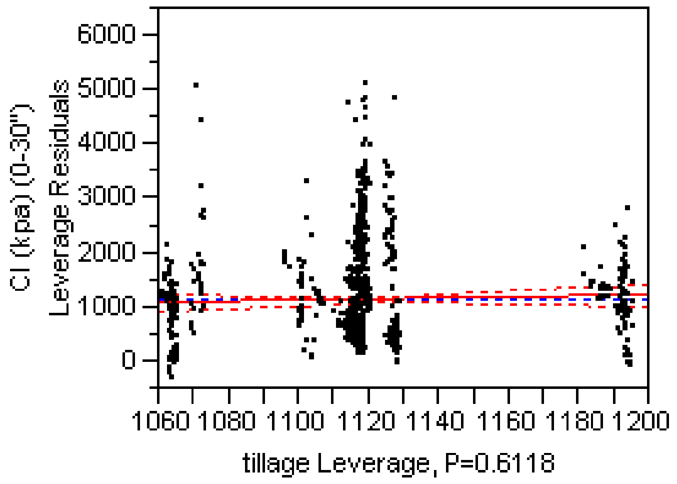
**Figure 10. Residuals and Least Squares Means for Soil Type (0-30")**

Figures 12-14 show one-way comparisons between the cone index for each tillage type at 0-6" and 0-30" depths. The plots show the CI data plotted on the y axis versus the treatment type on the x axis. Each set of data includes bars delimiting the 95% confidence interval for the set. Tukey-Kramer's means comparisons are used to inspect the effect of different tillage method on cone index. The results of means separation are presented on the right hand side of each plot. Circles with same color indicate same group. At the bottom of each plot, the tillage methods followed with same letter are not significantly different (p<0.05).

In this study there were no significant differences in cone index that could be attributed to tillage alone. The only detectable exception was that the Paraplow treatment appeared to reduce the cone index of the 0-6" layer of clay loam when compared to the other treatments. This difference was marginal when the 0-30" averages were compared.

**tillage**

**Leverage Plot**

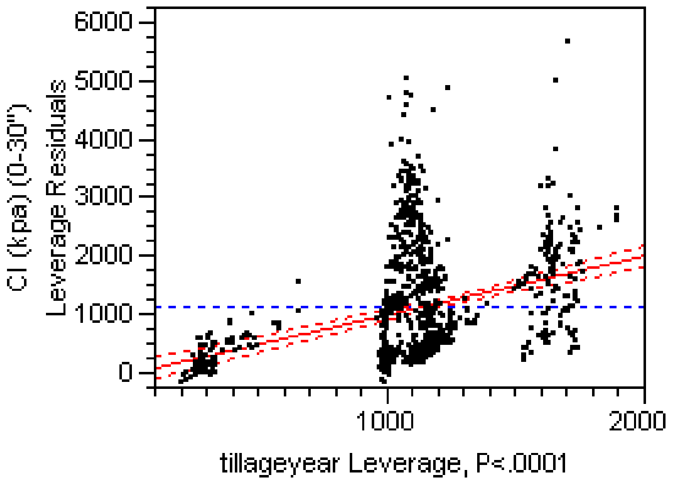


**Least Squares Means Table**

| Level | Least Sq Mean | | Std Error | Mean |
|---|---|---|---|---|
| control | . | NonEstimable | . | 970.93 |
| DMI | . | NonEstimable | . | 1525.34 |
| KSK | . | NonEstimable | . | 1509.93 |
| RIP | . | NonEstimable | . | 2081.19 |

**tillageyear**

**Leverage Plot**

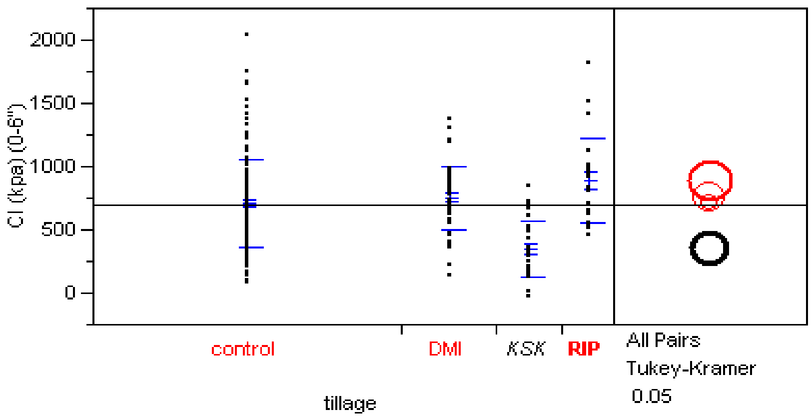


**Least Squares Means Table**

| Level | Least Sq Mean | | Std Error | Mean |
|---|---|---|---|---|
| 1 | . | NonEstimable | . | 2171.62 |
| 2 | . | NonEstimable | . | 542.26 |
| n/a | . | NonEstimable | . | 970.93 |

Figure 11. Leverage Plots for Tillage and Years After Tillage (0-30")

### Oneway Analysis of CI (kpa) (0-6") By tillage



#### Means and Std Deviations

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 149 | 714.598 | 347.182 | 28.442 | 658.39 | 770.8 |
| DMI | 46 | 755.392 | 250.642 | 36.955 | 680.96 | 829.8 |
| KSK | 31 | 352.465 | 223.614 | 40.162 | 270.44 | 434.5 |
| RIP | 25 | 889.152 | 329.887 | 65.977 | 752.98 | 1025.3 |

#### Means Comparisons

#### Comparisons for all pairs using Tukey-Kramer HSD

| q* | Alpha |
|---|---|
| 2.58663 | 0.05 |

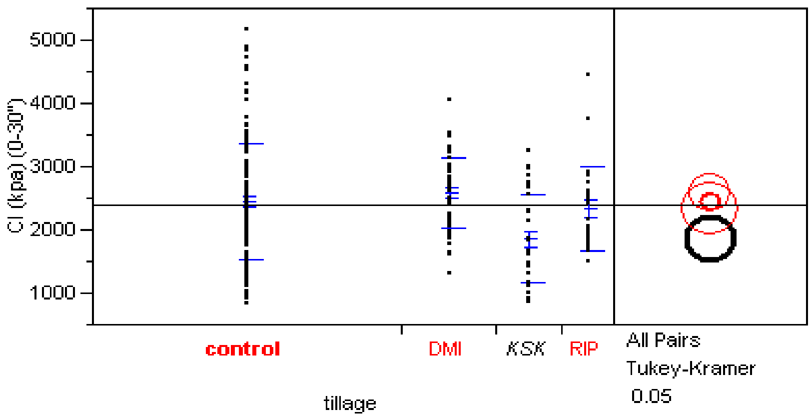
Abs(Dif)-LSD

| | RIP | DMI | control | KSK |
|---|---|---|---|---|
| RIP | -231.72 | -69.80 | -2.51 | 316.46 |
| DMI | -69.80 | -170.83 | -97.39 | 212.55 |
| control | -2.51 | -97.39 | -94.92 | 200.41 |
| KSK | 316.46 | 212.55 | 200.41 | -208.09 |

Positive values show pairs of means that are significantly different.

| Level | | | Mean |
|---|---|---|---|
| RIP | A | | 889.15238 |
| DMI | A | | 755.39221 |
| control | A | | 714.59801 |
| KSK | | B | 352.46519 |

### Oneway Analysis of CI (kpa) (0-30") By tillage



#### Means and Std Deviations

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 149 | 2442.27 | 921.503 | 75.49 | 2293.1 | 2591.4 |
| DMI | 46 | 2582.99 | 557.854 | 82.25 | 2417.3 | 2748.7 |
| KSK | 31 | 1859.37 | 701.401 | 125.98 | 1602.1 | 2116.6 |
| RIP | 25 | 2328.57 | 663.867 | 132.77 | 2054.5 | 2602.6 |

#### Means Comparisons

#### Comparisons for all pairs using Tukey-Kramer HSD

| q* | Alpha |
|---|---|
| 2.58663 | 0.05 |

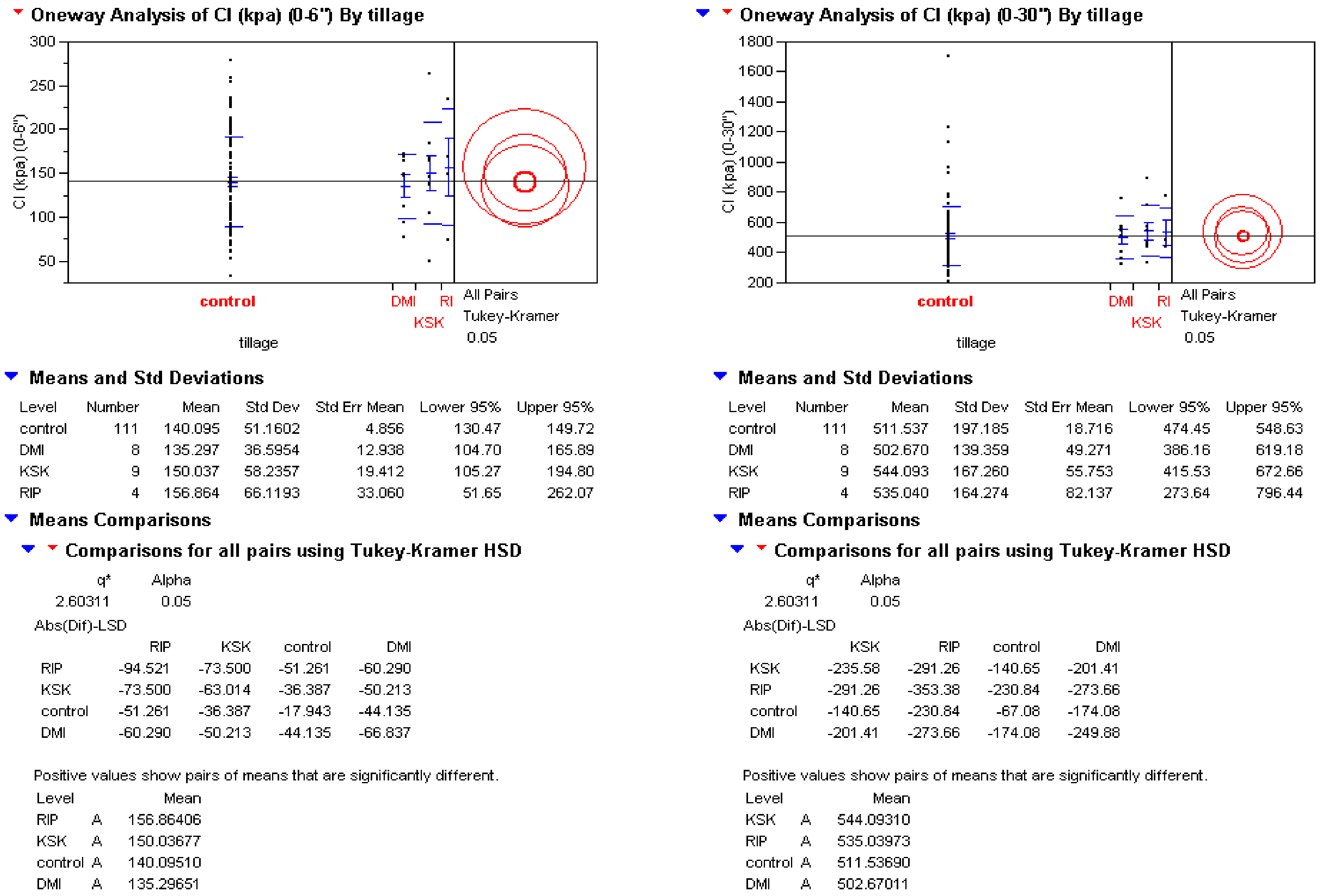
Abs(Dif)-LSD

| | DMI | control | RIP | KSK |
|---|---|---|---|---|
| DMI | -440.85 | -215.88 | -270.91 | 232.34 |
| control | -215.88 | -244.95 | -343.25 | 165.54 |
| RIP | -270.91 | -343.25 | -597.99 | -99.12 |
| KSK | 232.34 | 165.54 | -99.12 | -537.01 |

Positive values show pairs of means that are significantly different.

| Level | | | Mean |
|---|---|---|---|
| DMI | A | | 2582.9949 |
| control | A | | 2442.2660 |
| RIP | A | B | 2328.5736 |
| KSK | | B | 1859.3689 |

**Figure 12. Statistical Analysis Cone Index by Tillage Clay Loam**



### Oneway Analysis of CI (kpa) (0-6") By tillage

#### Means and Std Deviations

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 111 | 140.095 | 51.1602 | 4.856 | 130.47 | 149.72 |
| DMI | 8 | 135.297 | 36.5954 | 12.938 | 104.70 | 165.89 |
| KSK | 9 | 150.037 | 58.2357 | 19.412 | 105.27 | 194.80 |
| RIP | 4 | 156.864 | 66.1193 | 33.060 | 51.65 | 262.07 |

#### Means Comparisons

##### Comparisons for all pairs using Tukey-Kramer HSD

| q* | Alpha |
|---|---|
| 2.60311 | 0.05 |

Abs(Dif)-LSD

| | RIP | KSK | control | DMI |
|---|---|---|---|---|
| RIP | -94.521 | -73.500 | -51.261 | -60.290 |
| KSK | -73.500 | -63.014 | -36.387 | -50.213 |
| control | -51.261 | -36.387 | -17.943 | -44.135 |
| DMI | -60.290 | -50.213 | -44.135 | -66.837 |

Positive values show pairs of means that are significantly different.

| Level | | Mean |
|---|---|---|
| RIP | A | 156.86406 |
| KSK | A | 150.03677 |
| control | A | 140.09510 |
| DMI | A | 135.29651 |

### Oneway Analysis of CI (kpa) (0-30") By tillage

#### Means and Std Deviations

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 111 | 511.537 | 197.185 | 18.716 | 474.45 | 548.63 |
| DMI | 8 | 502.670 | 139.359 | 49.271 | 386.16 | 619.18 |
| KSK | 9 | 544.093 | 167.260 | 55.753 | 415.53 | 672.66 |
| RIP | 4 | 535.040 | 164.274 | 82.137 | 273.64 | 796.44 |

#### Means Comparisons

##### Comparisons for all pairs using Tukey-Kramer HSD

| q* | Alpha |
|---|---|
| 2.60311 | 0.05 |

Abs(Dif)-LSD

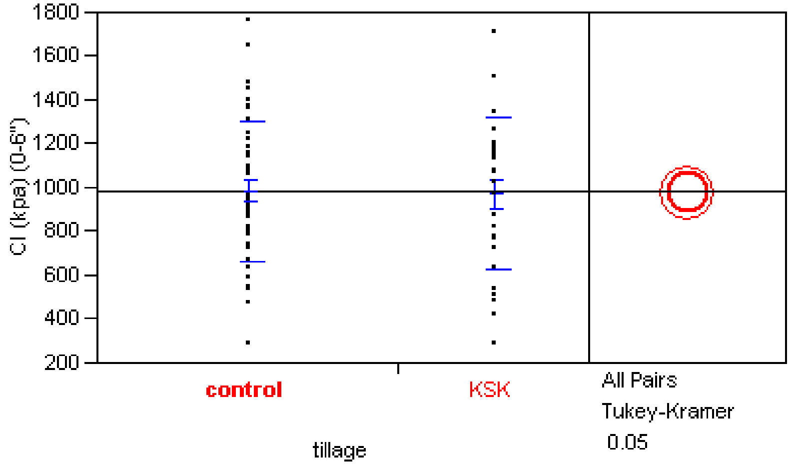
| | KSK | RIP | control | DMI |
|---|---|---|---|---|
| KSK | -235.58 | -291.26 | -140.65 | -201.41 |
| RIP | -291.26 | -353.38 | -230.84 | -273.66 |
| control | -140.65 | -230.84 | -67.08 | -174.08 |
| DMI | -201.41 | -273.66 | -174.08 | -249.88 |

Positive values show pairs of means that are significantly different.

| Level | | Mean |
|---|---|---|
| KSK | A | 544.09310 |
| RIP | A | 535.03973 |
| control | A | 511.53690 |
| DMI | A | 502.67011 |

**Figure 13. Statistical Analysis Cone Index by Tillage Sandy Loam**

**Oneway Analysis of CI (kpa) (0-6") By tillage**



**Means and Std Deviations**

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 43 | 983.232 | 321.029 | 48.957 | 884.43 | 1082.0 |
| KSK | 27 | 972.619 | 347.012 | 66.783 | 835.35 | 1109.9 |

**Means Comparisons**

**Comparisons for all pairs using Tukey-Kramer HSD**

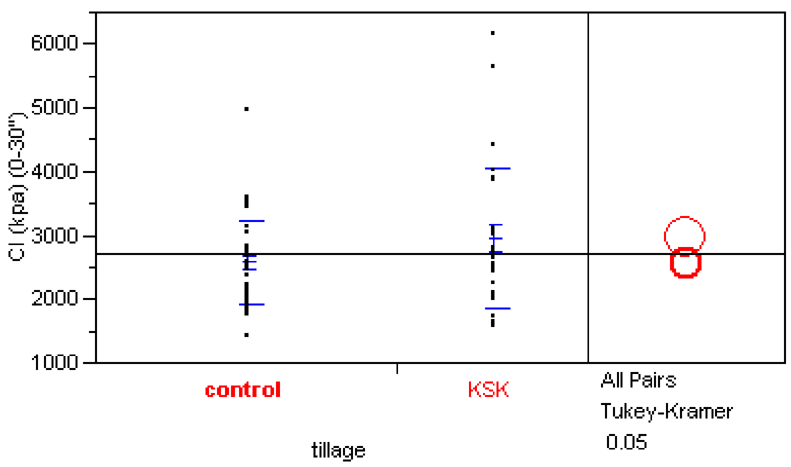
| q* | Alpha |
|---|---|
| 1.99554 | 0.05 |

Abs(Dif)-LSD

|  | control | KSK |
|---|---|---|
| control | -142.54 | -151.68 |
| KSK | -151.68 | -179.88 |

Positive values show pairs of means that are significantly different.

**Oneway Analysis of CI (kpa) (0-30") By tillage**



**Means and Std Deviations**

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 43 | 2577.27 | 646.33 | 98.56 | 2378.4 | 2776.2 |
| KSK | 27 | 2963.39 | 1103.37 | 212.34 | 2526.9 | 3399.9 |

**Means Comparisons**

**Comparisons for all pairs using Tukey-Kramer HSD**

| q* | Alpha |
|---|---|
| 1.99554 | 0.05 |

Abs(Dif)-LSD

|  | KSK | control |
|---|---|---|
| KSK | -461.97 | -30.67 |
| control | -30.67 | -366.07 |

Positive values show pairs of means that are significantly different.

**Figure 14. Statistical Analysis Cone Index by Tillage Silty Loam**

## Infiltration Models

Analysis of infiltration included the following factors: soil type, tillage operation, flat/slope, in furrow/between furrow, moisture content, and years after tillage. For this study, the saturated hydraulic conductivity (Ks) was chosen to characterize the surface water infiltration.

Model 3. Hydraulic Conductivity (Ks) = [Soil Type, Tillage, F/S, IF/BF, YAT] $\beta + \varepsilon$

**Table 1. Summary table of factors explaining variability in saturated hydraulic conductivity Ks**

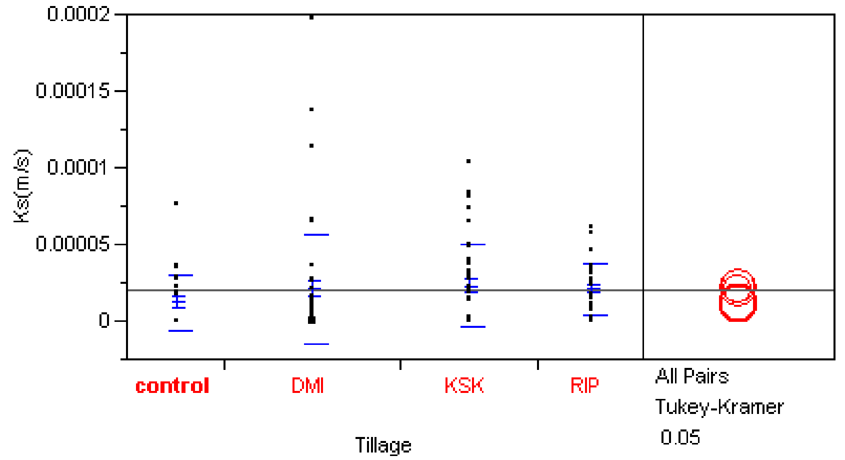
| Factor | Parameters | DF | F Value | P > F |
|---|---|---|---|---|
| Soil Type | 2 | 2 | 17.499 | <0.0001 |
| Tillage Operation | 3 | 3 | 2.507 | 0.059 |
| Flat / Slope | 1 | 1 | 0.081 | 0.776 |
| In Furrow / Between Furrow | 3 | 3 | 1.543 | 0.203 |
| Year after Tillage | 2 | 2 | 4.828 | 0.009 |

This analysis showed that the soil type and years after tillage are both are significant (p<0.05) in explaining variability in hydraulic conductivity. Overall the tillage was marginally significant in the model (p=0.059). Slope (p=0.776) and location in the furrows (p=0.203) were less significant in the model.

## Infiltration by Soil Type

The hydraulic conductivity was further investigated by conducting a comparison of means for each tillage treatment by each soil type. The findings are summarized in Figures 15-17.

**Oneway Analysis of Ks(m/s) By Tillage**

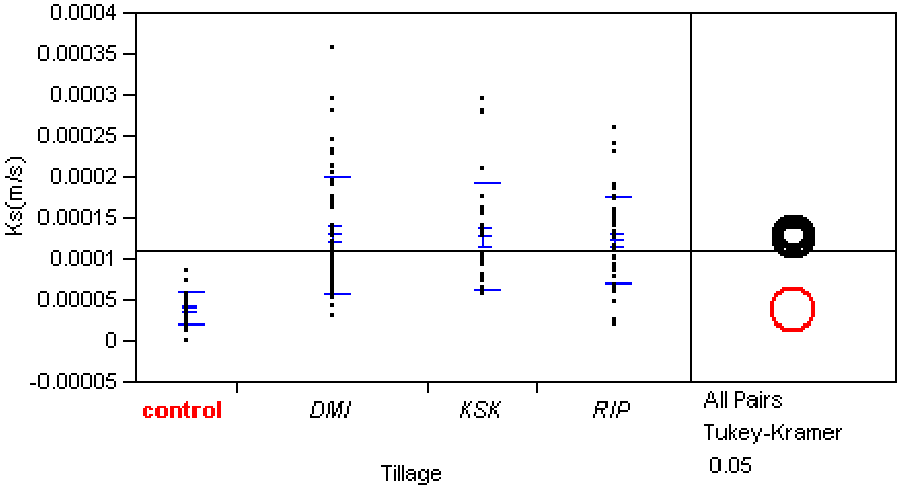


**Means and Std Deviations**

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 30 | 0.000012 | 0.000018 | 3.3021e-6 | 5.68e-6 | 0.00002 |
| DMI | 54 | 0.000021 | 0.000036 | 4.8922e-6 | 0.00001 | 0.00003 |
| KSK | 42 | 0.000023 | 0.000027 | 4.1853e-6 | 1.43e-5 | 3.12e-5 |
| RIP | 32 | 0.000021 | 0.000017 | 2.9806e-6 | 1.5e-5 | 2.72e-5 |

Figure 15. Clay Loam Hydraulic Conductivity Means Comparison

**Oneway Analysis of Ks(m/s) By Tillage**

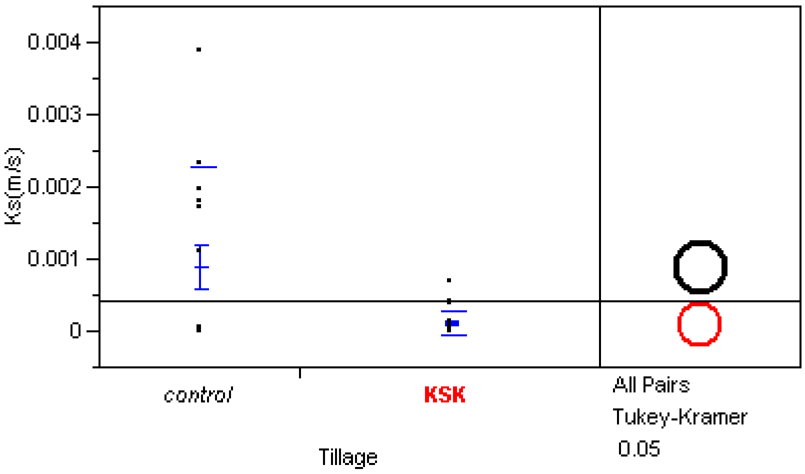


**Means and Std Deviations**

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 29 | 0.000039 | 0.000020 | 3.79e-6 | 3.14e-5 | 4.7e-5 |
| DMI | 55 | 0.000130 | 0.000071 | 0.00001 | 0.00011 | 0.00015 |
| KSK | 31 | 0.000127 | 0.000065 | 1.17e-5 | 0.00010 | 0.00015 |
| RIP | 44 | 0.000122 | 0.000053 | 8e-6 | 0.00011 | 0.00014 |

Figure 16. Sandy Loam Hydraulic Conductivity Means Comparison

**Oneway Analysis of Ks(m/s) By Tillage**



**Means and Std Deviations**

| Level | Number | Mean | Std Dev | Std Err Mean | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| control | 20 | 0.000882 | 0.001385 | 0.00031 | 0.00023 | 0.00153 |
| KSK | 30 | 0.000102 | 0.000163 | 0.00003 | 4.12e-5 | 0.00016 |

**Figure 17. Silty Loam Hydraulic Conductivity Means Comparison**

The major factor that influences hydraulic conductivity is soil type. Tillage operations were most effective on the sandy loam soil; however, no differences could be detected between tillage implements in this instance. Tillage operations did not appear to influence hydraulic conductivity for the clay loam or silty loam soils. Recently tilled sites have marginally higher hydraulic conductivity than a soil tilled one or two years prior. For the sandy loam soils, infiltration was higher on the sloping ground when compared to flat uplands, and infiltration was also higher in the furrow made by the tillage tool shank.

Measurements of saturated hydraulic conductivity on the clayey and silty sites showed no improvement over the control. On the silty site (MnROAD), the conductivity was marginally lower when measured the year after tilling with the Paraplow.

A modeling exercise was conducted to quantify the improvement in infiltration due to tillage in the sandy loam soils. Figure 17 shows the results of the comparison. The infiltration rate is equal to the rainfall rate until surface ponding occurs. The time to ponding is dependent on the initial moisture content, the saturated hydraulic conductivity, and the rainfall intensity. An expression developed by Mein and Larson (1973) provides a prediction of the ponding time. Once ponding occurs, the infiltration rate decreases exponentially with time. This exponential decrease can be calculated using the Green and Ampt (1911) equation. In this study, a Green-Ampt model for infiltration was used. The parameters used in the model for sandy loam were:

- Cumulative infiltration (cm) variable
- Wetting front suction (cm) 15 cm
- Depth of ponding (cm) 0 cm
- Measured saturated hydraulic conductivity (cm/hr) Control 1.8 Tilled 5.4 cm/hr

- Saturated water content 35%
- Initial water content 25%

The ratio between the infiltration times can used demonstrate that one third of the tilled ROW area (sandy loam) would have the capacity to infiltrate the same volume of water for a given rainfall event when compared to the same situation with untilled soil.

**Table 2. Predicted Infiltration Time**

| Rainfall (in/hr) | Control (hr) | Tilled (hr) | Ratio |
|---|---|---|---|
| 0.5 | 0.19 | 0.06 | 3.17 |
| 1.0 | 0.59 | 0.20 | 2.95 |
| 2.0 | 1.59 | 0.53 | 3.00 |
| 3.0 | 2.73 | 0.90 | 3.03 |
| 4.0 | 3.94 | 1.31 | 3.01 |

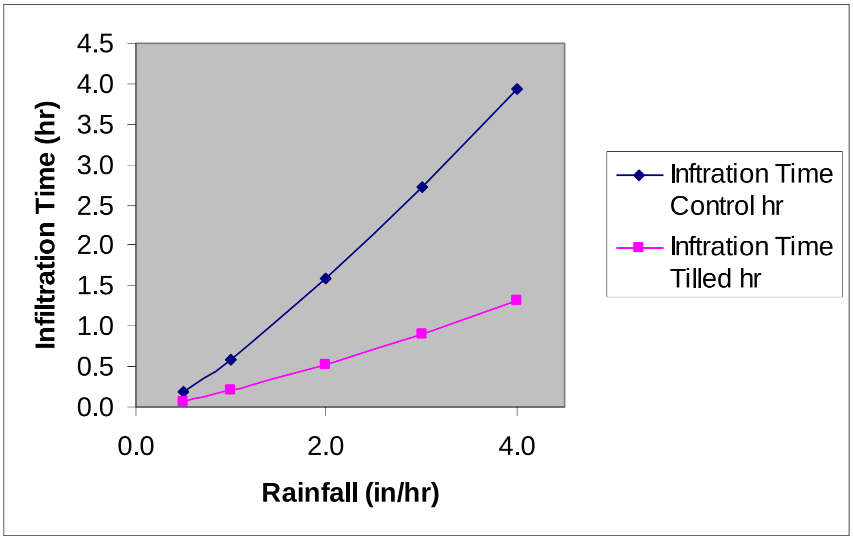


**Figure 18. Infiltration Time vs. Rainfall for Sandy Loam Soil**

## Vegetation Assessment

An informal vegetation coverage assessment was made by analyzing digital photographs before and after tillage. No statistical models were fitted to this information. The purpose of the study was to provide a qualitative assessment of the tillage from an aesthetics and vegetative disruption point of view. The photographs below were taken immediately after tillage and also in the subsequent growing seasons.

**Figure 19.**

**Figure 20.**

The basic method used for calculating the vegetation coverage is to use image processing to separate the soil pixels from the vegetation pixels. The digital image was first turned from RGB format to a gray scale, and then a threshold value was selected to convert the gray scale image to a black and white image. In the example photographs shown above, the white pixels show vegetation and the black pixels correspond to soil. By counting the percentage of white pixels, the percentage of the vegetation coverage can be estimated. This methodology was demonstrated by Li and Chaplin (1998)

For recently tilled sites, the contrast between soil and vegetation was usually obvious, and it was easy to separate them. However, for the images which are taken after several years of vegetative re-growth, it was difficult to determine the vegetation coverage or tillage disturbance. Figures 21 and 22 illustrate the difficulty in determining what percentage of re-growth has occurred and what effect the tillage had on re-growth. Ambient lighting and camera angle all influence the image captured and ultimately the differentiation between tillage and control.

**Figure 21.**

**Figure 22.**

The thresholds were adjusted in the image processing program to differentiate poor plant re-growth from healthy plants.

It was clear that the effect of tillage on vegetative re-growth is long lasting. The important observation from this part of the study was the benefit of the Paraplow, which leaves the vegetation largely intact and growing, and therefore there was less risk of erosion, and the aesthetic appeal of the site was not affected.

**Table 3. Vegetation Assessment**

| | **Tillage** | **Belle Plaine** | **Janesville** | **Brainerd** |
|---|---|---|---|---|
| DMI | 50% | 91% | 96% | 53% |
| Paraplow | 93% | 92% | 99% | 37% |
| Ripper | 43% | 70% | 80% | 48% |

## Cost Analysis

A cost analysis was conducted using the Cost Analysis and Traction Simulation Software (CATSS) developed by Pulley (2007). This software uses an innovative approach that melds weather prediction routines with tractive performance and the economics of field operations. The software can predict the field day availability for a region for the weather that is predicted. The working days are then used along with tractive performance information to optimize the size of tractor and implement needed in any situation. The tractive performance is a routine that uses basic soil parameters to predict the soil strength and hence the tractive performance of the machine. 2WD, 4WD, and track-laying tractors can be used in the simulation.

**Table 4. Cost Analysis Parameters**

**COST PARAMETERS**

| | | |
|---|---|---|
| LABOR COST | 12.42 | $/hr |
| FUEL COST | 2.75 | $/gal |
| HOUSING COST | 0.33 | $/FT$^2$ |
| INTEREST RATE | 6.15 | % |
| INSURANCE RATE | 0.72 | % |
| LIFE OF MACHINE | 10 | yrs |
| OFFSEASON HOURS | 0 | hrs |

**CLIMATE AND SOIL PARAMETERS**

WEATHER PATTERNS FOR ST CLOUD
SANDY LOAM SOIL TYPE (CLAY ~= 10.5%, SAND ~= 64.5%)
36" A HORIZON SOIL DEPTH (because of the unnatural soil)
0.5% ORGANIC MATTER
1.3" RANDOM SURFACE ROUGHNESS
STAC SOIL MODEL
DF = -1.3
0.25" RAIN TOLLERANCE
25-yr SIMULATION

**TRACTOR TIRES**

DUAL MAIN-DRIVE WHEELS, 16" TREAD WIDTH
MAIN-DRIVE WHEELS TYPE R-1 480/80R42
DRIVEN FRONT WHEELS TYPE R-1 420/85R28
STEERING FRONT WHEELS TYPE F-2M 11L-15 SL

MAXIMUM SLIP ALLOWED OF 50%
80% FIELD EFFICIENCY
5% LABOR EFFICIENCY

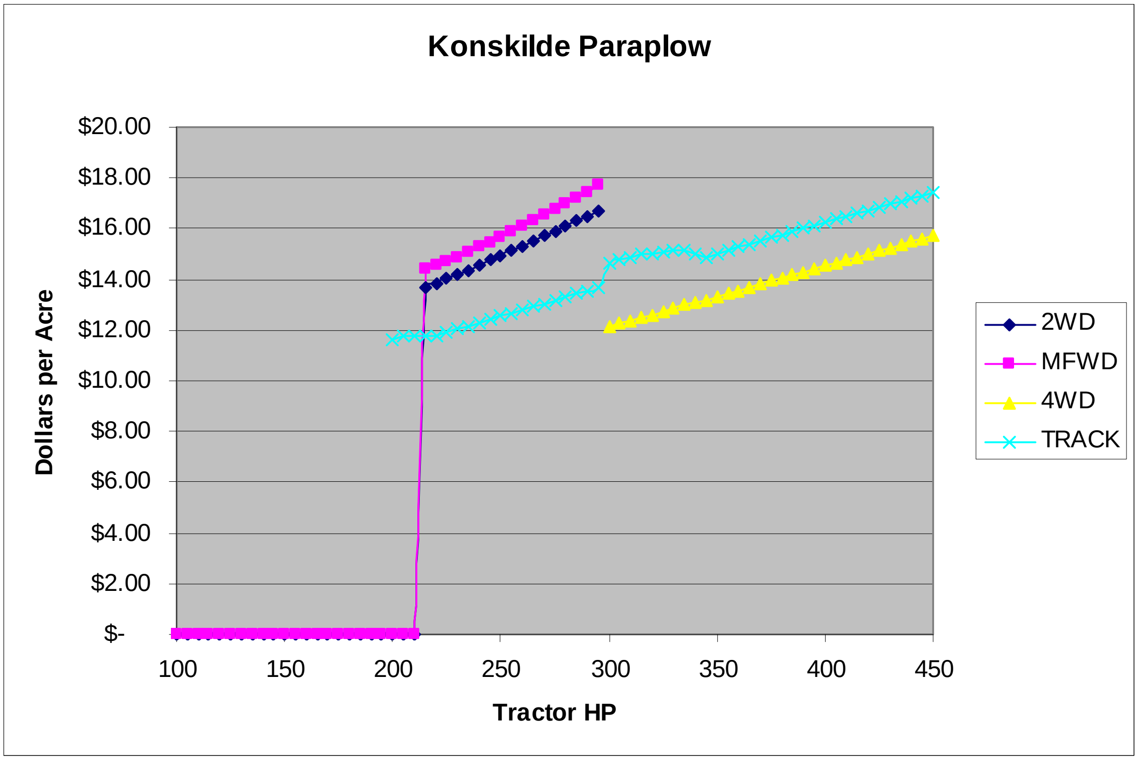


Figure 23. Total cost for Paraplow vs. Tractor power

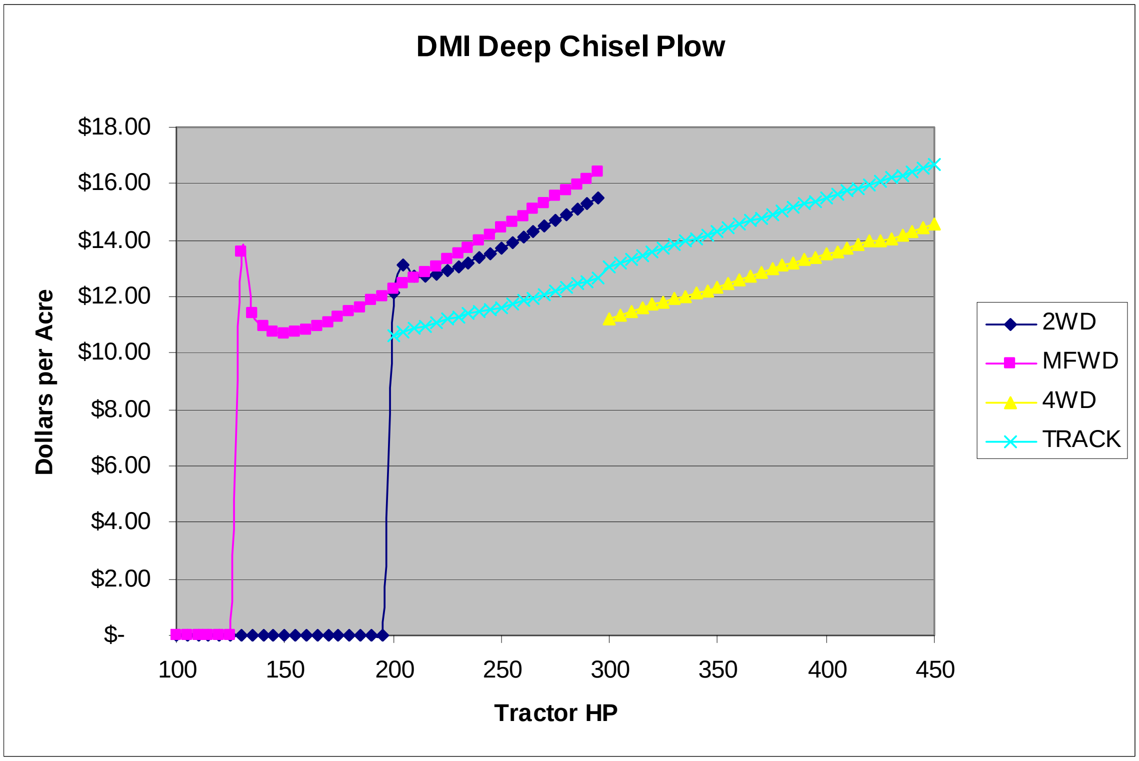


Figure 24. Total cost for DMI vs. Tractor power

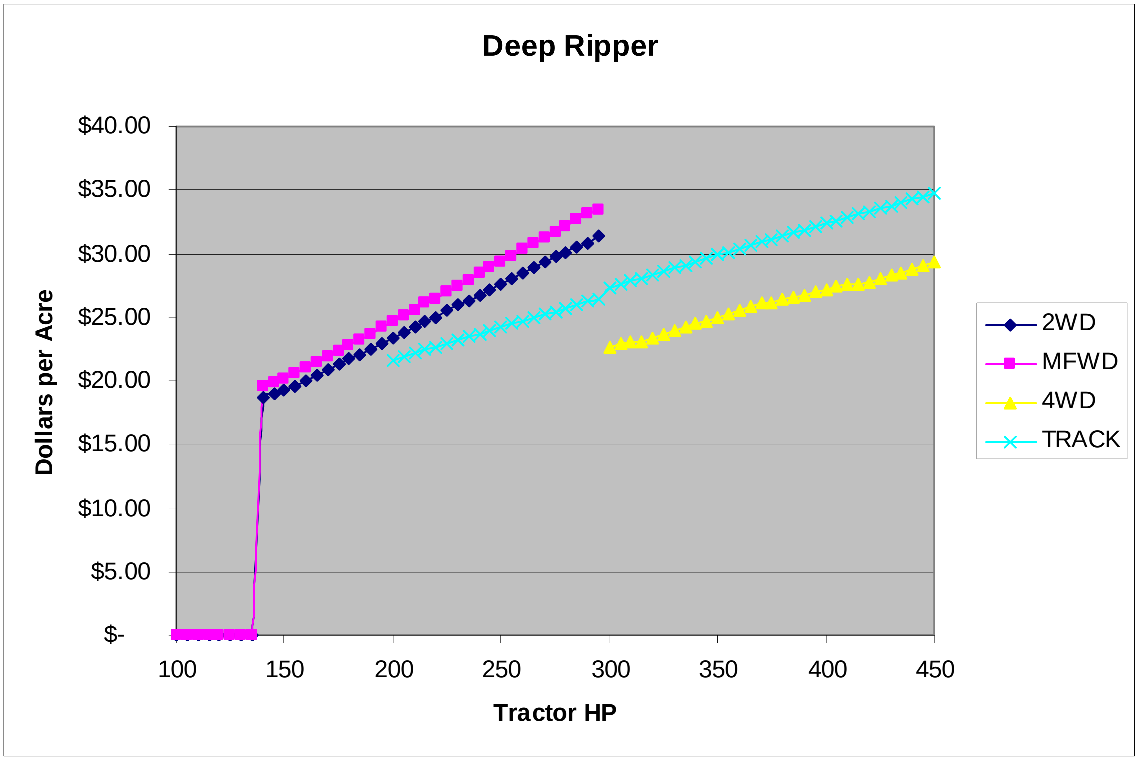


**Figure 25. Total cost for Ripper vs. Tractor power**

The analysis results shown in Figures 19-21 indicate that the cost of tillage would range from $11/acre to $33/acre. The costs assume that the tillage operations will be performed from the last frost of the spring until the first frost of the fall, recognizing that tillage could continue for up to one month into the winter. The tractor was assumed to travel at 5 mph, with an annual use of 1500 hrs. A break even analysis was not attempted as the reduction in land area in sandy loam soils would have many cost savings that are not readily apparent. The tillage costs are minimal compared to the savings that would result from purchasing smaller areas of land for ROW.

## Discussion of Results and Recommendations for BMP

This study has clearly revealed the complexity of improving infiltration in and around the areas of ROW. The main factor influencing infiltration is the soil type. It is apparent that improving infiltration will be more successful in lighter sandy loam soils. In this study, the silty loam soil was the most compacted of those investigated. The greatest cone index recorded was 5000 kPa at a depth of 30" in silty loam. This level of compaction is well above the accepted range (2000-2500 kPa) that impedes the development of roots. The surface cone index for the sandy loam was below 2000 kPa. The cone index increased to 3000 kPa at 12-18"; this could lead to poor root development and ponding in low lying areas.

Measurement of soil strength alone is not a good indicator of potential for infiltration improvement by tillage. It appears that the soil texture is very important in assessing the impact of tillage treatments to a particular area of ROW. Other important factors need to be considered before using tillage to improve infiltration. Below is a list of factors to be considered:

1. Tillage operation needs to be conducted when the soil will shatter as the tine passes through the soil matrix. The tine needs to be deep enough to fracture the soil over its greatest volume. None of the implements used in the study were specifically optimized for each soil type and condition.
2. The slope of the ROW was difficult to till using mounted equipment on a 4WD tractor. The tractor tended to crab down the slope, making directional control difficult while using the implant.
3. The location of buried utilities made it difficult to get a consistent bout length for tillage. Unrestricted utility distribution on the ROW made for short bout lengths and, therefore, the potential for inconstant tillage results from lower speeds on short bouts.
4. Tilling soils of high moisture content will not improve their physical state. There is strong evidence (Gill and Vanden Berg 1967) that smearing of the furrow walls will result in reduced infiltration. ROW with standing water (ponded) should be investigated and allowed to drain before tillage.
5. The non-homogeneity of ROW where soil types have been mixed makes their assessment difficult. Lenses of heavy clay soils, concrete, and other inclusions will have a detrimental effect on the infiltration patterns. Tillage is only recommended on ROW that is classified as silty tending toward sandy.
6. Results indicate that it is possible to reduce the ROW area by up to 1/3 and still get sufficient infiltration where tillage has been carried out. However, this recommendation must not be allowed to supersede any safety parameters already in place on the ROW.

## Conclusions

The study showed that there are low cost benefits to deep tillage of ROW. Heavy clay soils are problematic in that improvements in infiltration could not be detected after a single tillage operation. In lighter sandy soils, the benefits of tillage are such that significant increases in infiltration can be gained following a single pass tillage operation. The differences in tillage implement used could not be detected.

The post-tillage aesthetic appeal when using a non-inverting plow (Kongskilde Paraplow) was apparent in this study. The vegetation was largely undisturbed following tillage, and this would be beneficial in preventing erosion on slopes. The ripper and the DMI inverted more soil, and therefore the tillage operation was less appealing to motorists.

The relatively low cost of ownership and operation for the tillage is overshadowed by the high land cost when new roads are constructed. Tillage would be beneficial on lighter soils, however the “utility congestion” that is likely in such a scenario would make machinery management difficult.

In this study only one pass of the tillage implement was used. It is likely that multiple passes and time will begin to improve a compacted topsoil structure. This is highlighted in McKyes (1985) discussion of “Tillage of Compacted Soils”.

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